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SESSIONS 13/113 – 16/116

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FOREWORD

This volume is one of five volumes of conference proceedings, including the 4th IALA Heritage seminar proceedings, and contains abstracts, biographies and full papers, where these have been prepared and provided. We hope they enhance your conference experience and act as a useful reference source for future discussion and research in the Marine Aids to Navigation sector.

The volumes are compiled as follows:

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"S2.4 Case Study – Inspection of floating AtoN by drone (153)"

is session event 2.4 and the unique paper number is 153. Any sessions with numbers 1 to 16 formed the main auditorium programme, whilst sessions starting 101, 102 etc. formed the Speaker's Corner programme held concurrently. Papers, where submitted are included, otherwise the paper abstract only is included. These can be found by session number through the main table of contents or by their unique conference paper number via the index at the back of the document.

Tenga en cuenta que a lo largo de las deliberaciones, el título del documento está precedido por el número de evento de la sesión de la Conferencia y seguido por el número único del documento entre paréntesis, por ejemplo:

"Estudio de caso S2.4 – Inspección de AtoN flotante por dron (153)"

es el evento de sesión 2.4 y el número de papel único es 153. Las sesiones con los números 1 a 16 formaron el programa principal del auditorio, mientras que las sesiones que comenzaron 101, 103, etc. formó el programa Speaker's Corner celebrado simultáneamente. Los artículos, cuando se presentan, se incluyen, de lo contrario solo se incluye el resumen del artículo. Estos se pueden encontrar por número de sesión a través de la tabla de contenido principal o por su número de conferencia único a través del índice en la parte posterior del documentos

SESSIONS 13 AND 113 – RISK MANAGEMENT

S13.1 Assessment of volume of traffic and degree of risk for UK Overseas Territories (013)

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ABSTRACT

The International Maritime Organisation Instruments Implementation Code audit requires signatories to demonstrate compliance with the Safety of Life at Sea (SOLAS) convention Chapter V Regulations. Eight UK Overseas Territories (Anguilla, Bermuda, British Virgin Islands, Cayman Islands, Falkland Islands, Montserrat, St Helena and Turks & Caicos Islands) undertook to assess the need for SOLAS Chapter V Regulations 10 (Routing Measures), 11 (Reporting Measures), 12 (Vessel Traffic Services (VTS)) and 13 (Aids to Navigation (AtoN)), using the IMO approved IWRAP quantitative risk management software, to demonstrate compliance with the SOLAS convention.

Eight individual assessments were undertaken to assess the "Volume of Traffic" and "Degree of Risk" for each Overseas Territory Territorial Waters and Economic Exclusion Zone (or equivalent). A review of the methodology undertaken to deliver the assessments, including the issues and solutions found, along key findings will be presented. A key recommendation from the coastal State obligations (IWRAP) project was the need to assess navigation risk within eight internal waters and 24 individual harbour / port areas of these UK Overseas Territories. This was due to these areas, especially in complex archipelago states, having complex navigation and high traffic density. IWRAP was not considered suitable for this due to the complexity of navigation and the multiple control / mitigation measures in place in these areas.

Therefore, a qualitative assessment was undertaken using the Simplified IALA Risk Assessment (SIRA) methodology which involved analysis of available data and documentation, widespread stakeholder engagement and expert judgement. A key finding of the SIRA included the need to implement Marine Safety Management Systems, ideally based on a mandated code of practice for marine operations, that aims to enhance and manage marine risk and safety in both harbour/ports and internal waters of coastal States.

(No paper submitted)

AUTHOR BIOGRAPHY

Dr Ed Rogers is a recognised technical maritime risk expert and is a founding director of NASH Maritime - a shipping, navigation and maritime risk company specialising in understanding and mitigating maritime risk. Ed has a background in delivering complex navigation risk assessments for coastal states, ports, harbours, oil and gas installations and offshore windfarms using both qualitative stakeholder engagement approaches and complex quantitative risk models.

Ed leads on NASH Maritime projects related to SOLAS V obligations for coastal states, and has managed over 32 assessments for both territorial, EEZ and internal port water assessments using IALA SIRA and IALA IWRAP methodologies.

Ed also works closely with the NASH Maritime Technology team in defining user needs, specifying requirements, evaluating vendors and supporting the implementation of navigation management technology such as Vessel Traffic Systems, Port Management Information Systems and in the development and implementation products such as the IALA OPRA online software.

Ed is a strong believer in evidence-based advice that combines practical maritime experience with data science technology. He ensures that NASH Maritime deliverables are; founded on practical solutions rooted in real-world maritime experience, underpinned by data to provide a robust evidence-base and built on scientifically rigorous methodologies.

S13.2 IALA Risk Management Guideline: Theoretical basis and future needs (050)

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ABSTRACT

The objective of the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) is to promote the safe, economic and efficient movement of vessels through improvement and harmonisation of aids to navigation worldwide, and other appropriate means. To support its objectives, the organisation has recently introduced a new risk management guideline for the competent Aids to Navigation (AtoN) authorities. The guideline is based on the International Maritime Organization's Formal Safety Assessment procedure, the ISO 31000:2018 standard on risk management, and the IALA Risk Management Toolbox. By using these three components, the guideline aims to i) provide a broad understanding of the risk management process, ii) strengthen the practice and increase the objectivity of maritime risk assessment, and iii) offer general guidance for the choice of appropriate tools to execute the risk assessment process. Considering this, the aim of this article is to outline the theoretical basis of the IALA risk management guideline as well as provide an overview of its risk management process and the content of the toolbox. Finally, the results of the current study are discussed with a particular focus on the needs for future development in the context of IALA risk management activities.

KEYWORDS: Risk management; Risk assessment; Waterway risk; Aids to navigation risk management

1 INTRODUCTION

The aim of the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) is to promote the safe, economic and efficient movement of vessels through improvement and harmonisation of aids to navigation (AtoN) worldwide, and other appropriate means [1]. To ensure safe and efficient navigation, various measures are continuously needed from the AtoN authorities at both the national and international levels, considering also the views and requirements of their key stakeholders. These measures could involve e.g. the installation of new AtoN systems, establishment of Vessel Traffic Services (VTS), and implementing or modifying traffic separation schemes. The process to make decisions in this context should consider the degree of risk in the sea or waterway area of interest. This requirement stems from Chapter V, regulations 12 and 13 of the International Maritime Organization´s (IMO) Convention for the Safety of Life at Sea (SOLAS).

To support the achievement of the IALA objectives and the technical work of its Contracting Parties in performing maritime waterway risk assessments, the organisation provided a risk management guideline for the AtoN authorities. As this guideline did not reflect the current state of affairs anymore, IALA decided that this guideline needed a thorough update. This task was assigned to an expert group of the ARM Committee, and resulted in a new and consistent risk management guideline with reference number IALA G-1018 [2]. To ensure alignment with the IMO risk management guideline and best practices in the shipping industry, this new IALA guideline builds on the IMO´s Formal Safety Assessment (FSA) [3], the ISO 31000:2018 standard on risk management [4] and the IALA Risk Management Toolbox. Through applying and integrating these three components, the guideline aims to i) provide a broad understanding of the risk management process, ii) strengthen the practice and increase the objectivity of maritime risk assessment, and iii) offer general guidance for the choice of appropriate tools to execute waterway risk assessments in practice.

In light of the above, the objectives of the current article are twofold. First, it aims to outline the theoretical basis of the IALA risk management guideline. For this purpose, a brief overview is given on the recent academic literature of maritime waterway risk management, and descriptions of the main ideas of IMO´s FSA guidelines and ISO 31000:2018 standard. Second, the article aims to present the new IALA risk management process, including the associated risk assessment tools. Finally, a brief discussion is provided, with a particular focus on the future development needs of the toolbox in the context of IALA risk management activities.

2 BACKGROUND AND THEORETICAL BASIS

2.1 Risk management in the maritime industry

In recent decades, risk-based decision-making has steadily gained ground across various sectors and applications within the maritime industry. In the past, major shipping accidents were often the acute, reactive reasons for making improvements to the maritime regulatory framework on safety and environmental sustainability. However, since the turn of the millennium, the commitment to proactive risk management using explicit risk assessment models and techniques, aimed at reducing the probability of accident occurrence and mitigating its potential consequences, has grown ever more prominent.

The IMO FSA guideline [3] is widely considered a cornerstone of risk-based decision-making in maritime administrations and industry (see, Section 2.2). Another major development in the maritime sector is the use of goal-based standards, where risk assessments are applied to develop and verify the functional requirements of the defined safety goals [5]. Since the adoption of the International Safety Management (ISM) Code in 1993, shipping companies are also required to identify and assess the risks for their ships and personnel, and to develop appropriate measures for managing these risks [6]. A final example is from the area of Pollution Preparedness and Response (PPR), where international risk management guidelines [7], as well as tailored risk assessment models and techniques, have been presented for various regional sea areas across the world [8].

In addition to efforts of maritime administrations and industry, considerable work has been done in academia over the past two decades to develop advanced models and approaches for waterway risk assessment. These works are often based on advanced mathematical techniques such as Network and Simulation models, Bayesian Networks, Fuzzy logic and Regression models [9]. In many of these models, data from the Automatic Identification System (AIS) are used as a key input, especially in ship-to-ship collision models [10]. Some research also advances the use of qualitative approaches, including the Delphi procedure [11], Systems-Theoretic Process Analysis [12] and Functional Resonance Analysis [13].

Notwithstanding the advances and growing interest in maritime risk analysis in academia, there is still room for improvement in this area. First, the current methods often lack an explicit accident-theoretical basis, ignore the influence of human factors, or do not explicitly account for the AtoN systems in the study area. Second, most academic work remains at a basic level of proposing new concepts and techniques but does not pass beyond the stage of showcasing illustrative scenarios [14]. Third, only limited academic work has been conducted on the reliability and validity of risk assessment methods, which raises concerns about the robustness of the results, as application of different methods can lead to quite different conclusions [15, 16]. For a comprehensive review of the academic literature in this field, the reader is referred also to [17, 18].

2.2 Formal Safety Assessment

The IMO FSA guideline is a structured and systematic methodology to assess maritime risks in terms of safety, security and environmental sustainability, as well as consider the cost-effectiveness of different risk control options. The guideline establishes a formal and transparent approach for risk-based decision-making and has been used by both the public maritime administrations and private shipping industry. This IMO-based approach to risk management involves five interlinked steps that are as follows:

1. *Hazard identification*, to list all relevant accident scenarios with potential causes and consequences.
2. *Risk assessment,* where the likelihood and consequences of different identified hazards are estimated.
3. *Risk control option*s, to identify and consider the effects of different risk control options to reduce the likelihood or potential consequences of the hazards.
4. *Cost-benefit evaluation*, to compare the costs of different risk control options with their benefits.
5. *Recommendations for decision-making*, to document and summarise the information obtained from the previous steps, and to facilitate deliberations by the appropriate decision-making bodies.

The IMO FSA guideline also suggests several methods and techniques to carry out this five-step process. These so-called tools mostly follow a quantitative approach to estimate the probability and consequence aspects of risk. Examples include Fault Tree Analysis, Human Reliability Analysis, Bayesian Networks and Cost-Benefit Analysis. The availability of suitable data is often a key consideration when applying these tools. When quantitative data are unavailable or not useful, expert judgement, physical and analytical models, and simulations may be used to obtain results.

2.3 ISO 31000:2018 standard on risk management

The ISO 31000:2018 standard of the International Organization for Standardization provides generic guidelines for organisational risk management. This standard is based on the best practices and has been applied in several industrial sectors and research applications, including maritime response operations. The standard includes three key components to support effective risk management, namely i) the underlying principles, ii) the framework of how risk management is tied to specific activities and processes in a particular organisational setting, and iii) the risk management process that is carried out by using the following five-step approach:

1. *Establishing the context*, which defines the basic parameters for managing risk and sets the analysis scope and criteria for the further stages of the process, including decision-making.
2. *Risk identification,* where hazards, threats, possible failures and unwanted events associated with the system or activity are identified, elaborated and described.
3. *Risk analysis*, to characterise the nature of risk and, where appropriate, estimate the risk level.
4. *Risk evaluation*, to support decision-making by comparing the risk analysis results with the risk evaluation criteria established in step 1 in order to determine where additional action is required.
5. *Risk treatment*, to select and implement options for risk mitigation.

The ISO standard also emphasises the importance of communication and consultation with the stakeholders during the risk management process and associated decision-making. Additionally, it stresses the need for monitoring and review of the risk management process, and commitment to continuous improvement.

3 IALA RISK MANAGEMENT PROCESS

The IALA 1018 Guideline for Risk Management integrates the IMO FSA and ISO 31000:2018 risk management processes with one another. Figure 1 provides an overview of this integration, whereas Figure 2 illustrates in more detail the content of its FSA component. The following Sub-sections 3.1 and 3.2 provide further information on this chosen approach.

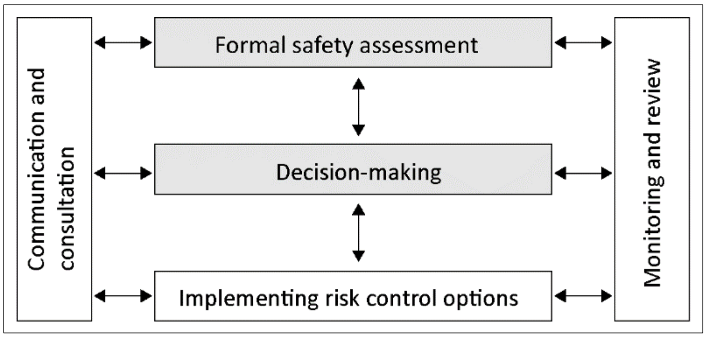

Figure 1. IALA G-1018 Risk management process

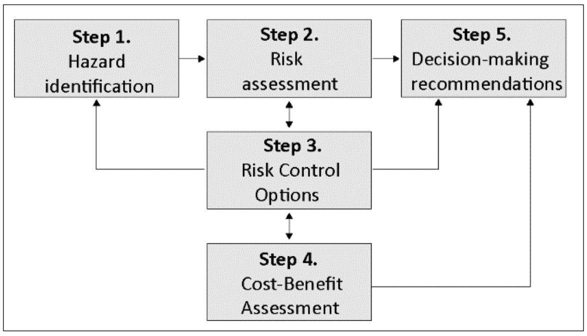

Figure 2. The IMO FSA part of the process

3.1 Part I: Application of the Formal Safety Assessment process

The IMO FSA part of the guideline focuses on producing risk-related information and associated recommendations for the decision-makers of AtoN organisations, see Figure 2. In the IALA risk management guideline, this FSA-based process can be executed through three different strategies, depending on the scope and context of the problem for which a risk assessment is performed. The basic setup of these strategies is as follows:

- *Strategy 1* focuses on small-scale assessments (e.g. marking of a shipwreck), and includes only steps 1, 2, 3 and 5 of the FSA process.
- *Strategy 2* concerns medium-scale assessments (e.g. new AtoN installations) and also contains the cost-benefit Step 4 of the FSA process, in addition to those included in Strategy 1.
- *Strategy 3* addresses large-scale assessments (e.g. construction of an off-shore wind farm) and includes all steps of the FSA process, as well as an iteration procedure to assess and mitigate new hazards that could be introduced in the system.

When proceeding from *Strategy* 1 to *Strategy* 3, the associated processes become more comprehensive, resource-intensive and demanding in terms of skills and knowledge. Therefore, the organisation's top management, risk management experts and stakeholders should discuss the selection of a suitable strategy for the problem at hand.

3.2 Part II: Application of the ISO 31000 standard process

The following part of the guideline is based on the ISO 31000:2018 risk management process. Its aim is to address decision-making, practical implementation of risk control options, and communication and consultation with stakeholders. In this part, the AtoN organisation should focus on the following topics:

1) Quality of the IMO FSA based risk assessment results, including deliberation of the selected strategy, risk assessment tools and data sources.
2) Consideration of the risk assessment results along with other concerns, such as available resources, legal constraints and stakeholder views.
3) Decisions on whether the risks are at an acceptable level, as low as reasonably practicable, or at a non-acceptable level.
4) Implementation of the new risk control measures, while taking into account the responsibilities of stakeholders and cost-benefit aspects.

5) Monitoring and reviewing the risk levels on a regular basis to ascertain that these remain acceptable or as low as reasonably practicable.

In case the risks are no longer at an acceptable level or new emerging risks have been identified, the IALA G-1018 based risk management process should be repeated, possibly through a more comprehensive strategy.

4 IALA RISK MANAGEMENT TOOLBOX

The IALA Risk Assessment Toolbox comprises several methods and techniques to support the risk assessment tasks of AtoN authorities. This section briefly outlines the main features of these tools and their applicability for executing the different steps of the IMO FSA based risk assessment process, described in Section 3.

The IALA Risk Assessment Toolbox currently contains a total of six methods or techniques that are freely available to the AtoN authorities. Table 1 provides an overview of this toolbox, giving a brief description of the tools and their key features in terms of required resources and skills, and type of output. For example, the table shows that the use of the One Page Risk Assessment (OPRA) tool requires only low resources, whereas more resources are needed for the IALA Waterway Risk Assessment Programme (IWRAP) tool. As another example, the Navigation Simulator (SIMULATOR) tool can provide quantitative output, while most other tools result in a qualitative output, such as the Ports and Waterways Safety Assessment (PAWSA).

Table 1 IALA Risk Assessment Toolbox: Overview and key features

Tool ID	Description	Resources needed	Skills required	Can provide quantitative output	Reference
IRMAS	A standardised approach to document the risk assessment process, which also provides for a repository of operational risk assessments undertaken for small-scale applications.	Low	Low	No	G-1018
OPRA	A simple tool for operational small-scale assessments of navigation risk, e.g. those associated with a temporary marking of a wreck, the small change of an Aid to Navigation characteristics or the establishment of a virtual Aid to Navigation.	Low	Low	No	G-1018
PAWSA	A qualitative tool for assessing risk in a defined waterway area by means of a structured workshop. This is undertaken by carrying out a knowledge-based assessment of the risks in that waterway, strongly relying on the experience of maritime experts and other stakeholders.	High	Medium	No	G-1124 G-1018
IWRAP	A modelling tool aimed to provide authorities with a standardised quantitative method for estimating the probability of collision and grounding accidents in a given waterway or sea area. The tool requires access to AIS data.	Medium	Medium	Yes	G-1123 G-1018
SIRA	A simple inductive tool to structure an expert panel risk assessment. The basis of the tool is the risk matrix, in which the probabilities and consequences of the most relevant accident scenarios are rated and supporting justification filled.	Low	Low	No	G-1138 G-1018
SIMULATOR	Navigational simulation may provide both quantitative and qualitative data, and can be applied in two different ways: Fast-time simulation and Real-time simulation. The tool can be valuable e.g. to better understand the effects of risk control options being considered.	High	High	Yes	G-1058 G-1018

Figure 3 indicates the applicability of the IALA risk assessment tools for conducting the different steps of the IMO FSA based process. As shown in the figure, these tools can be used especially for the hazard identification (Step 1), risk assessment (Step 2), and estimating the effects of risk control options (Step 3) related to ports, waterways and sea areas. These steps can be conducted e.g. by using the PAWSA, IWRAP MK II or SIMULATOR tools. One can also notice that only SIRA, IRMAS and OPRA tools are applicable to directly provide decision-making recommendations (Step 5), while none of the IALA tools can be used for the cost-benefit assessment (Step 4). For that purpose, and also for information on other more generic risk assessment methods, the original IMO FSA guidelines can be utilized.

Overall, the current IALA Risk Assessment Toolbox provides a fairly comprehensive set of different risk assessment tools, which can produce useful risk-related information to support the follow-up ISO 31000:2018 standard based decision-making process.

Tool ID	Name	Hazard identification	Risk analysis	Risk control options	Cost-benefit assessment	Decision-making recommendations
IRMAS	IALA Risk management Summary	grey	grey	grey	black	grey
OPRA	One Page Risk Assessment	grey	grey	grey	black	grey
PAWSA	Port and Waterways Safety Assessment	white	white	white	black	black
IWRAP	IALA Waterway Risk Assessment Programme	grey	grey	grey	black	black
SIRA	SIRA	white	white	white	black	white
SIMULATION	Navigation Simulation	white	white	white	black	black

Figure 3: Tools included in the IALA Risk Assessment Toolbox
(Note: black colour = not applicable, grey colour = applicable, and white colour = strongly applicable).

5 DISCUSSION

The IALA guideline G-1018 as well as the associated methods and techniques arguably provide a relatively comprehensive basis to perform the risk management tasks of AtoN authorities. However, several points of discussion are worth being raised to contextualise the efforts and guide future developments.

First, it should be acknowledged that the IALA G-1018 document is only a guideline. In other words, the risk assessment processes and tools contained in this document are not mandatory in order to comply with SOLAS Chapter V, regulations 12 and 13. Nevertheless, this guideline and its toolbox can be considered as current best practice to support compliance in this context.

Second, in the same reasoning as above, the IALA Contracting Parties are allowed to use other risk assessment methods and tools to achieve the objectives and comply with the relevant SOLAS requirements. Indeed, authorities have already developed advanced navigational risk assessment methods and electronic tools to analyse and monitor the risk levels in their waters. This includes, for instance, the AISyRisk tool of the Norwegian Coastal Administration and Marin Risk Index of the Maritime Research Institute Netherlands. Hence, the IALA 1018 guideline and its tools are aimed primarily for countries which do not yet have dedicated tools available, but wish to enhance their operational capacity to assess risks in a systematic and documentable manner.

Third, further developments in the IALA toolbox are possible and desirable. As indicated in Section 4, only six tools are currently included in this toolbox. Considering the fast developments towards Maritime Autonomous Surface Ships (MASS) in particular, it may be fruitful to consider also the applicability of the current tool selection for these innovations. In other words, there could be a need to develop, test and implement new methods and techniques to support AtoN authorities in risk-informed decision-making to enable such technological developments. In this context, collaboration with the academic sector is also recommended, as the MASS evolution is one of the recent top research areas in the maritime field.

Fourth, the current IALA G-1018 guideline and its toolbox focus primarily on the hazard identification and risk analysis steps of waterway risk management, as indicated in Section 4. Recognising this, it may be useful to extend the scope of the guideline further and address issues related to the risk acceptability, i.e. whether the analysed risks are at an acceptable level or not. The importance of this phase has recently been emphasised also in the academic maritime risk field.

Fifth, the current IALA training courses on risk management focus primarily on the use of the methods and techniques included in the IALA Risk Assessment Toolbox. While this arguably is worthwhile, it may be worth it for the organisation to partly revise the contents of these courses to better align these with the updated IALA G-1018 guideline, and further highlight the importance of understanding the risk management process. In addition, the IALA training courses could more systematically stress the issue of what tools to select for the problem at hand.

Finally, a future possible development path that IALA or individual AtoN authorities can consider is to develop guidelines and processes for integrating risk assessment into the organisational processes. In this context, they can also consider the development of a specific risk maturity model for AtoN authorities, which can be used to assess the organisational performance in understanding, implementing and making use of risk assessments.

6 CONCLUSIONS

The first aim of this article was to outline the theoretical basis of the IALA G-1018 risk management guideline. As such, a brief overview of the state-of-the-art in the academic maritime risk field and key ideas underlying the IMO's Formal Safety Assessment and the ISO 31000 standard were given.

The second aim of this article was to present the risk management process of the IALA guideline. To this end, it has described two parts of the process that are based on the IMO FSA and ISO 31000 approaches, while providing an overview of the methods and techniques included in the IALA Risk Management Toolbox. Moreover, the article has discussed possible future development paths for the guideline and academic research in this context.

With this in mind, it is hoped that this article can assist AtoN authorities to appreciate the potential of the new IALA G-1018 guideline to support their work and meet their responsibilities, and ultimately to enhance the navigational safety and efficiency in their waters.

7 ACKNOWLEDGEMENTS

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Before his current assignment at Traficom, Laine has worked for more than 30 years in various positions and organizations in the maritime field. These include but are not limited to the duties of chief officer in cargo and cruise ships, as well as the duties of competent pilotage authority of Finland. The list of his earlier employers comprises, for example, Spliethoff BV, Princess Cruises Ltd. and Finnish Maritime Administration. Some years ago, Laine was also managing a project in the Helsinki Commission to provide new risk assessment tools and processes for the European Response authorities. The work in this context was carried out in close cooperation with the IALA-AISM personnel.

In addition to his comprehensive work experience in the maritime field, Laine has an extensive educational background. He holds the diplomas of Master Mariner and Master of Science, and conducts currently his doctoral studies at the Aalto University, Finland. When not working with the maritime administrative tasks or academic studies, Laine is an avid traveller and loves spending time in the great outdoors with his dog. It goes without saying that this dog named Luka is a Skipper dog.

S13.3 Risk Management: Italian experience and best practices (056)

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ABSTRACT

Risk Management is a methodological and systematic principle for defining measures or interventions in an effective, proportionate and goal-oriented way. The present work intends to illustrate the experience matured in Italy regarding the risk assessment of the most important national ports and areas of interest with regard to:

- using IALA Risk Management toolbox
- determination of possible risk scenarios related to the interaction of VTS with allied services, and
- best practice and outcomes related.

The aim of the present work is to highlight areas of continual improvement in the risk assessment process, sharing opinions and practises coming from knowledge in the field.

KEYWORDS: Risk assessment, risk management, Italian experience, risk methodology, IWRAP, PAWSA, SIRA.

1 FOREWORD

Rules 12 and 13 of SOLAS Convention Chapter V [1] identify two possible criteria for implementing aids to navigation (AtoN): the volume of traffic and the degree of risk. Thanks to modern monitoring systems, today the first element is easily measurable. IALA, for the second step, has identified a set of tools to facilitate the assessment of the risk and strengthen the decision-making process by the competent national authorities: *IALA Risk Management Toolbox*.

2 THE RISK MANAGEMENT IN NUTSHELL

In order to describe such a specific topic, it is necessary to identify a common taxonomy as a means to correctly identify the phases that distinguish the risk analysis and management process. Risk is generally defined as the likelihood that an unintended event will occur and the impact or consequences this event has. In mathematical terms, the risk is in fact solved by the following equation:

R= LxC (where L is L*ikelihoods* and C is *Consequences*)

To explain this simple function, it is necessary to set, in series, some simple steps that define Risk Management [2] [3]. The first step is to define the context i.e., the scope of application of the system that we are going to analyse in terms of risk. In this phase, the boundaries of the system must be analysed from various points of view: environmental, financial, industrial, IT, etc. The analysis of the context in VTS environment is particularly important, for example, to understand which could be the participating vessels and to exclude from participation part of the traffic flows that specifically affect a port. For each variation of the flows, a new analysis of the context should be performed.

The second phase aims at identifying the causes that determine the risks by evaluating the probability of their occurrence and the impact on the system. This phase is called risk assessment and it's divided into specific steps. The first is the identification of the risk in which it is necessary to determine and describe the most significant events that could arise during work and generate threats. This is also the most difficult phase of the whole process. It tends to focus on past experiences, such as the number of accidents that have occurred over the years, rather than identifying new or never-happened scenarios. Practically, models based on experience are preferred rather than those based on creativity which aims to explore new trends. Today there are various systems to help the identification phase with support techniques (interviews, checklists, brainstorming etc.)

and analysis techniques (What is, Ishikawa, SWOT, Event Tree Fault Tree etc.) which also take into consideration the creative phase. Another tendency, which occurs very commonly in this phase, is to take paths that end in the so-called *"black swan/grey rhinoceros"* [4] [5] effect i.e., concentrating on the search for a very rare but very impactful risk, and not identifying a major danger you are facing.

The next stage is the analysis. In simple terms, the risk analysis activity is the process that solves the risk equation R=LxC, analysing the probability that the event will occur and the impact that this can have, where the parameters of *Magnitude/Consequences (M,C)* and the *Probability/Likelihood (L)* are studied. Depending on the circumstances, the analysis can be:

- Quantitative (provides values demonstrating overall scores)
- Qualitative (provides the details and in-depth analysis necessary to fully understand the related implications)
- Semi-quantitative or qualitative
- A combination of the above

As it is easy to understand, this is the phase in which many tools have been developed to assist organizations in "weighing" the risk. The risk matrix is well known, but there are also more complex ones, from Bayesian networks to the Monte Carlo method. Even the tools made available by IALA to analyse the risk associated with maritime navigation can be classified according to this methodology.

As a final point on risk assessment, there is risk appetite. Risk appetite allows the prioritization in the risk treatment, because it compares the results of the risk analysis with the criteria set by the organization to determine the acceptability threshold. Each organization, in relation to its risk appetite, can represent the hazards on different scales, the simplest of which is made up of three levels: Low, Medium, and High. Defining an organization's risk appetite in the abstract may seem like a gamble, but when the concept is contextualised, everything appears much clearer. Considering, for example, the entrance manoeuvre of a ship into a port. According to PIANC (Permanent International Commission for the Navigation Congress) guidelines [6], the port entrance should have a width equal to the overall length of the project vessel. In Italy, for example, many ports do not meet this requirement and yet even large ships (400 meters L_{oa}) are able to call because of port safety measures such as tugs, piloting services, etc. that mitigate this scenario. The residual risk, which is by no means close to zero, is precisely the risk appetite of the port organization.

The last stage is risk management. The purpose of this phase is to identify the necessary and appropriate measures to manage the risk. The risk can therefore be mitigated through risk control tools (Risk Control Measures/Options) or avoiding it through outsourcing processes, sharing it with another organization or with insurance institutions, running the risk, or considering it as a possible business cost, etc. Being able to identify the right management action is a very complex and delicate phase, characterized by reasoning related to the costs and the benefits that are derived from them (CBA Cost Benefit Analysis). The final part of the process is the composition of recommendations and reports. The recommendations must be written and contain all the phases described above in order to make the whole process verifiable and traceable in order to allow the decision maker to be able to take the appropriate actions aimed at keeping the risks as low as reasonably practicable (ALARP).

3 OFF-LINE AND ON-LINE RISKS

After having mapped the analysis and management process, it is also necessary to define the risk from another point of view related to when it is determined. When examining the impact of risk management processes on a system, it is essential to consider at what stage to intervene. Two conditions can be determined, but not necessarily experienced: in the first, the system is being designed or modifications in whole or in part are being planned; in the second, the system is running and needs to be managed and controlled. We can consider the two cases reciprocally as planning (off-line) and as management and control (on-line). In an off-line condition if a potential event, that is inadmissible for the proper functioning of the system, emerges from the risk identification process, it is usually possible to take action by providing some specifications to implement and modify parts of the system. In the online condition, it is possible to act as a practice by foreseeing and implementing corrective actions. In practice, the first is a design phase where it is expected how the system will work and any risks are estimated, while the second is an operational phase where it is necessary to manage, in some way, the occurrence of the risky event.

Making a comparison with the world of risk analysis in maritime navigation, the requirement to implement a VTS, can be considered an off-line or strategic risk analysis [7] while the drafting of standard procedures [8] and therefore of communications with the ship [9] on-line analysis. This distinction is particularly important, for example, to verify the value of the so-called operational risks, or if new ones arise after that specific risk control option was implemented, as we will see later in this document.

4 RISK ANALYSIS AND VTS

As mentioned, the decision-making process underlying the choices whether to implement a VTS or not is, at an international level, also recommended by a risk analysis process. IALA has developed and published the guideline G1018 [10], with the aim of assisting the competent national authorities to fulfil the obligations referred to in the international provisions, mentioned in the introduction. IALA identifies 4 support tools:

- IALA Waterway Risk Assessment Program (IWRAP)
- Ports and Waterways Safety Assessment (PAWSA MK II)
- Simplified IALA Risk Assessment method (SIRA)
- Navigational simulation (SIM)

Some of them have been endorsed by International Maritime Organization (IMO) with a circular in 2010 [11].

4.1 IWRAP

IWRAP (IALA Waterway Risk Assessment Program) is a modelling tool used for quantitative risk assessment in the maritime waterways. Its algorithms were developed in the 70s by some researchers, in particular Fuji and McDuff, subsequently perfected by University of Copenhagen. The functionality is described in the IALA guideline G1123 [12]. With the use of IWRAP it is possible to estimate the frequency of collisions and groundings in an area, based on the volume and composition of the traffic, on the directions of the routes and on the bathymetric information of the seabed. The outcomes of IWRAP are:

- Powered groundings
- Drifting groundings
- Powered Allisions
- Drifting Allisions
- Overtaking Collisions
- Head-on Collisions
- Crossing Collisions
- Merging Collisions
- Bend Collisions

4.2 PAWSA

PAWSA (Port and Waterway Safety Assessment) is a qualitative tool described in IALA guideline G1124 [13]. PAWSA is a methodology developed by the United States Coast Guard in which a series of experts (panel) meet, in a 2-day workshop, to identify and mitigate the risks associated with navigation in a specific area. The process requires the participation of professional users with local expertise in navigation, waterway conditions and port operations. Stakeholders are also included in the process to ensure that important environmental, public safety and economic impacts receive adequate attention when certain interventions are selected. The theoretical concept that characterizes the PAWSA process comes from Delphi methodology, a technique for transforming the opinions of a group of professionals into quantifiable data and to reach consensus during the decision process. The main keys to the PAWSA are:

- structured workshop
- facilitators, and
- experts (panel)

During the structured workshop, 24 risk factors, divided into 6 risk categories, are discussed and the panel also provides personal ideas to improve those risk factors that are not adequately mitigated or balanced by the existing mitigation measures. The outcome of PAWSA is a report where all activities and recommendations are described.

4.3 SIRA

SIRA (Simplified IALA Risk Assessment) is a qualitative (or semi-qualitative) analysis tool illustrated in the IALA guideline G1138 [14]. Specifically designed by IALA for those countries that do not have technologies and skills to conduct a risk analysis with IWRAP or PAWSA. SIRA uses several correlated risk analysis methodologies including the Risk Matrix and the ALARP system. Fault Tree or the Decision Tree Analysis are also encouraged to be used in risks assessment. The risk management involves a structured process, but not as complex as PAWSA, which identifies the dangers (hazards) and scenarios (scenarios) in a confined area and finally the actions to be taken to reduce the risk as low as reasonably practicable (ALARP). The outcomes of SIRA is a report where all activities are described including a risk matrix where the relative analysis and suggested measures are reported for each scenario.

4.4 NAVIGATIONAL SIMULATIONS

Navigation simulation systems are tools that can provide both qualitative and qualitative results and their operation is described in the IALA guideline G1050 [15]. IALA divides navigational simulation into two categories:

- fast-time, and
- real time.

Fast-time simulation is carried out by a virtual navigator that sails a vessel through a specific area, navigational channel, etc. in fast time, producing a large number of sailings for each possible scenario of ship types, weather conditions, loading conditions, etc. within a short period of time, hence the quantitative approach. In real-time simulation, the vessels are controlled by a real navigator, typically producing fewer simulations, not necessarily covering all possible scenarios, hence the qualitative approach. Which type of simulation to use depends on the goals the simulation is addressing.

5 ITALIAN EXPERIENCE IN WATERWAYS AND PORTS RISK ANALYSIS

The Italian experience referred to risk analysis in maritime navigation is linked to the need to evaluate the existing VTS Centres considering the change of intensity in the maritime traffic flows which have affected the major national ports. A working group of specialised personnel has been set up at national level to perform risk analysis using IALA Risk management toolbox. In this regard, in 2014 the staff of the working group was deployed to follow IALA courses.

The first analysis began in 2016 and continued until the effects of the Covid-19 pandemic outbreak, which significantly slowed down the work to almost zero. The areas subject to risk analysis were Mazara del Vallo, Trapani, Augusta, the Strait of Messina, Gioia Tauro, Catania, Cagliari, Olbia, La Maddalena, the Ligurian Sea, Puglia and Ravenna. The most interesting case studies related to the experience on the use of IALA tools for the analysis of the risk associated with maritime navigation are reported as follows.

5.1 Trapani

The risk analysis of Trapani area was performed between the years 2017 and 2018 by using IWRAP and PAWSA analysis. At the moment Trapani is the only port in Italy where both methodologies have been used.

Trapani is a port in Sicily classified as being of national interest with functions related to the commercial freight, passenger traffic, fishing, and pleasure crafts. Historically the port was famous for the trade of salt and wine to Northern Europe. Today Trapani is an important passenger port connecting to the nearby Egadi Islands. The archipelago is situated in the largest marine park in Europe covers approximately 54,000 hectares. Moderate cruise, commercial traffic (containers and bulk) and fishing activity, especially with gill nets (artisanal fishing), are also present.

The risk analysis in Trapani port began with an important collection of statistical data referring to the previous 10 years which concerned many aspects of the port: commercial traffic, numbers of accidents, port configurations, nature of the seabed, meteorological and oceanographic data, etc. The collection of data has become essential to describe the context of the maritime area of interest, improve the discussion among the experts called to analyse the area and increase awareness about the real aspects of the port.

IWRAP analysis was performed by collecting AIS data for 12 months. The data showed that around 80% of traffic flows refer to HSC and Ro/Ro passenger ships. The area was not affected by transiting as ships tend to circumnavigate the marine national park area without passing through it. The greatest probability of collision is for head on situations of passenger ships with a value equal to 1.26×10^{-4}. This risk is represented in the area joining the port of Trapani and Levanzo island, where there is a restriction of the waterway due to the shallow waters and therefore the traffic is routed into a smaller fairway. The area most likely to run aground is the one in front of the Favignana island mainly due to the arrival of HSC with routes that involve sharp bends near the port entrance and the coast. The probabilistic value is 0.055 incidents per year.

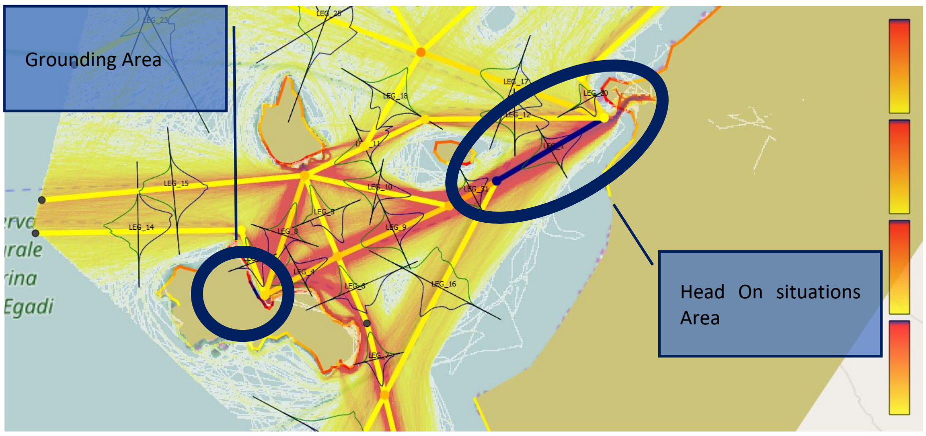

Figure 1: Trapani IWRAP results

Table 2: Collisions results

	Value	Unit
Overtaking	$7{,}192 \times 10^{-5}$	Incidents/Year
Head On	0,0001267	Incidents/Year
Crossing	$3{,}925 \times 10^{-5}$	Incidents/Year
Merging	$1{,}694 \times 10^{-5}$	Incidents/Year
Bend	$1{,}174 \times 10^{-5}$	Incidents/Year
TOTAL	0,0002665	Incidents/Year

Table 3: Groundings results

	Valore	Unit
Powered Grounding	0,05232	Incidents/Year
Drifting Grounding	0,003088	Incidents/Year
TOTAL	0,05541	Incidents/Year

PAWSA workshop was held in April 2018 at the "Tonnara di Bonagia", an old tuna farm converted into a 4-star hotel. The meeting included discussions among a team of experts on 24 risk factors divided into 6 distinct categories. The experts were asked, for each risk factor, to express themselves on certain questions which can be grouped into:

- How dangerous is the area in relation to individual risk factors regardless of existing measures?
- How effective are the existing measures in the area in terms of risk reduction and are there any better ones?
- What would you do to improve residual risks?

As regards to the procedures, it was decided to comply with the guideline and the related manual in determining the risk factors and to follow the simplified procedure with the use of 4 books instead of 5, in order to increase the time for discussions and remove from the process an object that often leads to bad interpretations. The procedure adopted was definitely unconventional, as the port's first PAWSA, but the benefits were greater than using standard method. The reference is to the book n. 2 called "Risk Factors Rating Scale", which determines the danger scale of the risk factors (Measurement Scale). During the Trapani workshop the average of the previous international workshops were used as standard values. On the 24 risk factors taken into consideration 44 observations were made. The most interesting ones are reported below:

- the average age of seafarers deployed on local passenger ships (HSC and Ro/Ro) is close to 60, due to national regulatory measures on the extension of the retirement age.
- During the work shift, which can last up to 14 hours, up to 34 mooring and unmooring manoeuvres are carried out.

These two factors, analysed together, show a risk scenario linked to the age of the crew and the fatigue that occurs especially at the end of the shift. These factors could have been the cause (root cause) of two accidents with hydrofoils which occurred in the port of Trapani in the years 2007 (Giorgione on August 9) and 2008 (Ettore M. on August 07), both occurring at the end of the shift, and which unfortunately, in the first case, led to the death of a passenger. The investigations were closed indicating human error and the poor illumination of the breakwater as causes of the incidents without, however, mentioning the fatigue. Other factors that emerged concerned:

- dangerous behaviours of pleasure boats anchoring near the port breakwater, significantly reducing the navigable area for ingoing and outgoing vessels. Especially during summertime lots of small boats anchor alongside each other for recreational purposes (dancing, having meals, consuming alcohol, etc.) very close to the breakwater
- port tugs which are not very powerful and have old designed propellers
- wind gusts in the Egadi archipelago which can reach severe values and can be well above those expected, and
- traffic congestion of HSCs in conjunction with the arrival of the Ro/Ro ship. The Ro/Ro takes a long time to moor, effectively occupying the basin used for the manoeuvres of the high speed passenger' ships. This implies a congestion outside the port, especially in the summer.

As regards the unbalanced and unmitigated factors, 18 proposals were made, including:

- enhancing law enforcement coordination especially on weekends and in the summer period to increase control at port's breakwater
- training and information for yachtsmen through the preparation of conferences and brochures indicating the most dangerous behaviours to avoid in the port of Trapani. The documentation should be delivered when renting pleasure boats to increase the awareness of them, especially for those who rent without a boat license
- new port tugs with azimuth thrusters and with greater bollard pull
- purchasing and installation of anemometers in the Egadi archipelago, and
- re-scheduling of arrivals and departures of HSC and Ro/Ro vessel.

Figure 2: Panel of experts and facilitators

The use of this tool has allowed for the discussion of scenarios and hazards that are difficult to appreciate during an analysis carried out without the involvement of the interested parties. During the stand-alone analyses, there is a tendency to focus more on technical factors relating to the movement of ships (navigation and manoeuvring), rather than analysing issues concerning the human factor which instead represents the root of many accidents.

5.2 Catania

In 2020, a risk analysis was conducted in the Catania area using only the quantitative methodology (IWRAP). This example demonstrates the importance of using these systems to identify collision scenarios, which are otherwise difficult to predict. The port of Catania is located in eastern Sicily and classified as being of international interest with cargo handling of bulk goods. Ferry lines heading to central and northern ports of Italy have been activated for some decades to carry commercial vehicles in order to avoid the poor southern motorways. There is also passenger traffic, limited to cruise ships and ferries.

The quantitative analysis of the area (IWRAP) was performed by collecting AIS data for 12 months. The data showed that the traffic is composed of Ro/Ro and general cargo vessels. The data referring to the probability of collision are limited and related to:

- collision for head on situations in the precautionary area located outside the port where simultaneous traffic is permitted, and
- merging and crossing in the waypoint WP41.

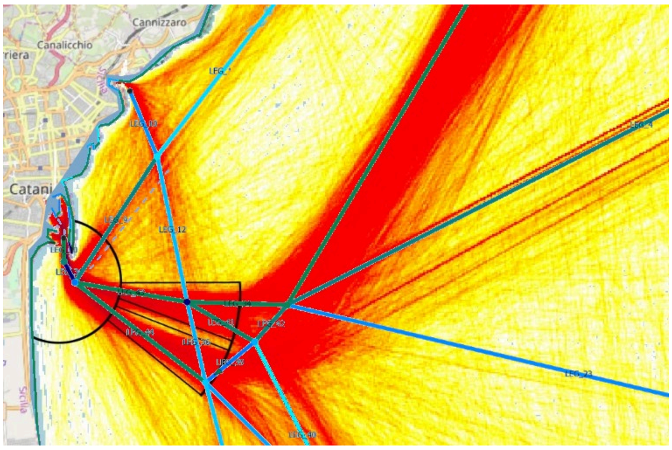

Figure 3: Catania port, overlay of TSS, traffic density and legs

The data regarding merging collisions in WP41 is consistent with the existing routing measure (Traffic Separation Scheme TSS) which directs, in a single lane, the traffic flows coming from the North and South. While the data referring to crossing situations appears unexpected at that point. The intersection occurs with the flows originating further north from a small harbour of the town of Ognina and the risk is represented by fishing vessels that cross the traffic separation scheme to reach the fishing areas. It is a seasonal flow, which is very modest (on average about 1 crossing every 3 days) and not perceptible during daily activity, but still well displayed by the IWRAP system. The analysis that emerges is therefore the result of the use of the system and only thanks to this, it’s possible to identify the hazard and therefore take the appropriate initiatives aimed at weighing it and, possibly, undertaking corrective measures through appropriate risk control options. Since the number of crossings is limited, the competent authority could accept the risk as it is and possibly implement a ship reporting system for fishing units to and from the port of Ognina in order to increase awareness and verify the probability of a crossing. An extra option could be deviating the traffic in another direction. The local maritime authority requested to simulate trawler traffic within the precautionary area and see how this option affected movement to and from the port. The system allows this option and on the relative leg (n. 9) the traffic flows were loaded and the simulation started, delivering the results to the local authority.

5.3 Messina Strait

In 2020, a risk analysis was conducted in the Messina Strait area using the quantitative methodology (IWRAP). The example is useful to illustrate the reliability of the data using the IWRAP.

The Strait of Messina is an important crossroad in the Mediterranean which connects the ports of the Tyrrhenian Sea with those of Africa, the Middle East and the countries within the Ionian-Adriatic region. Inside the Strait there are 4 ports, mainly used to allow territorial continuity between the Italian peninsula and the island of Sicily, the most important of which is Messina. The port of Messina is included in the Ten-T European network of comprehensive ports, along the Scandinavian-Mediterranean Corridor (The Scandinavian-Mediterranean Corridor represents a crucial north-south axis for the European economy. The corridor stretches from Finland and Sweden in the North, to the island of Malta in the South, taking in Denmark, Northern, Central and Southern Germany, the industrial heartlands of Northern Italy and the southern Italian ports). It is a natural port classified as being of international interest and a portion of it is dedicated to Navy military purposes. Messina is the most important national port for the transport of passengers from Ro/Ro, HSC and cruise ships, the latter having developed over the last few decades thanks to the generous depths of the port (about 10 million passengers per year were carried before the Covid-19 pandemic).

The IWRAP was performed by collecting AIS data for 12 months. The data showed that the traffic is very complex and mainly affected by passengers. The recorded movements amount to about 100k a year, 300 a day, and involve both the transit in the North-South axis of the Strait, and the transversal East-West one. Since 2008 in the Strait, as a traffic routing measure, a Traffic Separation Scheme has been active, consisting of 2 traffic lanes separated by precautionary area with a roundabout. The establishment of TSS was decided following a serious accident between an HSC and a container vessel where 4 crew members of HSC lost their lives. Analysing traffic flows was a complex operation.

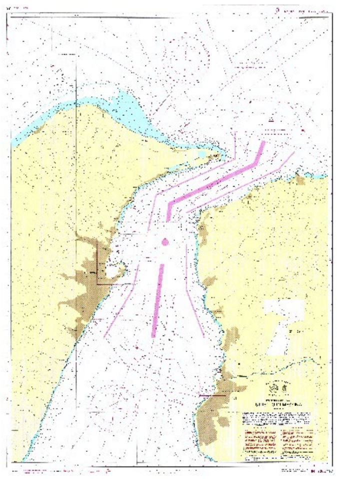

Figure 4: Messina TSS

The data referring to the highest probability of collision were:

- a head on collision situation in the port of Tremestieri. In the other ports of the Strait there is a one-way traffic system while in this port the ships can move in both directions simultaneously
- collision due to merging at the Messina port entrance due to the flows coming from different directions: North South and East traffic inbound.
- crossing situations in front of Villa San Giovanni port. This is due the location of the port near the northern traffic lane. Handling of the ships cause an interaction with northbound traffic.

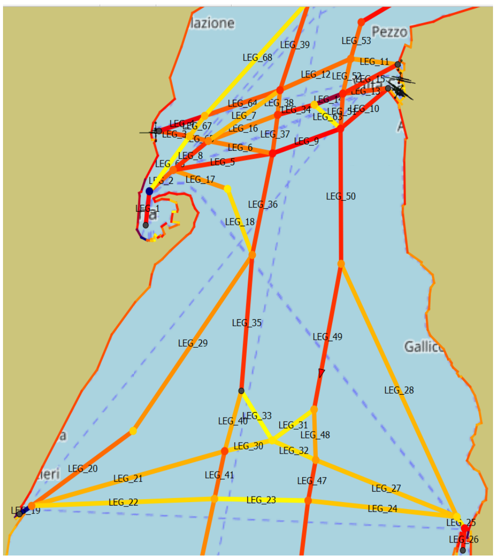

Figure 5: Messina Strait IWRAP Anlysis

Table 4: Collisions results

	Value	Unit
Overtaking	0,0004767	Incidents/Year
Head On	0,0001052	Incidents/Year
Crossing	0,0004103	Incidents/Year
Merging	0,0003487	Incidents/Year
Bend	0,0006772	Incidents/Year
TOTAL	0,002018	Incidents/Year

The data referring to the greater probability of grounding is instead in the area of the entrance of the Reggio Calabria port due to the sharp bend that the ships make near the breakwater. From a statistical point of view, two accidents occurred right at that point, in 2013 and 2015, with the grounding of two HSC vessels inbound the port. Furthermore, if we compare the data resulting from the IWRAP analysis with the historical data of the accidents that occurred in the Messina Strait, we realize that the values are very similar and close to 1 accident per year. This makes us understand how reliable the analysis conducted with this type of tool is.

Table 5: Groundings results

	Valore	Unit
Powered Grounding	0,438	Incidents/Year
Drifting Grounding	0,4488	Incidents/Year
TOTAL	0,8868	Incidents/Year

Table 6: Historical data

Year	Ship movements	Incident per year	Like-hood
2010	116761		
2011	116598		
2012	115323	1	8,6E-06
2013	115527	1	8,6E-06
2014	114863	1	8,7E-06
2015	114868	1	8,7E-06
2016	114874	2	1,74E-05
2017	114051	2	1,75E-05
2018	114052		
Average	115213	0,889	7,715E-06

ON-LINE RISKS

As mentioned, on-line or operational risks are those that occur during normal daily activity using all the procedures and options identified in order to mitigate the risk scenarios. According to the general principles of risk management, in order to be able to deal with operational risks, they should be mentioned in the same register as the risks indicated in the design phase (A risk register is a record of information about identified risks. The document is used as a risk management tool and to fulfil regulatory compliance acting as a repository for all risks identified and includes additional information about each risk, e.g., nature of the risk, reference and owner, mitigation measures. It can be displayed as a scatterplot or as a table. The risk assessment matrix mentioned in SIRA could be used as risk register). In a VTS operational context, this type of risk comes from the use of the standard operating procedures (SOP) drawn up to mitigate the scenarios relating to navigation (ships entering the area, ships in transit, ships departing, etc.). These are risks that are difficult to identify and are often overlooked and not assessed during the risk analysis.

A very significant case study on operational risks concerns the grounding of container vessel Gustav Maersk on 27 August 2017 in the Messina Strait. The ship, coming from Rijeka (Croatia) and bound for the port of Gioia Tauro, was supposed to pass through the Strait during the night. The weather conditions were strong north-westerly winds, about 40 knots, and a northern current of 3-4 knots. That night due to the bad weather conditions, the procedure to disembark pilot inside the traffic lane was agreed between VTS Authority and the Pilot as the sea state outside the Strait did not allow for a safe transfer for all northbound vessels. The pilot also agreed to this procedure for the container vessel Gustav Maersk and, having passed the turning point at Punta Pezzo, asked ~~to~~ the captain to make a turn to starboard in order to make a lee. The vessel altered course to 85-90 degrees off the traffic lane track. When the pilot disembarking was completed, the ship was a few hundred meters from the coast and the captain was no longer able to put the ship back on track due to the combined action of the strong wind and current. This example clearly shows the negative effects of the application of a procedure which did not provide for any supervision by the VTS authority on the pilot's actions, a control which was also omitted by the ship's master, on his first experience on this type of vessel. In the chain of events, which led to the grounding of the ship, the possibility to insert a cross check by VTS was omitted, due to an over-reliance on pilotage and the complacence of the pilot. The lesson learned led to:

- a review of the disembarking procedures with the possibility of providing Shore Based Pilotage in case of severe weather conditions (according to a study, the Shore Based Pilotage (SBP) in Italy is not residual but it covers 36% of total pilot fees) [16]
- a new cooperation between pilots and VTS with greater control for the pilot disembarkation in case of adverse meteorological conditions

- a communication procedure between the VTS and the captain of the vessel to increase the on-board situation awareness
- updating of the risk register, and
- the start of a discussion on possible negative interferences between Shore Based Pilotage (SBP) and VTS.

The case study also demonstrates the need to move from a Bridge Resource Management regime to Port Resource Management ones, involving the VTS in the dynamics that can arise on the bridge during the entrance into a VTS area.

The appropriate tool for identifying and assessing these operational risks could be the OPRA (One Page Risk Assessment), introduced by IALA in the new edition of the G1018 guideline. Indeed, IALA defines OPRA as a tool designed to support small-scale operational assessments related to navigational risks. The OPRA could, for example, be used to identify operational risks associated with the use of standard operating procedures (SOPs).

6 SIRA IN GIOIA TAURO PORT

Some SIRA analyses are being conducted in Italy (Genoa and Palermo). Actually, a project is currently being studied to facilitate harbour masters' ability to perform risk analysis using the SIRA methodology. The project involves an analysis on a sample port, identified in the port of Gioia Tauro, in order to enhance the technique and write a practical manual to be provided to the maritime authorities. The manual will also include a methodology for quantifying the effectiveness of risk reduction tools as required in the IMO Formal Safety Assessment (FSA) [17].

7 STRENGTHS AND WEAKNESSES OF THE TOOLS

Below is an analysis of the strengths and weaknesses found during the Italian experience in the use of the tools made available by IALA.

7.1 IWRAP

Advantage
The IWARAP is a very simple and intuitive quantitative system with a well-known and tested algorithm that allows studies on ~~the~~ waterways and maritime navigation.
Disadvantage
It is a tool that requires AIS data and the purchase of software licenses to simplify the analyst's work. It allows checking only collisions and groundings but it does not allow the determination of the risk formula for the reason that it does not identify the impact that groundings and collisions could cause. It can be used to determine the risk related to navigation but not for operations (towing, fuel transfer, lightening of cargo, etc).

7.2 PAWSA

Advantage
PAWSA is a semi-qualitative tool as the opinions of the experts are still evaluated and represented in numerical form. It is a very well-structured tool with well-defined risk factors. The risk matrix could be comparable with others analyses for the same waterway across different waterways in a country or in another country. The participation of the experts and stakeholders is an added value and broadens the point of view on risk analysis especially in hazards determination.
Disadvantage
It is a very complex tool which requires a long preparation and familiarization. Facilitators and participants play a pivotal role. The participant selection process can be as challenging as facilitators' training.

7.3 SIRA

Advantage
It is a very flexible and easy to use tool. In this case the analysis is semi-qualitative and the Risk Assessment Matrix makes it possible to evaluate the identified scenarios numerically. The participation of experts in the process is also certainly an added value.
Disadvantage
Risk Control Options (RCO) or Risk Control Measures (RCM) are not valued in their risk reduction activity, as required in the IMO Formal Safety Assessment (FSA). The methodology used in the SIRA aims more to focus on existing scenarios or deriving from previous experiences rather than on new trends or events that have never occurred.

8 CONCLUSIONS

First of all, the IALA association must be applauded for having developed and made available to the maritime community the IALA risk management toolbox that allow the competent national organizations to fulfil the international obligations relating to the design, installation and maintenance of aids to navigation.

The traditional approach to making decisions concerning marine safety is based on “learning from experiences,” the essence of which is that what people learn and accumulate from experiences predominates over their decision-making process. The maritime world has its roots in centuries-old traditions and it’s not so simple to change them, considering that the Risk Based Decision Making (RBDM) approach requests many investments in terms of human resources and time, but this methodology is very valuable in long-term policy. In this respect, the tools made available by IALA are very useful support instruments and allow for risk analysis in ports as well as in the main waterways in a professional and efficient way.

This takes on an added value also in the light of the new IMO resolution on VTS which is consistent with risk management principles, especially as regards the elimination of information, traffic organization and navigation assistance as three different services. In fact, every VTS centre must have all available tools to mitigate the hazards deriving from maritime navigation. The ship uses STCW and ISM procedures, such as bridge watch and route planning to maintain the “ship domain” and mitigate navigational risks. Even, a coastal State should improve a “coastal domain” by delivering services that come from risk analysis in a specific area, such as pilotage, VTS, etc. So, when a “ship domain” enters into a “coastal domain” a “Combined Interference Risk Assessment” (risks generated by interference between activities conducted simultaneously in the workplace) should be defined. In doing so, attention must be shifted from a consolidated and traditional ship-centric point of view to a VTS point of view in order to ensure safer and more efficient navigation to all domains.

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AUTHOR BIOGRAPHY

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Author of several articles related to the VTS, published in Italian scientific journals dealing with transport and maritime, air and aerospace navigation law.

S13.4 Analyses of AIS data for real time risk detection in maritime traffic (028)

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ABSTRACT

This article will provide an overview of the Japan Coast Guard (JCG)'s technological development for timely and automatic identification of potential risks of maritime accidents from shore stations. The development of technologies, which are based on AIS data that the JCG has stored for about 10 years, deals with collisions and dragging.

Between the two scopes of the developments, the risk identification of dragging anchors is the main focus because of frequent damage of typhoons in Japan and the possible damage to the Japanese economy; an accident that was caused by a dragging anchor in October 2018 disturbed the operation of a floating airport in Japan for 14 days. The JCG has found that dragging anchors can be detected by the combination of vessel movement patterns, which can be modelled by pattern recognition based on AIS data analyses. The result of the evaluation shows that the proposed method could detect the possible dragging faster than VTS operators with high accuracy.

Additionally, the JCG has also found that the proposed collision prediction algorithm, which considers relative distance, relative speed, and the relative direction of two vessels, could perform at higher accuracy compared to the traditional CPA/TCPA method; the proposed method could reduce false alerts from current VTS system(s).

KEYWORDS: the Japan Coast Guard (JCG)'s technological development, collisions and dragging anchors, the combination of vessel movement patterns, collision prediction algorithm

1 INTRODUCTION

As maritime traffic and gross capacity of vessels increase year by year, the difficulty of navigating is also increasing. The larger the vessel, the longer it takes for the navigating to be reflected from vessel manoeuvring[1]. Therefore, more and more forward-looking navigating is required. Thus, it is becoming necessary VTS operation to accurately predict concerned risks at maritime traffic and to provide effective information to vessels.

Moreover, in recent years, typhoons have become larger and more frequent in Japan. For example, in September 2018, Typhoon 21 surged Japan, causing some maritime accidents due to dragging anchors[2]. As a result, severe damage to infrastructure has occurred by dragging anchors, and the function of an offshore airport was suspended for 14 days. Additionally, there have been many other accidents caused by dragging anchors year by year. Thus, dragging anchors are one of the most urgent hazards[3].

Currently, we operate a VTS system that utilizes a combination of AIS and radar at VTS centres and other facilities. At VTS centres, with the aim of accident prevention and maritime traffic management, VTS operators predict the vessels motion or risk, and provide information to vessels. However, it is difficult to detect and predict the motion of many vessels at the same time and determine the risk for each vessel. When to provide information and which vessel to provide information are highly dependent on the experiences and skills of the VTS operators. Thus, we have conducted technological development to prevent maritime accidents such as vessel collision or dragging anchors. In this paper, we show the utilization of the technological development in order to identify of potential risks of maritime accidents timely or automatically[4].

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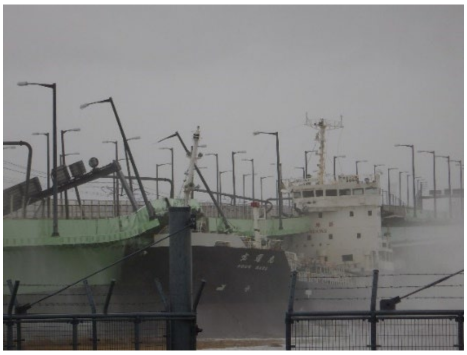

Figure 1 - Cargo ship collided with Kansai International Airport access bridge in Sep. 2018[5]

2 TECHNOLOGICAL DEVELOPMENT OF COLLISION PREDICTION TECHNOLOGY

2.1 Reduction of Over-detection with Conventional Technology

In 2019, we developed the conventional vessel collision prediction technology by outsourcing to Fujitsu Research and conducted field trials at VTS centres. The vessel collision prediction technology utilizes the ensemble risk model and hotspot theory that were developed by Fujitsu Research. Thus, by applying this method to the risk prediction technology, we can compute the overall risk ratio, which incorporates various perspectives. Furthermore, considerations enable computation on risk ratio fitting the actual maritime traffic flows while reducing false alerts and overlooking, with the following:

- calculating the possibility of course change for each vessel's relationship, speed or size, and
- considering the risk of vessel course deviation based on past AIS data; and
- adjusting the risk ratio depending on relationship.

We have considered appropriate thresholds for field trials at Tokyo Bay. Thresholds in each body of water differ due to differences in fairway shapes and maritime traffic conditions. It is easy to assume that the level and timing of risk to be detected would differ between the differences in operation methods at each VTS centre. Reduction of detection and time to spare for actions are factors that need to be adjusted in the thresholds depending on the VTS operations to apply the vessel collision risk prediction analysis to, but these are trade-offs.

The evacuation method of conventional technology, which is the theoretical background of conventional vessel collision risk calculation, assumes that a vessel navigates in a straight line. Therefore, even if a vessel navigates safety along the fairway or designated lane, the collision risk may be overestimated at a fairway bend. Consequently, if over-detection, including false alerts, occur frequently, the attention of VTS operators would be distracted. Moreover, in VTS operation where risks for multiple vessels are monitored simultaneously, a situation with too many false alerts or over-detection which could disturb VTS operation, might increase human errors among VTS operators. As it turned out, VTS operators may overlook really dangerous situations.

Thus, in the development of the new technology, we consider that machine tuning is necessary to reduce excessive over-detection at VTS operation, with the following:

- In each case, there are individual differences in subjective perception of the VTS operators;
- It is more important to predict collision risk or provide information for around 10 minutes before than to warn at the moment in which collision risk is maximum; and
- While operating an all waters, give attention to the total amount of alerts that would support VTS operation.

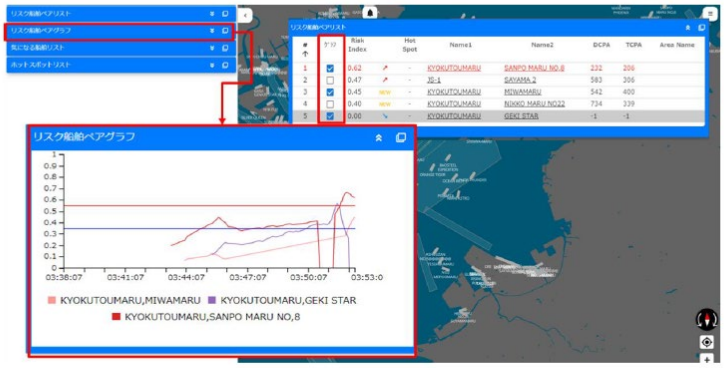

Figure 2 - Screenshot of vessel collision prediction technology

2.2 Risk Analysis by Prediction of Hotspot Situations

Fujitsu Ltd. has proposed a method to predict hotspots, which is a fundamental theory of vessel collision prediction technology. The method defined a hotspot as a hazardous situation in which the collision risk is concentrated highly and has undergone continuous changes, and in which many vessels might interact each other. Moreover, due to the interaction of many vessels with each other, if once a hotspot has manifested, it would be difficult to resolve dangerous situations by the decision of an individual mariner or the instruction of VTS operators. Therefore, a prediction method that includes which vessels are affected and where a hotspot is manifested is considered as one of the most significant functions that a VTS operation support machine should be equipped with.

The more collision risk is detected simultaneously as the number of detections increases, the more hazardous situations would occur at the hotspot. Detecting each specific collision risk related to the manifestation of a hotspot individually, and providing information to vessels would be excessive and burdensome for VTS operation. Therefore, in such a situation where risk is concentrated, in order to prevent the distraction of the VTS operator's attention, it is considered that detection as a single event through the hotspot detection function as per this technological development is effective.

The hotspot prediction technology is based on a logic that detects a hotspot if two or more CP are in a congested situation. Due to this logic, auto-detection of hotspots is possible. Moreover, based on the near-miss risk ratio of vessel pairs that compose the hotspot, another logic is also applied to quantify the hotspot level. Thus, if many hotspots have manifested, we would be able to prioritize what we need to deal with by judging from the hotspot level.

Figure 3 - Screenshot of hotspot predicted by vessel collision prediction technology

2.3 Over-detection and Hotspot at Tokyo Bay

The conventional technology at Tokyo Bay frequently causes over-detection or false alerts on VTS operation. Fig. 4 shows Uraga-Suido Traffic Route, Nakanose Traffic Route, and Nakanose West Sea Area that are officially defined by laws and regulation like the Maritime Traffic Safety Act at Tokyo Bay[6]. Tokyo Bay is one of the most congested waters in the world, and it is difficult to manoeuvre vessels due to the necessary S-shaped bend in the fairway from the mouth to head of the Tokyo Bay. Moreover, despite the length of the bay, approximately 70km from the mouth to head of the Tokyo Bay, the navigable waters for large vessels are limited due to these geographical conditions.

Fig. 5 shows the ratio of hotspot pairs at Tokyo Bay. At Tokyo Bay, in situations with more than 10 vessels pairs detected simultaneously, approximately 60 to 70% of the pairs are related to hotspot situations. Such a high number of vessel pairs relating to hotspot situation suggests that hazards with congestion risk have occurred. Moreover, the higher the number of risk vessel pairs detected simultaneously, the higher the proportion of hotspots.

Thus, a previous field trial has suggested that a typical situation in which over-detection is caused by bends in the fairway is one of the problems for this technological development. Additionally, one issue concerning the technological development is the detection of dangers in risky situations, such as crossing ahead or releasing from fairway with conventional technology that only reduce over-detection at the bend when vessels navigate along the fairway.

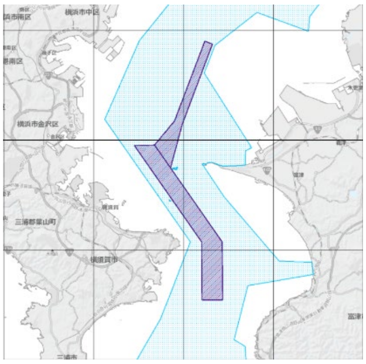

Figure 4 - The fairway at Tokyo Bay

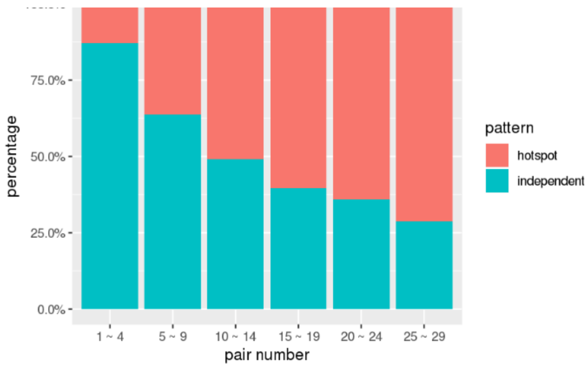

Figure 5 - The ratio of hotspot pairs at Tokyo Bay

2.4 Statistical Analysis of Machine Tuning

We investigated the statistical analysis for the over-detection reducing effects of the new technology. As shown in Fig. 4, the fairway is subdivided into the southbound route, the northbound route, and Nakanose Traffic Route. Whether a vessel navigates along the fairway or not is judged by the angle difference between the direction of the vessel and the fairway. Also, the angle between the centreline of each subdivided area and the vessels' orientation is calculated. If this angular difference is within a certain threshold, the vessel is considered as following the fairway. And if it exceeds the threshold, the vessel is considered as not following the fairway, such as being considered crossing or releasing from fairway, etc. A situation that follows along the fairway is classified into the following three patterns:

- a pair of northbound vessels;
- a pair of southbound vessels; and
- pair of head-on vessels on the lane of fairway.

Through machine tuning, we implemented a route-correction technology that reduces unnecessary over-detection at a bend in the fairway with the new technology. As shown in Fig. 6, the results of statistical analysis of machine tuning, the records in which each pair of vessels on the fairway and where the risk value exceeds

0.35 are aggregated. According to bar charts, the number of records is reduced through machine tuning. In the risk prediction by conventional technology, many of the vessel pairs in the fairway bend were over-detected as high collision risk because the conventional technology judged that two vessels would keep navigating straight at the current direction. In contrast, as both vessels would be assumed to navigate along bends in the fairway which are defined under the relevant laws and regulations, the collision risk has been judged lower by the new technology. Especially, the records of head-on vessels in lanes greatly declined by approximately 98%.

The records of situations that are classified as following along the fairway were greatly reduced. Thus, many alerts were detected as over-detection with conventional technology, but the new technology detected really dangerous situations such as crossing ahead or releasing from the fairway. The new technology was proved effective in reducing over-detected records.

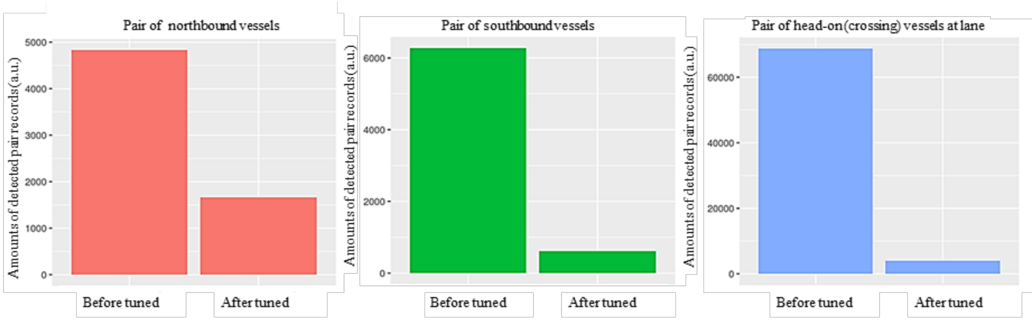

Figure 6 - Comparing effects of machine tuning (conventionally and newly)

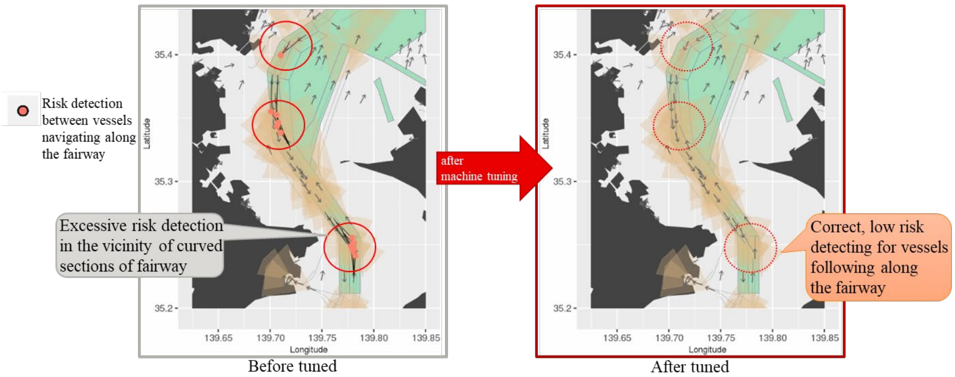

Figure 7 - Screen comparison image of vessel collision prediction (conventionally and newly)

2.5 Collation Analysis of the Operational Records

Furthermore, we investigated the operational utility of the new technology under the supervision of VTS operators and concluded its effectiveness for the following three effects: early detection, prevention of overlooking, and prevention of misses. Especially, in hazardous situations which probably fall into cases of instruction or recommendation at operational records, the new technology predicts risk judgments early and correctly. With the early detection function, approximately 80 % cases were detected by the new technology as risk situations earlier than the timing when VTS operators issued warnings or recommendations. Moreover, for the overlooking prevention function, approximately 50% cases which were unreported on operational records were detected by the new technology. Thus, the new technology has raised alerts suitably, even if VTS operators did not notice hazardous situations. Thus, when VTS operators do not issue warnings or recommendations, the new technology would be effective in preventing overlooking. Thus, VTS operators positively evaluated the new technology because the new technology is useful as a VTS operation support machine. Therefore, the new technology has performed as well as VTS operators.

On the other hand, some problems have arisen as well. In cases of no operational records, about 10% of the high-risk alerts by the new technology were not at the level of warning or recommendation. But, because of utilizing alerts by the risk prediction technology as a support for decision making of VTS operators, 50% records are considered to be an acceptable result as long as the suggestions do not overlook anything. Also, the new technology could be used to determine the thresholds of risk indicators with two threshold values (providing information level 0.35, warning and recommendation level 0.55), and each threshold can be classified into two further categories, with the lesser threshold being a list of risk events for the operational implementation, and the higher one being a method to verify whether the relevant operations are being performed or not. Moreover, a method of raising alerts for other conditions, such as direction changing for evacuation and bumper overlapping, is to be added to the high-risk determination by risk ratios, and these are considered to be specific problems that require consideration when the system is implemented.

3 TECHNOLOGICAL DEVELOPMENT OF DRAGGING ANCHOR DETECTION

3.1 Theory and Method of Dragging Anchor Detection

We have developed a conventional method of monitoring anchored vessels by a VTS centre. An alarm circle is set up around the anchored vessels to be monitored. When a vessel deviates from an alarm circle, a dragging anchor is detected. Unfortunately, when the vessel deviates from the alarm circle, opportunities for information sharing would have already missed. On the other hand, narrowing the radius of the alarm circle could increase unnecessary alarms. Therefore, the determination of dragging anchor is highly dependent on the experience and skill of the VTS operators.

The aim of this technological development is to provide timely and appropriate information provision to prevent dragging anchor accidents, and, at the same time, to reduce the burdens of the VTS operators related to monitoring anchored vessels too. The conventional alarm circle method takes into account the length of the vessels and wind speed. However, it doesn't take into account the actual vessel's speed or the times at which vessel moved. Thus, we focus on the vessel's characteristic swinging motion of dragging anchor obtained from AIS data.

We classified the motion and state of vessel into following dragging anchor pattern. *Inoue* (1998) argues that a pattern that leads to dragging anchor could be explained by the following states [7]:

- State A: State A is the normal state; the vessel is in swinging motion.
- State B: State B is a transient state; the anchor slides downwind gradually but the vessel keeps swinging around.
- State C: State C is a dragging anchor state; the vessel is swept downwind at constant speed and posture.

We focused on the characteristic motion of the vessel leading to dragging anchor, and conducted a cluster analysis of AIS data for the last 10 years. As a result, we obtained the results to classify the motion and states of the vessel into 8 clusters. Additionally, we scored each motion, according to the degree of risk.

The concept is "Moving continuously in dangerous conditions is risky". At a time t_n, evaluation value at the time $e(t_n)$ shall be obtained from the formula:

$$e(t_n)=wd$$

where: degree of danger (w) multiplied by distance moved in that state (d).

When the accumulation of the evaluation value (e) exceeds the threshold, we detect the vessel is dragging anchor.

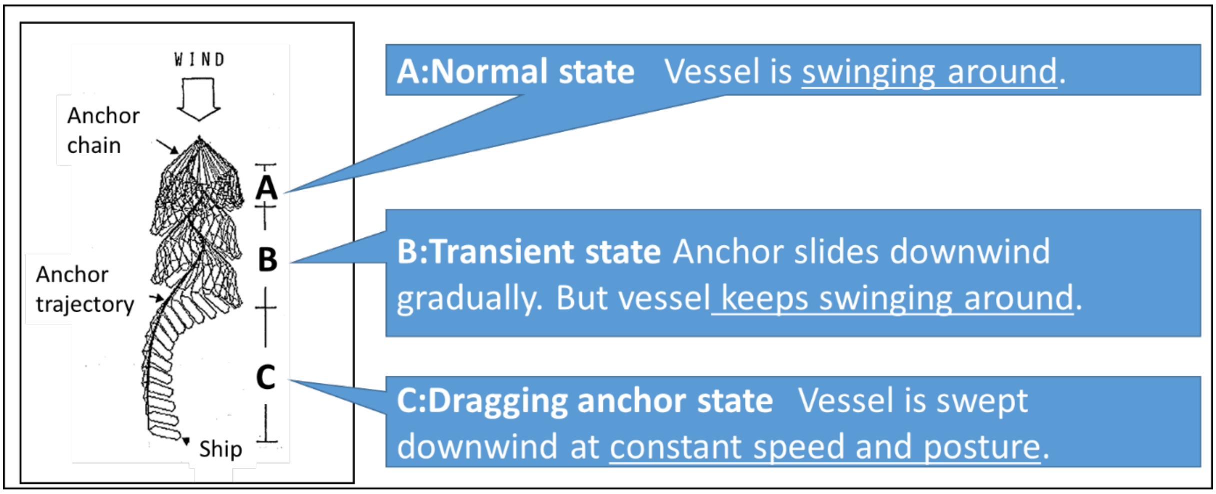

Figure 8 - Typical anchor dragging pattern

3.2 The Demonstration of Dragging Anchor Detection

We developed an emulator with the newly developed algorithm. We optimized the parameters by analysing the anchor monitoring of the past 7,500 vessels.

Fig. 9 shows the case of a new method demonstration (Tokyo Bay, 2 Oct. 2015). On October 2, the weather of Tokyo Bay was very rough due to a severe storm that developed dramatically, and a moderate gale exceeding 15 m/s was observed [8]. Thus, there was greater risk of dragging anchors arising on that day, and a dragging anchor had actually occurred at Tokyo Bay.

We denoted with the vessel's trajectory and elapsed time as per the diagram of Fig. 9. From 0 minutes to 30 minutes, the vessel is swinging around. This is in the normal state. After 30 minutes, the anchor slides downwind gradually. However, the vessel keeps swinging around. This is in the transient state. at 45 minutes, the new method detected a dragging anchor, and, consequently, the emulator raised an alarm by indicating with a red dot. At 48 minutes, the vessel deviates from the alarm circle. The conventional alarm circle method detected a dragging anchor at this point. After the vessel deviates from the alarm circle, the vessel is swept downwind at constant speed and posture. Thus, it shows that dragging anchor can be detected during the transient state (B) leading up to dragging anchor. Moreover, the new method can detect faster than the conventional method.

However, problems have arisen as well. Unnecessary alarms may occur depending on vessel state. There is a trade-off between early detection and unnecessary alarms. Therefore, further optimization of various parameters is required to improve the new method. In order to solve those problems, JCG plans to continue the verification process at VTS centres.

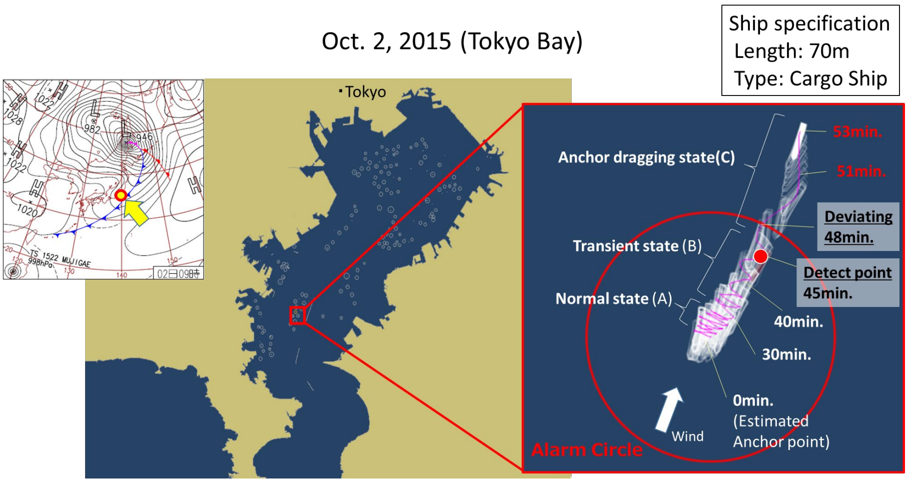

Figure 9 - Demonstration of new dragging anchor detection technology

4 CONCLUSION

To deal with issues such as vessel collision or dragging anchors, we conducted a technological development of stored AIS data. According to the results of the technological development, in order to prevent maritime accidents, it would be effective for VTS operators to apply vessel collision prediction technology and dragging anchor detection technology to the VTS system. Moreover, since these technologies support VTS operators in providing information and performing navigational controls, these technologies would be highly useful for VTS operators. A further trial of the technological development will be required to consider the implementation of the new technology for VTS centres nationwide.

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AUTHOR BIOGRAPHY

Hideki Noguchi graduated from the Japan Coast Guard school in 1980. He studied Aids to Navigation services in the USCG headquarters as the government short-term fellowship student in 1994. He was dispatched to the PCG headquarters in Manila as the expert of the search and rescue and the safety of navigation from 2005 to 2007. He was appointed as the coordinator of the IMO NAV Sub-Committee Correspondence Group on AIS AtoN from 2011 to 2013. He has been appointed as the chair of the IALA e-Navigation Information and Communication Committee since 2017 and also chaired the IALA Workshop on MASS in 2021 and on Maritime

Digital Communication in 2023, both hosted by the Japan Coast Guard. He is currently the member of the Japanese delegation to the IMO MSC and NCSR Sub-Committee.

S13.5 Leveraging emerging technologies combining behavioral analysis and data exchange (119)

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ABSTRACT

Digitalized maritime services are no longer a future possibility. We stand at the doorstep of rapid developments in the use of AI and BigData, which combined with sensor fusion, will be important support systems for future maritime safety, efficiency and sustainability as well as autonomous operations. On behalf of the Norwegian Coastal Administration, Kongsberg Norcontrol has developed the first version of BEAN (Behavioral Analysis), a decision support system that combines historical data, sensor fusion and AI (smart algorithms).

When implemented with e-Navigation services, such as Reference Route and Just-In-Time Arrival, onshore operators have flexible and powerful resources to both plan for safer, efficient, and more environmentally friendly movements within Norwegian waters, as well as be alerted hours in advance to abnormal behavior and potential conflicts along ship's routes.

These services are integrated into the Norwegian Coastal Administration's next generation management information system, which serves as a hub for delivering a growing variety of shore-based digital maritime services. This presentation provides an overview of the current state of the art, enabling technologies and activities, key projects and initiatives in Norway, and the real-world consequences these have on the safety and security of maritime traffic.

(No paper submitted)

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Björn Coster is Kongsberg Norcontrol's Market Manager for the VTS market globally as well as Managing Director Kongsberg Norcontrol Singapore. Björn has held this position since 2018 with responsibility for Operations and Marketing & Sales in East Asia and Oceania. Björn first joined Kongsberg in 2011 as Project Manager and worked with numerous VTS delivery and development projects worldwide.

Björn has a MSc in Electrical Engineering from Chalmers University of Technology and worked with ship propulsion-, electrical distribution- and automation systems in Siemens and Aker Kvaerner before joining Kongsberg Norcontrol.

S113.1 Cruise ship Safety - Potential Risk Reduction Measures (120)

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ABSTRACT

In February 2022, a committee appointed by the Norwegian Government delivered a report with recommendations on how to improve maritime safety and emergency preparedness for Cruise ship activity in Norwegian waters. The direct background was the severe incident involving the Cruise ship Viking Sky on March 23, 2019. The vessel lost propulsion in strong wind and rough sea in littoral waters, and 466 passengers were evacuated by helicopter before the crew regained control of the vessel.

The Committee stresses that it is not feasible to have sufficient search and rescue resources to handle worst-case scenarios, but they propose 66 risk-reducing measures with an emphasis on preventive measures. In this paper, we will give a short overview of these measures and investigate a little deeper into the measures that fall under the IALA toolbox.

The paper will also give a brief overview of the cruise activity and trends in Norway, review some accidents and risk factors emphasising those associated with cruise activity in the winter season, before reviewing some of the risk reducing measures.

KEYWORDS: Cruise ship, maritime safety, risk reduction, Viking Sky incident, accident prevention, emergency preparedness, VTS, IALA.

1 INTRODUCTION

The cruise ship Viking Sky experienced a very serious near-miss grounding at Hustadvika on the coast of Norway in March 2019. The ship with 1373 persons on board (915 passengers) had a blackout and drifted towards the shoreline in severe weather conditions. One of the ship's anchors slowed down the drifting, and by using severely limited engine power the crew and pilot barely managed to avoid grounding. During the incident 466 passengers were lifted from the vessel by helicopter over a period of 17 hours. There were no fatalities, but 23 people were injured. The conditions made it impossible to use lifeboats or rafts.

The cruise ship traffic in Norway has increased over several years. Larger ships, more traffic in the shoulder seasons and winter months, as well as increased activity to remote destinations, such as Svalbard, is challenging for both the industry and the Government.

The Government appointed a Cruise Committee by Royal Decree in 2020 to assess the safety and emergency preparedness challenges and advice on risk reduction measures for the cruise ship traffic in Norwegian waters and adjacent sea areas [1]. The Committee presented its report to the Minister of Justice and Public Security in February 2022 with 66 recommendations on improved cruise ship safety.

In this paper, we will give a short overview of these measures and investigate a little deeper into the measures that fall under the IALA toolbox. Even though the focus is on Norwegian waters, most of the safety challenges and the risk mitigations should apply to a global audience.

The paper will also give a brief overview of cruise activity and trends in Norway and review some accidents and risk factors with an emphasis on those associated with cruise activity in the winter season.

2 CRUISE SHIP TRAFFIC STATISTICS

The global cruise ship fleet consists of approx. 420 ships with an average age of 21 years. During the Covid-19 pandemic, the fleet has been reduced and the scrapping of older cruise ships increased in 2020 [1]. In Norway, 121 unique cruise ships operated in 2019, which means that roughly 29% of the global fleet visited Norway on one or more occasions.

Most cruise ships visited Norway in May through August, but from 2015 to 2019 there was an increase in the shoulder seasons, i.e., in April, September and October, as well as in the winter months. In 2022, this trend was even stronger with the restoration of the traffic after the Covid-19 pandemic.

The biggest increase has been in large cruise ships (Number of persons on board POB >3000) and in the smaller range (POB 50-500).

The increased activity in Norway includes our Arctic area Svalbard. The expedition cruise ship has typically 13-500 passengers with an average capacity of 200 passengers. In total, 66 cruise ships of all categories visited Svalbard in 2019 [1].

Figure 6: The Official Norwegian Report NOU 2022:1

3 ACCIDENTS AND INCIDENTS WITH CRUISE SHIPS

Mileski et al (2014) [2] provide an overview of cruise ship incidents and accidents.

The most serious recent accident happened on Jan. 13th, 2012, when the cruise ship Costa Concordia grounded outside Isola del Giglio (Tikkanen, 2019) [3]. At the time of the accident, the ship had 3206 passengers and a crew of 1023 on board. The ship deviated from its original voyage plan, and the ship grounded on an underwater rock, which resulted in a 53-meter tear in the hull. The accident resulted in 32 fatalities and a financial cost of $ 2 billion (Lloyd´s, 2018) [4].

In Norway, there have been several incidents and accidents involving cruise ships and passenger ferries. On November 26th, 1999, the high-speed passenger ferry MS Sleipner left Haugesund in the evening bound for Bergen. The weather conditions were rough, it was dark with low visibility, strong winds, and rainy. Shortly after departure from Haugesund, Sleipner grounded on the rocks (Store Bloksen) north of Ryvarden due to navigational errors. The ferry sank within 30 minutes, and the evacuation means did not work properly, leaving many people in the cold sea and 16 persons drowned (Bakka, 2020) [5].

The Norwegian Coastal Express (Hurtigruten) has been travelling along the Norwegian coast between Bergen and Kirkenes with cargo freight and passengers since 1893. The last major accident with fatalities occurred on Oct. 21st 1962 when Sanct Svithun grounded due to navigational errors and sank. 41 out of 89 persons (passengers and crew) drowned (Kjerstad, 2021) [6].

4 RISK - CRUISE SHIP ACCIDENTS

Several studies on drifting risk, accident risk or frequency of grounding of Cruise ships has been made (Utne, Dimmen, 2022) [7], and different risk factors (ship related, external, human, organisational, etc.) investigated. One study states that the risk is in the As Low As Reasonably Practicable (ALARP) area. For this paper, it is sufficient to acknowledge that although the probability of a serious accident is low, the potential consequence is high or even catastrophic. In addition, harsh weather conditions both increase the probability of an accident and make any rescue operations difficult, which increases the overall risk.

During the Viking Sky incident, six rescue helicopters were available and 3-4 helicopters used in the most efficient “rotation”. The average rescue time per person from the ship was 2,2 minutes. After approx. 17 hours only about 1/3 of the people on board had been rescued.

Viking Sky did not have a helideck, and the method of evacuating personnel was by hoisting them with a sling in a rope lowered from the helicopter. Compared to landing on a dedicated platform, this is a relatively slow way to fill up the helicopter with passengers (AIBN, 2019) [8], but could be the only practical possibility for evacuation, since lifeboats and rafts on board cruise ships can be impossible to use in bad weather. This is due to the ship movements in the waves and damages that may result from the lifeboats crashing into the ship hull if launched. Ships losing propulsion will experience rougher movements in the sea than when vessel speed is maintained.

5 RISK REDUCING MEASURES

The Cruise Committee suggested in total 66 risk reduction measures, emphasizing preventive mitigation, grouping them into categories [1]. Utne, Dimmen, 2022, [7] describes these categories as follows:

> *“**A holistic approach is needed:** There is a lack of an overall plan for the cruise industry in Norway, with clearly stated goals and priorities. The current focus of the authorities is mainly on environmental impact, but sustainability also includes maritime safety. The Norwegian authorities should therefore prepare a national plan for cruise traffic as part of the tourism industry, including safety, emergency preparedness and rescue. Furthermore, Norway, as a shipping nation, should also play a leading role in strengthening relevant international regulations of the cruise traffic.*
>
> ***Improved cooperation between the cruise industry and the authorities:** Cooperation is important to handle the challenges of the cruise traffic. The cooperation between the authorities and the cruise industry has so far been characterized by a more random approach but should be more structured and predictable in the future.*

Operational limits: *The ship operator and crew may not consider the additional risks that are present in Norwegian waters, especially during winter cruises, sufficiently. Different risk perceptions about when a voyage should be performed or not, have been pointed out as a challenge. Due to the limitations with respect to Mass Rescue Operations, and the limited capacity in the health service to receive and treat many injured at the same time, the Committee suggests that cruise ships with length > 150 m should be subject to traffic restrictions. This should be based on weather criteria, such as wind speed or wave height, as well as seasonal restrictions. In Svalbard, there are large distances and very limited rescue and health resources, and weather and ice conditions can change quickly and unpredictably. Therefore, a majority of the Committee members recommend implementing a limit of 500-750 people onboard cruise ships in the territorial waters off Svalbard. There are concerns about an increasing trend of cruises towards the North Pole, and Norway should take the initiative for an international regulation of this traffic.*

Access to data and information: *Easy access to quality-assured and up-to-date information contributes to greater predictability and is therefore important when it comes to reducing the likelihood of serious accidents and their consequences. Navigation charts have insufficient quality in some areas along the coast including Svalbard, and this should be improved. Also, the Norwegian Meteorological Institute must prepare ice maps for all days of the week. Today, relevant information is spread among many different government actors, but official information from the Norwegian authorities to the cruise industry should be available from one single resource.*

Communication systems*: Reliable communication systems are important for safe navigation, SAR, and emergency communication. Extensive development of satellite-based broadband solutions is underway in the High North. The Norwegian authorities should actively take advantage of this opportunity that enable new appropriate services for maritime safety, emergency preparedness, and rescue.*

Training and competence on board: *Norway has a demanding coast with rough and rapidly changing weather conditions, particularly in winter. These additional challenges are not fully reflected in the international competence requirements. Thus, the Committee proposes to implement various competence requirements, and Norway must be a driving force internationally.*

Research and development: *There is a need for improved knowledge through more systematic efforts in research and innovation related to the prevention of major maritime accidents and emergency preparedness with cruise ships. Furthermore, the cruise industry should also increase its involvement and contributions.*

Risk assessment: *A thorough risk assessment must consider the relevant RIFs, cf. Table 2. Good risk assessments contributes to increased situation awareness and reduced risk. The Norwegian authorities should develop a guideline on risk assessment for the cruise industry.*

Voyage planning: *Existing requirements to voyage planning could be more specific, and Norway should therefore work to ensure that the IMO guidelines for voyage planning are updated. The Norwegian Coastal Administration should create more reference routes for cruise ships along the coast.*

Cooperation plan for SAR: *There are IMO requirements for a co-operation plan for SAR, which purpose is to enable cruise ships on international voyages, shipping companies, and rescue centres to co-operate more efficiently together in emergencies. The Norwegian authorities have not systematically followed up these requirements, and further, more passenger ships than those currently covered, should be included.*

The ship´s technical safety and certificates: *The requirements to technical safety on cruise ships have been developed over time and are generally not introduced with "retrospective" effect. This means that the ships sailing in Norwegian waters have somewhat varying technical and safety standards. Many of the cruise ships do not have real redundancy in their propulsion machinery. Norway should therefore* *work through the IMO to introduce requirements for operational assessment related to the certification of all passenger ships, as well as to introduce requirements for redundant propulsion machinery for larger passenger ships.*

Emergency towing equipment: *When sailing close to the coast, the time available to get a tow established and prevent grounding is short. Good solutions for emergency towing equipment and devices on board, are therefore important. Norway should work through the IMO to introduce international requirements for towing equipment on board all cruise ships. Furthermore, exercises including emergency towing should be practiced more often.*

Rescue equipment: *Although the cruise ship will often be the safest place to stay in a serious incident, sometimes it will be necessary to evacuate the ship. Today's requirements for rescue equipment are not sufficiently adjusted to the sailing conditions, and more stringent requirements are needed. The Norwegian authorities should stimulate research and innovation related to rescue equipment, including lifeboats. The cruise industry should ensure that new and safer technology for lifeboats and rescue equipment is used.*

Traffic monitoring and reporting: *Monitoring the cruise ship traffic is important and automatic positioning reporting systems, such as Automatic Identification System (AIS) and Long-Range Identification and Tracking (LRIT), are key tools, in addition to data in ship registers and ship reporting systems. Nevertheless, such data does not always contain information on resources onboard that may be relevant in a rescue operation. Also, smaller expedition cruise ships do not always have AIS onboard. This is a requirement the Norwegian authorities should introduce for all passenger ships. Vessel Traffic Service (VTS) areas should be expanded. Furthermore, the authorities should require cruise ships to immediately report any changes that may affect the ship's automatic position reporting or operational capability.*

Resource allocation: *A correct overview of available resources needed to handle serious incidents with cruise ships is important for the stakeholders involved. The Barents Watch (2022)* [9] *service should thus be further developed.*

Communication during an incident: *A common situation awareness, communication, and coordination are important for any handling of serious incidents. Currently, this is a challenge due to the use of different communication platforms. Hence, the Norwegian authorities should consider a common platform for digital communication.*

Crisis management onboard: *How the master and crew onboard utilize the time window in an emergency may have a major impact on the consequences. The Norwegian authorities should therefore consider setting stricter requirements for medical competence onboard cruise ships. They should also collaborate with the cruise industry to facilitate better technological solution for passenger lists and lists of evacuees.*

Mass Rescue Operations: *Mass evacuation from a large cruise ship is a complex, and time-consuming operation, and in many scenarios, it can be an impossible task to save everyone onboard. In remote areas, other cruise ships may arrive first, and the Norwegian authorities should therefore encourage the cruise industry to cooperate to be able to assist when sailing in such areas.*

Reception onshore: *Serious incidents with cruise ships can occur anywhere along the coast and may be a very big burden for any municipality that may be affected. Coastal municipalities and central authorities should prepare for handling cruise incidents onshore. Especially in Svalbard, it may be necessary to establish an emergency camp onshore or on the ice while waiting for rescue resources. Emergency camps are also particularly challenging in Svalbard, where low temperatures, challenging weather conditions, large distances and the risk of polar bear attacks must be considered. Here, cruise operators have a responsibility according to the Polar Code to ensure that they are adequately equipped* *to take care of passengers and crew until help arrives, and the industry must use equipment that ensures real survival.*

Exercises: *Exercises are an essential tool for strengthening crisis management skills and cooperation between actors. Norway´s Joint Rescue Coordination Centre should be strengthened and enabled to arrange regular rescue exercises with cruise ships, in collaboration with other relevant stakeholders. Learning from exercises is also very important and this needs to be improved.“*

6 IALA RELEVANT MEASURES

The 66 recommendations can be found in an excerpt of the official report in English [10]. A subset of the recommendations is particularly relevant for the IALA, and guidance to some of them can be found in the IALA standards, recommendations, and guidelines.

Traffic regulations / Operational limits: The committee recommends that some particularly exposed coastal areas should be regulated by the authorities. The purpose is to minimise the risk of incidents in severe weather conditions by closing the areas for large cruise vessels in strong wind conditions. The effect would be that affected vessels must wait before transiting the affected area or divert by choosing a different route.

The NCA is currently working on draft regulations in close dialogue with the industry to achieve this. A key element is the monitoring of the area by the VTS operator and the availability of good quality Metocean data.

Voyage planning / Reference routes: One finding is that good voyage planning can improve the operator's ability to take the local conditions into account. This will also help in handling situations that might occur while underway. One important part of good voyage planning is to choose safe routes, including knowledge of local regulations. The Norwegian Coastal Administration offers quality-assured routes for vessel less than 150m LOA and 9m draft, and the committee recommends that NCA should offer similar service for larger cruise vessels.

The NCA has started to publish reference routes for larger cruise ships and will evaluate this before implementing this for the entire coastline.

VTS monitoring: VTS operations has a risk-reducing effect in the VTS service areas. The Norwegian coastline is long, and some of the areas with high cruise activity are not within VTS service area today. Formal safety assessments and cost-benefit analysis show that, despite low overall traffic, it is recommended to expand the VTS service areas. In addition, the committee recommends using more big-data analysis to assist the VTS operators in alarm functions and decision-making, even outside the traditional VTS service areas.

The NCA has, in cooperation with the VTS vendor Kongsberg and the Norwegian defence research establishment FFI, developed a prototype of real-time automatic detection of abnormal behaviour in our fairways. This is based on big-data analysis, where vessels are categorised into groups and the various groups' "normal behaviour" is determined through long-term AIS data. The system is currently undergoing operational testing and evaluation at our VTS centres.

e-Navigation services: The committee recommended that several of the e-Navigation services should be implemented for cruise vessels. This was particularly mentioned for Metocean data distribution (MSP 13,14), Maritime Safety Information (MSP 5), VTS services (MSP 1,2,3,8), but also data relevant to other MSPs. Special emphasis was made to help emergency responders to have a good situational awareness. This includes data from ocean monitoring, AIS, VTS information as well as operator provided data on the capacity of each vessel when it comes to being able to assist other vessels when incidents occur. This would typically include information on medical capacity, availability of "expedition boats" ("Zodiacs"), Helipad capability, etc.

The implementation of e-Navigation services will deal with some of these recommendations. In addition, the Norwegian Coastal Administration is operating an information service for vessels operating in Arctic waters, “ArcticInfo” (https://www.barentswatch.no/arcticinfo/?lang=en) [9], where some of the requested functionality could be implemented.

7 CONCLUSIONS

This paper sums up the risk of cruise ship traffic along the Norwegian coastline and gives an overview of measures recommended by the “Cruise committee” established by a royal decree. Measures particularly relevant for the IALA toolbox is identified, and the status of some current work relating to this is given.

8 ACKNOWLEDGEMENTS

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S113.2 Nautical Risk Assessment and Real Time Manoeuvring Simulation and integrated approach (160)

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ABSTRACT

The qualitative assessment of risks associated with nautical operations can be performed using the Preliminary Hazard Analysis (PHA) technique. Hazards are identified by experts, who assess the frequency and severity of their consequences. The risk is then quantified, and possible mitigation measures are proposed. The Real-Time Ship Manoeuvring Simulations, commanded by real pilots and tugmasters, reduce uncertainty regarding the consequences of some hazards, especially when there is no consensus among specialists.

The integration between the PRA and the Ship Manoeuvring Simulations, in a systematic and organized way, is a powerful tool for evaluating new ports and operations. Furthermore, the effectiveness of the proposed mitigation measures can be verified. The University of São Paulo has successfully applied this methodology in several port projects in Brazil, and this work will present some case studies.

KEYWORDS: manoeuvring simulations, risk assessment, preliminary hazard analysis.

1 INTRODUCTION

The integrated methodology of risk assessment and real-time manoeuvring simulations was applied by the University of São Paulo (USP) to a total of 22 nautical projects, in different regions of Brazil, as illustrated by Figure 1. These studies included the manoeuvres of several types of merchant vessels (containerships, takers, bulk carriers) in maritime and river ports, as well as barge convoys in rivers.

This methodology was initially developed to comply with the new international guidelines [1], and afterwards incorporated in the Brazilian regulations [2]. The research expertise on risk assessment of the LabRisco-USP (Analysis, Evaluation and Risk Management Laboratory) was merged to the TPN-USP Ship Maneuvering Simulation Center [3] to develop and improve this technique.

2 INTEGRATED METHODOLOY OF RISK ASSESSMENT AND REAL-TIME MANOEUVRING SIMULATION

The Preliminary Hazard Analysis (PHA) is a technique that supports the risk assessment of new systems, processes, and procedures, especially when the current experience provides limited insights regarding the potential safety issues. Its application involves the systematic listing of hazards and hazardous events in tabular format – see Figure 2 for a typical table header. For each hazardous event, the analysts should list causes and consequences, assign frequency and severity estimates, and propose risk control measures (RCM). By combining the frequency and consequence categories, it is possible to classify the hazardous events in terms of risk.

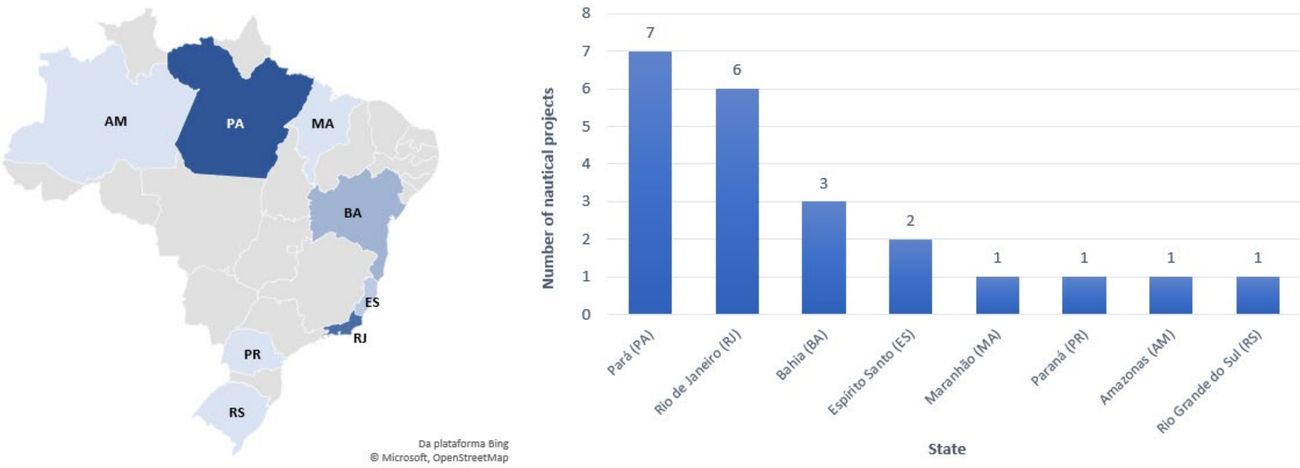


Figure 7: Number of nautical projects developed per state in Brazil

Hazardous event	*Causes*	*Frequency*	*Consequences*	*Severity*	*RCM*	*Risk*

Figure 8: Typical PHA table header

When applying the PHA, it is important to gather as much information as possible. In the case of nautical projects, this includes, but is not limited to, nautical charts, local environmental data, updated bathymetry, and reference ships. It is highly recommended that local nautical experts take part in the process, as well as other stakeholders, since they can provide valuable information that is not formally documented and raise concerns that may not be obvious to the risk analysts. Furthermore, the real-time simulations are an interesting resource to evaluate several aspects such as expected consequences, and the effects of RCMs (e.g., how an additional tugboat can influence the impact of grounding accidents).

The process illustrated by Figure 3 was developed by the authors [4] to apply the PHA to nautical risk assessment while addressing all the aspects presented above. The process was improved after several studies and feedback from stakeholders. It includes seven activities and takes into account the participation of experts and the execution of real-time simulations. Two case studies are presented in this paper to demonstrate the application; the first involves the navigation on the Amazon River (see section 4), and the second involves the navigation on a port approach channel (see section 5).

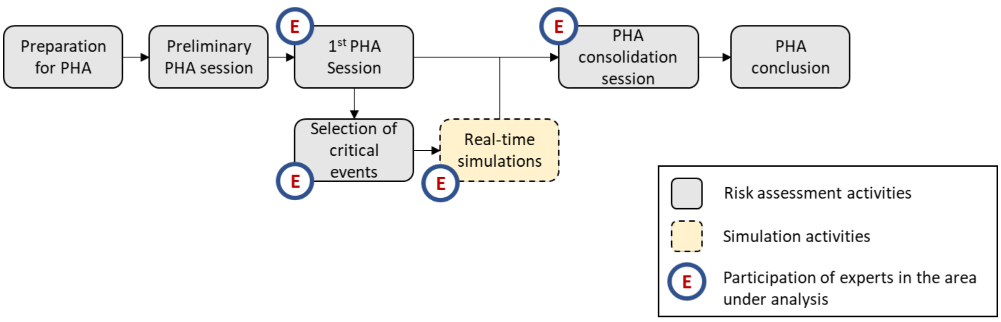


Figure 9: Activities for risk assessment supported by real-time simulation

The process starts by the preparation for PHA, in which the risk analysts familiarize with all the available documentation and data applicable for the specific area of study. It may include the analysis of similar projects, if applicable. The second step refers to the preliminary PHA session, where the risk analysts develop the initial PHA table, based on the information gathered during the preparation phase. If done by experienced analysts, the second step could cover the most common hazardous events, as well as incorporate data from previous analysis.

The following four steps include the participation of stakeholders and experts in the area under analysis (e.g., pilots, merchant vessel captains, tugboat captains). The 1st PHA session involves the familiarization of the experts with basic risk analysis concepts and the PHA technique. Afterwards, the participants become involved with an workshop to build the PHA table. The mediators can present and validate the results from the preliminary PHA session to guide the workshop, but there should always be room for the proposition of new events and the revision of historic data from other studies that may not be applicable for the current case. In short, independently on the approach, the result of the 1st PHA session should be a table that is representative of the accumulated knowledge of all participants.

When the PHA table from the 1st PHA session is available, the participants have to select critical events to be reproduced in the real-time simulations. Typical criteria of selection include, for instance: a) the non-tolerable risk events; b) events with significant uncertainty; c) events that motivated divergences among the experts; d) events with RCM whose effectivity can be checked in the simulator. The list of selected events is used to create simulation scenarios to be reproduced in the real-time simulations. Section 3 addresses the requirements for the ship manoeuvring simulator.

After the real-time simulations, the results are used to update the PHA table. The new evidence typically supports the review of the severity of consequences and addition or removal of RCMs. At this point, new hazardous events can be added too. However, it is important to note the real-time simulations are not a good source of information for the review of frequency assignments. Rare events are forced to occur during the manoeuvres (e.g., propulsion system failure, helmsman errors) and, therefore, they do not occur by chance. Furthermore, the number of simulations is small in terms of statistical significance.

After the PHA table is consolidated, the last activity refers to the conclusion of the PHA. At this point, the analysts generate a formal report detailing the whole risk assessment process, the results, and suggestions to the decision-makers. The results could also suggest the detailed analysis of specific hazardous events or aspects such as the human factor contribution to the risk. In this case, more sophisticated techniques should be adopted – see references [5 – 9].

3 SHIP MANOEUVERING SIMULATOR REQUIREMENTS

In order to carry out Real-Time Ship Manoeuvring Simulations to support Risk Analysis, the Simulation Center must be provided with a minimum infrastructure in terms of facilities and software.

The simulation session must be controlled from a separate room Control Room, in which the operator performs the complete configuration of the scenario, starts the run, monitors its execution and imposes, at certain times, the failures or hazards to be analyzed, without the knowledge of the pilot or captain. It is important that this room be physically separate from the simulators. The following figure shows the TPN-USP infrastructure, with Full Mission simulators and Tugstations being controlled by the operators in the Control Room.

The instructor / operator software must be able to simulate a large number of failures and hazardous events, such as:

- Propulsion system failure, blackout
- Rudder failure (including rudder jam in non-neutral position)

- Tugboat failure (blackout, line rupture, communication problem)
- GPS, AIS, Radar failures
- Helmsman errors and bridge communication
- Sudden variation of environmental conditions (example: wind gust, strong currents, fog)
- Target ships crossing the route of the ownship

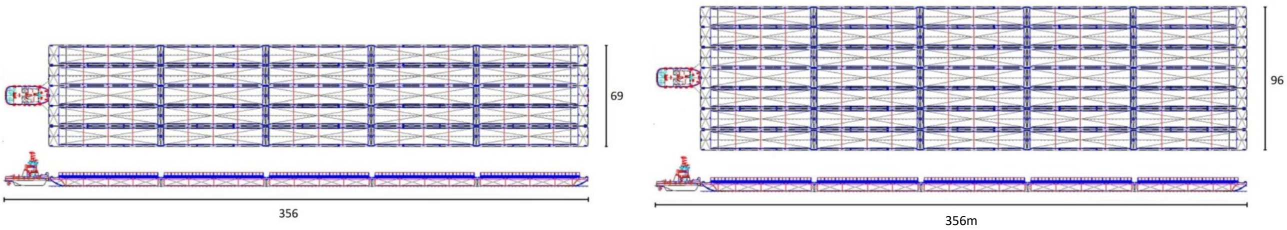
Figure 10: Control Room and Ship Simulators

4 CASE STUDY 1: AMAZON RIVER NAVIGATION

There is significant traffic between the Amazon River and the ports in the Belém region, located at the mouth of the Tocantins River. A complex network of narrow channels, known as "furos," connects the two estuaries, and numerous river convoys, mostly transporting agricultural products, navigate these channels. The "furos" encompass a series of estuaries, bays, and channels where local communities live in stilt houses along the riverbanks. Additionally, small villages can be found along the coast of the channels. Figure 4 provides a general overview of the Amazon and Tocantins Rivers, highlighting the link between the two rivers' mouths through the narrow channels, as well as the primary navigation route used by the large river convoys.

Figure 11: Amazon and Tocantins rivers and the set of narrow channels connecting them, including a photo of a 5x5 convoy in that area.

In the Amazon River, there is the simultaneous navigation of cargo ships (usually Panamax class) and 7x5 convoys (35 barges), which cross frequently. In the "furos", due to the narrow width, the largest authorized convoy has 25 barges (5x5), and there are no crossings with cargo ships. The study's main focus was to evaluate navigation safety for these 5x5 convoys along critical bends or stretches in the "furos" as well as overtaking and crossing maneuvers involving convoys and containerships on the Amazon River, using Real-Time Simulations and Risk Analysis. Both operational and failure maneuvers were tested to determine their feasibility and identify possible mitigation measures. The figure below provides an overview of the main characteristics of the river convoys.



5x5 convoy
Displacement 97.200ton (Loaded draft 4,5m)
Conventional Propulsion
2 x Rudders + 2 x 2250kW Propellers

7x5 convoy
Displacement 135.300ton (Loaded draft 4,5m)
Azimuthal Propulsion
3 x 1600kW Azimuth Thrusters

Figure 12: Main characteristics of the river convoys

In collaboration with local nautical experts, we identified and simulated four critical areas along the "furos". These areas include narrow straight channels, bends with small radii, sections with strong currents, and areas with populations residing near the margins. We conducted 26 maneuvers under the guidance of an experienced river skipper familiar with the area and responsible for controlling the convoys. Some of these maneuvers involved crossing with cargo ships controlled by a pilot in the Amazon River (as shown in Figure 6). Additionally, we accounted for potentially hazardous situations identified during PHA meetings, such as wind gusts, unexpected strong currents, pusher boat blackouts, and unsafe crossings due to miscommunication between the pilot and river skipper.

Figure 13: Two simulators used in the study: (left) full mission cargo ship bridge + pilot; (right) pusher boat simulator + river skipper

One example is the "Volta do Mutunquara", a sharp bend section with strong currents and houses near the banks (Figure 7). To evaluate the safety of navigation, we conducted three simulations of a fully-loaded convoy going down. During these simulations, we identified the need for an additional tug with a bollard pull of 16T to mitigate the risk of dangerous events. In Run #16, when the pusher boat experienced a blackout, this extra tug played a crucial role in reducing the convoy's speed and ensuring that the collision with the bank happened at a lower forward speed, resulting in minimal damage.

We conducted crossing and overtaking simulations between 35 barges convoys and cargo ships in critical areas with heavy vessel traffic or where bank changes were necessary. During these simulations, we tested for difficulties in communication between the pilot and the river skipper and inadequate timing. However, in all cases, we found that the space available was sufficient for the convoy to alter its course in time to maintain a safe distance of at least 0.2 miles from the passing ship. An example of such a crossing near Urucuricaia Island (Amazon River) is shown in Figure 8.

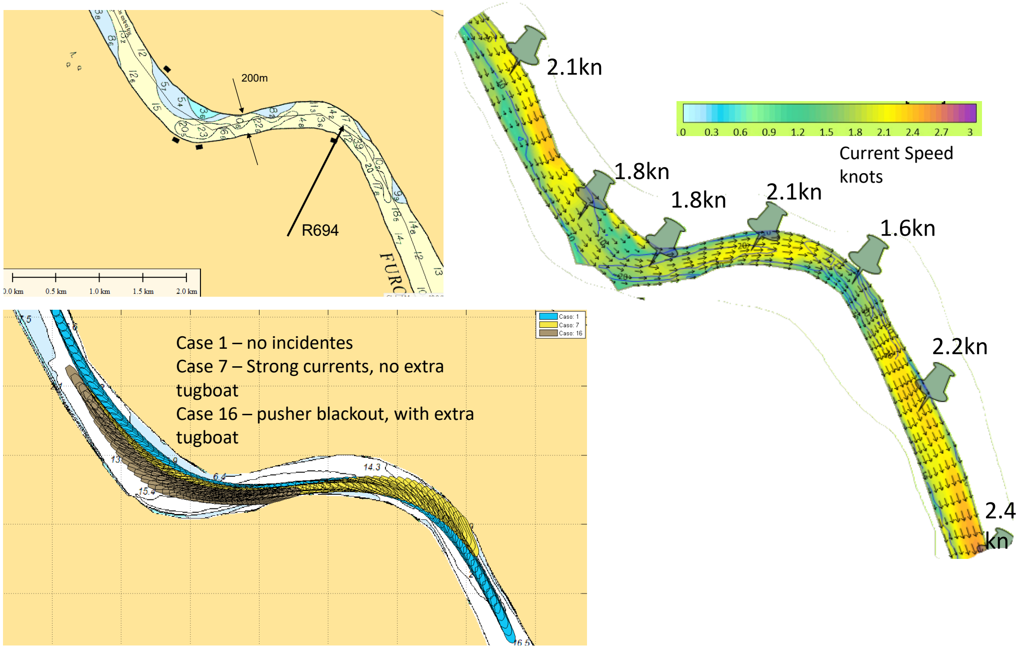


Figure 14: “Volta de Mutunquara”: main dimensions, current obtained from a hydrodynamic model of the river and trajectory of the 5x5 convoy during three simulations

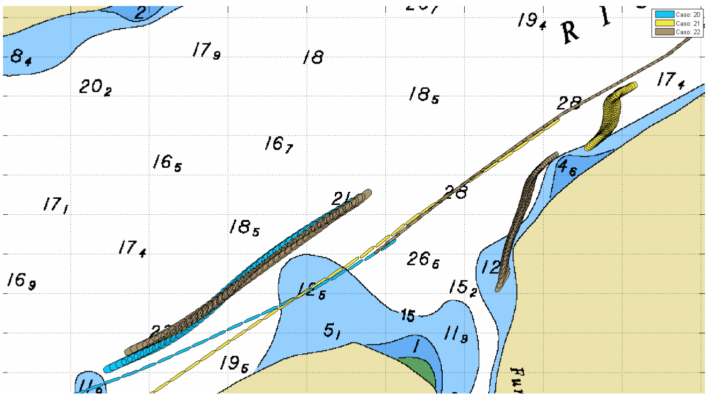


Figure 15: Crossing and overtaking maneuvers: Cargoship and Convoy with 35 barges – near Urucuricaia Island (Amazon River)

The PHA developed for this study registered 164 hazardous events, considering the river convoy types, navigational areas, and navigation destinations. The types of hazardous events included: propulsion system failure, steering system failure, blackout, close proximity with other convoy, close proximity with merchant vessel, close proximity with small boats, adverse wind conditions, adverse current conditions, and human error of the convoy pilot.

The risks were assessed using the risk matrix of Figure 9a, which contain three categories: tolerable (T), moderate (M) and not tolerable (NT). The events classified as NT necessarily need to be treated by the proposition of risk control measures. For the events classified as M, risk control options are not mandatory, but should be applied if economically feasible, following the "As low as reasonable possible" (ALARP) principle. The results for case study 1 are presented in Figure 9b, which shows the number of hazardous events classified according to each category. The definition of consequence and frequency categories followed the proposal of refercence [4].

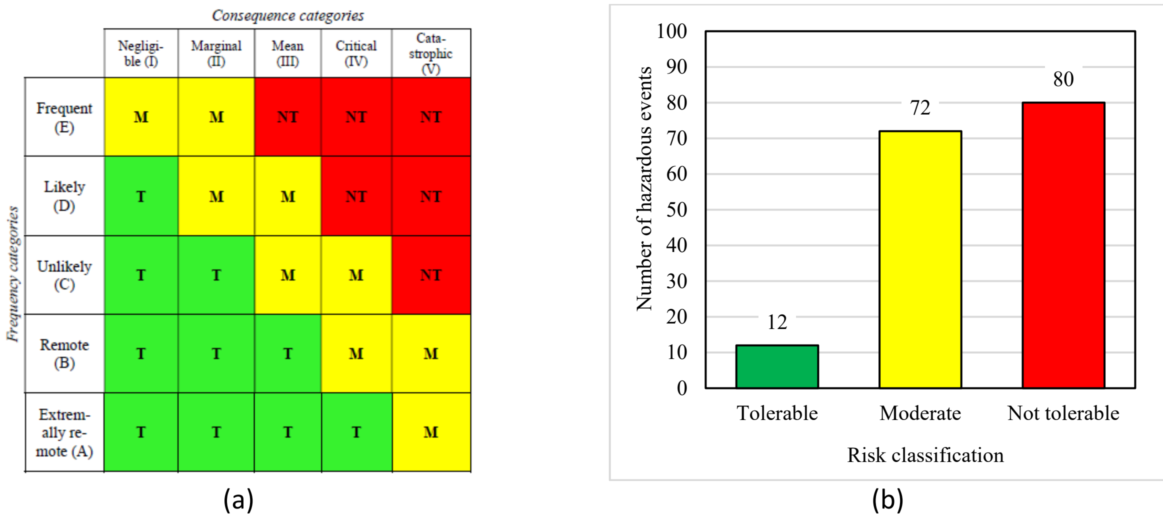


Figure 16: (a) the risk matrix; (b) the risk assessment results for the case study 1

The number of NT events is relatively high and account for 48.8% of all events. Therefore, several risk control options were proposed, such as traffic priority schemes, repositioning of aids to navigation, employment of an escort tug to support the convoys, and use of portable pilot unit equipment to support the navigation.

5 CASE STUDY 2: PORTO SUDESTE BRASIL (PSB)

Case Study 2 involves a Qualitative Risk Analysis supported by Real-Time Ship Manoeuvring simulations of oil tankers in the access channel and turning basin of the Porto Sudeste Brasil Terminal (PSB). The PSB is located in Sepetiba Bay in the state of Rio de Janeiro, Brazil. The study scenario is presented in Figure 10. The 20m depth access to the PSB is divided into three parts: the Access Channel, Turning Basin, and Approach Area. The Access Channel consists of two bends and a 206m wide straight section, while the Turning Basin has a diameter of 600m.

The study analysed the manoeuvring of both Conventional and DP (DynamiC Positioned) Suezmax tankers. The main characteristics of the vessels are listed in Table 1. Simulations were conducted at full and half loaded conditions to evaluate the vessels' manoeuvrability under various scenarios.

Table 7: Main characteristics of the vessels analyzed in the case study 2

Vessel Suezmax	Full Loaded	Partially Loaded	Propulsion and Thrusters
LOA	278.5m		Conventional: Fixed Pitch Propeller, 17.100kW, no thrusters
LPP	264.0m		
Beam	48.0m		
Draft	17.2m	12.5m	DP: Controllable Pitch Propeller, 17.100kW, Bow Thruster 2200kW, Stern Thruster 1935kW
Deadweight	160000DWT		
Displacement	183870 ton	128103 ton	

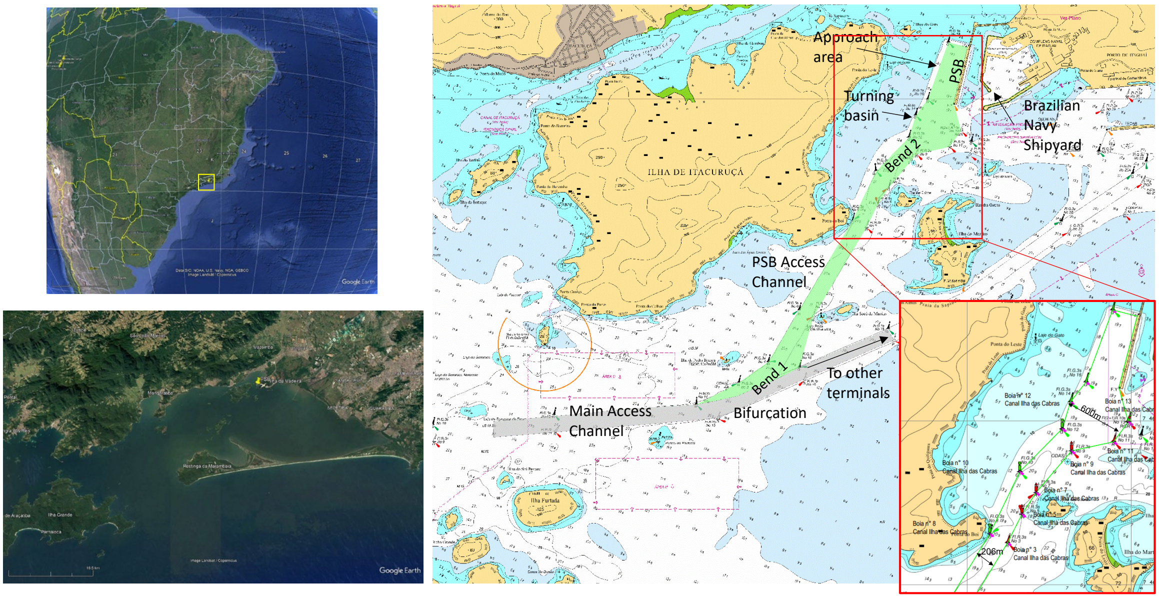


Figure 17: Location of the Porto Sudeste Brasil Terminal (PSB)

A total of 29 manoeuvres were carried out within the current limits of 0.8kn in flood and 1.0kn in ebb conditions (measured at the Bifurcation). Winds of 20 knots were simulated from the W, SSW, WNW, N, NNE, NE directions. The effect of waves in the manoeuvring area was not considered, as the access channel is sheltered. The manoeuvres considered operational and hazardous situations such as wind gusts, unexpected stronger currents, rudder or propulsion failure, tug line rupture, and miscommunication with tugmaster or helmsman. The manoeuvres were controlled by a local maritime pilot using a full-mission simulator. A tugmaster with expertise in the area controlled the center-aft tug, and the simulator crew commanded the remaining tugs using a vector tug system, as depicted in Figure 10.

Part of the inbound and outbound manoeuvres are presented in Figure 11. The only non-admissible failure for the inbound tests was the Run#23, after a rudder jam 30° to portside (Figure 12). Besides the use of four tugboats and the engine in full astern, it was not possible to avoid a collision with the rocky bank close to the Buoy 5. After that, the vessel did a "zig-zag" and crossed the channel, almost reaching the green buoy 10.

Figure 18: Simulators, Control Room and 3D model

In this second case study, the scenarios for PHA were composed of navigation area, ship type, ship loading conditions, and tide conditions. A total of 528 events were identified considering all scenarios and the following hazardous events types: steering system failure, propulsion system failure, blackout, adverse wind conditions, adverse current conditions, human error when steering the ship, latency in the tugboat response, tugboat failure and towing cable failure, traffic monitoring error, error during simultaneous ship manoeuvres.

Figure 14 presents the results for the case study 2 in terms of number of hazardous events per risk category. The same risk matrix shown in Figure 9 was adopted. Most of the events were classified as M (about 84%). However, a non-negligible number of events was classified as NT (about 9%), demanding the proposal of risk control options. The following measures were proposed: a) improvement of metaoceanographic information system; b) communication with the local community to avoid dangerous interactions between merchant ships and local small boats; c) improvement of the emergency contingency plan to include drowning rescue measures; d) improvement of the access channel design and aids to navigation; e) employment of a second pilot.

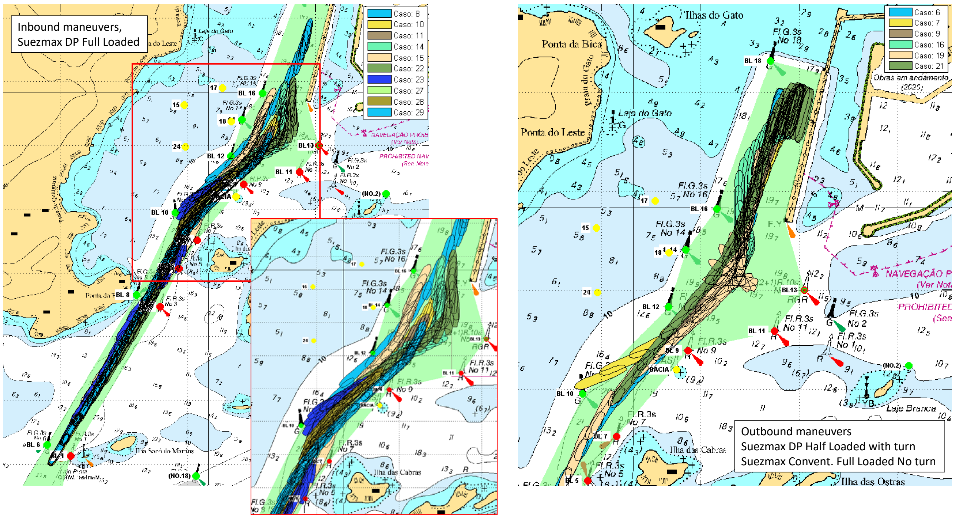


Figure 19: (left) Inbound manoeuvres, Suezmax DP Full Loaded, No turn (Starboard side alongside the berth). (right) Outbound manoeuvres, Suezmax DP Half Loaded with turn and Suezmax Conventional Full Loaded without turn

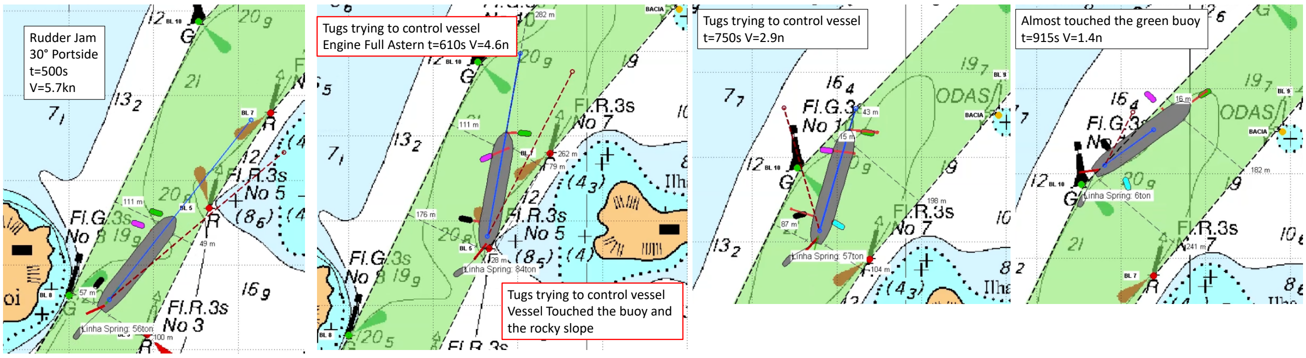


Figure 20: Sequence of the events, Run #23, Rudder Jam

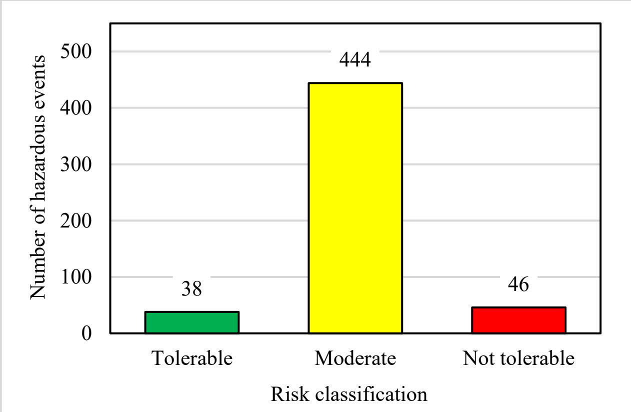


Figure 21: Risk assessment results for the case study 2

6 CONCLUSION

This paper showed the integration between the PRA and the Ship Manoeuvring Simulations, in a systematic and organized way, as a powerful tool for evaluating new ports and operations, including the evaluation risk-reduction and mitigation measures. Two case studies were presented in order to illustrate the methodology.

7 ACKNOWLEDGEMENTS

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S113.3 Integrating New Ship Simulation Technology int Port and Waterway Risk Assessment (053)

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ABSTRACT

Simulation is a proven method in risk management and is part of related IALA Seminars for Port & Waterway Risk Management. In contrast to statistical methods used in the seminar e.g. IWRAP, SIRA and PAWSA, simulation tools are focussing on dynamic process simulation and allow for improved risk assessment by integrating human as well as technical elements. For those purposes the innovative system “Simulation-Augmented Manoeuvring Design, Monitoring & Control” (SAMMON) has been developed and demonstrated in IALA seminars. The system consists of various modules for planning, monitoring & control of manoeuvres. It is a unique tool based on Fast Time Simulation for complex ship dynamic models for simulating all kind of manoeuvres under different environmental conditions – The tool is unique because it simulates up to 1000 times faster than real time and allows for steering by humans via a smart interface. It can be adapted to all kind of reference ships required for port and waterway design or further risk assessment and in VTS areas as well. In this paper, we introduce the potentials of the toolbox and provide exemplary case studies for port and waterway investigations as well as for enhanced objective risk assessments. The design of “Manoeuvring Plans” for complete port approaches in only minutes and in accordance with IMO guidelines for voyage planning is shown and the potential for optimising procedures and to find limits for manoeuvring is demonstrated. Moreover, manoeuvring areas can be calculated for sets of steering orders to visualize the shape of the areas for given time period for objective risks assessment of encounters onboard and ashore in a VTS.

KEYWORDS: Risk Management, Fast-Time Simulation, Port- and Waterways design, Port Risk Studies

1 INTRODUCTION

This paper provides a broad overview on new simulation technologies and its application for risk assessment by extracting some elements from lectures on "Simulation" as part of the seminars provided by the IALA World Wide Academy on the use of the "IALA Toolbox for Port & Waterway Risk Management" (see e.g. [9]). Within these seminars the software tools IWRAP, PAWSA / SIRA and the method of Simulation is introduced – specifically in this paper some parts of the lecture on simulation is shown. For maritime simulations it is standard that smaller or bigger simulators are used, up to so called Full Mission Simulators which are time consuming and expansive because they are running in real time to be very realistic. But also new innovative methods using Fast Time Simulation are already established to be more effective.

In this paper methods are described for the application of various simulation methods at the Maritime Simulation Centre Warnemuende and assessment of simulator runs with respect to risk levels. Simulation methods shown comprise Ship Handling and VTS Simulation as well as the specific Fast Time Simulation using SAMMON software. Discussions are made to understand the new methods and their advantages using samples to indicate what can be done to use simulation from two perspectives, i.e. from a waterway administration and from a shipping company.

2 INNOVATIVE SIMULATION AT THE MARITIME SIMULATION CENTRE WARNEMUENDE

2.1 Full Mission and Fast Time Simulation System SAMMON for Simulation-Augmented Manoeuvring Design, Monitoring & Conning

The Maritime Simulation Centre Warnemünde has proven high standard and reliable equipment since its inauguration in 1998 and was upgraded just recently for a budget of several Million Euro in 2023. The innovative equipment is based on latest on-board technology and guarantees to meet up-to date challenges to extend and refresh practical skills of ship personnel and port studies or fairway design risk assessment.

The complete assembly sets new international standards for improving maritime training by not only providing comprehensive simulation of separate procedures alone: due to the interfacing of the simulators there is a higher realism in simulation of operational interchanges e.g. between navigators and engineers which can be reached by interfacing the Ship handling simulator to the ship engine simulator. Specifically, for VTS and coast guard training there is an interface to link VTS simulator and SHS.

Ship Handling Simulation for simulator training has a proven high effect for the qualification in training and was described earlier in context to complex ship operations (see e.g. [9]). However, it is based on real-time simulation, and i.e. one sec calculation time by the computers represents 1 sec manoeuvring time as in real world. This means despite of all other advantages of full mission ship handling simulation that collecting/gathering of manoeuvring experiences remains an utmost time-consuming process. For instance, a training session for a berthing manoeuvre might take one hour – if the first attempt fails or an alternative strategy should be tried then the next session needs another hour – this is not very effective.

Therefore, the method of Fast-Time Simulation FTS has been developed and will be used in future for increasing the effectiveness of training and also the safety and efficiency for manoeuvring real ships. The basic principle of that FTS system is to represent the full information from Pilot Card, Wheelhouse Poster and Manoeuvring Booklet (and additional trial results), condensed in a ship dynamic simulation model, which is even capable of simulating wind, current, and restricted water effects by using the innovative "Rapid Advanced Prediction & Interface Technology" (RAPIT). Even with standard computers it can be achieved to simulate in 1 second computing time a manoeuvre lasting about to 20 minutes. These RAPIT-based FTS tools were initiated in research activities of the Institute for Innovative Ship Simulation and Maritime System ISSIMS at the Maritime Simulation Centre Warnemuende, which is a part of the Department of Maritime Studies of Hochschule Wismar, University of Applied Sciences - Technology, Business & Design in Germany. They have been further developed by the start-up company Innovative Ship Simulation and Maritime Systems (ISSIMS GmbH [7]).

A brief overview is given for the modules of the FTS tools and its potential application - SAMMON is the brand name of the innovative system for "Simulation Augmented Manoeuvring – Design, Monitoring & Conning", consisting of the following software modules:

- Manoeuvring Design & Planning Module: Design of Ships Manoeuvring Concepts as "Manoeuvring Plan" for Harbour Approach and Berthing Manoeuvres (steered by virtual handles on screen by the mariner)
- Manoeuvring Monitoring & Conning Module with Multiple Dynamic Manoeuvring Prediction: Monitoring of Ships Manoeuvres during Simulator Exercises or Manoeuvres on a Real Ship using bridges handles, Display of Manoeuvring Plan and Predicted Manoeuvres in parallel; Calculation of various prediction tracks for full ships dynamic Simulation and Simplified Path prediction as Look Ahead for the future ships motion.

These modules are made for both:

- application in maritime education and training to support lecturing for ship handling to demonstrate and explain more easily manoeuvring technology details and to prepare more specifically manoeuvring training in Ship Handling Simulator (SHS) environment, i.e. for developing manoeuvring plans in briefing sessions, to support manoeuvring during the exercise run and to help in debriefing sessions the analysis of replays and discussions of quick demonstration of alternative manoeuvres and
- application on-board to assist manoeuvring of real ships e.g. to prepare manoeuvring plans for challenging harbour approaches with complex manoeuvres up to the final berthing/cast off of ships, to assist the steering by multiple prediction during the manoeuvring process and even to give support for analysing the result and for on board training.

2.2 SAMMON Planning Tool Interface

An important issue is the behaviour of the vessel under wind impact that can be easily explained and investigated by means of the SAMMON Manoeuvring Design & Planning tool. Some basic functions and interface display for the FTS are shown in the next figures (Several movies for the handling and application of this software can be found on [8]).

Figure 1 explains the interface, which combines:

- the interface window for the steering panel of the ship (right) for adjusting the controls for the selected Manoeuvring Point MP (actual position in red) and to select the desired environment conditions down below, e.g. wind, current and water depths,
- the electronic navigational chart ENC window (centre) to visualise the simulated ship's motion: black contours indicating the positions in time intervals for the display range, by means of the time slider at the bottom the reference position can be shifted to any position of the already predicted track where a new MP can be set and controls may be changed there – with this method chains of manoeuvring segments can be generated as e.g. in
- Interface elements to display the status of the current navigation data and actual ship manoeuvring controls (left and top) at the ship position on the track up to the positions of the next MP which is indicated as ship shape in blue colour in the ENC.

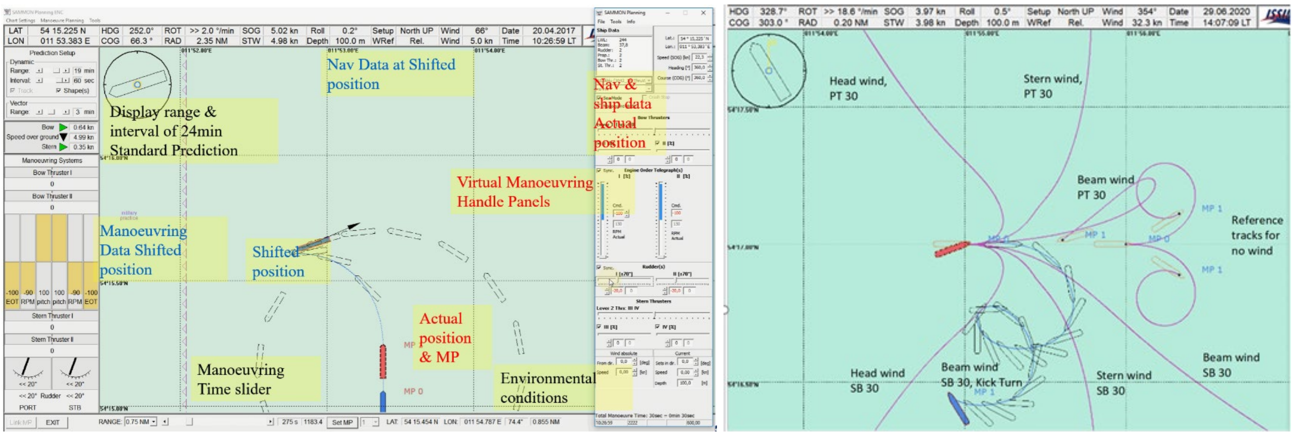


Figure 22: SAMMON Manoeuvring Design & Planning tool - left: Interface Elements with Explanations; - right: Simulation results for turning circles tracks (magenta curves) with Hard Rudder for a cruise ship at slow speed (EOT 30%, i.e. 6.2kn without wind)

In the same figure on the right-hand side several manoeuvres under different wind conditions are compared and the efficiency of the FTS can be seen in the fact that all these simulations and the preparation of the figure took less than 15 minutes (- In contrast to Full Mission Simulation, where a Turning Circle Manoeuvre of a ship takes up to 1 hour for big and slow ships - because it is Real Time Simulation!).

The manoeuvring tracks for hard rudder 35° turning circles with no wind on the right side serve as reference manoeuvres. All manoeuvres with wind are placed on the left side to be better visible. The turning tracks for head wind have smaller advance: due to the wind pressure the ship reaches not so much out into the initial direction. This is the contrary under stern wind, where the wind pushes the ship in wind direction. However, the wind does not allow the ship to turn further than the equilibrium on straight track – i.e. there is no chance to identify a transfer distance.

3 SAMPLE FOR RISK ASSESSMENT IN SHIP MANOEUVRING OPERATION

3.1 Sample for Description of Risk in Operating Vessels in Ports & Waterways:

There is a big difference in the risk assessment using

a) statistical simulation methods as e.g. in IWRAP or PAWSA measuring the probability of accidents in years (or even incidents) and

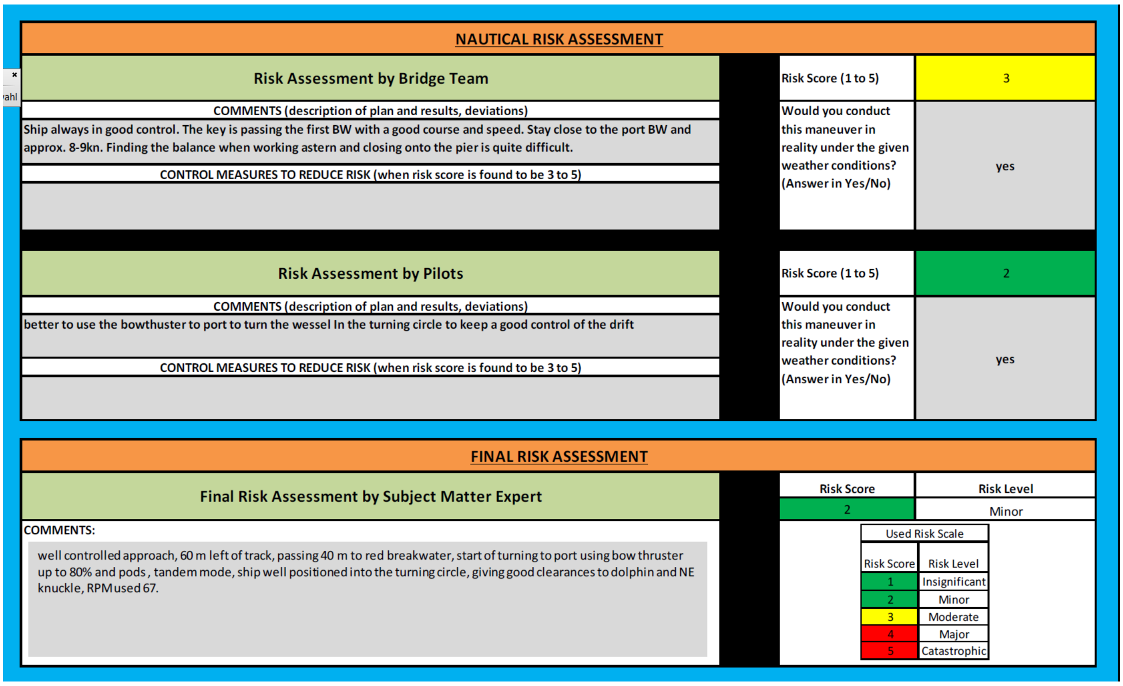
b) dynamic process simulation as for instance in SHS, SES or VTSS focussing on avoidance of violation of certain limits instead, e.g.:

Run:202	Maneuver: Arrival/163/SternIn	Wind:NW/20kn	Current/Swell:No	Tug use: No

NUMERICAL RISK ASSESSMENT

Risk Associated with Maneuvering Margin Reserve	Agreed Range				Values during the run	% Reserve used
	NO GO	Planned	Planned	NO GO		
Hazards	Min	Min	Max	Max		
Passing speed first entrance (bow enters BW)	3	5	8	10	8.6	30
Minimum Distance from 10 m depth line north of port entrance (during swing)	0	100	NA	NA	127.0	0
Minimum distance from Dolphin (during swing)	0	100	NA	NA	167.0	0
Minimum distance Red First Entrance	0	50	NA	NA	40.0	20
Minimum distance Green First Entrance	0	50	NA	NA	92.0	0
Passing speed Second entrance - bow first (bow enters BW)	2	3	5	6	NA	NA
Passing speed Second entrance - stern first (stern enters BW)	2	3	5	6	3.1	0
Final Risk Score Associated with Maneuvering Margin Reserve					3	

Risk Associated with Power Reserve	Powering Units	Time of exceedance of safety criteria (min)	Risk Score of Individual Powering Units
If a powering unit is not available, please put NA.	Steering	0:13	1
	Engine	3:25	4
	Bow Thruster	0:24	1
	Stern Thruster	NA	NA
	Tug 1	NA	NA
	Tug 2	NA	NA
Final Risk Score Associated with Power Reserve		2	



NAUTICAL RISK ASSESSMENT

Risk Assessment by Bridge Team	Risk Score (1 to 5)	3
COMMENTS (description of plan and results, deviations) Ship always in good control. The key is passing the first BW with a good course and speed. Stay close to the port BW and approx. 8-9kn. Finding the balance when working astern and closing onto the pier is quite difficult.	Would you conduct this maneuver in reality under the given weather conditions? (Answer in Yes/No)	yes
CONTROL MEASURES TO REDUCE RISK (when risk score is found to be 3 to 5)		

Risk Assessment by Pilots	Risk Score (1 to 5)	2
COMMENTS (description of plan and results, deviations) better to use the bowthuster to port to turn the wessel In the turning circle to keep a good control of the drift	Would you conduct this maneuver in reality under the given weather conditions? (Answer in Yes/No)	yes
CONTROL MEASURES TO REDUCE RISK (when risk score is found to be 3 to 5)		

FINAL RISK ASSESSMENT

Final Risk Assessment by Subject Matter Expert	Risk Score	Risk Level
	2	Minor

COMMENTS:

well controlled approach, 60 m left of track, passing 40 m to red breakwater, start of turning to port using bow thruster up to 80% and pods, tandem mode, ship well positioned into the turning circle, giving good clearances to dolphin and NE knuckle, RPM used 67.

Used Risk Scale

Risk Score	Risk Level
1	Insignificant
2	Minor
3	Moderate
4	Major
5	Catastrophic

Figure 23: Sample for Final Risk Assessment Form: Numerical risk assessment and Nautical risk assessment

For the assessment of simulation results the following methods are helpful:

1. Defining limits as Safety zones /Margins: Distances to prior defined Hazard Zones (red circle, black polygon) will be used as risk criteria (see Figure 3 centre)
2. Defining Manoeuvring Reserves as Margins / Thresholds: use of manoeuvring devices (Rudder, Engines, thrusters…) to the limits of capacity, e.g. thresholds as shown in Figure 3 right (alternatively also in time histories for other parameters as for instance rudder angle plots with max/min deflections and zero crossings or graphs for collision avoidance parameters like distances / CPA or TCPA time histories).
3. Allocating suitable scores for measuring the performance or violating thresholds.

As a result, several overviews can be made (see sample sheets in Figure 2)

- a matrix summarising the scores for assessing several risk parameters
- final global assessment by experts is the outcome of a risk assessment investigation and final risk scores for level “Insignificant” (green) to Catastrophic” (red).

Some of these parameters were used in the studies on risk in cruise shipping [5] or for waterway designs [4].

3.2 Sample for Risk Management in Ship Operation - Port risk Assessment

Normally risk assessments are made in Full Mission ship handling simulators in real time, under variation of parameters like wind or current conditions and various speed rates in order to find out optimal strategies for conning the ship but specifically to find out the limits of external effects for safe manoeuvring (see e.g. [6]). This is very time consuming! Therefore, it is very effective to use Fast Time Simulation which can be used very effective to try out initial strategies and to estimate the technical limits of manoeuvring capabilities of the vessels. In Figure 3 a sample is shown for a concept to investigate the arrival manoeuvre of a cruise ship at the Port of Rostock. This will be done by creating a Manoeuvring Plan by Fast Time Simulation with SAMMON Planning Tool.

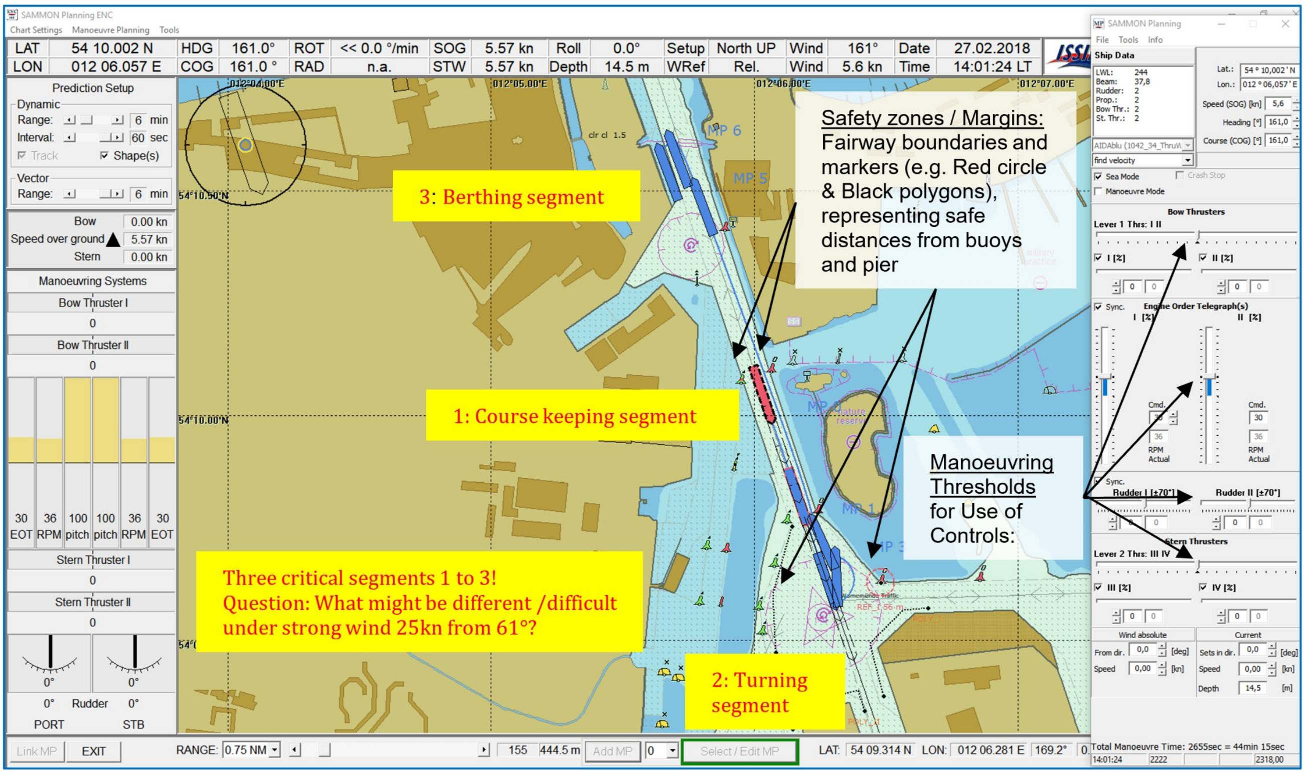


Figure 24: Concept for Risk Assessment Methodology - Definitions of Margins & Reserves and of three critical segments for Arrival manoeuvre at Rostock Port without wind. Creating a Manoeuvre Plan using SAMMON - Fast time simulation (Start at red ship shape at Manoeuvring point MP0)

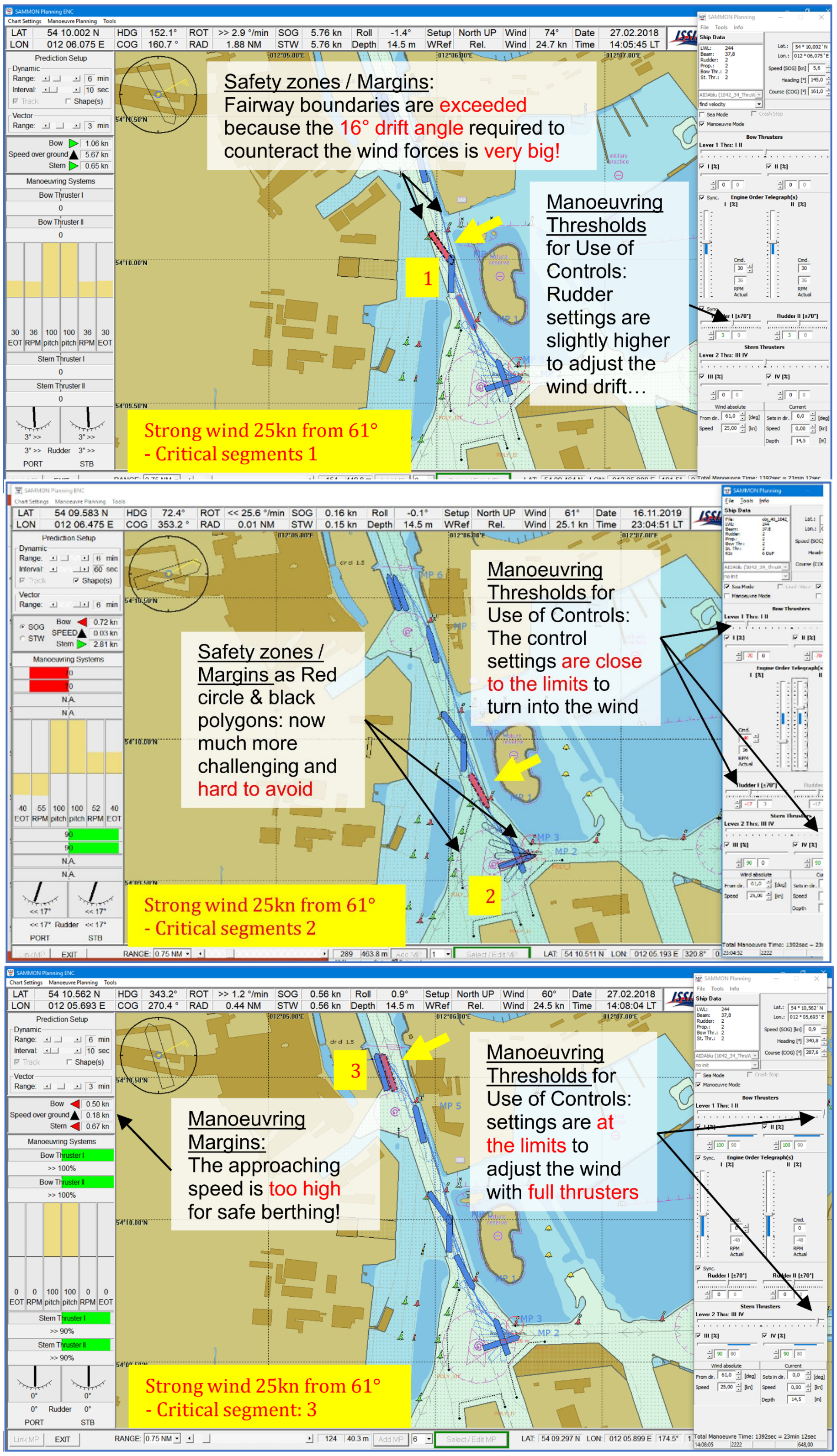


Figure 25: Application of Risk Assessment Methodology with SAMMON Planning – Sample for violation of thresholds at Port arrival Rostock with consideration of strong easterly winds when creating the Manoeuvre Plan highlighting the situations at the red ship shapes representing the three segments defined in Figure 3

The manoeuvre in Figure 3 is divided into three segments:

- segment 1 for the initial conditions going straight with constant speed in the fairway,
- approaching the turning basin in segment 2 to turn the ship and
- then going back in the fairway to final berth the ship in segment 3.

This manoeuvring plan can be done manually in only 10 min by using the SAMMON planning: you simply choose suitable manoeuvring handle positions on the right panel to adjust the ship's motion, and then move along the predicted manoeuvring track up to the desired position where you set the next manoeuvring Point MP (description see movie under [5]). So, a chain of manoeuvring points (respectively manoeuvring segments) is generated up to the final position. And the advantage is: all manoeuvres are PROVEN BY SIMULATION with Advanced Math-Model same as in a full mission ship handling simulator.

Whereas this manoeuvre plan in Figure 3 was created assuming calm or no wind, in Figure 4 the same arrival manoeuvre is made under the assumption of a strong wind 25kn from easterly direction, discussed separately for the three segments. Under this strong wind it turned out that the risk is much higher at the positions represented by the red shapes:

a) In Segment 1 at start the ship exceeds the Safety zones / Margins: it can be hardly accommodated within the fairway boundaries due to high drift angels for balancing side wind
b) In Segment 2 the Safety zones are hard to avoid during Turning and Manoeuvring Thresholds are exceeded: the thrusters are at the limits!
c) In Segment 3 the approaching transverse speed is too high for safe berthing even with full thrusters, so Manoeuvring Thresholds are exceeded.

The sample demonstrates, that the Fast Time Simulation is an efficient tool for Pre-Study and pro-active risk assessment, allowing for a quick estimation of the potential of the manoeuvring capabilities and trying out several strategies or what-if decisions when the environmental conditions are changing. This method is very useful for pre-studies to be later checked for human factor impact e.g. for impact of visibility constraints or bridge resource management.

4 RISK MITIGATION IN SHIP HANDLING AND VTS- OPERATION

4.1 Dynamic Manoeuvring Prediction by FTS during ship handling operation

For risk mitigation and safe steering during the execution of the manoeuvring plan the SAMMON Monitoring & Conning tool was developed: In Figure 5 the interface is displayed for a sample steering a Cruise ship during arrival at Marseille and berthing. The main features provided with this module are:

- Display of Manoeuvring Plan together with current position and Predicted Manoeuvres in parallel;
- Calculation and display of new **Multiple Dynamic Prediction** tracks:
  - **Dynamic Prediction** based on full ship dynamic Simulation for future ships motion – due to the **input from actual bridges handle settings**
  - **"Path Prediction"** Presentation as existing Look Ahead in ECDIS, simply taking the current **rate of turn and speed as constant** for the prediction time period.

This feature allows for much more safe and efficient manoeuvring which has been proven in several tests see e.g. [10].

However, FTS can provide also very detailed estimations for Collision Avoidance Manoeuvres, e.g. of the time needed for any manoeuvre intended for an escape action in case of crossing traffic as Stand-on-Vessel. In this way decision making for the selection of a course and/or speed alteration respectively could be performed on a much more profound and reasonable basis than it is done in today's practice. It becomes obvious that this technology allows for dynamically adapt such limit values and provide situation dependent support, which might be needed in a critical situation with less available time, and increasing pressure to take a right decision.

By means of FTS and dynamic prediction it is possible to give advice when and where the so called "Last line of defence (LLoD)" will be reached. The further development and implementation of the concept for defining and using the LLoD has been already discussed earlier (i.a. [7]) and many research works are dealing with this exact problem (to give just one dominant sample, see [12]). Now, in the following example its implementation can be demonstrated.

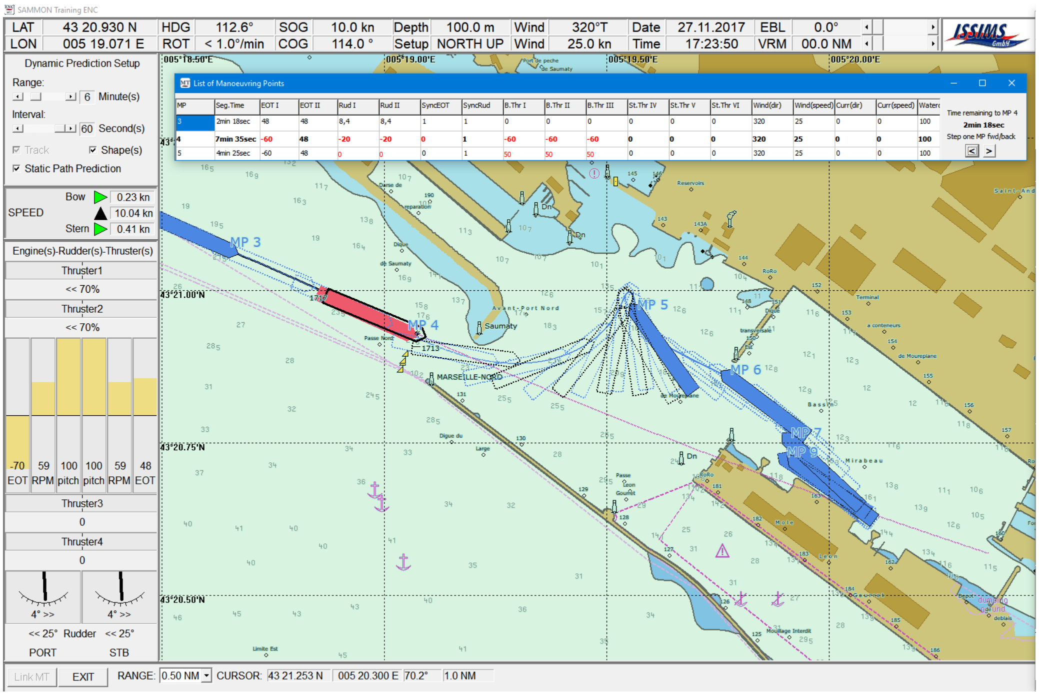


Figure 26 SAMMON Monitoring & Conning Tool with Multiple predictions: Real time simulation and Manoeuvring Prediction integrated into ECDIS with comparison of Full Dynamic Predictions (black dotted ship contours) and the simple static prediction (magenta curve, no shapes) together with planned manoeuvring track (blue line and ship shapes) for a Cruise ship arrival at Marseille and berthing at Pier 163

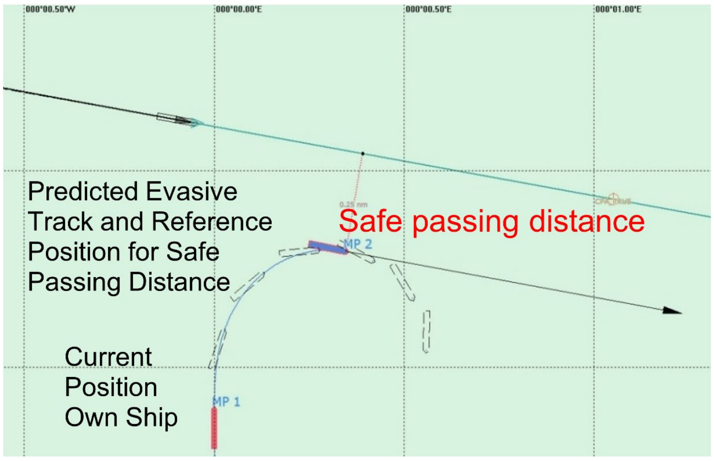


Figure 27 Concept for „Last Line of Defence – LLoD" for a given safe passing distance of 0.25 nm at the moment when ships are moving on parallel course: Sample for Lower Limit of manoeuvre of "Stand on Vessel" (1,3 nm)

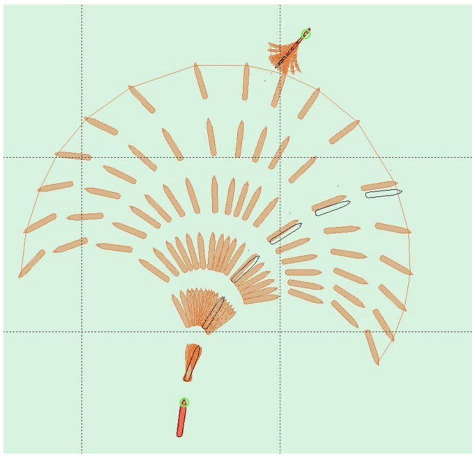
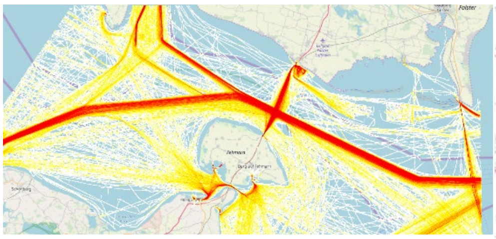


Figure 28 Manoeuvre zones represented by ship domains for collisions avoidance calculated by FTS to support operator's decision making

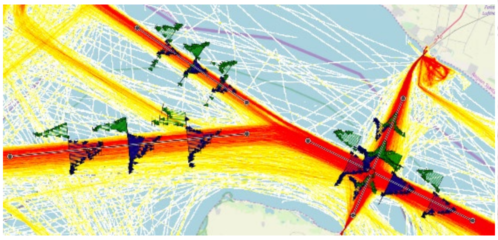
Figure 6 shows a visualization of an encounter situation in an ECDIS environment. The own ship (marked by the red ship shape in the lower centre of the screenshot) is on north-easterly course and is approaching another vessel on her port side sailing on a south-easterly course and crossing the bow of the own ship at a very short distance. By means of the prediction it is highlighted, that the closest approach will be reached when the heading of the own ship equals to the course over ground of the target ship. To achieve a pre-defined safe passing distance provided e.g. by standing orders MP 1 indicates the corresponding position, where the own ship at the latest, has to initiate the hard wheel over command to ensure a minimum passing distance of 0.25 nm at the CPA (marked MP 2). Figure 7 shows a sample for the calculation of manoeuvring zones for CA by calculating a series of potential manoeuvres using FTS as an application of the concepts described in [11].

4.2 Training and Measures for new VTS Operational Challenges – sample for traffic management during tunnel construction

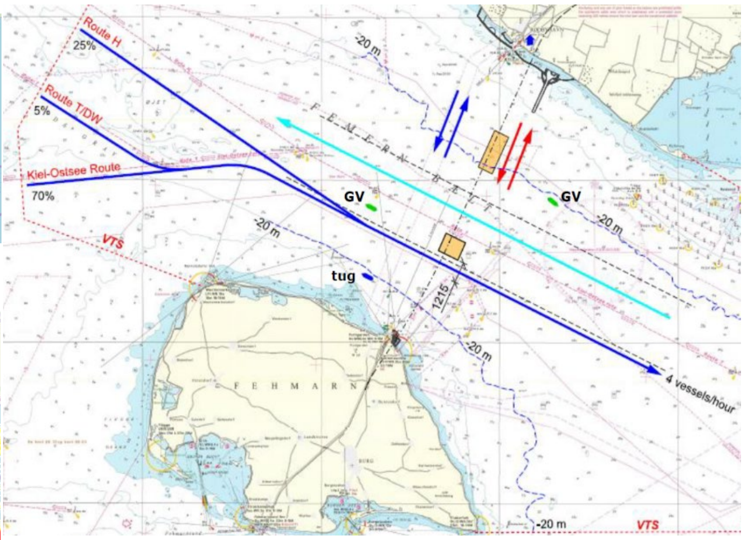
This is now a sample for risk management in the VTS domain: It describes the simulator application for the specific phase of tunnel construction presently ongoing in western Baltic Sea to connect the German island of Fehmarn with the Danish islands. The most relevant problem is the increase of traffic density due to less navigational space during the construction phase. Initial investigations were made using IWRAP to assess the current traffic recorded by AIS and to estimate the risk for the potential traffic patterns (including encounter and collision rates) during the future construction. Finally, the main routes were identified which will be blocked during the construction, in particular the busy ferry traffic crossing the main shipping routes. Measures were suggested for the VTS operators to assess and inform transiting traffic, to advice and warn the ships to optimise the organisational procedures and avoid safety-critical encounters.



Current traffic recordings from AIS



Extract of Traffic load & distribution assessed in IWRAP by German Waterway Administration



Planned Routes and crossing traffic lanes with Working areas (Yellow boxes) in VTS area taken from safety concept: construction traffic (red arrows) and ferries (blue)

Figure 29: Risk Management in VTS Domain - Fehmarn Belt Tunnel Construction needs to be managed:

- Left: Traffic in the area and potential change during construction phase investigated by IWRAP
- Right: Concept for VTS Management as Basis for VTS simulation training / assessment and optimisation of operational procedures, even including Ship Handling Simulators

4.3 Training in VTS Simulator interfaced to the Ship Handling simulator for collaborative exercises

Exercises in VTS simulator were made to familiarise with the new situations during training for the operators both for the German and Danish VTS centres; additionally, investigations and training were made using the Ship handling simulator Figure 9 interfaced to the VTS simulator, playing the role of:

- traffic ships navigating in the area of critical zones close to the tunnel construction and also
- guard ships to approach and warn those ships, not acting according to the regulations or warnings.

These exercises were very helpful, the VTS operators were able to play also the role of navigation officers on the guard ships because they hold a CoC as navigators.

Figure 30: Training exercises in Training exercises in VTS simulator for Fehmarn Belt Tunnel Construction (top left) and scenarios in interfaced Ship Handling (Top right: SHS Instructor station; bottom left: Bridge view from Passing Traffic ship; Bottom right: Bridge view from Guard vessel in action)

5 CONCLUSION

Simulation is a proven method in risk management and is part of related IALA Seminars for Port & Waterway Risk Management. Specifically, the innovative system "Simulation-Augmented Manoeuvring Design, Monitoring & Control" (SAMMON) has been developed and demonstrated. The system consists of various modules for planning, monitoring & control of manoeuvres. It is a unique tool based on Fast Time Simulation i.e. simulating up to 1000 times faster than real time and allows for steering by humans via a smart interface. The potentials of the toolbox were shown in exemplary case studies for port and waterway investigations - The design of "Manoeuvring Plans" for complete port approaches in only minutes and in accordance with IMO guidelines for voyage planning and the potential for optimising procedures and to find limits for manoeuvring capabilities is demonstrated. Moreover, the required manoeuvring space can be calculated for sets of steering orders to visualize the areas needed for given time periods to be used for objective risks assessment of encounters onboard and ashore in a VTS. The potential was shown that the multivalent use of simulation methods and integrated use of simulators are suitable for effective risk assessment.

6 ACKNOWLEDGEMENTS

Investigations and preliminary results presented in this paper were partly carried out and achieved within the Polish-German RTD project CADMUSS - Collision Avoidance Domain-Method Used by Ships and Ashore. This project belongs to the MARTERA program supported by the European Commission. It is funded by the German Federal Ministry of Economics and Technology (BMWi), and supervised by the German Research Centre Jülich (PTJ). Moreover, some of the materials presented in this paper, are partly achieved in the national research project "Shore-side decision support for traffic situations with highly automated or autonomous vessels using AI (LEAS)" funded by the German Federal Ministry of Education and Research (BMBF) . It is supervised and surveyed by VDI Technologiezentrum Düsseldorf.

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AUTHOR BIOGRAPHY

Knud Benedict, born in 1948, was graduated at the Faculty of Naval Architecture of the Rostock University in 1972. He achieved Doctoral degrees in Ship Hydrodynamics / Manoeuvrability (1978) and on Ship Operation Technology / Advisory Systems (1990). Since 1992 he has been Professor for Ship's Theory at Hochschule Wismar (HSW), University of Applied Sciences /Germany. Until 1997 he was the Dean of the Department of Maritime Studies at Wismar University and from 1998-2013 he was the Head of its Maritime Simulation Centre Warnemuende (MSCW). Now he is the Head of the Institute for Innovative Ship Simulation and Maritime Systems ISSIMS at HSW.

He has been Visiting Professor at World Maritime University Malmoe for Marine Technology and expert consultant to the IALA World Wide Academy. He has been actively involved in the development and deployment of the IALA Port & Waterway Risk Seminars, specifically for the role of simulation in maritime risk management.

S113.4 Navigation Risk Analysis along an Entrance Channel using Probabilistic Simulations (055)

Marcos Silva Admiral Moraes Rego" Aids to Navigation Center (CAMR), Head of Navigation, Brazil

ABSTRACT

Navigation simulator is a system that reproduces on shore, under certain predefined conditions, some of the activities performed on board. Some theories are described in the literature for the application of simulators to assess safety in navigation channels. However, these works do not address the use of wind and current data applied to simulators in the fast-time mode, which, by running the simulations more quickly, allow the analysis of the channel as a whole, for each combination of wind and current.

The present work aimed to develop a probabilistic method for analyzing navigation safety along a channel using a fast-time simulator combining wind and current data. For that, simulations were carried out in the fast-time mode considering wind and current data, having as scenario the access channel to the Guaíba Island terminal. The obtained data were classified according to intensity and combined in scenarios, which were applied in the simulator. For the probabilistic analysis, the theories developed by Briggs et al (2003) and Gucma et al (2018) were considered.

In total 399 simulations were carried out in CASNAV simulator. Results showed that the entrance channel in terms of horizontal dimensions presents an adequate degree of safety for navigation, however, comparatively the sections of channel 96, 101 and 128 have presented relevant risks, especially in combinations of environmental data of severe and moderate categories. The methodology used proved to be efficient in the navigation safety analysis of entrance channels using different environmental scenarios on simulators in the fast-time mode.

(No paper submitted)

AUTHOR BIOGRAPHY

Marcos Silva is the Aids to Navigation Department Chief in "Admiral Moraes Rego" Aids to Navigation Center (CAMR) since 2019. In Brazilian Navy since 1999, have made Courses and developed qualifications at Maritime and Hidrography Sector. In Brazilian Navy has served in "Niterói" Frigate – Division Operations Assistant Officer (2006 – 2007); Combat Car Landing Ship "Garcia DÁvila" – Division Operations Assistant Officer (2007 – 2008); Deck Division Officer (2009-2010); "Admiral Graça Aranha" Lighthouse Hydro-oceanographic Ship - Hydro-oceanographic Division Officer (2010-2011), Navigation Division Officer (2011-2012) and Operations Department Chief (2012-2014); Navy Hydrographic Center (CHM) – Tide Section Officer (2014 – 2015). Recently, has the opportunity to get expertise in Aids to Navigation working at CAMR in different functions as Estudies and Projects Division Assistant Officer (2015-2016), Estudies and Projects Division Officer (2016-2019) and now as Aids to Navigation Department Chief (2019-today). Concluded in 2020 his Master in Science in Ocean Engineering by Federal University of Rio de Janeiro (COPPE/UFRJ) with the Master Thesis: "Navigation Risk Analysis along a Channel using Probabilistic Simulations". During these time working at CAMR has made contribution together with the Department Team in the development of the Aids to Navigation in Brazil.

S113.5 Collision Risk Assessment of Major Ports in the Republic of Korea (037)

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ABSTRACT

Coastal waters are often subjected to complicated encounters between ships due to the high volume of maritime traffic, which contributes to elevated collision risks. Although multiple models have been developed to identify collision risks, most studies fall short of identifying perennial collision risks within and near port waters. In order to avoid possible collisions and to plan safer routes in congested waters, it is imperative to identify locations with high collision risks. This study evaluates eight major ports in the Republic of Korea, based on annual maritime traffic and tonnage, to identify the highest-risk locations in-and-near port waters. Statistical data of each port are comprehensively analysed to identify traffic patterns. Perennial collision risk is evaluated based on maritime traffic and Automatic Identification System (AIS) data following a modified gas model approach, which describes the expected frequency of collisions. All areas enclosing the harbour limits of each port were assessed and locations with the highest cumulative collision risk in each respective port were identified. Results obtained through the proposed gas collision model are validated considering traffic patterns and volumes in respective ports.

KEYWORDS: Collision risk, Maritime traffic

1 INTRODUCTION

Maritime transportation is, and has been, an activity of great significance for centuries. However, recent advancements in the maritime world – from smart logistics to optimum and specialized ship design – and the growth of international trade and the global economy have increased the number of operational ships in the world. Consequently, the traffic patterns and volumes of ship routes as well as of harbour limits have become complex over the years. This has made manoeuvring of vessels and conventional ship operations in tight, congested waters riskier and more complex. Furthermore, maritime transportation and navigation involve inherent hazards such as collisions, grounding, spilling of hazardous substances etc. [1], and they threaten both human lives as well as the environment. Thus, understandably, collision risk evaluation, risk avoidance and route planning in congested waters have become some of the most researched and focused concerns in both the commercial and academic world, in terms of providing navigational safety.

The management of risks associated with maritime transportation is a vast research field that encompasses multiple disciplines. One of the significant disciplines involved in this research is collision risk management. This is because ship collisions are responsible for a significant proportion of the total number of marine casualties and have been widely studied by researchers [2]. While technological advancements within the information and maritime sector, such as GNSS (Global Navigation Satellite System), GMDSS (Global Maritime Distress & Safety System), ECDIS (Electronic Chart Display and Information System), ARPA (Automatic Radar Plotting Aids), and GNSS (Global Navigation Satellite System) have paved paths for much safer navigation in international waters, congested coastal waters and/or port areas still include considerable navigational risks, and are more susceptible to collision accidents between ships, and between ships and structures.

Collision risk between vessels has been studied by several researchers over the years, and several pragmatic models too have been developed. These models and research have focused on various rational scenarios such as conventional ship-ship collisions [3] as well as collision risk assessments between ships and structures [4] [5] [6]. Due to the emergence of autonomous surface ships, research has also focused on evaluating and discussing the collision risks involving smart vessels and operations [7]. It should also be noted the importance the Automatic Identification System (AIS) has had on this research domain. AIS has undoubtedly enabled the collection of accurate data on vessel information, such as position over ground, speed over ground and the course of vessels. The possibility of accumulating large amounts of AIS data over certain user-defined time windows helps formulate statistical data that can be used to comprehensively study maritime traffic, route patterns and collision risks [8]. and this, consequently, helps develop collision risk models [2]. Furthermore, the importance of understanding the maritime collision risk, as well as the spatial distribution [9] [10] of collision risk and probability, is prominent.

It is, therefore, clear that defining a common definition of a collision risk can be difficult [11], and there exists a lack of statistical data that can help understand the perennial risks of enclosed waters. Driven by this prominent need, this study aims to provide insight and information on high-risk locations of eight major harbours in South Korea. The evaluation of the perennial risk is carried out based on the maritime traffic information, and the Automatic Identification System (AIS) data of respective ports, following a modified gas model approach [12] [13]. The basis for choosing the areas of application is detailed in subsequent sections. The maritime traffic information of each major harbour was used to identify and model the traffic patterns and volume, which were used to validate the cumulative risk calculated by the proposed model. Identifying the high-risk areas of enclosed and congested in-and-near port waters would not only help provide data for collision risk probability calculations but also would provide means for planning safer routes within harbour limits. The second section of the paper provides a detailed description of the methodology followed in this study leading to the next section, where the results of the study are discussed. Finally, the last section of the paper summarizes the concluding remarks.

2 METHODOLOGY

2.1 Selection of candidate application areas

Within the literature, one can find several models and examples of assessing collision risk in the maritime domain. While these models have their own benefits and drawbacks, they can fall short in defining collision risk on a universal ground due to various factors, such as the complexity of the marine environment, lack of information, uncertainty, and many other variables [14]. Thus, it is imperative to identify the candidate application areas suited for this particular study so that one can analyse the required perennial collision risks in detail. The Republic of Korea has a total of 29 ports, which handle a significant amount of cargo traffic and contribute significantly to the country's economy. First, the tonnage and traffic volume information from the Port Management Information System (PortMIS) were used to identify the eight busiest ports based on traffic volume and the number of ships operated over a period of five years. Based on the location, these eight ports can also be divided into three categories – the ports in the West Sea, South Sea, and East Sea.

Figure 1 illustrates the number of ships reported in each respective port from 2016 to 2020. On a global scale, it is possible for a port to be considered "busy" based on the operations of smaller or recreational vessels. However, these eight ports were also cross-checked with the respective tonnage to understand the traffic density posed by commercial vessels, and the comparison is shown in Figure 2. It should be noted that the "Busan port" here includes both the old and new commercial ports.

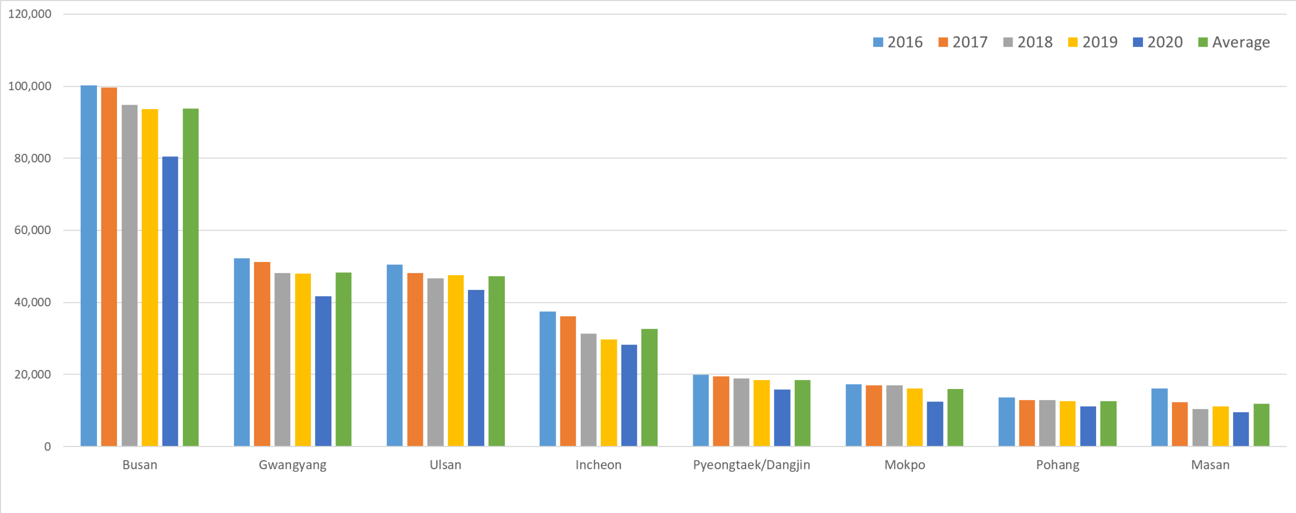


Figure 31: Number of ships reported in eight major ports in the Republic of Korea between 2016 - 2020.

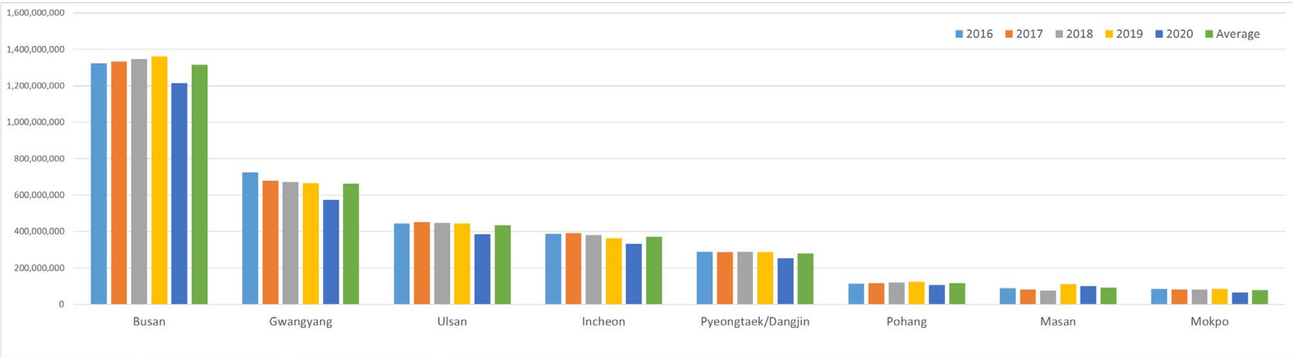


Figure 32: Tonnage reported in eight major ports in the Republic of Korea between 2016 - 2020.

2.2 Mathematical model

This study follows a statistical approach to calculate the qualitative risk of collision within a user-defined area of assessment based on traffic volume data. The mathematical model is a combination of earlier work [15] [13], and the collision risk analysis (CoRiAn) program, which was developed, tested and used by the authors to analyse the spatial distribution of maritime collision risk. [12]. The model adopts an approach that treats ships as moving gas molecules, similar to the gas model theory used to predict mid-air collisions of gas molecules. The program uses AIS data of vessels in waterways to calculate the geometrical collision possibility using a mathematical model where the total risk is defined as,

$$Total\ Risk = \partial_{cell} \sum_{i=1} \sum_{j \neq 0} D_{ij} V_{ij} \quad (1)$$

Where, i and j denote two groups of ships, D_{ij} is the Geometrical Collision Diameter, V_{ij} is the relative velocity between the two ship groups, and ∂_{cell} denotes the marine traffic density of a particular user-defined area. These terms can further be modelled as follows,

$$\mathrm{D_{ij}} = \frac{L_i^{(1)} V_j^{(2)} + L_j^{(2)} V_i^{(1)}}{V_{ij}} \sin\theta + B_j^{(2)} \left\{ 1 - \left(\sin\theta \cdot \frac{V_i^{(1)}}{V_{ij}} \right)^2 \right\}^{\frac{1}{2}} + B_i \left\{ 1 - \left(\sin\theta \cdot \frac{V_j^{(2)}}{V_{ij}} \right)^2 \right\}^{\frac{1}{2}} \quad (2)$$

$$V_{ij} = \sqrt{\left(V_i^{(1)}\right)^2 + \left(V_J^{(2)}\right)^2 - 2V_i^{(1)}V_J^{(2)}\cos\theta} \qquad (3)$$

$$\partial_{cell} = (\text{number of ships})/(\text{cell area}) \qquad (4)$$

where, L and B denote length and breadth of a ship, and θ is the angle between two ship headings. Complete derivations are omitted in this paper to avoid repetition but can be found in earlier studies [15], [13, [12].

Once the candidate ports were chosen, the areas of assessment were defined within harbour limits, and Table 2 shows the dimensional details of the areas of assessment. Again, the area of assessment of the Busan port is the sum of the area of two (Busan old port and Busan new port) ports.

Table 1 Area of assessment of each candidate port

	Port	Total area of assessment (km^2)
1	Busan	218.367
2	Gwangyang	460.5198
3	Ulsan	78.166
4	Incheon	1131.5
5	Pyeongtaek & Dangjin	895.1052
6	Pohang	355.725
7	Masan	53.3936
8	Mokpo	282.4975

In order to assess the quantitative navigational collision risk in the chosen ports, AIS data were accumulated for 5 consecutive days. This data included the Maritime Mobile Service Identity (MMSI), Length, Breadth, Speed over Ground (SOG), Course over Ground (COG), location (latitude and longitude) and time of ships. Each port area was then divided into a grid of m x n cells, where the numbers m and n depend on the area and the average ship size of each area of assessment. Accumulated AIS data were decoded and clustered based on the MMSI, and the collision risk was calculated for every 30 minutes. Once each and every cell within a particular area of assessment was analysed, the average collision risk of each port was declared. Cumulative risk is then presented as an overlay on Google Earth, with a qualitative range. Moreover, the inbound and outbound maritime traffic of each candidate port was plotted alongside the cumulative collision risk plots.

3 RESULTS AND DISCUSSION

Figures 3, 4, and 5 illustrate the cumulative collision risk of each port, together with the maritime traffic on the assessment date. The numbers 1 ~ 8 denote the eight candidate ports, which were chosen for the study, as tabulated under Table 1. As mentioned earlier, “Busan port” refers to both the new and old ports, and thus, 1a and 1b refers to the Busan old port and Busan new port, respectively. (a) and (b) denote collision risk, and inbound and outbound traffic of the respective port. Moreover, it needs to be noted that the candidate port number 2 (Gwangyang port) has a considerably high area of assessment. When the respective plot is considered, one can see that the area of assessment must be high due to the shape of the port. Similarly, the candidate port number 4 and 5 have a higher area of assessment due to the same reason.

Observations of the overlayed plots clearly show higher qualitative collision risks near terminals, and other physical structures as well as within smaller channels in-and-near port waters. This is consistent with the previous findings [12]. Further, it can be seen clearly that the high qualitative risk areas coincide with high traffic volumes when the inbound and outbound traffic patterns of respective ports are compared.

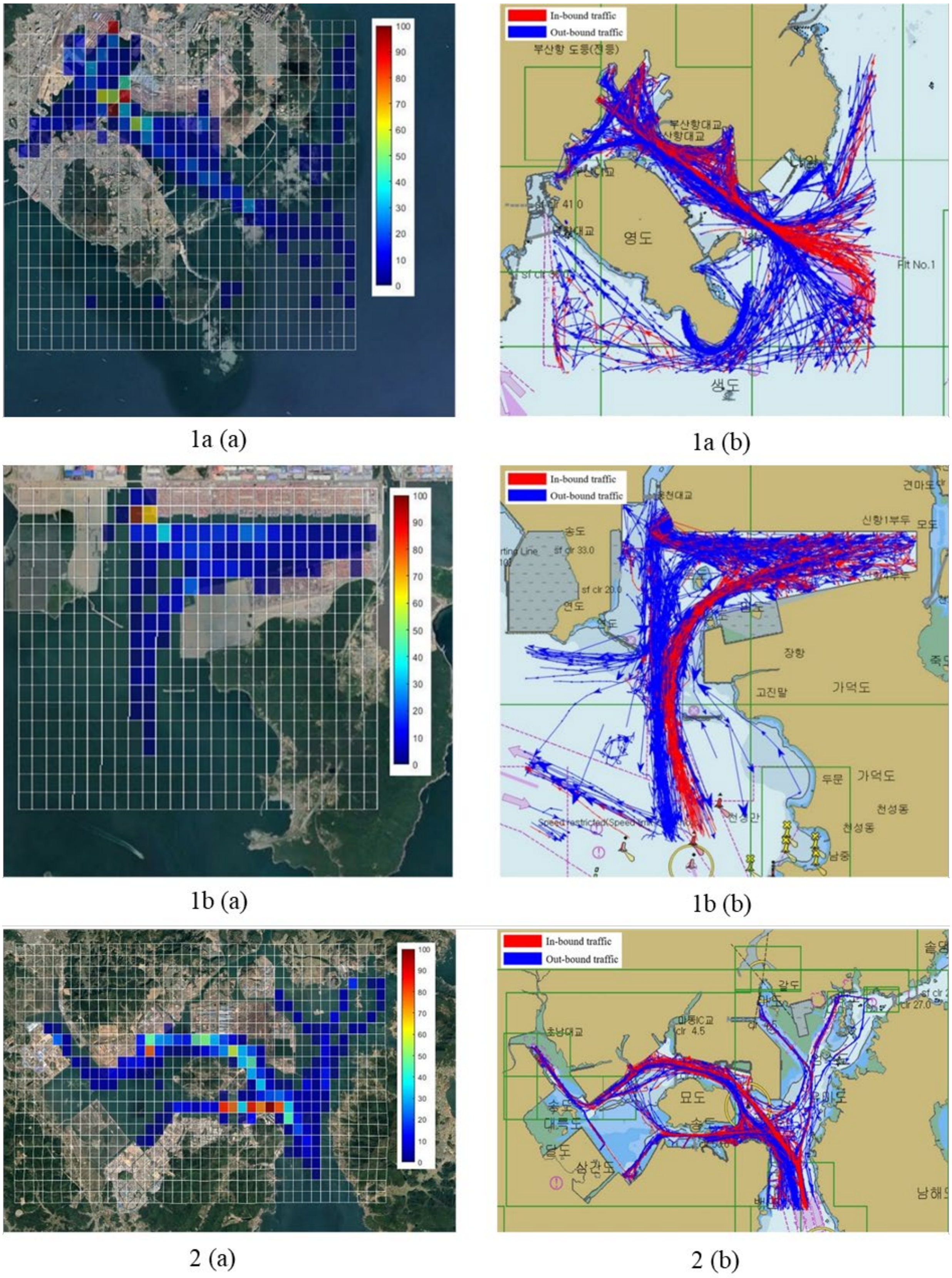


Figure 33: Qualitative maritime collision risk and the marine traffic trends in Busan and Gwangyang ports.

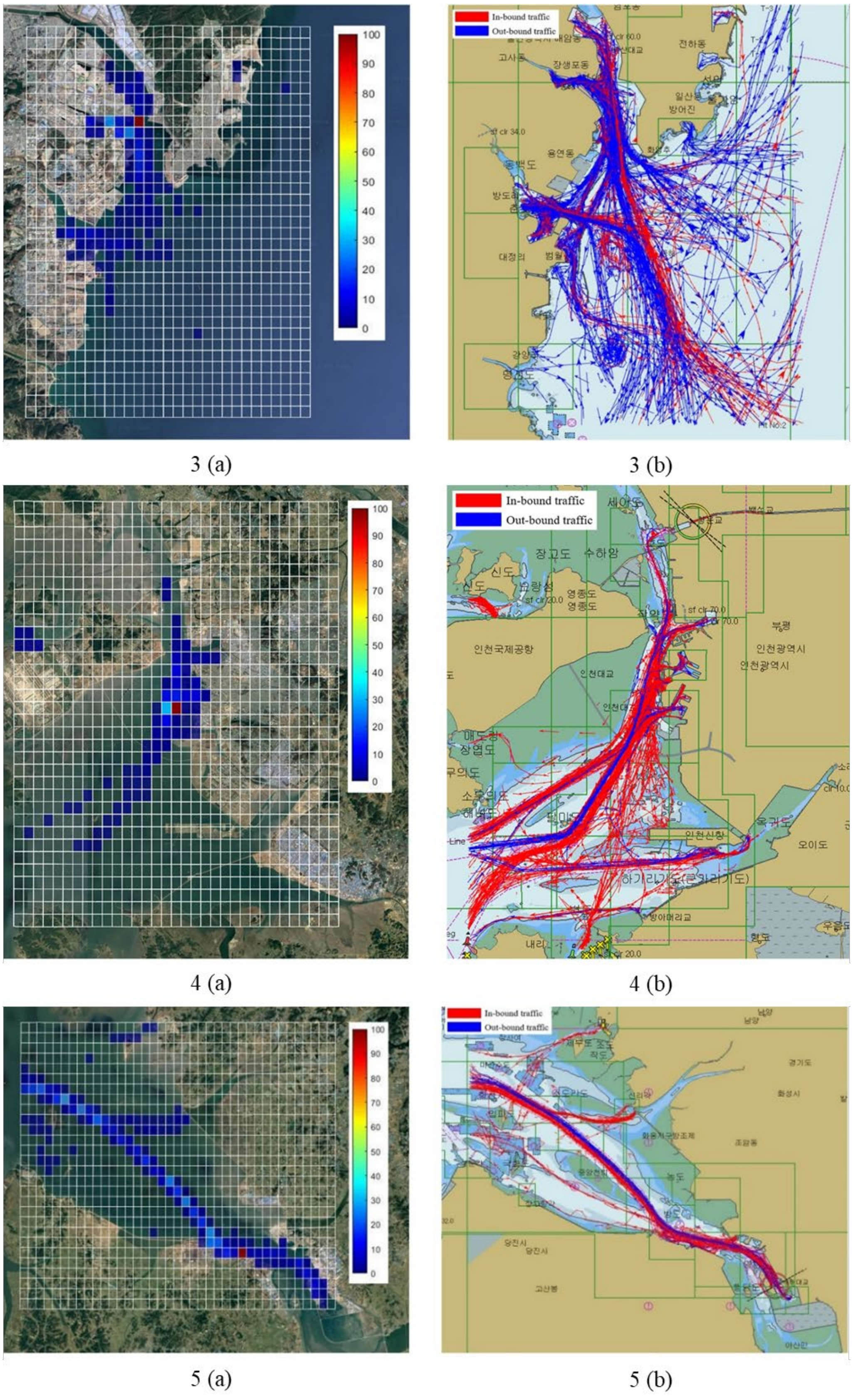
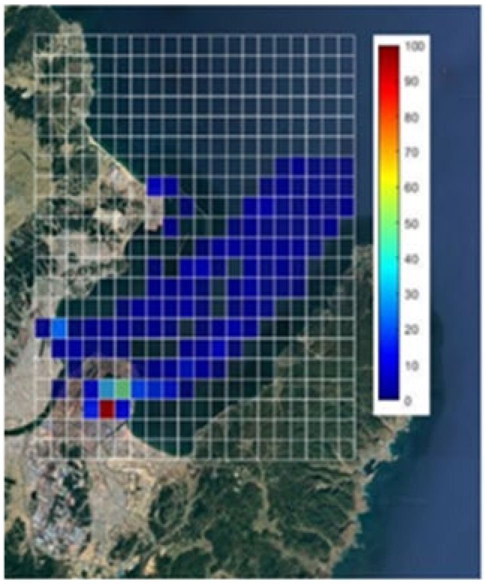
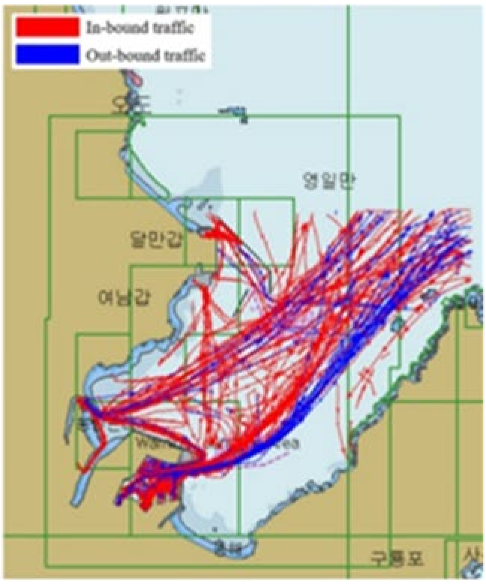


Figure 34: Qualitative maritime collision risk and the marine traffic trends in Ulsan, Incheon and Pyeongtaek & Dangjin ports.





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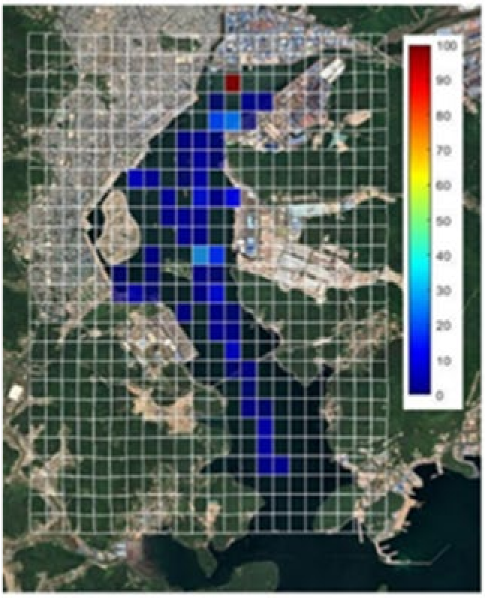
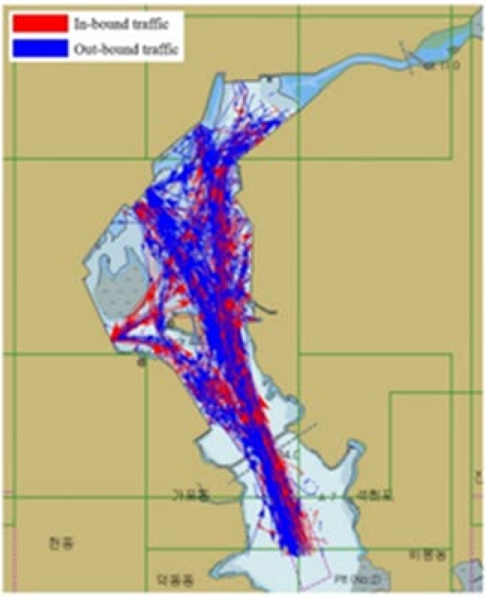
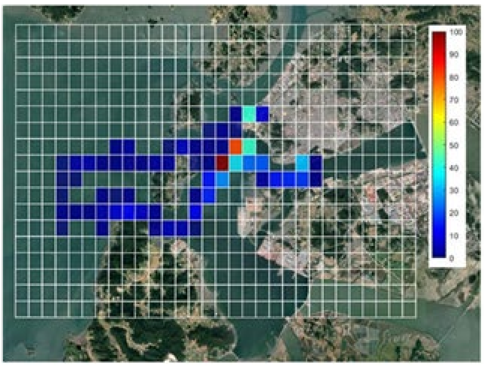
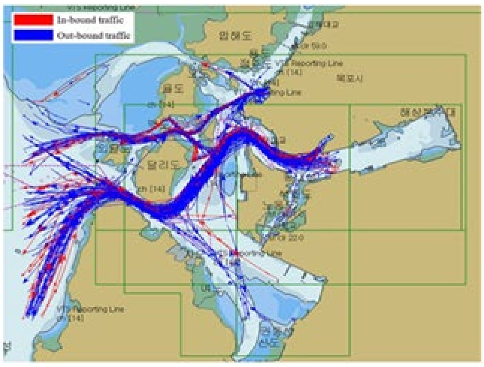




7 (a) 7 (a)





8 (a) 8 (a)

Figure 35: Qualitative maritime collision risk and the marine traffic trends in Pohang, Masan and Mokpo ports.

4 CONCLUSION

This study aims to provide a qualitative yet complete assessment of maritime collision risk within eight major ports in South Korea. The focus was driven by the idea of developing a reduced fidelity model that can evaluate collision risk in a user-defined area of assessment. The collision risk assessment model based on the gas model theory, which was developed prior to the study [12], was utilized to study and analyse several ports, which included a larger data cluster. This suggests the capability of the approach to handle complex areas of assessment.

Identifying the busiest ports based on the number of ships and reported tonnage provided the candidates to be analysed, and moreover, this large volume of statistical data provided the means of calculating the average cell size of a particular area of assessment based on vessel dimensions. This is important since the safe route design could include these two sets of information – vessel size and maritime traffic volumes – in a rather pragmatic way. For this study, a total area of 3,475.2741 km^2, and AIS data over a period of 7 consecutive days were analysed. The analysis based on the proposed model was again compared with the maritime traffic data and clear trends were identified.

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SESSIONS 14 AND 114 – RESILIENT PNT

S14.1MaRINav - a system of systems resilient PNT concept (134)

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ABSTRACT

The vulnerabilities to satellite navigation systems are well documented and the need for resilient positioning, navigation and timing (PNT) is clear. It is also recognised that the mariner needs a solution that is scalable to meet the needs of different operational requirements and one that works in different locations where different positioning solutions are available. National service providers' inevitably need resilient PNT to support critical national infrastructure, across maritime and other sectors. Solutions that meet the need for multiple use cases are likely to be more cost effective than those that only serve one user.

This paper introduces the MarRINav project that investigated the PNT requirements to support UK critical national infrastructure, set out a logical approach to identifying a suitable mix of solutions and proposed a scalable and cost-effective approach to realising PNT for maritime users. MarRINav concluded that GNSS supported by eLoran, VDES R-Mode and radar absolute positioning, integrated with dead reckoning information in a form of multi-system receiver and data processor unit, would provide the level of performance required.

The paper is supported by publications that set out an approach that can be easily ported to consider options suitable for other administrations and their specific requirements.

KEYWORDS: Resilience, PNT, CNI, system-of-systems.

1 INTRODUCTION

Shipping is essential to the UK economy as 95% of all goods are imported or exported by sea [1]. Vessels operating within UK and Irish waters are increasing in number and size, and are expected to continue doing so for the near to medium future. At the same time, sea space around the UK and Ireland is likely to become more complex with the introduction of autonomous vessels and the room to manoeuvre is expected to decrease as more space is devoted to offshore renewable energy infrastructure.

The safety, efficiency and environmental protection necessary for shipping and port operations is like to require increased management of sea traffic, all of these aspects point to the growing importance of resilience and integrity for positioning, navigation & timing (PNT) information, whether that's utilised on the vessel or ashore.

Global Navigation Satellite Systems (GNSS) are the primary means of position and timing information for most, if not all, vessels. GNSS systems share common vulnerabilities that can affect their performance, and resilience in PNT information is recommended [2]. Resilient PNT can be achieved by using a mix of systems that have different failure modes, but it is often difficult to understand which systems to consider and how to choose.

This paper reports on Phase 1 of the 'MarRINav' (Maritime Resilience and Integrity of Navigation) project, funded by the European Space Agency (ESA), which focused on the requirements and possible solutions for the UK. The project considered the many different maritime requirements and the many different positioning, navigation and timing solutions available today. It considered how these systems could be used together to enhance integrity and considered the high-level cost benefit for taking the proposed mix of systems forward.

While MarRINav focused on requirements for a UK national capability, the approach and many of the project's findings will be applicable to other areas and are in the public domain should any other maritime administration seek to consider something similar.

2 REQUIREMENTS GATHERING

The project reviewed a number of maritime operations to understand their dependence on GNSS for position and timing information, including ports and port hinterland operations. It drew upon a number of authoritative sources, including resolutions from the International Maritime Organisation (IMO), and national and international reports into the economic impact due to the loss of GNSS. In addition, the project identified a series of stakeholders and their thoughts and requirements were included.

The concepts of maritime resilience and integrity were set out, along with definitions for accuracy, availability and continuity. Definitions were drawn from maritime literature but defined within the context of the MarRINav project, as these terms can often have different perceived meanings.

The project developed a comprehensive report (Deliverable D1 [3]) that describes how GNSS data is currently used and the overall need for resilience. It then sets out the scenario of a single cargo container travelling aboard a large cargo container vessel from mid-ocean to berth in a UK port, and onward through the logistics chain. This scenario was used throughout the project and contains a number of distinct activities, each of which was broken down further to consider how PNT data is used and by which device/system.

3 SYSTEM REVIEW

Having established the PNT requirements for the different activities within the scenario, the next stage in the project was to consider likely candidate sources. It recognised that augmented GNSS (multi-constellation and multi-frequency) would rightly remain the primary means of position and timing information, but also considered a number of alternatives including other space based, terrestrial and shipborne systems.

MarRINav deliverable D4 [4] provides a comprehensive overview of available positioning, navigation and timing technologies setting out their expected performance and operational area, their technology readiness level (TRL) and the current status of standardisation etc.

Systems were considered from a global, regional and local coverage area basis and their operational approach was studied in terms of the amount of infrastructure required and the overall performance.

Table 1 shows an example of the analysis that was undertaken within Deliverable D4. A number of requirements sets were defined that correspond to the activity within the project scenario. Each candidate technology was then considered against the scenarios to identify which could support that requirement set.

Table 8: Comparison of candidate PNT systems to sets of requirements [4].

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

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

It was clear early on in the project that one alternative positioning solution would not meet all of the different performance requirements and that a mix of systems would be required.

4 SYSTEMS OF SYSTEMS CONCEPT

While the MarRINav project was focused on the requirements for vessels operating within and around the United Kingdom, it was designed with a more global audience in mind. In recognizing that vessel's transit through international waters and will need resilience when navigating in different locations, the overall approach had to be scalable to use whatever solutions are available.

While space based PNT options are configured to provide a coherent performance around the world, terrestrial systems are largely limited by geography and the topography of the network at any given time can affect the overall performance. A solution suitable for UK waters may be different to that deemed suitable for operations in and around the Mediterranean for example. At the same time, it is widely recognised that mariners and ship owners would support the use of a single receiver on the vessel, rather than have to purchase and maintain various regional solutions.

To address these concerns the project proposed a system-of-systems solution. It sought to define and use an approach that could scale and accept all available position systems, whether they are GNSS, augmentation or terrestrial solutions.

Figure 1 below provides an overview of the system-of-systems concept. By utilizing signals from global, regional and local systems, the vessel's receiver can calculate a combined navigation solution that seeks to use the benefits of each individual data source to overcome the weaknesses of each other.

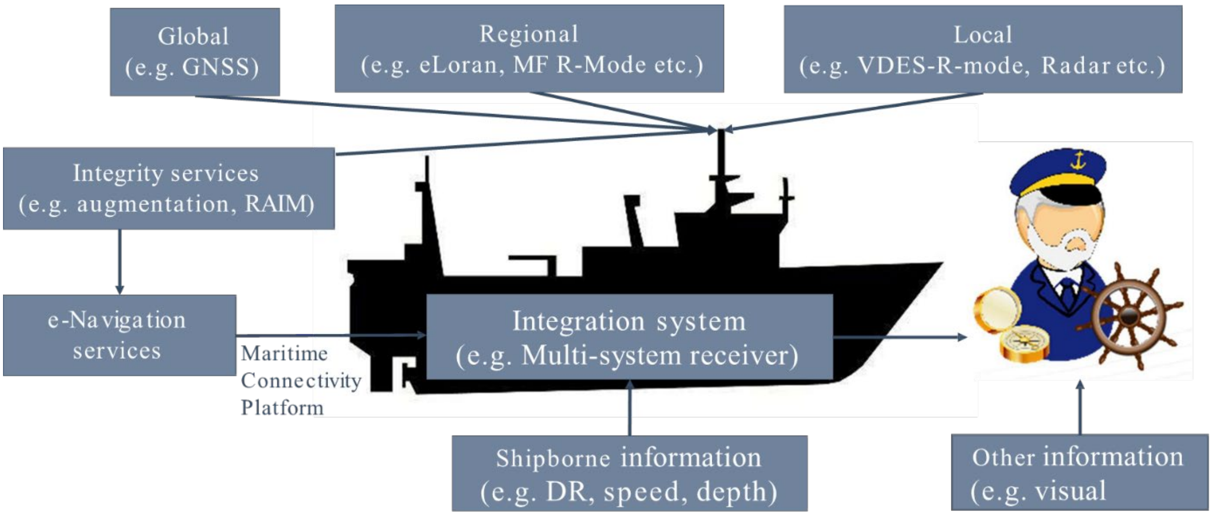

Figure 36: The system-of-systems concept of combining multiple pieces of information in an adaptable way.

5 INTEGRITY OPTIONS

A significant part of any resilient positioning solution is to understand how the different pieces of information can be brought together and used to aid the overall resilience and not reduce it. The use of multiple dissimilar systems is beneficial as it should remove the common mode failures, but the individual failure modes for each system must be considered to ensure one failure doesn't affect the result.

The system-of-systems approach can help achieve this be providing a common point of data integration, something akin to the Multi-System receiver and data processor unit [5]. This receiver could make use of all the received PNT signals, corresponding augmentation data whether provided by SBAS, RAIM or a yet to be defined e-Navigation service, and combine that with shipborne data such as dead reckoning, speed and depth data. Bringing this information together would help corroborate the combined positon and enhance the overall integrity.

Recognising that positioning integrity is a complex subject, the MarRINav project focused on the potential benefit of combining augmentation derived through EGNOS, with Receiver Autonomous Integrity Monitoring (RAIM). The approach considered is scalable to consider any Satellite Based Augmentation System (SBAS) and noted that there is no one defined approach to RAIM within the maritime sector.

Two evolutions of the EGNOS service were considered. The first was the initial period of 2022-25 when it was expected that EGNOS would provide its new maritime safety of life service (known as EGNOS 1046 maritime service). This service would provide corrections for the mariner based on GPS single frequency data. The second time period considered was 2025-2030 where EGNOS V3 is expected to be available, providing augmentation for dual frequency, multi-constellation users.

The project considered a number of alternative integrity approaches and derived its own version of Maritime RAIM (M-RAIM), an adaption of the aviation Advanced RAIM approach. The M-RAIM approach was verified with experts at Stanford University with the resulting approach detailed in full within MarRINav Deliverable D3b [6], with the intention to promote its development on a freely available and licence free approach.

The work concluded that there was no perfect solution and that more work is required to advance the integrity assessment, recognising that little information is available currently on vessel GNSS noise and multi-path models, and how they may change during the vessel's passage.

6 PROPOSED SOLUTION FOR THE UK

The project considered the requirements for the UK and in particular, the requirements for vessels operating within the UK Exclusive Economic Zones (EEZ) of the UK and Ireland. It also considered port and land side operations, recognising that the delivery supply chain extends beyond maritime into road, rail, and other sectors.

MarRINav Deliverable D5 [7] provides a comprehensive overview of the selection process and details how individual PNT systems were considered and compared, from the Global, Regional and Local perspective. By reviewing each candidate solution with the requirements and how they could be combined.

The conceptual solution considered UK sovereign solutions that complement GNSS (specifically GPS, Galileo and EGNOS). Terrestrial components of the architecture are geographically limited to being sited within the UK, insofar as a UK-only solution is feasible, whilst conforming to international standards and fully supporting international shipping operations within the EEZ.

- The candidate systems considered for use within the UK solution were:
- Enhanced Long Range Navigation - eLoran
- Ranging mode of the VHF Data Exchange System - VDES R-Mode
- Radar Absolute Positioning
- LEO Satellite Timing and Location (STL), subject to performance confirmation
- LOCATA at ports
- Onboard systems, to integrate traditional and/or inertial Dead Reckoning.

A Geographical Information System model was developed using coverage models for each system, with assumptions clearly noted, and example is given in Figure 2 below which shows the potential eLoran coverage for a network of 5 stations in the UK.

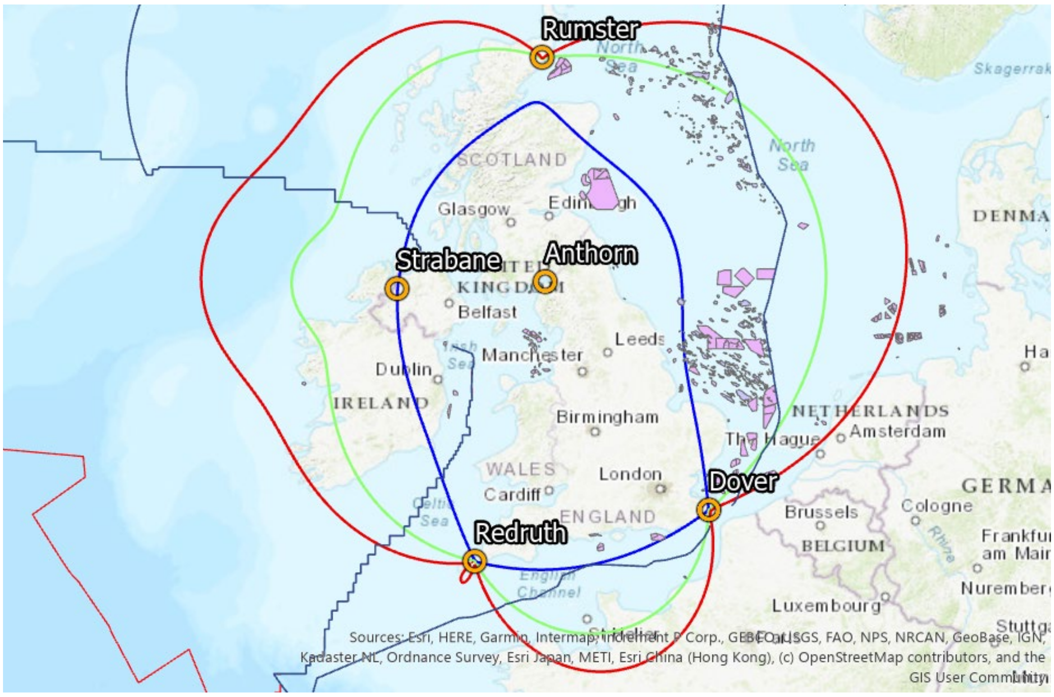

Figure 37: MarRINav GIS plot showing accuracy coverage contours of UK based eLoran. Blue = 10 m (95%), Green = 20 m (95%) and Red = 30 m (95%) [7].

By considering the use of a mix of systems, the MarRINav project supported the hybrid system-of-systems approach. It promoted using the wide area eLoran system for maximum overall geographic coverage, then supplementing this with regional VDES R-Mode and/or radar absolute positioning to fill capability gaps due to geometry. With a common time source, where more than one PNT solution is available, a suitable receiver such as the MSR could then look to combine them, either in a tight or loose-coupled manner.

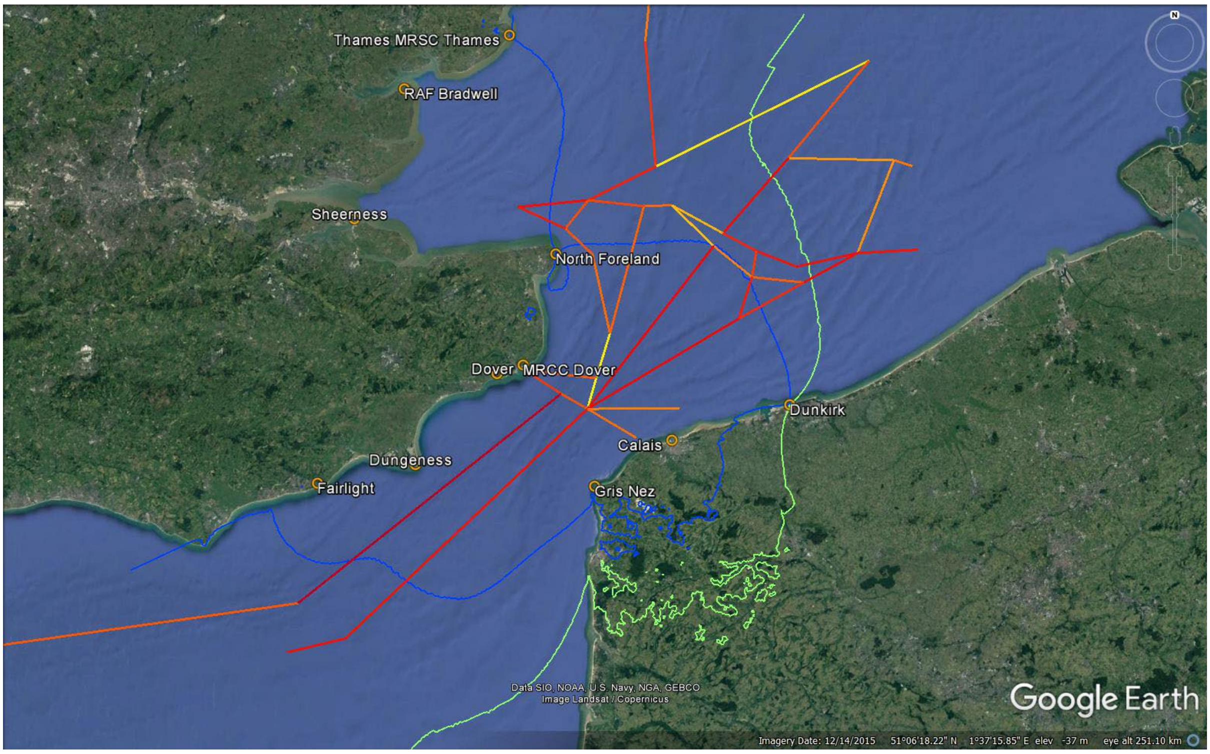

Figure 38: Loosely coupled integration of eLoran with VDES R-Mode in the Dover region. Blue = 10 m (95%), Green = 20 m (95%) [7].

Deliverable D5 builds the solution for the UK piece by piece and concluded that a system comprising of GNSS, with eLoran and VDES R-Mode working in a hybrid format, supported by absolute radar positioning would be sufficient to provide resilient PNT in support of vessel operations in UK waters. It concluded that GNSS and LOCATA could support port operations.

7 COST BENEFIT ANALYSIS

The project prepared a cost benefit analysis (CBA) to accompany the proposed resilient PNT architecture. It considered the central economic case and assumed that one 5-day outage of GNSS would take place within the next 10 years. It focused on a scenario with container ships calling at 10 major ports of the UK, with the benefit considered the loss avoided by having resilient PNT, against the cost of implementing and maintaining the systems.

MarRINav deliverable D8 [8] provides a full breakdown of the CBA, while only a very high-level summary is captured here.

The CBA considered that maritime transportation would be hit by a maximum loss of efficiency during the GPS outage and that if port cranes stop working, unloading does not occur and therefore the cascading effect will induce delays and even freeze operations in major ports. With the proposed MarRINav architecture in place to provide resilient PNT during the GNSS outage, the loss is less. Without the MarRINav solution, the total economic loss was measured at £601m whereas, with the MarRINav system-of-systems in place, the total loss is reduced to £180m. Therefore, with assumptions, the total economic value saved is £421m.

Costs were split into ashore infrastructure costs and ship-owner costs. The present value of costs for onshore technologies is £80m over 10 years (as shown in Table 2), with shipborne equipment costs of £120m (or £23k per vessel based on 5,200 container ships) due in year one.

Table 9: Cost of ashore infrastructure considered in the MarRINav CBA [8]

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

As shown in Table 3 below, the CBA reported a positive outcome equal to £221m. This is equivalent to a benefit-cost-ratio of 2.2. This is based on a number of assumptions and considers 5,200 container ships and 10 major ports. The results indicate that the investment in a resilient solution is highly beneficial.

Table 10: Summary of MarRINav CBA benefits and costs [8]

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

8 CONCLUSIONS

The MarRINav project reviewed the requirements for a resilient PNT architecture to support maritime operations within the UK Exclusive Economic Zone. Having reviewed available supporting technologies, the project concluded that a scalable approach was required – promoting the development of a system-of-systems solution.

Considering the specifics for a UK national capability, the project concluded that augmented GNSS, supported by terrestrial systems (eLoran and VDES R-Mode), combined with shipborne data (radar absolute positioning, depth sounder, inertial etc.), brought together within a suitable receiver, such as the Multi-system receiver, would provide resilient PNT for vessels operating within the UK EEZ.

The project developed a number of detailed, in-depth reports, along with a methodology for assessing the risk and selecting the most appropriate mix of PNT. These reports and the approach are all in the public domain and can be readably used by other maritime administrations when considering resilient PNT within their waters.

Importantly, the project set out the need for a scalable solution, one that is capable of supporting resilient PNT globally so that national administrations can choose the appropriate mix for their waters, while mariners, ship owners, manufacturers and standards bodies only need to develop, standardise and fit one receiver unit on the ship.

The project also set out a number of recommendations for further work, including how to advance the technology readiness levels for some of the identified solutions, what standardisation activities will be required and how to further understand and develop the approach to maritime integrity. Some of this work has been taken forward but the opportunity remains to progress maritime resilience further.

9 ACKNOWLEDGEMENTS AND FURTHER INFORMATION

The authors of this paper are summarizing the work of the MarRINav project that was led by NLA International and funded by the European Space Agency. May people across the consortium contributed to the work reported on in this paper and they rightfully deserve recognition, however there are too many to list.

The MarRINav project documentation is all in the public domain and is available on the project website (www.marrinav.com).

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Alan has supported the work of IALA for many years and is the out-going chair of the ENG Radionavigation services working group, having been in the role for the last decade. He is as a Fellow and Council member of the Royal Institute of Navigation (RIN), a member of the US Institute of Navigation (ION) and is a Chartered Engineer and a Chartered Physicist.

Alan has written and co-authored over 120 journal papers, magazine articles and conference papers over the course of 20+ years' experience in this sector.

S14.2 Status of the EGNOS Services Development for Maritime Applications (016)

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ABSTRACT

Maritime community is interested in using SBAS, especially where there is no back-up infrastructure or in poorly covered environments. For this reason, EC (European Commission) and EUSPA (European Union Agency for the Space Programme) with the support of the ESSP (European Satellites Services Provider - the EGNOS service provider) are working on the development of an EGNOS L1 maritime service that ensures a safe navigation for ocean waters, coastal waters and harbour entrances/approaches according to operational requirements (IMO Res. 1046(27) [1]). The EGNOS L1 maritime service will complement the existing maritime radio-navigation systems (e.g. DGNSS) providing pseudo-range corrections and alert information to the GPS L1 signals for maritime navigation, obtaining enhanced accuracy and integrity information over Europe.

EGNOS L1 Maritime service is planned to be declared by end of 2023 or beginning of 2024, in parallel, the IEC SBAS L1 standard is expected to be published. Besides GPS pseudorange corrections and alerts (system, satellite, iono) provided by signal in space, the service will include as well performance monitoring, reporting and provision of Maritime Safety Information (MSI).

KEYWORDS: IEC, SBAS, EGNOS, Maritime, accuracy, integrity, IMO Res A.1046

1 INTRODUCTION

Satellite Based Augmentation System (SBAS) is designed to augment Global Navigation Satellite System (GNSS) by broadcasting additional signals from geostationary (GEO) satellites over a specific service area (e.g. EGNOS is the SBAS system over Europe). Using a reference monitoring network that receive GNSS signals, the SBAS systems broadcast satellite and ionospheric correction messages that improve accuracy against GNSS standalone solution along with some integrity data that increase the confidence in the navigation position.

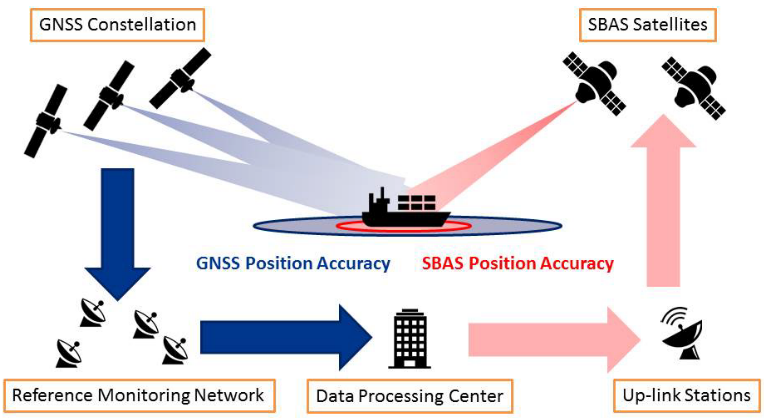

Figure 39: SBAS high level architecture

Apart from EGNOS, several other SBAS system are currently operational or under development around the world.

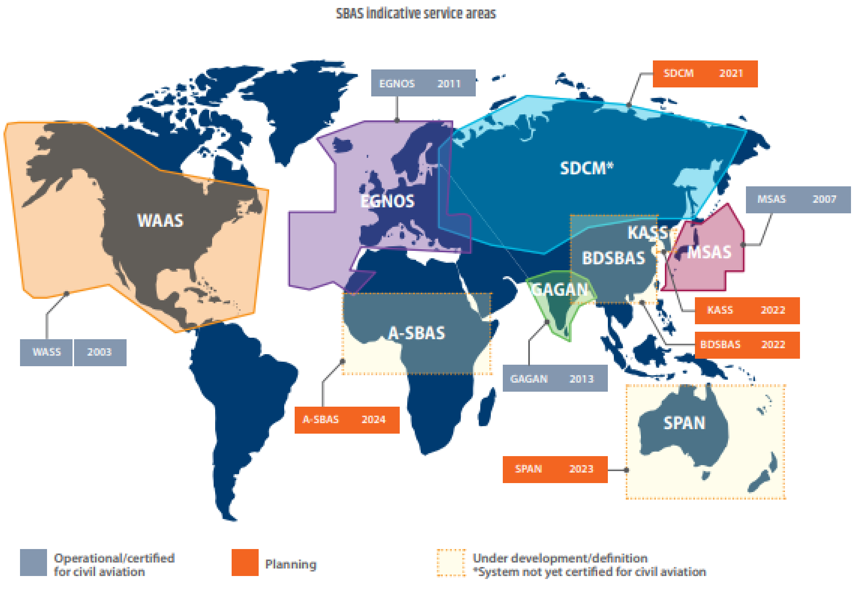

Figure 40: SBAS indicative service areas. Source: EUSPA User Technology Report 2020

The purpose of this paper is to inform Maritime community about the status of the ongoing activities aimed at the declaration of the EGNOS (European Geostationary Navigation Overlay Service) L1 maritime service.

2 EGNOS L1 MARITIME SERVICE

2.1 SBAS Benefits for Maritime applications

SBAS services are able to provide, over a wide area, the same type of information offered by a DGNSS service (i.e. differential corrections and system integrity information) which can be used to improve the position estimation accuracy and to protect the user from possible system-related failures. Therefore, depending on the application requirements, SBAS can be used to effectively complement DGNSS in Maritime domain, with performances in the same order of magnitude than the DGNSS ones (e.g. accuracy <5m (95%) - IALA Guideline 1112).

The main SBAS generic benefits for maritime applications can be summarised as follows:

- SBAS provides increased accuracy, availability and continuity in comparison with other navigation aids and in line with IMO resolution A.1046(27) contributing to the safety of navigation.
- SBAS comply with common global standards and are compatible and interoperable, thus providing the user with a “seamless”, augmented, navigation solution.
- SBAS services are available for free.
- SBAS services cover large areas including locations currently not served by other navigation aids. Actually, SBAS are able to complement the coverage area of a DGNSS service to increase the availability and the continuity of the provision of correction data and integrity information.
- SBAS may support the rationalization of ground-based Navigation Aids.

2.2 EGNOS for maritime adoption strategy

EGNOS (European Geostationary Navigation Overlay Service) is the European Satellite Based Augmentation Service (SBAS) that provides services based on the Global Positioning System (GPS) signals as well as enhanced accuracy and integrity information. EGNOS currently supports three services: the Open Service freely available to the public in Europe, the Safety of Life Service for aviation safety-critical applications and EGNOS Data Access Service (EDAS).

EGNOS Strategy roadmap for maritime is based on three steps:

1. Use of EGNOS corrections retransmitted via existing Aids to Navigation (AtoN).
2. Use EGNOS L1 Signal in Space (SiS) directly with adapted receivers (EGNOS L1 maritime service).
3. Use EGNOS DFMC with new Dual-Frequency receivers.

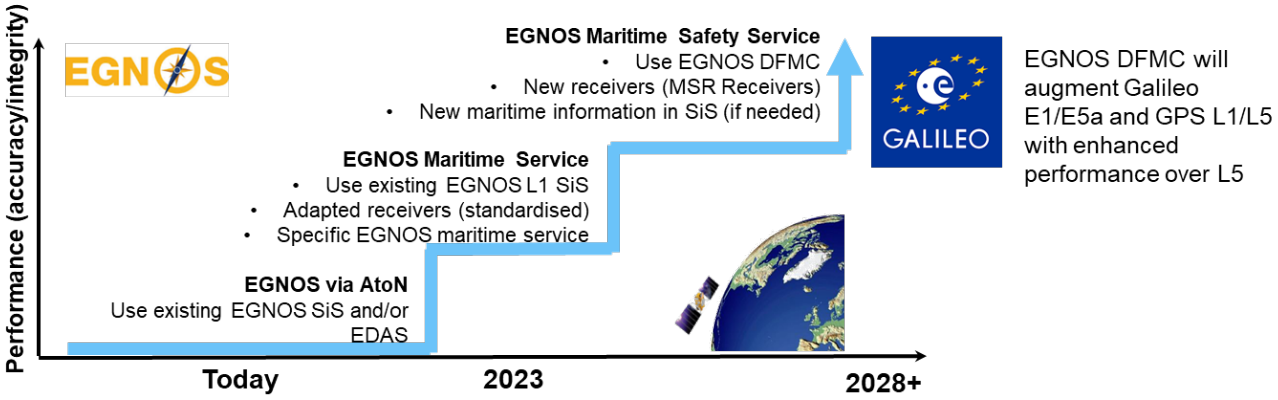

Figure 41: EGNOS maritime adoption planning

The European Commission, EC (EGNOS owner), the EU Agency for the Space Programme, EUSPA (EGNOS Services Programme Manager), the European Satellite Services Provider, ESSP (EGNOS service provider) and the European Space Agency, ESA (EGNOS design agency) are working in close collaboration to declare an EGNOS L1 maritime service by end of 2023/beginning of 2024 to support navigation in "Harbour entrances/approaches and Coastal waters" and in "Ocean Waters" over Europe. The EGNOS L1 Maritime service aims at providing pseudo-range corrections and alert information to GPS L1 signals to let shipborne receivers compute an enhanced navigation solution with respect to GPS standalone, meeting operational requirements included in the *IMO Resolution A.1046 (27) [1]*. The service will provide as well performance monitoring, reporting and provision of Maritime Safety Information (MSI).

EGNOS L1 performance (accuracy, availability, continuity, integrity, time to alarm, coverage) was already analysed in 2018 (ENG8-11.7 [13]) and 2019 (EGN9-2.1.17 [14]) concluding that EGNOS L1 is able to meet the operational requirements stated in International Maritime Organization (IMO) *Resolution A.1046 (27)* [1] for "Harbour entrances/approaches and Coastal waters" and for "Ocean Waters" over Europe. Assessment is ongoing to define the potential service area for the EGNOS L1 maritime service, which plans to cover most of European coast.

The service will provide GPS pseudorange corrections and alerts (system, satellite, iono) via signal-in-space, as well as performance monitoring reporting and provision of Maritime Safety Information (MSI).

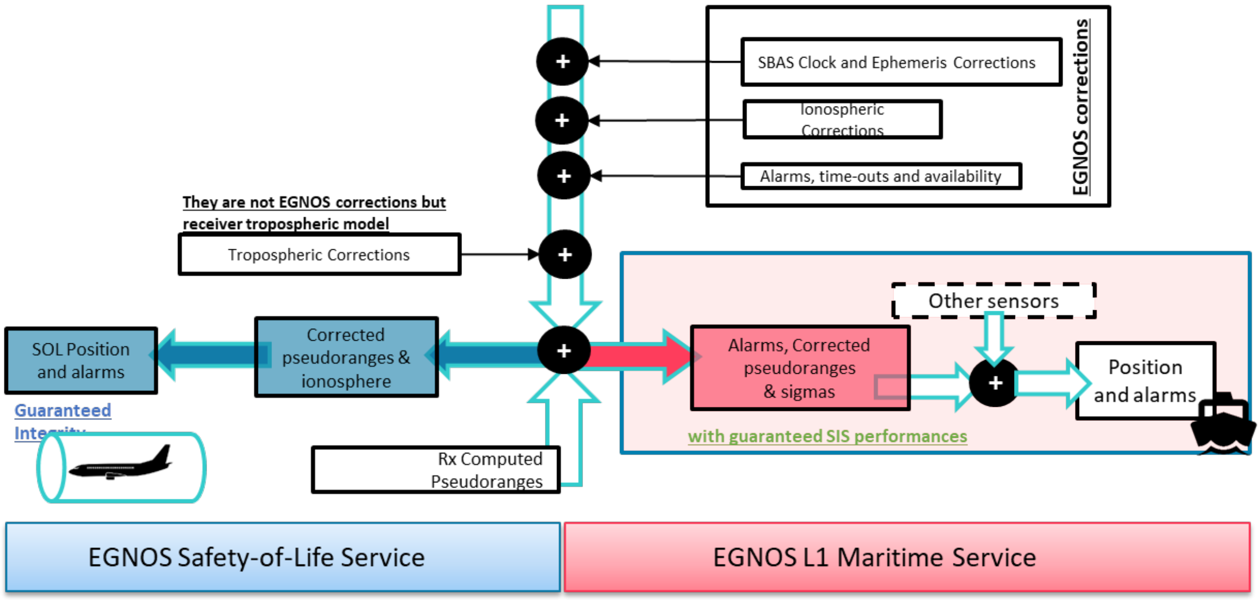

Figure 42: EGNOS Safety of Life service (left) and EGNOS Maritime Service (right)

In order to provide guidance to the maritime authorities on the use of SBAS capabilities for maritime navigation the main elements of the two first steps in the roadmap have been considered in different documentation of the IALA workplan 2018-2022 e.g.:

1. IALA Guideline G1129 THE RETRANSMISSION OF SBAS CORRECTIONS USING MF-RADIO BEACON AND AIS
2. IALA Guidelines G1152 SBAS MARITIME SERVICE

SBAS/EGNOS is expected to be an important element to be considered in the on-going IALA Resilient PNT Guideline.

2.3 Current Status

Currently, GNSS systems (i.e. GPS, Galileo, GLONASS and BeiDou) are recognised by the International Maritime Organization (IMO) as components of the World Wide Radio Navigation System, but they are not fulfilling the operational navigation requirements for harbour entrances/approaches and coastal waters without augmentation. For this type of operations, differential services, like DGPS/DGLONASS, are used to broadcast augmentation data in order to fulfil the performance levels required by *IMO Res A.1046(27)* [1].

EGNOS performance is compliant with *IMO Res A.1046 (27)* [1] operational requirements for ocean/coastal waters and harbour entrances/approaches as shown, presenting the following differentiators from GNSS standalone systems:

- EGNOS provides instantaneous integrity warnings of system malfunction
- EGNOS enhances horizontal accuracy to meet 10 m at 95%.
- Capable of multiple satellite failure detection, of constellation failure detection and of local ionospheric effect detection (such as scintillations).
- Better error estimation due to real time error components estimation from SBAS messages

Complementing those areas not completely covered by DGNSS services and the rationalization process initiated in some countries (e.g. Australia, Ireland, Japan, United Kingdom, United States) that are discontinuing the DGNSS services for maritime operations, the maritime community considers SBAS as a suitable augmentation system supporting maritime navigation services. The focus is today on coastal waters and harbour entrances/approaches, especially where there is no back-up infrastructure (i.e. DGPS/DGLONASS) or in poorly covered environments. In order to fulfil the accuracy and integrity international operational performance requirements (*IMO Res A.1046(27)* [1]) SBAS Services will provide alarms based on satellite clock/ephemeris corrections, ionospheric corrections and Maritime Safety Information (MSI).

IMO MSC.401(95) [2], *MSC.432 (98)* [12] and *IEC 61108-4* [6] (Shipborne DGPS and DGLONASS maritime radio beacon receiver equipment) allow the use of different augmentation signals in shipborne receivers but there is neither an IMO nor IEC standard on how to process and implement SBAS signals in shipborne receivers. Most of recent maritime GNSS receiver models are SBAS compatible but present important differences in their performance since they are not certified according to any specific test standard. Thus, in order to ensure a safe and harmonised use of SBAS by all shipborne receivers, a new IEC 61108 standard for SBAS L1 receiver equipment is being developed.

IEC 61108 is a series of IEC standards for "Maritime navigation and radio-communication equipment and systems - Global navigation satellite systems (GNSS)". IEC has published International Standards for the following GNSS systems: *IEC 61108-1* [3] for GPS, *IEC 61108-2* [4] for GLONASS, *IEC 61108-3* [5] for Galileo, *IEC 61108-5* [7] for BeiDou and *IEC 61108-6* [11] for IRNSS. In addition, IEC has published International Standard *IEC 61108-4* [6] for DGPS and DGLONASS which are Differential Global Navigation Satellite System (DGNSS) enhancing the primary GNSS constellations (GPS and GLONASS). So, a new part within the IEC 61108 series is being developed for the SBAS L1 maritime receivers with reference *IEC 61108-7* [8].

Once the IEC 61108-7 [8] is published, vessels will start equipping type-approval receivers using SBAS and RAIM to ensure a safe navigation in harbour entrances/approaches and coastal waters.

One of the key elements for the EGNOS L1 Service is the provision of the maritime Safety Information (MSI) informing on the status of the EGNOS Service. The MSI function and scheme was agreed by IHO in September 2021 in the framework of the 13th MEETING of the IHO SUB-COMMITTEE ON THE WORLD-WIDE NAVIGATIONAL WARNING SERVICE (WWNWS13).

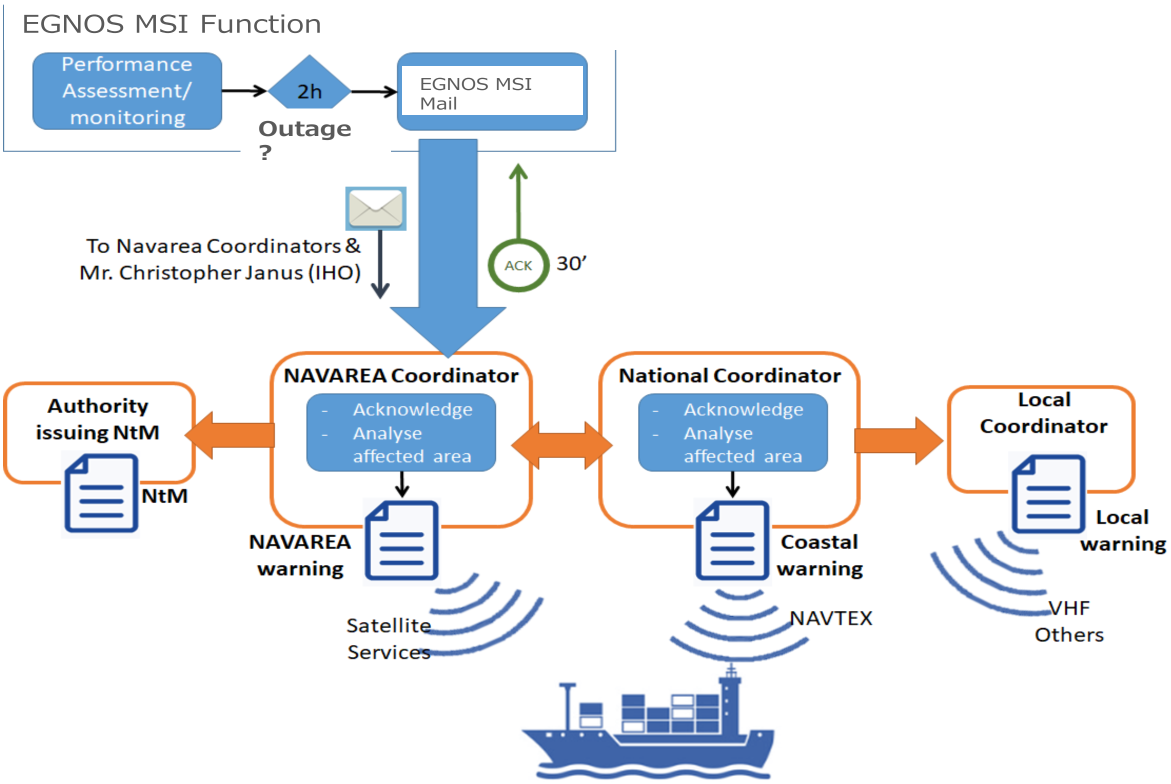

Figure 43: EGNOS Maritime Safety Information (MSI) Function and Scheme

In the core of the EGNOS Service Provision Scheme the EGNOS for Maritime Service Provider will play a key role:

- Monitoring and reporting of the EGNOS service for maritime performance to the users by means of the appropriate mechanisms.
- Managing the interfaces and liability scheme with the involved maritime stakeholders.
- Delivering the Service in accordance with the international regulation and notably with SOLAS.
- Managing and informing the maritime community about the EGNOS maritime Service Development and evolution.

3 CONCLUSIONS AND FUTURE WORK

EGNOS L1 maritime service is planned to be ready by end 2023 / beginning of 2024. Once the IEC 61108-7 [8] is published, vessels will start equipping type-approval receivers using SBAS and RAIM to ensure a safe navigation in harbour entrances/approaches and coastal waters. The publication of the SBAS L1 shipborne receiver standard *IEC 61108-7* [8] is key for the harmonised adoption of SBAS in the maritime domain.

IALA, in coordination with EUSPA/EC, together with EU Member States, Australia, China, New Zealand, ICS and the NI, co-sponsored the submission to IMO of a request for a new output for the development of minimum performance standards for Dual-Frequency Multi-constellation SBAS and Advanced-RAIM in shipborne radionavigation receivers. If the request is approved, IMO will develop the standard in 2024-25. After that, IEC will be approached to develop the standard to define the methods of testing, building as well on IEC-61108-7 for SBAS L1 and RAIM.

4 ACKNOWLEDGEMENTS

We would like to acknowledge the efforts done by the different teams of EC, EUSPA, ESA and ESSP for the work done at programme level enabling the coming provision of EGNOS L1 maritime service.

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S14.3 R-Mode Baltic World-Wide first R-Mode Testbed using MF and VHF (064)

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ABSTRACT

Position, Navigation, and Timing (PNT) is part of the critical infrastructure necessary for the safety and efficiency of vessel movements, especially in congested areas. Global Navigation Satellite Systems (GNSS) have become the primary PNT source for maritime operations. Unfortunately, GNSS is vulnerable to jamming and interference, intentional or not, which can lead to the loss or, even worse, to incorrect PNT information. Furthermore, system errors could be identified in the past. Thus, additional supporting and complementary systems are required to provide resilient PNT. One candidate system, which could provide alternative positioning and timing information, is known as R-Mode, or ranging mode. The idea of R-Mode is based on the transmission of a ranging signal or a ranging message via marine radio beacons, which operate in the medium frequency (MF) band, or from Very High Frequency (VHF) shore networks using the VHF Data Exchange System (VDES).

Over the last years a number of studies were performed which demonstrated the feasibility of R-Mode. In addition, first static tests validated the theoretical findings and showed the potential of R-Mode as a future contingency or backup system to GNSS.

Within the European Union co-financed projects “R-Mode Baltic” and “R-Mode Baltic 2” (2017-2021) the world-wide first operational and transnational R-Mode test bed was implemented, which utilises already existing maritime radio beacons as well as new VDES base stations. This test bed enables on-board dynamic positioning in a large area located in the southwest Baltic Sea between Germany, Sweden, Poland and Denmark.

This paper details that the existing maritime radio infrastructure of the southern Baltic Sea already fulfils the precondition for a successful implementation of a combined MF and VDES R-Mode system. The concept for the test bed was based on coverage prediction and accuracy estimation studies for MF and VDES R-Mode in the Baltic Sea. Further, the paper describes the implementation and operation of eight MF maritime radio beacons with R-Mode capabilities and the preparation of four VDES R-Mode sites. In addition, the paper provides detailed results from dynamic positioning campaigns, an overview about the results of a cost benefit analysis and a summary of ongoing standardisation activities related to R-Mode.

KEYWORDS: R-Mode, Resilient PNT, Positioning, R-Mode Baltic, Terrestrial radio navigation system, GNSS backup, VDES

1 INTRODUCTION

1.1 Motivation

Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, Galileo, and BeiDou have become the primary means of navigation for marine vessels. They provide accurate positioning, navigation and timing (PNT) information, which is essential for safe and efficient navigation. However, GNSS signals can be affected by various factors, including atmospheric conditions, signal jamming, signal spoofing, and solar flares, among others, which can lead to degraded or lost signals [1]. The Baltic Sea has a large number of islands and many coastal areas with reduced water depth, which makes it a challenging body of water for navigation. A GNSS backup systems can provide an additional layer of safety and reliability.

One of the main reasons for the need for GNSS backup in the Baltic Sea is the risk of jamming and spoofing. The Baltic Sea is a heavily trafficked area, and there is a risk that jamming devices could be used to disrupt GNSS signals, either accidentally or intentionally. This could lead to navigation errors and collisions, which could be dangerous for both commercial and recreational vessels.

Another factor that highlights the need for GNSS backup in the Baltic Sea is the risk of navigational hazards such as rocks and shallow waters. Accurate navigation is critical in these areas, and even a small deviation from the intended course could result in a grounding or collision. In the event of loss or manipulated GNSS signals, a GNSS independent terrestrial backup navigation system can help to maintain safe navigation and can deliver the required level of resilience for the provision of PNT data on board maritime vessels.

In recent years, there have been reports of GNSS signal disruptions in the Baltic Sea region, specifically in the areas near the Russian border. The disruptions are believed to be caused by Russian military activities, which involve the use of jamming equipment to interfere with satellite signals. The disruptions have caused problems for various users of GNSS, including civilian ships, aircraft, and even emergency services. On the other hand, GNSS disruptions are also reported in other areas of the Baltic, for example caused by jammers in vehicles on ferries [2].

It is important to note that GNSS signal disruptions are not unique to the Baltic Sea region, and occur in various other parts of the world as well [3].

1.2 The need for backup to GNSS on marine vessels including MASS

Unavailable PNT data, even for short periods, limits the situation assessment and results in numerous alerts raised by multiple systems on the bridge. Much more critical are hazardously misleading information as result of position errors that are large enough to have a severe impact on navigation.

Further, GNSS will also be a more critical component of future MASS (Maritime Autonomous Surface Ship) navigation system, as it provides accurate PNT to the vessel. To ensure the safety and reliability of MASS operations, it is essential to have a backup navigation system that can provide the required level of resilience and integrity as well a suitable accuracy for general maritime navigation.

To meet the requirements for resilient, reliable and highly available PNT information, the International Maritime Organization (IMO) has also required the use of GNSS backup systems. Within the Strategic Implementation Plan of e-Navigation, IMO has identified the user needs on improved reliability, resilience, availability and integrity of bridge equipment and navigation information as one of the five prioritized e-Navigation solutions NAV54, WP.6, [4].

1.3 Ranging Mode (R-Mode) as terrestrial GNSS backup

A variety of technological solutions provide the potential to fulfil the backup requirements from IMO. Within the radio frequency (RF) domain existing maritime radio infrastructure can facilitate ranging information to a user receiver. One concept for providing a GNSS backup system is the Ranging Mode (R-Mode). This concept uses existing maritime radio infrastructure that is already widely used in the maritime sector. The systems that can be most usefully deployed here are the medium frequency (MF) radio beacon system, currently providing GNSS augmentation data to maritime users and the emerging VHF data exchange system (VDES), which includes the frequency channels for Automatic Identification System (AIS), Application Specific Messages (ASM) and VHF data exchange (VDE) terrestrial and satellite channels.

While these existing signals are currently not primarily intended for positioning, a future navigation receiver may attempt to exploit them as such. Position determination by means of trilateration is possible if at least three (pseudo) ranges between the unknown receiver location and the known transmitter locations can be determined. The use of such ranging signals, transmitted from existing maritime radio infrastructure is called "R-Mode". Even if it is impossible to derive an R-Mode based position solution (e.g. due to insufficient number of received pseudoranges), the available pseudorange information, combined with measurements from other positioning systems or ship sensors, can provide a position solution. Furthermore, any R-Mode pseudorange can be used to improve PNT data integrity.

1.3.1 Concept and early work

First ideas of an R-Mode system making use of existing maritime radio systems were given as an input paper to the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) e-Navigation committee in 2008 [5]. The main idea was to add a synchronised timing information to existing radio infrastructure used in the maritime domain, which is derived from an R-Mode system time. A first detailed study on potential methods and an analysis of achieved R-Mode performance was performed in the European ACCSEAS project. This European collaborative project developed the idea of R-Mode by supporting a feasibility study, which considered the suitability of adding ranging information to maritime radio beacons and AIS base stations and considered it in combination with eLoran [6]. As the position is calculated through trilateration from terrestrial transmitters, the resulting performance is mainly a function of the received signal power, the noise level, the propagation path, the receiver observation time and the number and geometry of transmitter sites in view. A first field test validated the theoretical findings of the feasibility study for the MF R-Mode [7].

1.3.2 Background on MF R-Mode

The MF differential GNSS (DGNSS) system transmits its information via a binary modulation method known as Minimum Shift Keying (MSK) [8]. Assuming that the MSK transmission is controlled by a precise time/frequency source, both the times of the bit transitions (potentially once every 10 milliseconds) and the underlying phase of the transmitted signal (a sinusoid at approximately 300 kHz) could be exploited to estimate the time of arrival (TOA) for ranging applications. The R-Mode feasibility report examined the potential performance of estimators of TOA from these two parameters [7]. It was argued that with the existing signal strengths and beacon locations, the time of bit transition is too imprecise for effective ranging. However, assuming that the cycle ambiguity could be resolved, the carrier phase could yield sufficient accuracy. Further, while this level of performance is conceptually possible with the direct MF transmission, it would be significantly easier if in-band continuous wave (CW) signals accompanied the MF and the phase of this separate CW was estimated. The system proposed in [6] adds two CW signals to the MSK transmission; one below and one above the MSK carrier. Nominal values for the offset in frequency from the MSK carrier are ±225 Hz (recall that the European standards for DGNSS call for a 500 Hz channel bandwidth thus limiting the offsets from the carrier frequency to less than ±250 Hz).

Ranging on the CW signals was analysed and a bound for the estimation accuracy was determined. The Cramer-Rao lower bound for the accuracy is:

$$var\left(\sigma^2_{\widehat{\tau\, carrier}}\right) = \frac{1}{T\, f_{\mathrm{sample}} SNR}$$

in which T is the observation period, f_sample the sample rate and SNR is the received signal to noise ratio [9]. With respect to the carrier frequency ω_c and the speed of light c_0 we can calulate a distance in meter. Taking a square root yields the standard deviation for the range error [10].

$$\sigma_{MF\ carrier} \geq \frac{c_0}{\omega_{\mathrm{c}}\sqrt{T\, f_{\mathrm{sample}}\, SNR}} \text{ meters}$$

Thus, based on an observation time of 5 s and typical SNR values in a range between 30 dB (good) and 10 dB (weak) range errors of 1-10 m are possible (ignoring additional errors due to time synchronisation and propagation path).

During the R-Mode Baltic project first measurements for the validation of MF R-Mode were conducted at the sea in the Baltic test bed. For good conditions with three seen transmitters, less changes of the land-sea propagation path and no sky-wave interference, a horizontal positioning accuracy of 12 m was found over a time of about 5 hours at day-time [11].

1.3.3 Background on VDES R-Mode

The VDES R-Mode system transmits precisely timed VHF signals from a network of base stations on shore and possibly from offshore locations. A ship-based VDES R-Mode receiver will measure the timing (and other) parameters of the received signals to derive pseudo ranges. A PNT processor will use the observations to determine the user's position, speed over ground and other navigation parameters [12]. Herby, the VDES R-Mode should use the existing infrastructure as much as possible. VDES R-Mode is synchronised with an external time source that is traceable to a common time scale to facilitate interoperability with other PNT systems [12].

VDES R-Mode is based on the VDE-TER specification in ITU-R M.2092-1 [13]. The physical layer of the R-Mode application requires a ranging sequence and additional navigation data to determine the distance between VDES R-Mode base stations, transmitters, and receiver. The ranging sequence is predefined and adapted by the network depending on the expected coverage areas. VDE-TER schedules the resources based on a Time Division Multiple Access (TDMA) scheme between VDES base stations that are coordinated by the network providers. The VDES R-Mode base stations shall transmit their ranging sequence every second based on the configuration of link-ID 37. The additional navigation data shall be communicated every minute via the link-ID 11 within the network and via one VDES R-Mode base station.

The ranging sequence is a concatenation of two known sequences to customize the required performance based on the given scenarios. The scenarios considered are:

1. shorter distances with high SNR between shore station and vessels ($\gamma > 0.5$),
2. longer distances with lower SNR between shore station and vessels ($\gamma < 0.5$).

Figure 1 describes how both sequences are concatenated as part of the data message of a VDE-TER slot based on the γ factor.

Figure 1 Example of VDES R-Mode sequence concatenation [12]

1.4 R-Mode Baltic projects

The R-Mode Baltic and R-Mode Baltic 2 project (2017-2021), co-financed by the European Union within the Interreg Baltic Sea Region Programme, delivered extensive R-Mode service for a high-density traffic area within the Baltic Sea. A transnational team of 12 and 10 partners originating from four countries (Germany, Norway, Poland and Sweden) conducted the projects. The goal, to develop and demonstrate R-Mode as a potential backup system for maritime PNT data provision, has been established by the installation of the R-Mode Baltic test bed and will be available for navigation for the upcoming years. Within R-Mode Baltic the project research was conducted on the selection of optimised R-Mode signals for range estimation and positioning as well as time synchronisation methods for R-Mode transmitters, which meet the mariner's requirements on resilient PNT. Furthermore, solutions for R-Mode transmitter and receiver prototypes for use in the operational test bed were developed and inaugurated. The R-Mode Baltic project further installed and operates the first transnational R-Mode test bed world-wide. The test bed installations are fully based on already existing maritime radio beacons as well as VDES base stations. The R-Mode Baltic 2 project focused mainly on test bed validation and the development of near and far field monitors with the aim to improve the R-Mode system performance and observe the current status of R-Mode system parameters.

1.5 World-wide activities

Beside the R-Mode activities reported above a number of R-Mode activities are ongoing in other parts of the world. Table 1 provide a brief overview about the recent R-Mode activities known by the authors.

Table 1 Overview of known world-wide R-Mode activities

Country/Region	Activity
Baltic Sea Region with involvement of Sweden, Finland, Estonia, Norway, Germany, Poland and Denmark.	Implementation of the first transnational, large-scale R-Mode test bed. Future activities will focus on expanding the R-Mode towards Finland and Estonia. The aim is to implement a first R-Mode system that includes all essential functions of an operational system and a GNSS degradation monitoring system in the Baltic Sea. This planned initiative should continue the work performed in the R-Mode Baltic projects in the time frame 2023 till 2026.
South Korea	Korean R-Mode test bed project (TRACE). KRISO, the supervising agency of the Terrestrial Ranging-Augmented, Complementary and Enhanced (TRACE) project, commenced the R-Mode test bed project of the Republic of Korea in April 2020 and will develop the core technology and demonstrate its performance in the test ports by September 2023.
China	The AIS Ship Autonomous Navigation System (AAPS) project in China (2012-2015) initially realized the positioning function of the AIS R-Mode, and conducted theoretical research on the VDES R-Mode in 2016-2017. Based on the above research, the Project of VDES R-Mode test bed (2018-2020) has built an R-Mode test bed in the Yellow and Bohai Sea
Canada	Canadian Coast Guard (CCG) is implementing a MF R-Mode test bed 2022-2026 at the St. Lawrence river near Quebec. Further tests are also planned using VDES R-Mode
UK /Norway	VAUTAP (VDES R-Mode project) 2022-2024 Development of advanced VDES-R user technologies for alternative PNT
Romania	The RIPTIDE PHASE 2 project (2023-2024) targets the second phase in the development of a resilient PNT solution dedicated to the particularities of the Black Sea and Danube Lower Basin region.

2 R-MODE BALTIC TEST BED

2.1 Preconditions of the region

The Baltic Sea is a challenging water for shipping due to its small depth of about 52 m in average, the concentration of traffic in narrow channels in some areas and crossing traffic routes. The Baltic Sea is a small sea with an area of 390,000 km². It is somewhat elongated, so that every ship is in maximum about 120 km away from next island or mainland. Nine countries border the Baltic Sea. For them is fishing but also sea transport of people and goods and tourism important pillars for their economy.

At any time, 1500 ships navigate the Baltic Sea. To improve safety at sea, to reduce the risk of incidents and accidents and to protect the sensitive environment, the administrations of the nine countries established a dense and overlapping network of DGNSS radio beacons, which cover the entire Baltic multiple times, and a network of AIS base stations, which cover the sea area of about 20 to 40 km from shore. These two networks are the precondition for the R-Mode system in the Baltic Sea region. Here it is assumed that in the medium term all AIS base stations will be replaced by VDES base stations.

Therefore, the Baltic Sea is the perfect location for a test bed of MF as well as VDES R-Mode. To reach the requirements at least three R-Mode signals have to be received to enable 2D positioning on the water surface with a trilateration approach. That means, any combination of at least three transmitters of R-Mode enabled radio beacon (typical service range is 250 km) and R-Mode ready VDES base stations (range strongly depends antenna height; typical range is 20 nm) have to be in view. In addition, the geometry of the R-Mode transmitters to the R-Mode user is important for the achievable positioning accuracy. It is advantageous to receive R-Mode signals from as many sites as possible to achieve a low horizontal dilution of precision. Here, the Baltic Sea is predestined for R-Mode because the MF R-Mode signals reach across the elongated Baltic Sea. VDES base stations can be placed on smaller island to achieve good coverage for narrow channels.

Within the framework of the R-Mode Baltic project the R-Mode ranging and positioning performance was predicted for the Baltic Sea for the two types of transmitters and its combination [14] [15]. The prediction showed that the implementation of MF R-Mode into all available radio beacons would enable R-Mode based positioning at almost the entire area of the Baltic Sea. The expected accuracy is at day-time better than 15 m (95 %) and at night-time better than 35 m (95 %), except the northern tip of the Baltic Sea where we have low beacon coverage. At night-time in addition the area around Arkösund shows reduced performance due to larger distances to next transmitters. The reason for the reduced night-time performance is the interference of the ground wave, which is used for R-Mode, and an effective reflection of the sky wave during the night. At day-time the sky-wave part of the radio-beacon transmission is very strongly attenuated by the atmosphere.

For VDES R-Mode, the prediction [15] was based on existing AIS shore sites of Poland, Sweden, Denmark and Germany. It clearly showed that today only in few areas of the southern Baltic Sea between Denmark and Sweden; Denmark and Germany; and Poland and Germany the number of visible stations is high enough for R-Mode based positioning. A positioning accuracy of 10 m could be achievable. The other areas along the coastline have most often single and double overlapping service areas. Central Baltic is not covered. The region next to the border between Germany and Poland was selected for the VDES R-Mode component of the R-Mode Baltic Sea test bed. In contrast to MF R-Mode, VDES R-Mode has the same performance during day-time and night-time.

Furthermore, the prediction showed [15] that the combination of VDES and MF R-Mode would be the optimal solution because it increases the number of R-Mode transmitters which can be received, it reduces the distance to the nearest three to four R-Mode transmitters and it compensates the short range of VDES transmitters.

Based on the signal to noise ratio prediction of report [14] the MF R-Mode performance was calculated for different subsets of transmitters. This was used to define the initial MF R-Mode test bed. Figure 2 shows the predicted 95 % positioning performance for the day-time and night-time [16]. Again, highest accuracy can be achieved between the transmitters marked as triangles. During the night, the only partly considered R-Mode implementation causes strong performance reduction for the southern Baltic Sea. The performance could be improved by increasing the transmitter density by upgrading more existing radio beacons in Poland, Denmark and Sweden. The calculation was done in accordance with [14].

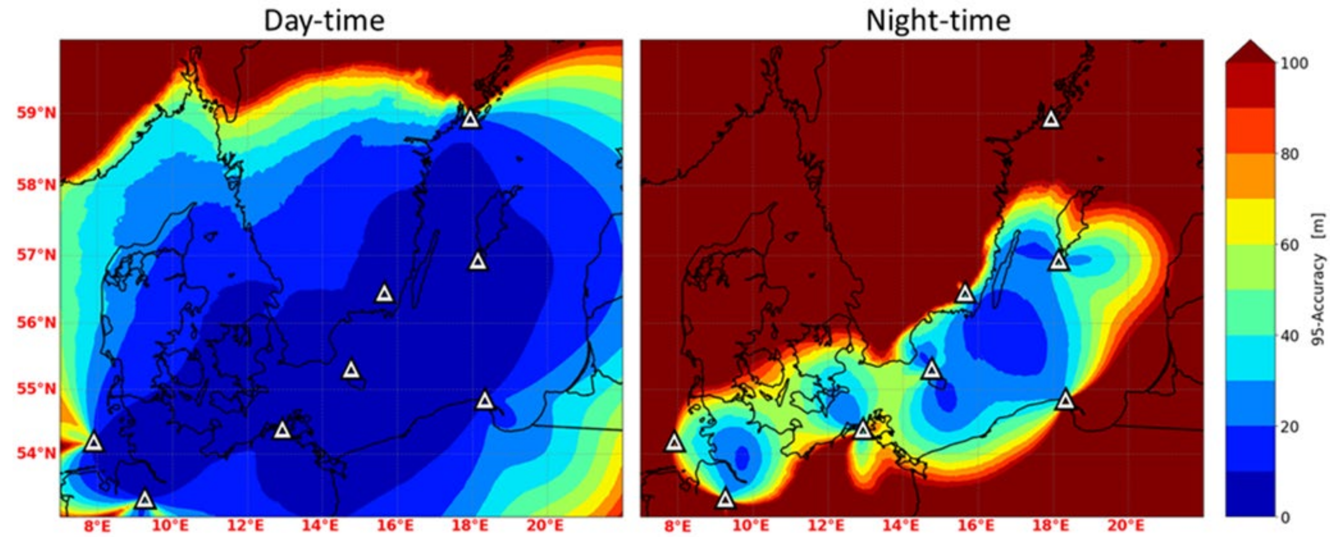

Figure 2 MF R-Mode test bed 95% horizontal accuracy at day-time (left) and night-time (right). The white triangles mark the position of the considered transmitters.

2.2 MF implementation at the sites and monitoring

The existing R-Mode Baltic test bed that was implemented in before mentioned EU co-financed projects consists of eight transmitters, two far field monitors and three near field monitors. It covers the southern Baltic Sea between Germany, Sweden and Poland as shown in Figure 3. For the future, it is planned to extend the test bed to the east with three new MF R-Mode transmitters in Finland (2) and Estonia (1).

The test bed provides a large proving ground for a variety of tests and further developments of the R-Mode system. It is the first operational transnational R-Mode test bed worldwide. The MF test bed installations are based on already existing maritime radio beacons.

On the Swedish site, the test bed consists of three transmitters in Hobrug, Holmsjö and Nynäshamn, and a far field monitor in Arkö. The Hoburg and Holmsjö stations are equipped with near field monitors. On the German site, it consists of the stations Helgoland, Zeven and Groß Mohrdrof, as well as a far field monitors in Groß Königsförde and Zecherin. The station Groß Mohrdorf is also equipped with a near field monitor. In addition, there are the stations Rozewie and Hammer Odde in Poland and Denmark. Within this test bed, the first MF R-Mode positioning in the far filed could be achieved [11].

Figure 3 MF R-Mode Testbed at the end of R-Mode Baltic 2 Project

2.2.1 R-Mode implementation

To enable an existing radio beacon site to transmit R-Mode signals, it is necessary to have a suitable modulator and precise clock. The existing components of the radio beacon, such as DGNSS message generator, amplifier and antenna, can usually be continued unchanged. Figure 4 illustrates on the left side the schematic structure of a radio beacon, which only transmits DGNSS correction data. The schematic below shows the modifications necessary to transmit a ranging signal in addition to the DGNSS messages. It is necessary to replace the modulator with an R-Mode capable modulator and add a precise time source, labelled as R-Mode System Time in Figure 4, (e.g. Rubidium Clock) is required.

During the R-Mode Baltic projects, it was possible to modify a number of MF stations. Figure 4 shows on the right side a picture of the system components of the MF station Zeven in Germany. Here, the left rack contains the amplifier cabinet and the right rack the DGNSS station components, the R-Mode modulator and a Rubidium clock as time source.

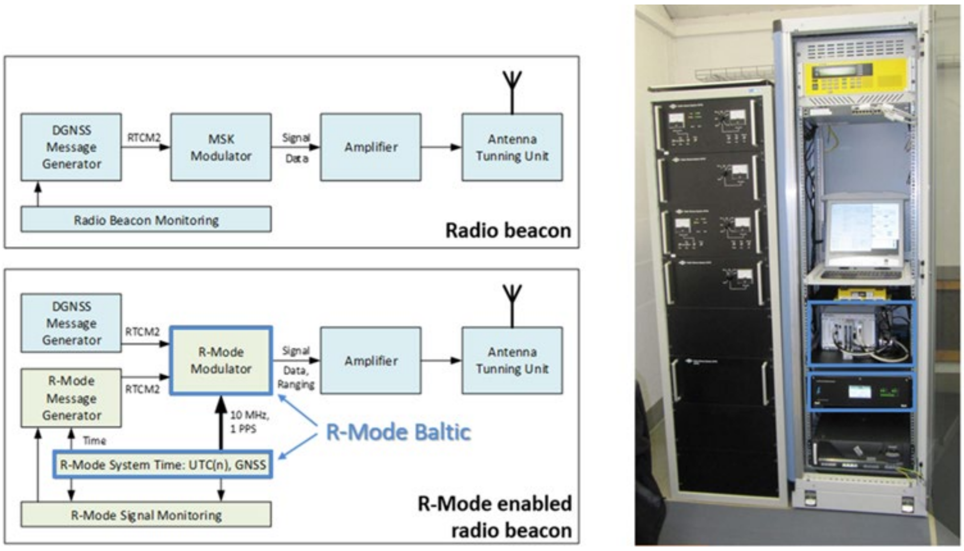

Figure 4 Schematic structure of an radio beacon (upper left), the adoption to R-Mode (lower left) and a picture from the R-Mode enabeled radio beacon in Zeven in Germany (right)

2.2.2 Onsite and far field monitoring

The onsite monitoring is used to determine the total time delay of all constant and dynamic values of an MF R-Mode transmitter chain. The time delays consist of the delays of all cables, amplifier and filter, the ATU and the MF antenna. The concept is to measure the radiated R-Mode signal by using a near field antenna in close proximity to the transmitter. A feedback loop to the R-Mode modulator allows the dynamic real-time calibration of an R-Mode transmitter. Figure 5 shows on the left the schematic structure of an onsite monitoring station.

In contrast to near field monitoring, far field monitoring considers the effects of the sky wave and the variable propagation speeds of the transmitted signals, e.g. changing parameter of the propagation path caused by weather influence. It is therefore important for a far field monitor to be able to receive as many R-Mode transmitters as possible so that all received signals can be evaluated and analysed. Figure 5 shows on the right the schematic structure of a far field monitoring station.

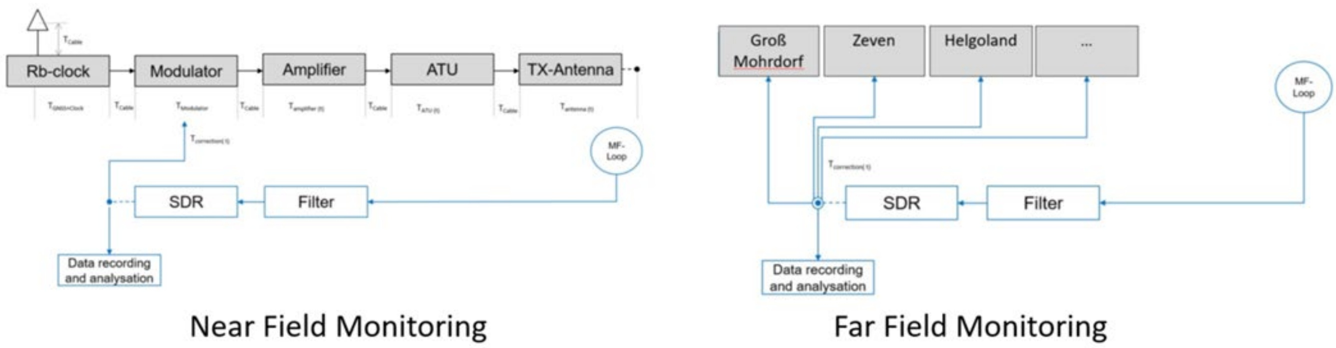

Figure 5 Schematic illustration of an MF R-Mode far field and near field monitoring station

2.3 VHF implementation at the sites and monitoring

During the R-Mode Baltic projects several VDES installations could be realised in the Baltic Sea area. The area between the island Rügen, the peninsula Usedom and the Polish port in Świnoujście was chosen for the installations. For the transmission of VDES R-Mode signals locations on Greifswalder Oie, in Thiessow, in Zecherin and in Świnoujście were prepared. In addition, a VDES station was established in the port of Gdynia.

2.3.1 VHF installation Poland - Port of Gdynia

During the R-Mode Baltic 2 project, a fully functional VHF system for a long-term, real-time position monitoring was developed [17]. This system allows to determine the receiver's position on the basis of static and dynamic measurements. The conducted measurement campaign, which took place in summer and autumn 2021, confirmed the effectiveness of this solution. The transmitting station (Figure 6 a) was installed in the port of Gdynia, with the Equivalent Isotropically Radiated Power (EIRP) power of 25 W. The antenna height was 28 m above sea level. The receiver (Figure 6 b) was located in Jastarnia Harbor – about 20 km away from the transmitter. In order to finally calculate the receiver's position on the basis of the calculated ranges, a measurement scenario was used where additional base stations were simply emulated. The coordinates of the emulated stations were chosen in such a way so that their respective ranges from the receiver in Jastarnia were the same as the distance between Jastarnia and the "real" transmitting station in the port in Gdynia.

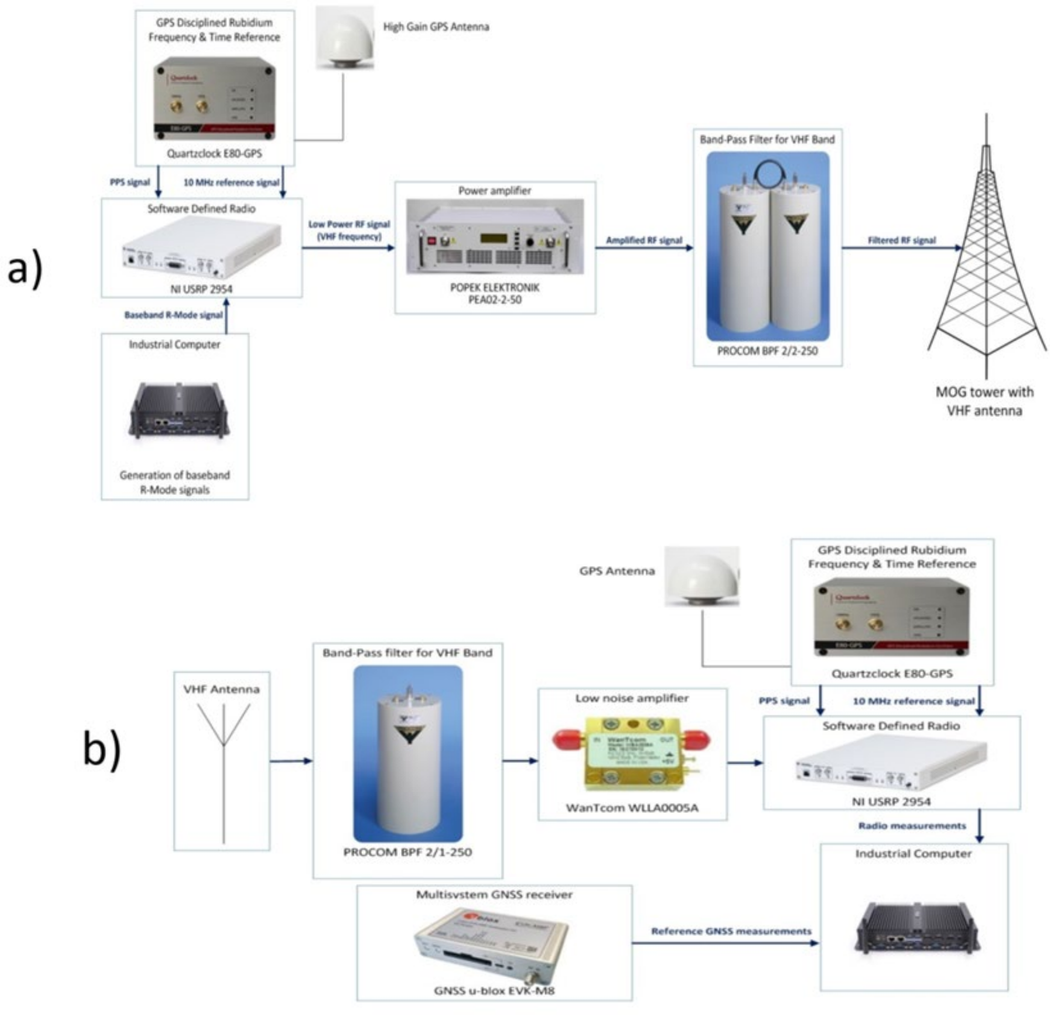

Figure 6 VDES R-Mode prototype equipment: a) transmitter block diagram (Port of Gdynia) b) receiver block diagram (Jastarnia Harbor) [18]

The receiving antenna height was 17 m above sea level. The transmission between the stations took place under Line of Sight (LOS) conditions and entirely over a sea path. Both stations were synchronised with rubidium disciplined oscillators. The receiver was additionally equipped with a Low-Noise Amplifier (LNA) amplifier (Noise Figure, NF=0.6 dB) and a VHF band-pass filter. The Figure 7 shows the values collected for the first few days of measurements.

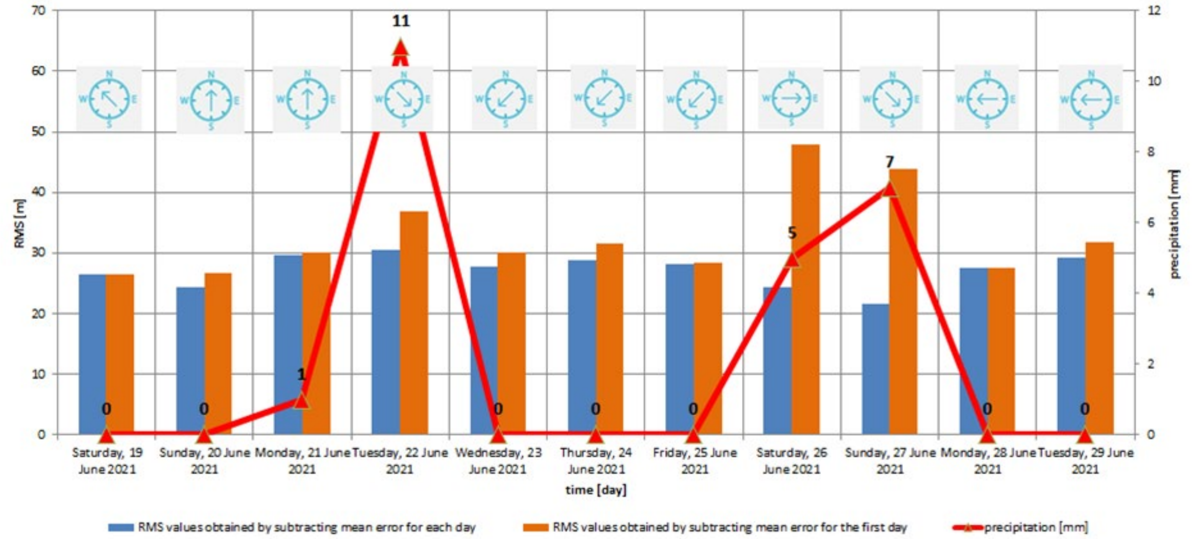

Figure 7 Analysis of the observed Root Mean Square (RMS) depending on the meteorological conditions [17]

First of all, the results obtained show the Root Mean Square (RMS) values for two cases: when the mean error from the measurements was subtracted: (a) every day and (b) just once – on the first day of measurements. This approach could potentially show the mean error accumulation. However, no such effect was observed during monitoring – as depicted in Figure 7. This confirms the reliability and stability of the measurements as well as long-term invariability of propagation conditions. The graph also indicates the atmospheric factors (wind direction and – most noticeably – precipitation) that affected the results and ranging accuracy obtained for the double delta correlator algorithm [17]. Above all, however, the presented values clearly show the need for continuous VHF propagation conditions monitoring for the purpose of the VDES R-Mode system. Final and more quantitative conclusions, however, need further studies based on much bigger data sets and diversified geographical distribution of monitoring stations around Baltic Sea.

2.3.2 VHF installation Germany – preparation of test bed

During the R-Mode Baltic 2 project, preparations were made to build a VDES R-Mode test bed in the Baltic Sea at the German-Polish border. The test bed covers three German and one Polish VDES station. In addition, a monitor station is planned on the German site in Karlshagen. Figure 8 shows the four stations of the test bed. Thiessow, Greiswalder Oie and Zecherin on the German site and Swinoujscie on the Polish site. During the R-Mode Baltic 2 project, the infrastructure of the German stations has been prepared to the extent that they are ready to be used as VDES R-Mode transmitters. The stations were equipped with appropriate VDES compatible antennas as well as with the appropriate system cabinets for the R-Mode components. The testbed could not yet be put into operation, as the corresponding VDES transmitter hardware for the operation is not available.

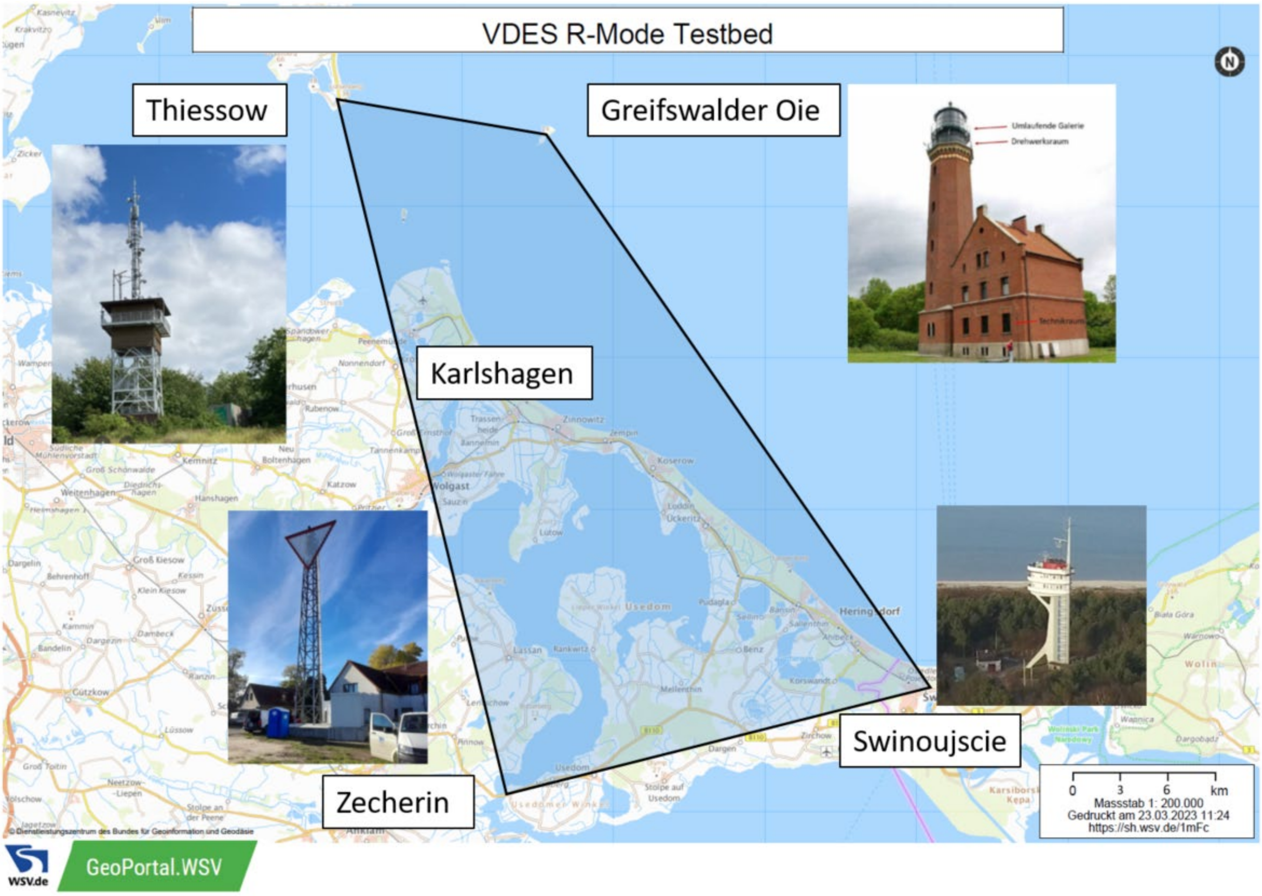

Figure 8 Prepared VDES R-Mode test bed at the German - Polish border

3 MEASUREMENT RESULTS

3.1 MF R-Mode

3.1.1 MF R-Mode receiver

A research platform developed by the German Aerospace Center [11] was used for the MF R-Mode measurements in the R-Mode Baltic Sea test bed. For the design, commercially available of the shelf components were used which can be divided into front end components, the time reference, Software Defined Receiver (SDR) and processing part. The front-end part consists of a low noise amplifier LNA and a bandpass filter. The amplified and filtered signal is then feed into the SDR (X310 or N2x0 from NI). The common feature of this family of SDR's is the possibility to synchronise it with an external clock using 10 MHz and PPS reference. For the experiments a Lange Time Reference Receiver LL-3760 was used which enabled us to analyse the received signals based on the time of arrival for each R-Mode transmitter separately. The obtained signals are processed on a user grade personal computer. All components are placed in a 19" rack for convenient transport (Figure 9).

Figure 9 MF R-Mode receiver used in static and dynamic measurements

The data recording and processing is conducted in a combined C++ and Python software framework. The calibration of the receiver and the transmitters were conducted at the beginning of the experiments with the help of an additional GNSS receiver [11]. The estimation of the range and the position can be conducted in real-time but also in post-processing.

3.1.2 R-Mode performance for dynamic measurements next to Rostock harbour

In February 2022, after first trails at the centre of the Baltic Sea in 2020, an R-Mode measurement campaign was conducted north of the German harbour Rostock. The ship was sailing for several days a surveying pattern at day-time and partially at night-time conditions. The determined R-Mode positioning performance will be compared with the theoretical bound in this section. Unfortunately, only a subset of the data could be used for the performance analysis because problems with the transmitters occurred. For the data analysis here only signals with continuous phase measurements and stable amplitude over several hours were used. Signals were sorted out which show

- sudden jumps of the phase, which cannot be explained by the ship movement,
- an unstable amplitude, which is caused by sky-wave interference,
- unstable phase measurements, which is caused e.g. by interference with an interferer next to the R-Mode receiver.

During the measurements the signals of six R-Mode transmitters of the test bed could be received. One of the nearest transmitters, Zeven, was not usable at that time due to maintenance activities. The eight, Nynäshamn, was too far away. The ship was operating southwest of Groß Mohrdorf (see Figure 3) a little outside the R-Mode Baltic core area. Due to unavailability of Zeven, the geometry was not optimal for positioning as it is shown later for the predicted R-Mode performance. The measured R-Mode performance was evaluated with the help of an GNSS Real Time Kinematic (RTK) reference receiver.

Table 2 shows the average distance between the ship and the received transmitters. A first important point to highlight is that the distance between some stations and the receiver was far more than the expected coverage of about 300 km. This shows how MF R-Mode can potentially provide its service over a larger area than the expected one.

Table 2 Average distance between receiver and transmitter during the campaign

Station	Average Distance [km]
Hoburg	481
Rozewie	414
Helgoland	266
Hammerodde	207
Holsmjö	328
Groß Mohrdorf	62

During 6 h at day-time the 95% positioning accuracy of 16 m was achieved. This level of accuracy satisfies the user performance requirements for backup navigation systems for coastal waters navigation [19]. The short day-time is due to the time of the year, winter.

For the received set of stations the R-Mode positioning performance was predicted as explained in Section 2.1. The result is shown on the right side of Figure 10. The yellow star represents the area of interest and white triangles the received stations. Compared to Figure 2 the missing signals of Zeven (southernmost station) and Nynäshamn (northernmost station) leads to a significant reduction of the area with 10 m accuracy. For the test area the predicted accuracy is between 10 and 20 m. This agrees with the 16 m accuracy obtained in the field during the campaign.

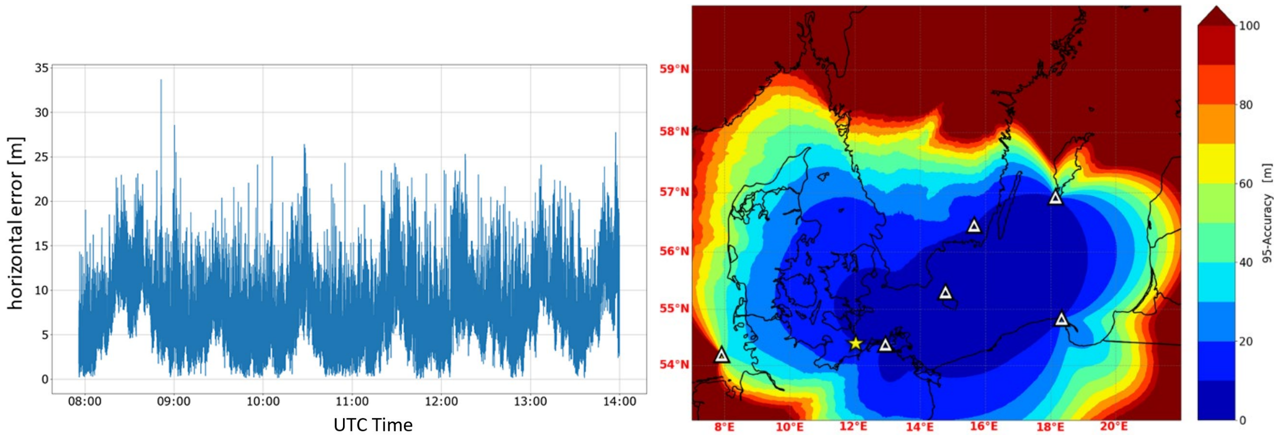

Figure 10 Left: Horizontal positioning error of R-Mode receiver related to GNSS RTK reference for the day-time measurement. Right: Predicted R-Mode positioning accuracy (95 %) for the received stations at day-time. Here the yellow star marks the area of the ship campaign and the white triangles the position of received stations.

At night-time the R-Mode performance is reduced due to the sky-wave as explained in Section 3.1.3. The R-Mode positioning solution has been analysed between 14:30 UTC and 17:10 UTC to evaluate the effect of the sky-wave interference on MF the R-Mode signals. During that time the ship was still performing its surveying activity. Therefore, also in this case we have dynamic conditions. With the same transmitters in use, the achieved accuracy was 51 m (95%). Figure 11 left presents the horizontal error in m. It can be seen that the position accuracy significantly changes after 15:30 UTC. At that time indeed, sky-wave starts to appear inducing larger errors in the R-Mode ranges. Nevertheless, the obtained accuracy would still satisfy the requirements for backup navigation [19].

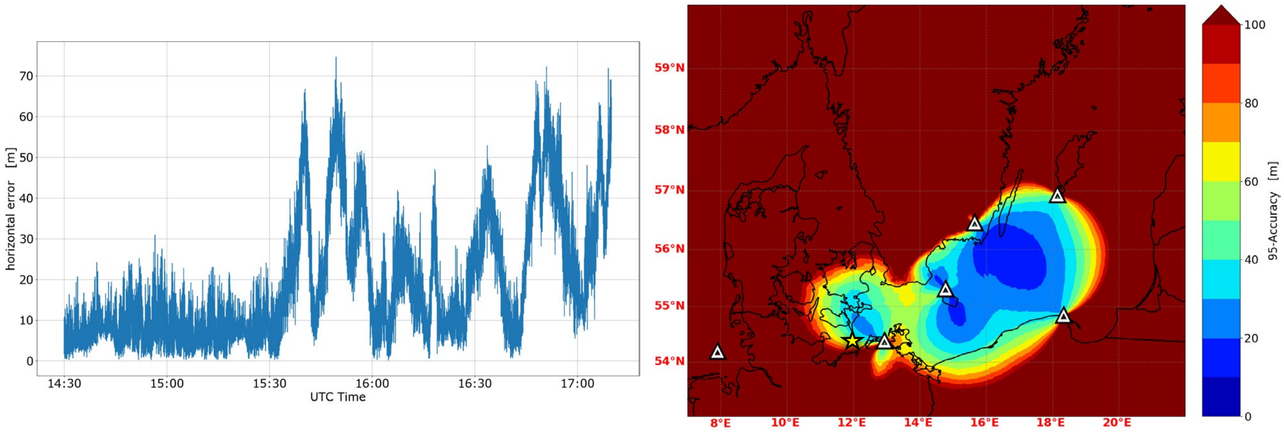

Figure 11 Left: Horizontal positioning error of R-Mode receiver related to GNSS RTK reference for the night-time measurement. Right: Predicted R-Mode positioning accuracy (95 %) for the received stations at night-time. Here the yellow star marks the area of the ship campaign and the white triangles the position of received stations.

The right plot of Figure 11 shows the predicted accuracy over night-time with the well-known subset of station in use. The yellow star represents the area of interest where it can be seen that the system accuracy ranges from 50 m to 60 m. This range of accuracy agrees with the 51 m accuracy obtained in the campaign.

For the measurements performed here, good agreement with the 95 % accuracy prediction was obtained. This underlines that MF R-Mode is a good candidate of an alternative PNT system which can support coastal navigation at the Baltic Sea and furthermore that the MF R-Mode accuracy prediction give a realistic estimate for the achievable MF R-Mode performance. Limits of this study are the amount of usable measurement data and the concentration of one area with comparatively poor conditions with respect of the geometry of the received stations and distance to them.

3.1.3 MF R-Mode challenges

The years of testing in the R-Mode Baltic test bed provided us a good overview of the challenges of the MF R-Mode technology, of the implementation and its use as a backup system for GNSS. They can be grouped as follows.

System design and implementation: The idea of R-Mode is to provide a backup system for GNSS which reuses already existing maritime infrastructure without disturbing the legacy services. This sets limits in the design of the MF R-Mode system and its implementation. The network of radio beacons was implemented to provide GNSS corrections to the mariner. It was never optimised to provide a sufficient number of accurate and well-synchronised signals with good geometry to enable positioning. Therefore, it is important to analyse the capabilities with theoretical estimations of the performance (e.g. [14]) and to perform site inspections to test the suitability of the radio-beacon transmitter chain for R-Mode signals before the implementation starts. Critical are bad geometry of the transmitters (e.g. all in one line) and radio beacon hardware which causes intermodulation, which were seen in case of nonlinear amplifiers. Additionally, it was found, the amplifier and the Antenna Tuning Unit (ATU) can introduce time-varying delays and distortions of the R-Mode signals [20]. The solutions to these challenges must be developed individually.

For site inspections of existing radio beacons, equipment is needed that is able to generate the synchronised R-Mode signal, which consist of two CW signals and an MSK modulated data stream, and a receiver which can be synchronised and which is able to track the phase of the carrier signals with at least 0.01 rad accuracy.

Signal propagation: The MF R-Mode signal propagates on two ways to the mobile user. The first is the ground-wave which is used in R-Mode to estimate the pseudorange to the transmitter from the time of signal arrival. Secondly, the sky-wave which is reflected at the lower ionosphere and which interferes with the ground-wave at the user site [14]. At day-time, the sky-wave is strongly attenuated in the atmosphere. R-Mode phase measurements used to estimate the pseudorange are unaffected by the sky-wave. At night-time, the attenuation of the sky-wave is much lower. The interference of both propagation paths will cause a time-varying error of the phase measurement. This effect depends furthermore on the attenuation of the ground-wave which is related to the land-sea composition of the propagation path.

At night-time the attenuation of the ground-wave can be stronger compared to the sky-wave. Considering also the longer way of the sky-wave (reflected in about 100 km height) we see a dominating ground-wave for distances of shorter than 70 km and increasing influence of sky-wave or even a dominating sky-wave at larger distances [21].

Another effect related to the signal propagation is a delay of the ground-wave when it propagates along the surface of the earth. Depending on the surface type this delay is higher (dry sand and ice) or smaller (sea water). Models or measurements are necessary to compensate the impact of the propagation path [22].

R-Mode receiver: The MF R-Mode uses signals with a wavelength of about 1 km. Measuring the phase of both R-Mode CW simultaneously allows to solve the ambiguity in the determination of distance when evaluating their beat signal. This is challenging because the ambiguity will be solved based on the phase difference of the individual aiding carrier phase measurements, which are noisy. To overcome this, the estimation and processing must be improved (e.g. using a windowing approach [23] and Kalman Filter [24] or the ambiguity is solved by proper knowledge of the position at a certain time by other means.

The calculation of the R-Mode pseudorange based on the time of the R-Mode signal arriving needs an estimate for the medium propagation speed of the ground-wave. Usually a value for the propagation over sea water is here assumed. To mitigate the impact of the propagation over land suitable correction functions or maps has to be applied on the pseudorange [22].

The reception of R-Mode signals in the radio beacon frequency band between 283.5 kHz and 325.0 kHz is sometimes affected by local interferences (temporary or permanent). This can affect the entire signal of one or more stations but also only a single CW. The receiver has to be able to detect such situation and do not use one or both CW of an affected station.

Sky-wave interference limits the range of R-Mode radio beacons as described above and reduces the R-Mode performance. Additionally, it reduces the range advantage of MF R-Mode compared to VDES R-Mode. Research is ongoing to find ways for the reduction of the sky-wave impact on the accuracy [25].

3.2 VDES

3.2.1 VDES measurements results Gdynia

Initially, during the R-Mode Baltic project, the VDES R-Mode component measurements were conducted using just a basic correlator and signals not fully optimized for ranging and different SNR levels (e.g. based on AIS). The article [18] presents a detailed analysis of these results obtained by the authors during the first two measurement campaigns. In the conclusions of that work authors mentioned that future measurement campaign was planned, but this time the double delta correlator would be employed to check, if there were any differences between the determined pseudo-ranges. Indeed, in June 2020 another measurement campaign was carried out on the Gdynia-Karlskrona route, where the VHF transmitting station, located in the port of Gdynia, and the receiver, placed aboard the Stena Line ferry, were used again [17]. The receiving station, initially designed for the purpose of long-term position monitoring, was modified, and reused for this measurement campaign – as a receiver station for dynamic tests onboard the vessel. Additionally, more optimised signals and some modifications to the VHF station were introduced as well [17].

In Figure 12, charts of the ranging errors observed during the measurements in 2020 are depicted. The orange line indicates the distance between receiver and the transmitting station. The blue points represent the error resulting from the difference between the correlator's output and the reference measurement (i.e. output of the EGNOS + GNSS device). In addition, for a better illustration, the main chart was divided into three environments in which the measurements took place:

- LOS Sea Path - i.e. the part of the measurements carried out in the Gdansk Bay,
- Sea+Land Mixed Path - i.e. measurements that took place when the ship was behind the Hel Peninsula,
- Non LOS (NLOS) - i.e. when the ship has left the LOS zone and sailed further into the open sea.

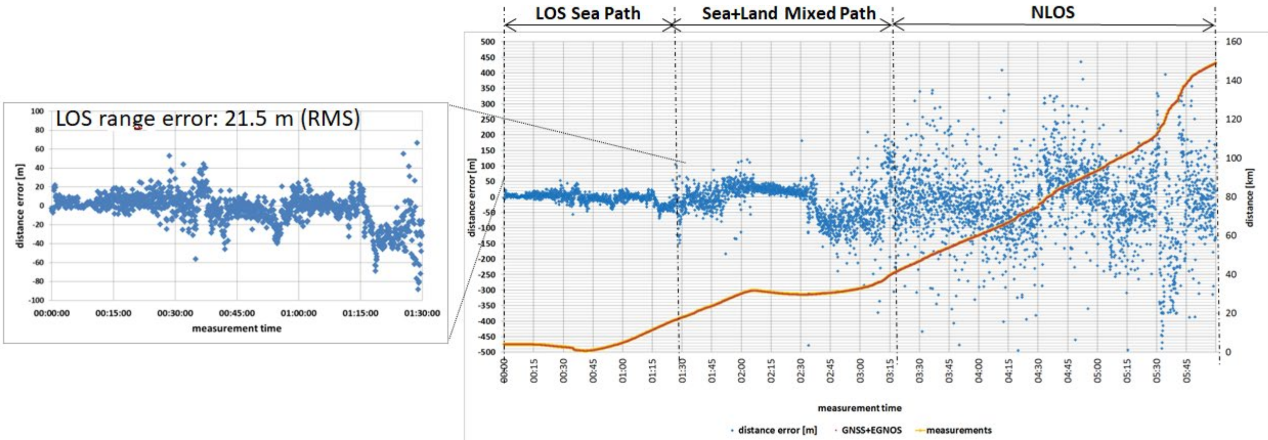

Figure 12 Ranging errors in the VDES 2020 measurement campaign for the double delta correlator [17]

In case of the LOS environment, the RMS of 20 meters was achieved with the double-delta algorithm, whereas in the previous measurement campaign these values were well over 30 meters [18]. The mixed path scenario also presents quite interesting case i.e., a good precision of ranging with a bad accuracy at the same time, caused by a constant error (offset) introduced most likely by the Hel Peninsula between transmitter and receiver locations. For illustrative purposes, Figure 13 shows the map of the measurement campaign route with depicted ranging error values.

Figure 13 Overview map - Measurement campaign 2020 Gdynia – Karlskrona [17]

For short distances from the transmitting antenna (and LOS conditions), it can be clearly seen that the ranges from the GNSS receiver almost coincide with those calculated by the signal correlation algorithm. Such results allowed for their subsequent transfer to the positioning software module and then calculation of the estimated position of the receiving station. This is very important, especially for port approach scenarios, where accurate, precise navigation is critical. For longer distances over about 66 km, the error of 180 meters was observed. This is an improvement compared to previous measurement campaigns [17]. It should also be added that at about 120 km, these accuracies were in the order of 300 meters, which for some applications could still be a satisfactory value – the VHF-based ranging system may still be usable in the NLOS conditions.

3.2.2 VDES R-Mode Measurements Lake Ammer

Separately from the experiments in Gdynia, R-Mode trials were performed on Lake Ammer near Munich [26].

Three base stations were set up on the shore of Lake Ammer. The stations were located in Buch, Schondorf, and Utting. The receiver station was placed on a boat. Figure 14 shows the transmitter located in Buch, and the antenna setup that was used on the boat.

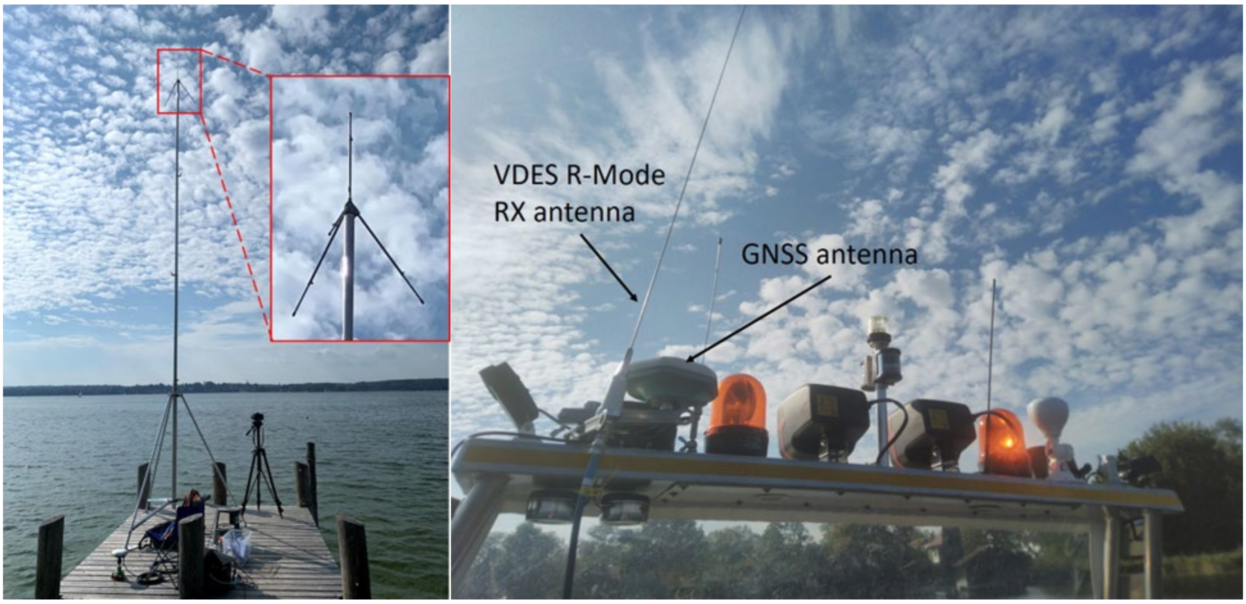

Figure 14 Exemplary setup of the transmitter site at Buch (left) and the antenna setup on the measurement boat (right), as used for the trials on Lake Ammer

Each base station transmitted an R-Mode signal once every second, and was assigned an individual time slot. Each time slot had a length of 26.7 ms, which is the duration of one VDE time slot. Figure 15 shows the transmission schedule that was used by the base stations.

Each base station, as well as the receiver station used a GNSS receiver for time synchronisation. The transmit power of the base stations was limited to 1 W EIRP for regulatory reasons. An operational VDES R-Mode system would be able to utilise the full 12.5 W that VDES is designed for.

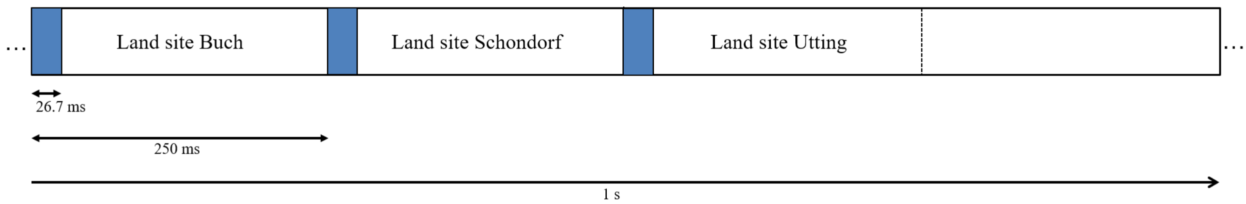

Figure 15 The transmission schedule of 26.7 ms in blue used by the transmitter stations on Lake Ammer

To evaluate the measurements, a maximum likelihood estimator was used for estimating the time of arrival and the Doppler shift for each base station. The time of arrival was used to calculate the range between the base stations and the receiver. The Doppler shift estimate was used to obtain information about the relative velocity between the base stations and the receiver.

To obtain a position estimate, an Unscented Kalman Filter was used to track the position of the boat. The Kalman Filter was initialised with the reference position obtained from GNSS, and then updated with the R-Mode measurements once per second.

The information contained in the Doppler shift was especially useful in tracking the position of the boat. Figure 16 shows the results of the trial; the reference track obtained from GNSS is shown as well as the estimated track from the R-Mode measurements. Also shown is the estimated track when only the range estimation was used. The measurement started in the south western part next to Utting and ended about halfway between Utting and Buch. It can be seen from Figure 16 that utilising the Doppler shift measurement significantly improved the accuracy. It was especially helpful in highly dynamic scenarios, such as east of Utting, where the boat drove three tight circles.

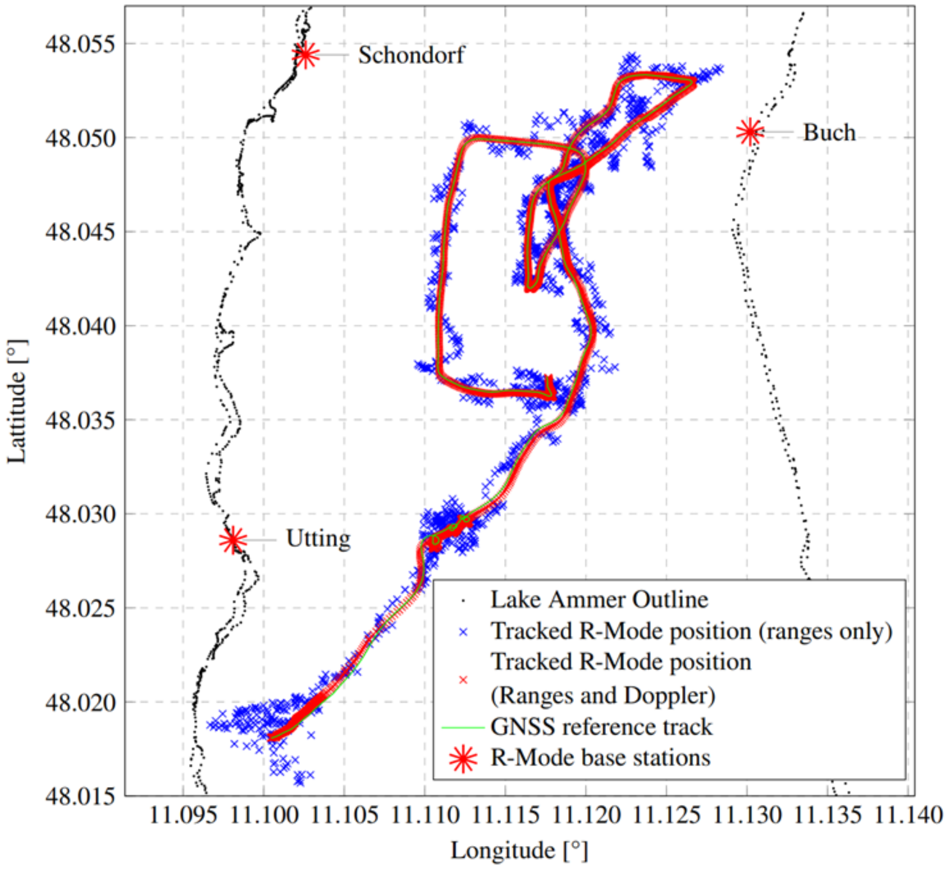

Figure 16 The reference track and the R-Mode based estimation of the boat's position on Lake Ammer. The estimation was done with and without utilizing Doppler shift measurements. The track starts in the southwest.

The measurements were the first experiment were a position estimate was successfully obtained from VDES R-Mode. By utilising an Unscented Kalman Filter for position tracking, and by making use of the Doppler shift information, it was possible to obtain a positioning accuracy better than 22 m during 95% of the time of the measurements.

3.2.3 VDES R-Mode challenges

VDES R-Mode enables vessels to determine their position independent of GNSS by utilizing the VDES navigation signals as foreseen in ITU-R M.2092-1. However, the benefits of an additional navigation system to increase the resilience is no free lunch. To estimate the distance between transmitter and receiver on a time-basis requires regular and timely accurate transmissions from each base station. Further, multiple base stations, spatially separated to provide a good geometric dilution of precision, are needed to cover the same area. A ranging signal is still useful beyond the service area of a VDES base station, and therefore, coordination to also provide interference management is helpful. It is crucial especially for neighbouring providers or even countries to cooperate with each other for their mutual benefit.

The base stations' transmissions must be synchronised with a higher accuracy than what is required in a wireless communication-only system. Therefore, especially for a longer hold-over time accurate clocks are required in the base station and additional synchronisation between the base stations is part of the system concept. Further, the regular transmissions limit the abilities of collocating AIS base stations to receive all AIS messages at the base stations from distant vessels.

The strong benefit of the presented VDES R-Mode system is the scalability for an unlimited number of vessels in the coverage area. Further, the hardware requirements on the vessel include only an additional processing unit that makes use of the received ranging signals to determine the position of the vessel. However, parallel voice and AIS transmissions will likely block the successful reception on board of the vessel. Nevertheless, the ranging signals could also be beneficial for the vessel VDES transceivers to support their synchronisation capabilities.

4 COST BENEFIT ANALYSES

Within the overall e-Navigation strategy, the IMO has identified the user need on improved reliability, resilience and integrity of bridge equipment and navigation information as one of the five prioritised e-Navigation solutions, whereby the resilient provision of PNT data ranks 3rd in line of addressed issues [27].

This chapter will deal with the costs involved, coming in hand with the needed investments in the existing infrastructure to enable basic R-Mode ranging and position on a GNSS contingency system basis, as defined in the IALA Recommendation R-129 [19]. Although higher levels of R-Mode system implementation are envisaged, the R-Mode Baltic projects realisation of R-Mode services are currently limited to bridge GNSS outages for a few hours, only. Main aspect of the R-Mode test bed in the Baltic Sea is the demonstration of suitable ranging and positioning capabilities as services for the maritime domain, fulfilling today’s demands on accuracy and availability.

Future steps may deal with the improvement of the R-Mode system to become either a full backup system for GNSS, offering accuracy as mentioned above and hold-over times of more than 12 hours, or even be available as a fully independent positioning service. Either realisation offers benefits for the safety and security of navigation in coastal waters in general, and in demanding waters like harbour approaches and traffic separation areas, respectively. Benefits will not occur for marine traffic solely, the reduced risk for incidents and accidents will have sustainable impact on shore-side economy like areas with prosperity due to tourism, and it will furthermore serve environmental protection as one utmost concerns of the European Commission.

The Cost Benefit Analysis (CBA) performed in the project bases on the requirements and implementations performed within the R-Mode Baltic project. Its figures, goals and conclusions as well as recommendations are referring to the activities as carried out during the project and its intended area of operation. This analysis lists investments on needed infrastructure as well as estimated expenditures for the operation and maintenance for continued nominal operation of R-Mode enabled land-infrastructure like IALA Beacon transmitter sites and upgraded VHF transmitter sites, formerly used as AIS base stations.

With an increase in jamming and spoofing incidents within the last years, countermeasures have become more important, not only for administrative and naval operations, but also for civil maritime traffic. This analysis evaluates the installation of R-Mode receivers on-board of vessels. It is expected, that Multi-System-Receivers will be used in future. Prototype R-Mode receivers have been integrated into existing GNSS receivers forming a part of the already available IALA-Beacon receiver. Installation and integration of R-Mode enabled GNSS equipment can be considered to be available at low costs and may come as a retrofit of GNSS equipment for existing vessels and as an integral part of new navigation systems.

Further work is required to provide a full CBA based required investments (CAPEX) and operational costs (OPEX).

5 STATUS OF STANDARDISATION

The standardisation of maritime radio navigation systems (RNAV) is essential for ensuring safety and efficiency in maritime transportation. There are several international organisations involved in establishing and maintaining standards for maritime radio navigation systems, including the International Maritime Organization (IMO), the International Telecommunication Union (ITU), the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), the International Electrotechnical Commission (IEC) and others. Some of the organisations are responsible for ensuring that on-board equipment will follow international agreed minimum performance standards (IMO) and appropriate test procedures (IEC). Both is necessary to use type-approved equipment, ensuring a defined level of safety and quality for marine navigation. IALA for example will provide standards (Recommendations and Guidelines), which ensure international harmonised standardisation of on-shore installations. Further, standardisation organisations such as Radio Technical Commission for Maritime Services (RTCM) are involved in the standardisation of RNAV systems by harmonising for example navigation or augmentation messages.

Within the development of R-Mode on MF and VHF frequencies and during the R-Mode Baltic project, standardisation activities where conducted in all above-mentioned organisations. Table 3 will provide an overview of the standardisation activities initiated within the R-Mode Baltic projects.

Table 3 Overview of recent R-Mode standardisation activities

Organisation	Task	Status
IALA	Guideline G1158 on VDES R-Mode	published
	Guideline on Implementation of R-Mode on MF&VDES frequencies	ongoing
IMO	MSC105 Information Paper “R-Mode (Ranging-Mode), terrestrial positioning for resilient navigation	submitted
	MSC108 Input paper “New work item for Performance Standard for VDES R-Mode”	in preparation
ITU-R	ITU-R M.2092-1 “Technical characteristics for a VHF data exchange system in the VHF maritime mobile band”	published
	ITU/IMO EG Information paper “VDES R-Mode allocation for radio navigation”	submitted
RTCM	Development of VDES R-Mode Receiver standards, RTCM SC 138	pending
	Development of R-Mode navigation messages (MF/VDES R-Mode)	ongoing
IEC	Development of R-Mode test procedures based on IMO Performance standards	pending

Figure 17 illustrates the planned roadmap for all required tasks, including development, implementation and standardisation, to enable operation of an R-Mode system for maritime usage.

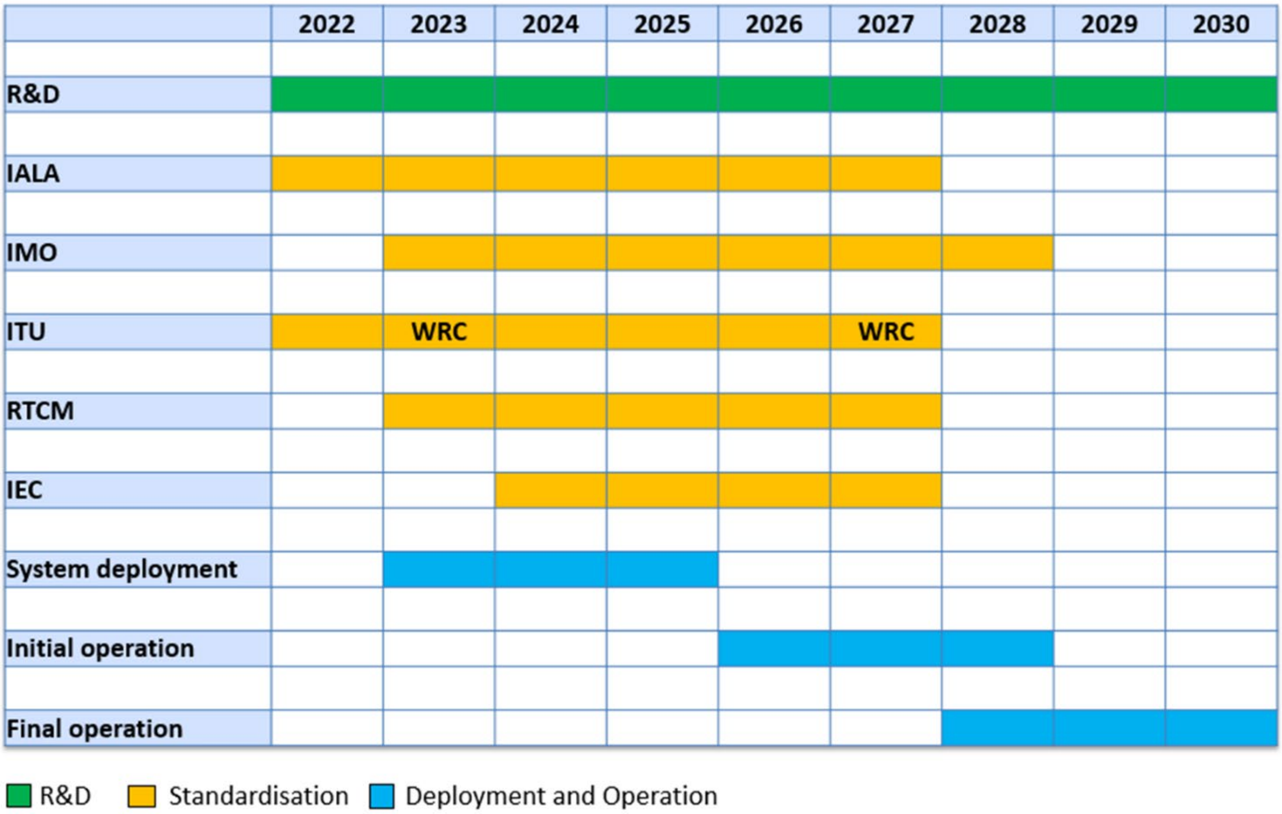

Figure 17 Proposed R-Mode development roadmap

6 CONCLUSION

Modern shipping relies on GNSS when estimating position and timing information with electronical systems. Unavailability of GNSS, as it was reported in different regions of the world, is a serious threat because it increases the risk for collisions and groundings. Upcoming MAAS, which are solely rely on proper functioning of electronical systems, are even more dependent on continuous provision of reliable PNT information. R-Mode, a terrestrial navigation system which does not share common sources of failures with GNSS, is a candidate to provide alternative PNT to increase resilient PNT for shipping as it was shown in different projects in Europe, Asia and America.

Starting from 2017, an R-Mode test bed was implemented around the southern Baltic Sea. It includes eight R-Mode enabled radio beacons as permanent installations and several temporary test sites for VDES R-Mode which are also located in Norway and in the south of Germany. Four additional sites at the Baltic Sea are prepared for the permanent transmission of VDES R-Mode signals. The sites for the permanent installation were selected based on coverage and performance predictions which were conducted for each R-Mode type separately and in conjunction. This theoretical work showed that R-Mode has the potential to support coastal navigation in wide areas of the Baltic Sea and nearly reaches an accuracy level, as it is defined in IALA Recommendation R-129, to support port approaches. Especially for the night-time, the combination of both R-Mode transmitter types is necessary to keep the level of accuracy next to shore but also in the centre of the Baltic Sea.

R-Mode is the idea of a cost-efficient navigation system which shares sites and installations with other maritime services. Necessary modifications of the radio beacons and VHF sites can be done within the scope of equipment renewal or with the service expansion to VDES. In both cases the new equipment has to support the generation of R-Mode ranging signal (MF: modulator, VDES – base station). Additional components are needed to keep the stations synchronised to the common time reference of the R-Mode system and to monitor the signal. For MF R-Mode a suitable monitoring approach includes near and far field monitors which can share the location with DGNSS monitors.

In the framework of the R-Mode Baltic projects several static and dynamic measurements were conducted and analysed. For MF R-Mode a recent result showed that dynamic positioning in the test bed can be done with a level of accuracy that was predicted. Positioning at the boundary of the core region of the R-Mode Baltic system could be conducted with 16 m at day-time and 51 m at night-time. These two results show, R-Mode can achieve an accuracy level for coastal navigation (better than 100 m) even in case of not optimal conditions. Surprising was the usability of the R-Mode signals far outside the DGNSS service area.

For VDES dynamic measurements in the port of Gdynia the range could be measured with an accuracy depending on the visibility between receiver and transmitter. In case of line of sight conditions an accuracy of 21 m (RMS) could be achieved. In case of land in between the transmitter and receiver and for non-line of sight conditions the VDES R-Mode signal was also usable but with reduced performance. A second dynamic measurement on lake Ammer in Germany was conducted with three VDES R-Mode transmitters. Here positioning with R-Mode was possible with 22 m (95 %) accuracy. That emphasis that also VDES R-Mode has the potential to serve as navigation system for coastal navigation.

The measurements in the two projects showed that each of the two R-Mode implementations has its own challenges which result from using a system designed for communication also for positioning. Individual solutions are developed to reduce or suppress their influence.

Furthermore, standardisation of maritime radio navigation systems (RNAV) is crucial for ensuring safety and efficiency in maritime transportation. Multiple international organizations, such as the IMO, ITU, IALA, and IEC, are involved in establishing and maintaining standards for maritime radio navigation systems. These organizations are responsible for ensuring that on-board equipment follows international agreed standards to ensure a defined level of safety and quality for marine navigation. Within the project phase, standardisation activities have been started within IALA, IMO, ITU and RTCM. It is very important that these activities are continued or started at the appropriate organisations to enable a future operational R-Mode system for maritime usage with harmonised standards for the corresponding shore and on-board equipment.

Within the R-Mode Baltic project also first work on a cost benefit analysis (CBA) were performed. This work is based on the costs involved in enabling basic R-Mode ranging and position on a GNSS contingency system as defined in IALA Recommendation R-129 [19], as well as the benefits it could offer. The R-Mode test bed in the Baltic Sea demonstrates suitable ranging and positioning capabilities for the maritime domain, fulfilling today's demands on accuracy and availability. The Cost-Benefit Analysis (CBA) performed is based on the requirements and implementations of the R-Mode Baltic project. The analysis lists investments needed for infrastructure and estimated expenditures for operation and maintenance for continued nominal operation of R-Mode enabled land-infrastructure, as well as the installation of an R-Mode receiver on-board vessels. Further work is needed to provide a full CBA based on required investments (CAPEX) and operational costs (OPEX).

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S14.4 A novel precise positioning and integrity monitoring system for Maritime Autonomous Applications (034)

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ABSTRACT

Maritime autonomous applications are becoming increasingly common with the use of advanced computer systems and sensors to control unmanned vessels or boats. One of the applications emerging with automation is cargo handling, where robotic systems are used to load and unload cargo from ships without human intervention. Precise positioning and navigation are crucial for the safe and efficient operation of these autonomous vessels and cargo handling systems. GNSS-based positioning and navigation systems are used to determine the position, velocity, and timing of the vessel, with GPS being the most commonly used system. However, GPS is not always reliable and does not provide the required positioning accuracy for maritime autonomous applications. These applications require high-precision positioning accuracy typically in the range of centimetre to decimetre-level for safe and effective operation. To achieve the required accuracy and reliability, GNSS-based augmentation technologies such as RTK, PPP, and PPP-RTK are used, which provide correction information from reference stations. This paper introduces the POINT project conducted by the Republic of Korea, which proposes a precise positioning and integrity monitoring system. A testbed port is selected for the verification of the proposed system under real sea environments, and performance verifications are conducted, showing that the proposed system can achieve centimetre-level positioning accuracy in the testbed. This paper emphasizes that precise positioning and integrity monitoring are essential components of maritime autonomous applications, enabling these vessels to operate safely, efficiently, and effectively in a range of environments and applications.

KEYWORDS: Maritime autonomous applications, Precise positioning and navigation, GNSS-based augmentation technologies, POINT project

1 INTRODUCTION

Maritime autonomous applications refer to the use of advanced computer systems and sensors to control unmanned vessels or boats. These autonomous vessels can be used for a wide range of purposes, including surveying, shipping, logistics, environmental monitoring, security and defence, fishing, and aquaculture. One of the applications that are emerging with the implementation of automation is cargo handling. Cargo handling automation involves the use of robotic systems to load and unload cargo from ships, without the need for human intervention. This can improve efficiency, safety, and reduce costs in the shipping industry. However, to operate safely and effectively, these autonomous vessels and cargo handling systems require precise positioning and navigation. Precise positioning and navigation are essential components of maritime autonomous applications, enabling these vessels to operate safely, efficiently, and effectively in a range of environments and applications. Navigation safety is paramount for autonomous vessels as they need to identify hazards in their environment, and take necessary precautions to avoid them. Additionally, they need to navigate accurately to reach their intended destination and complete their mission.

GNSS (Global Navigation Satellite System)-based positioning and navigation systems are used in maritime autonomous applications to determine the position, velocity, and timing of the vessel. The most commonly used GNSS system is GPS (Global Positioning System), which globally provides positioning and navigation data using a network of satellites orbiting the Earth. However, GPS is not always reliable, and it also does not provide the positioning accuracy required by maritime autonomous applications. To overcome these limitations, researches are being conducted on GNSS-based positioning and navigation systems that use additional sensors, such as LIDAR, radar, and sonar, to improve the accuracy and reliability of the positioning and navigation data. Among these sensors, GPS is the only system that provides absolute positioning data.

Maritime autonomous applications require high-precision positioning accuracy to operate safely and effectively. The required accuracy depends on the specific application, but in general, the accuracy required is typically in the range of centimetre to decimetre-level. For example, in applications such as hydrographic surveying, precise positioning is required to ensure that the vessel follows the intended survey line and collects accurate data. Even small errors in positioning can result in data that is unusable or incorrect. Similarly, in cargo handling automation, precise positioning is critical to ensure that the robotic systems can handle cargo precisely and safely, avoiding potential hazards. In addition to accuracy, positioning reliability and integrity are also essential components of maritime autonomous applications. Reliable positioning is critical to ensure that the vessel can navigate safely, even in challenging environments such as port and restricted waters. Integrity refers to the confidence level that the positioning data is correct and reliable, which is critical in ensuring the safety of the vessel and its surroundings.

To achieve the required accuracy and reliability, GNSS-based augmentation technologies such as RTK (Real Time Kinematic), PPP (Precise Point Positioning), and PPP-RTK are used in maritime autonomous applications. These technologies provide correction information from reference stations, which are used to improve the accuracy and reliability of the positioning data. This paper introduces the POINT (Precise Positioning and INTegrity monitoring) project conducted by the Republic of Korea (ROK) and describes the architecture of the precise positioning and integrity monitoring system proposed by the POINT project. A testbed port is selected for the verification of the proposed precise positioning concept under real sea environments, and performance verifications are conducted at the testbed port. The paper shows that the proposed system, along with the description of the built testbed port, can achieve centimetre-level positioning accuracy in the testbed. Finally, the implications and expected effects of the presented research results are discussed, and the next phase of the study is described.

2 POINT SYSTEM

2.1 Precise Positioning Technologies

Since the early 2000s, many users in the marine environment have claimed a need for precise positioning at the centimetre-level. In response, the International Maritime Organization (IMO) published resolution A.915(22), which mandates that the horizontal and vertical absolute accuracies be less than 10 cm for automatic docking, cargo handling, construction, and dredging [1]. In the Republic of Korea, the Ministry of Oceans and Fisheries is supporting the development of a new positioning service for maritime users to meet these accuracy requirements. The ground-based centimetre-level maritime precise Positioning, Navigation, and Timing (PNT) augmentation service called POINT will provide centimetre-level positioning using a state-space-represented (SSR) global navigation satellite system (GNSS) augmentation message to users within a maximum of 100 km from the coastline. The correction and integrity information will primarily rely on the Korean National Maritime PNT office's (NMPNT) reference station (RS) and monitoring station infrastructure, which is currently used for Differential GNSS (DGNSS) service.

In recent years, the SSR GNSS correction has rapidly developed and becomes widely used in various correction/augmentation systems [2-4]. In contrast to the RTK method, which uses observation-space-represented (OSR) correction [5], SSR correction distinguishes GNSS errors from the measurement domain into state variables, such as satellite orbit, satellite clock, ionosphere delay, and tropospheric delay, according to their characteristics. The traditional PPP technique widely uses SSR corrections of satellite orbit and clock to achieve decimetre-level accuracy. To further improve accuracy and reduce convergence time, PPP can be combined with phase bias to enable ambiguity resolution after combining an ionosphere-free combination, a technique known as PPP-Ambiguity Resolution or PPP-AR [6]. Additionally, the PPP-RTK technique [7], which includes ionosphere and tropospheric corrections as well as phase bias, has been introduced. PPP-RTK can reduce the convergence time of PPP-AR by interpolating spatial corrections in small- or medium-scale networks.

Governments, proprietors, and organizations operate numerous services that use PPP, PPP-AR, and PPP-RTK technologies. The Quasi-Zenith Satellite System with Centimetre-Level Augmentation Service (QZSS CLAS) is an open nationwide PPP-RTK service for Japan that has been operational since November 2018 and provides correction and integrity messages in Compact-SSR format [8]. The High Accuracy Service (HAS) of the European satellite navigation system, Galileo, is scheduled to provide open PPP correction through the Galileo E6-B signal and terrestrial means [9]. Galileo HAS will provide PPP corrections, including satellite orbit, clock, and biases for global users in service level 1 (SL1), and atmospheric correction for European users in service level 2 (SL2).

2.2 Architecture of POINT System

The architecture of the POINT system is divided into two segments: the service segment and the user segment [10, 11]. The RS, central processing station (CPS), and integrity monitoring station (IM) are the three main module blocks in the service segment, whereas the user segment includes the receiver platform (RP). Figure 1 shows the overall block diagram of the POINT system. The RS and IM in POINT form a Continuously Operating Reference Stations (CORS) network that receives GNSS signals from GNSS satellites. Consequently, the CPS receives raw data directly from the RS and IM.

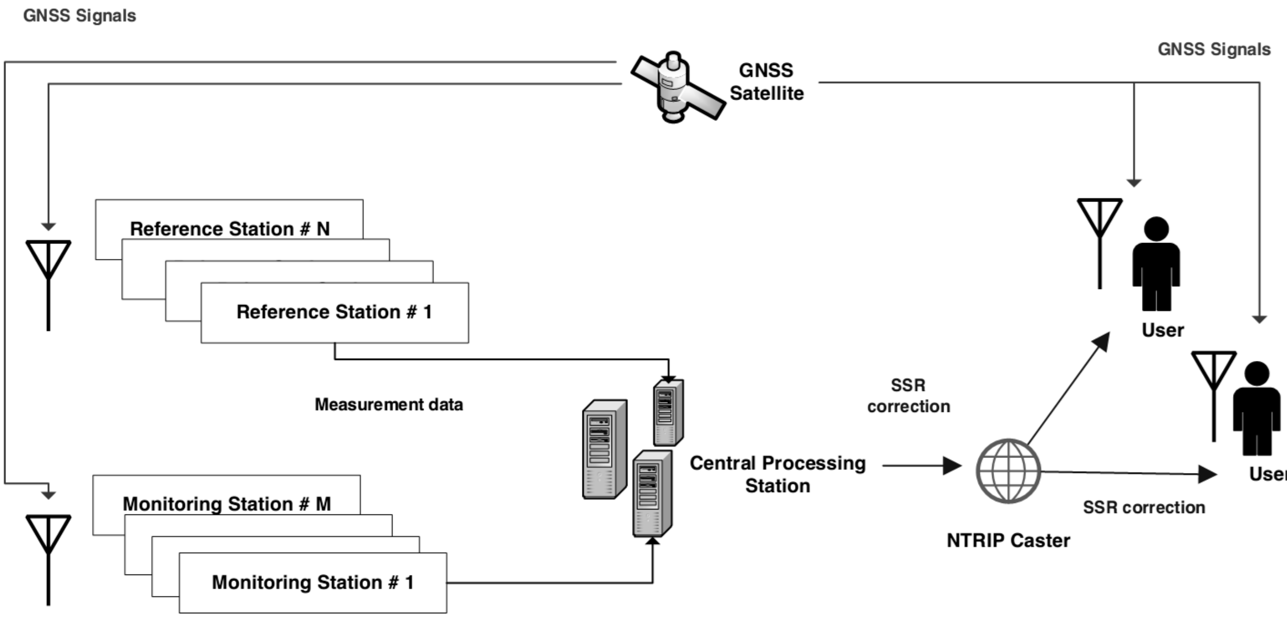

Figure 44: Overall block diagram of POINT system

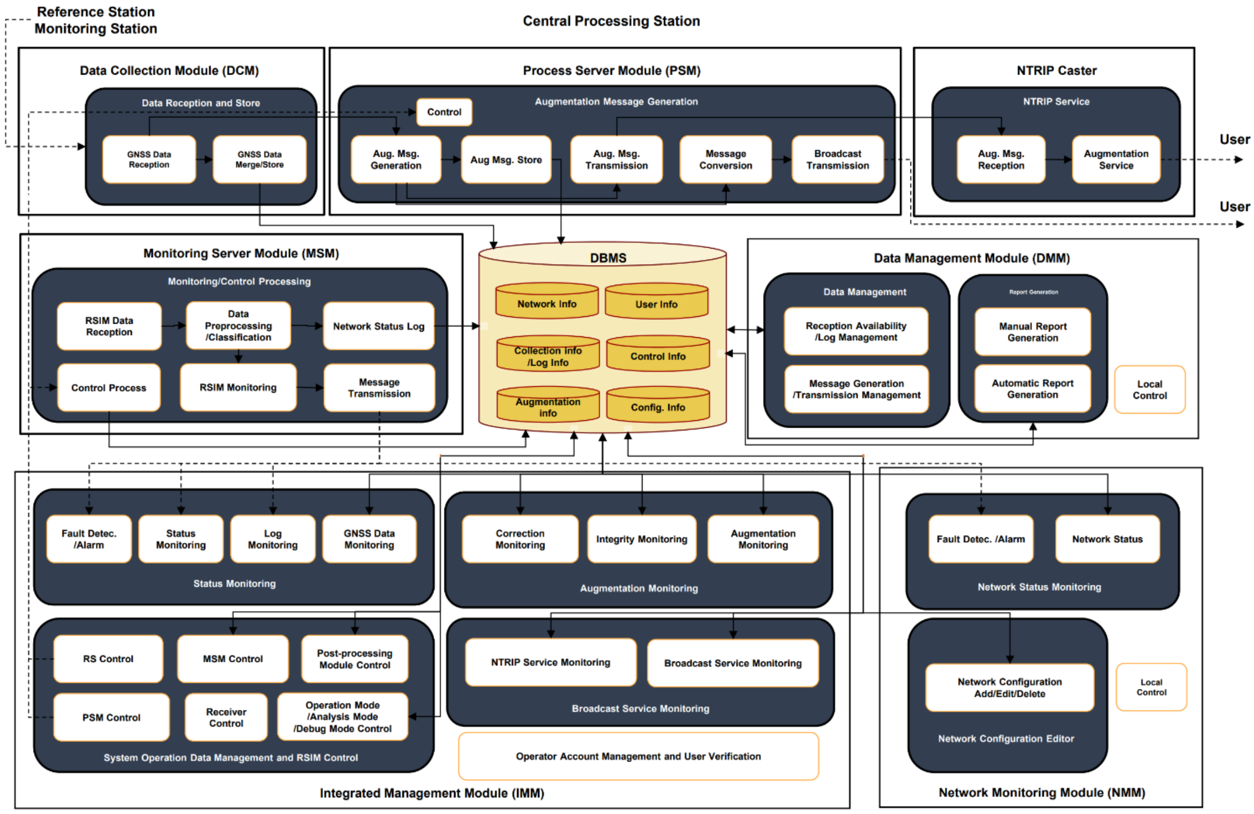

Figure 2: POINT CPS architecture

The CPS merges all navigation message data and rearranges the code and carrier phase observables. After pre-processing and applying a priori models, the CPS estimates PPP-RTK corrections based on the precise coordinates of the RS. Simultaneously, the PPP-RTK correction data are tested and verified in the IM measurement data. The SSR correction message is generated from the correction data through the designed POINT message format, and the binary message is transferred by the Networked Transport of RTCM via Internet Protocol (NTRIP) caster. Once the RP accesses the SSR correction message with the NTRIP client, in addition to the GNSS signals, the user can correct the GNSS raw measurement with SSR correction data parsed from the correction message.

The RS block comprises three parts: GNSS signal reception, environment, and operations/control. The GNSS receiver and antenna are part of the GNSS signal reception section, and if necessary, the receiver clock can be replaced with an atomic clock. Similarly, the IM block includes GNSS signal reception, environment, and operations/control parts. In most cases, IM stations are operated and controlled by the CPS, but they can also operate independently in a local operation mode.

The CPS manages most system functions, including data management, correction generation, integrity monitoring, and correction message transmission. Figure 2 illustrates the CPS modules and their interactions. The process server module (PSM) generates augmentation data from the data collection module (DCM) and converts it into POINT message format. A database management system (DBMS) and data management module (DMM) are implemented to store raw data, correction data, status, and logs of each module fed continuously.

3 TESTBED EXPERIMENTAL RESULTS

The testbed experiment was conducted in the northwest region of the service coverage area. Figure 3 shows the testbed POINT network and user position used for the experiment. The experiment utilized seven RSs, consisting of four NMPNT stations and three new POINT stations, to generate SSR corrections.

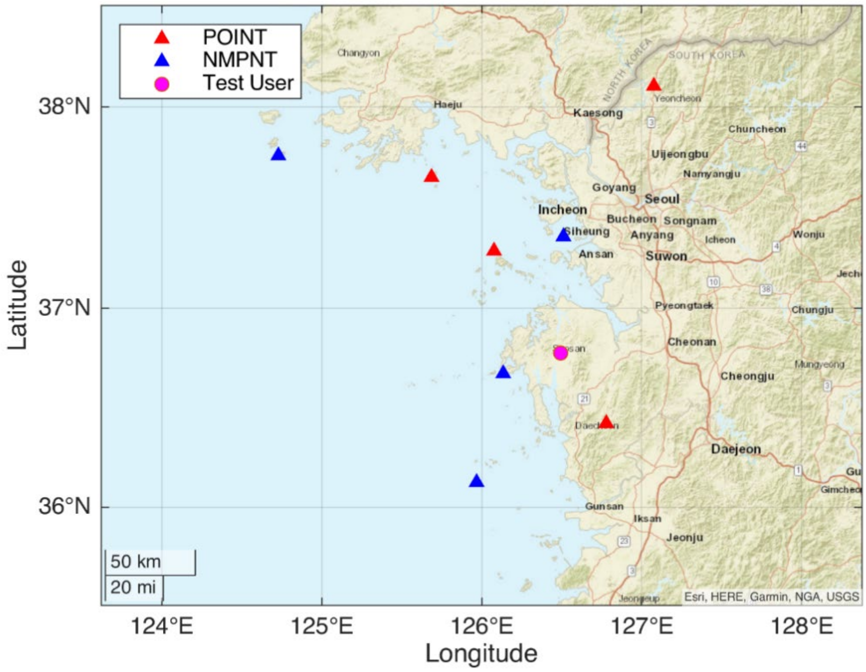

Figure 3: Location of testbed network RSs used to generate POINT corrections (in blue and red triangles) and test user location (in a magenta circle)

The positioning error is evaluated with respect to the post-processed daily precise position of the user receiver in the IGS14 coordinate frame. The post-processing process was conducted using Bernese software with data from International GNSS Service (IGS) stations [12]. Figure 4 shows the positioning errors in the east, north, and up directions. The float solution (in blue) shows initial convergence in every direction within 3 hours. The ambiguity-fixed solution (in orange) shows improved error and convergence time compared to the float solution. Table 1 shows the horizontal and vertical errors computed at each 3-hour interval. The average of the 95th percentiles of the 3-hour horizontal errors resulted in 2.63 cm, while that of the vertical errors resulted in 5.77 cm. The convergence time in Table 1 is computed as the time taken to first fix the phase ambiguity. The average convergence time was 2.13 s.

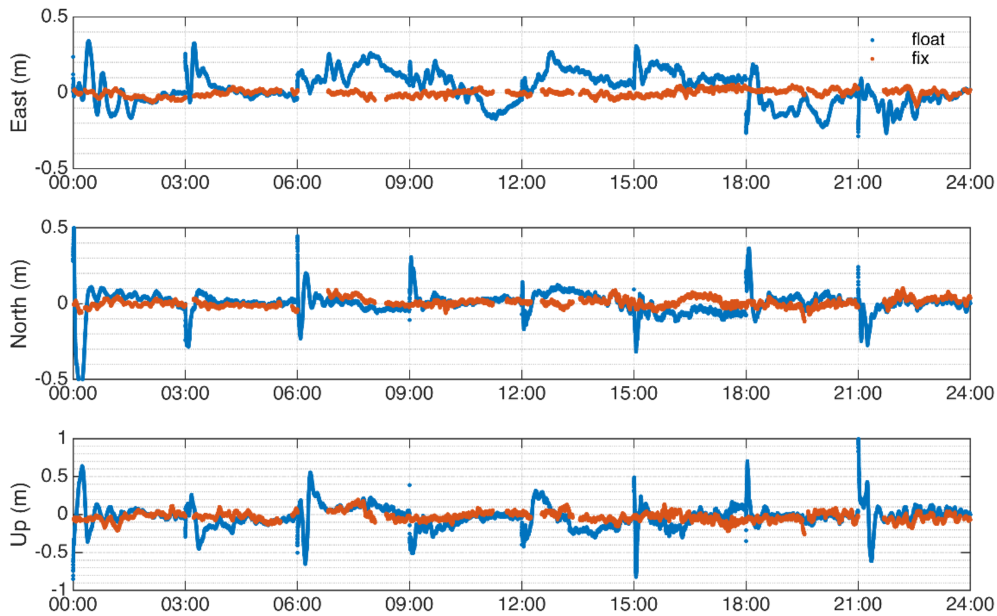

Figure 4: Positioning results with POINT correction generated from testbed network

Table 1 Testbed experimental results

Time	Horizontal error (cm) (rms / 95%)	Vertical error (cm) (rms / 95%)	Fix rate (%)	Convergence time (s)
00:00 – 03:00	1.48 / 2.77	2.69 / 5.48	99.96	5
03:00 – 06:00	1.14 / 1.92	2.43 / 4.69	100.00	1
06:00 – 09:00	1.24 / 2.00	2.38 / 4.24	99.87	3
09:00 – 12:00	1.90 / 3.28	3.40 / 7.66	100.00	1
12:00 – 15:00	1.43 / 2.73	2.26 / 4.56	99.91	3
15:00 – 18:00	2.20 / 3.98	4.85 / 9.40	100.00	1
18:00 – 21:00	1.60 / 2.90	3.46 / 6.07	100.00	1
21:00 – 24:00	0.90 / 1.43	1.73 / 4.07	99.86	2
Average	1.49 / 2.63	2.90 / 5.77	99.95	2.13

4 CONCLUSIONS

In 2015, a research was conducted in the ROK to plan precise positioning services and to confirm the demand and need for advanced maritime augmentation services. Based on this research, the ROK initiated the POINT project in April 2020. The POINT project aims to develop an infrastructure that provides users with precise positioning and integrity monitoring information in the maritime sector, with the goal of achieving an improved location accuracy and integrity of 10cm (95%, horizontal) within 100km of the Korean coastline.

In the POINT R&D project, GPS raw measurements acquired from RS and IM are provided to CPS to generate centimetre-level augmentation information (precise positioning and integrity monitoring information). This augmentation information is broadcasted through a ground-based communication media, enabling users within the service coverage area to get positions with centimetre-level accuracy and guaranteed integrity. Additionally, a RP is developed to avail the centimetre-level accuracy services provided by the POINT project, which will also be used to verify the performance of POINT system in real sea environments.

The POINT project carries out from 2020 to 2024, consisting of two phases. The first phase includes the completion of the critical design review for the RS, CPS, and RP for precise positioning services. Thereafter, validation of development technologies is scheduled to be completed, along with the verification of the positioning performance through the testbed. In the second phase, the critical design of the IM and RP for navigation service will be completed by 2023, aiming for Korean maritime pilot service in 2025.

Currently, the ROK is promoting the development of the Maritime Autonomous Surface Ship (MASS) R&D project, and the results of the POINT project will be associated with it. Moreover, after completing the verification of service performance, a pilot service covering all coasts, including the ports, is expected to be released in 2025.

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AUTHOR BIOGRAPHY

Dr. Sang Hyun Park is a prominent researcher and expert in the field of maritime positioning, navigation, and timing (PNT). He currently serves as the head of the Maritime PNT Research Office at the Korea Research Institute of Ships & Ocean Engineering (KRISO), a government-funded research institute in Republic of Korea. Sang Hyun received his Ph.D. in Electrical Engineering from the Chungnam National University, Republic of Korea in 2002. He had worked as a senior research engineer at Automotive Electronic R&D Centre for the Hyundai-Kia Motors. He has since focused his research on PNT, with a particular emphasis on the development of advanced PNT systems for maritime applications. He has been recognized for his contributions to the field of PNT, having received several awards and honors throughout his career. In 2008, he was awarded the Best Presentation Award at the Institute of Navigation GNSS Conference, and in 2015, he received the Award from the Minister of Ministry of Oceans and Fisheries for his research in maritime PNT.

As head of the Maritime PNT research office at KRISO, Sang Hyun is responsible for leading and coordinating research efforts in the field of marine PNT. He is known for his expertise in the development and implementation of new PNT technologies. His current research interests focus on precise positioning & navigation service, resilient PNT, and cyber security for maritime safety.

S14.5 Standardisation Process for SBAS Maritime receiver in the IEC (036)

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ABSTRACT

Maritime community is interested in using SBAS, especially where there is no back-up infrastructure or in poorly covered environments. For this reason, EC (European Commission) and EUSPA (European Union Agency for the Space Programme) with the support of the ESSP (European Satellites Services Provider - the EGNOS service provider) are working on the development of an EGNOS L1 maritime service that ensures a safe navigation for ocean waters, coastal waters and harbour entrances/approaches according to operational requirements (IMO Res. 1046(27) [1]). This EGNOS L1 maritime service could complement the existing maritime radio-navigation systems (e.g. DGNSS) and aims at providing pseudo-range corrections and alert information to the GPS L1 signals for maritime navigation, obtaining enhanced accuracy and integrity information over Europe.

In parallel to this, IEC (International Electrotechnical Commission) is finalising the process to produce a new standard in the IEC 61108 series that will be focused on SBAS L1 receivers for maritime applications, the IEC 61108-7 [2]. In the same way as other IEC 61108 standards, it specifies the minimum operational and performance requirements, methods of testing and required test results relative to the SBAS L1 receiver equipment. The IEC standardisation process started in February 2021, and is expected to be completed by end 2023. EGNOS L1 Maritime service is planned to be ready by end of 2023 or beginning of 2024, in parallel, the IEC SBAS L1 standard is expected to be published. Besides GPS pseudorange corrections and alerts (system, satellite, iono) provided by signal in space, the service will include as well performance monitoring reporting and provision of Maritime Safety Information (MSI).

KEYWORDS: IEC, SBAS, EGNOS, Maritime, accuracy, integrity, IMO Res A.1046

1 INTRODUCTION

Satellite Based Augmentation System (SBAS) is designed to augment Global Navigation Satellite System (GNSS) by broadcasting additional signals from geostationary (GEO) satellites over a specific service area (e.g. EGNOS is the SBAS system over Europe). Using a reference monitoring network that receive GNSS signals, the SBAS systems broadcast satellite and ionospheric correction messages that improve accuracy against GNSS standalone solution along with some integrity data that increase the confidence in the navigation position.

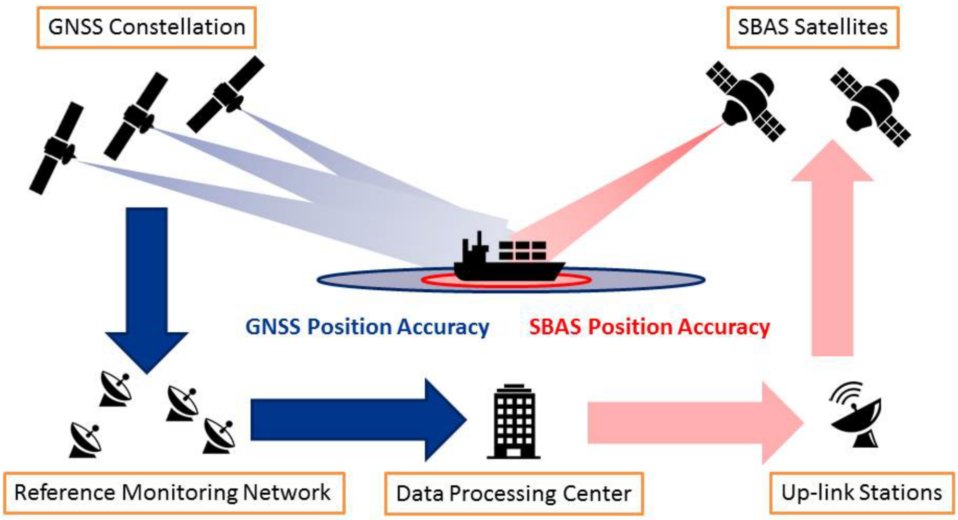

Figure 45: SBAS architecture

Apart from EGNOS, several other SBAS system are currently defined or under definition around the world.

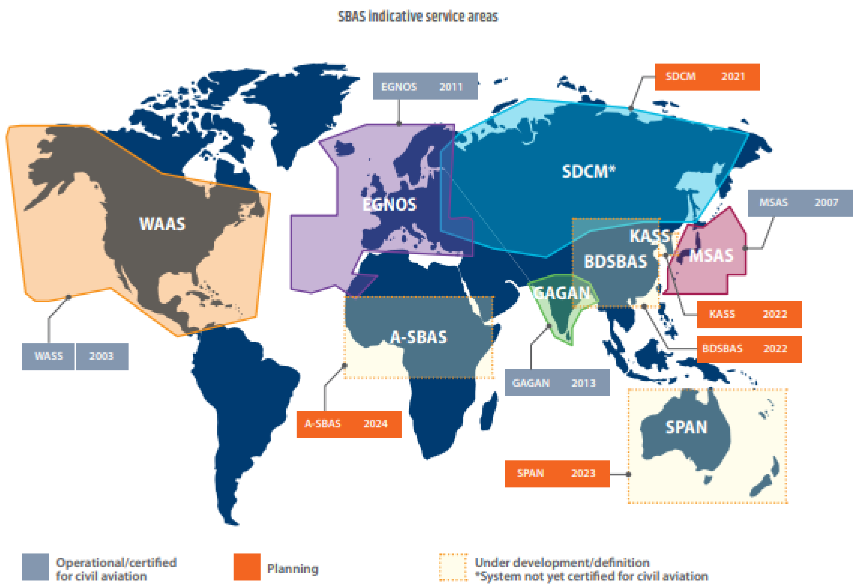

Figure 46: SBAS indicative service areas. Source: EUSPA User Technology Report 2020

The purpose of this paper is on one side to inform Maritime community about the ongoing activities adopted for the provision of EGNOS (European Geostationary Navigation Overlay Service) L1 maritime service and on the other side to explain the status of the IEC standardisation process to produce a new IEC (International Electrotechnical Commission) standard for SBAS L1 maritime receivers.

2 IEC SBAS L1 STANDARD

2.1 Purpose

Currently, GNSS systems (i.e. GPS, Galileo, GLONASS and BeiDou) are recognised by the International Maritime Organization (IMO) as components of the World Wide Radio Navigation System, but they are not suitable for harbour entrances/approaches and coastal waters without augmentation. For this type of operations, differential services, like DGPS/DGLONASS, are used to broadcast augmentation data in order to fulfil the performance level required by *IMO Res A.1046(27)* [1].

EGNOS performance is compliant with *IMO Res A.1046(27)* [1] operational requirements for ocean/coastal waters and harbour entrances/approaches as shown, presenting the following differentiators from GNSS standalone systems:

- EGNOS provides instantaneous integrity warnings of system malfunction
- EGNOS enhances horizontal accuracy to meet 10 m at 95%.
- Capable of multiple satellite failure detection, of constellation failure detection and of local ionospheric effect detection (such as scintillations).
- Better error estimation due to real time error components estimation from SBAS messages

Considering that DGNSS services do not cover wide areas of service and that some maritime authorities (e.g. Australia, Ireland, Japan, United Kingdom, United States) are discontinuing the DGNSS services for maritime operations, the maritime community is looking at SBAS as a suitable augmentation system for maritime navigation. The focus is today on coastal waters and harbour entrances/approaches, especially where there is no back-up infrastructure (i.e. DGPS/DGLONASS) or in poorly covered environments. In order to fulfil the accuracy and integrity international operational performance requirements (*IMO Res A.1046(27)* [1]) SBAS provides satellite clock/ephemeris corrections, ionospheric corrections and integrity information to GNSS signals.

IMO MSC.401(95) [3], *MSC.432 (98)* [4] and *IEC 61108-4* [5] (Shipborne DGPS and DGLONASS maritime radio beacon receiver equipment) allow the use of different augmentation signals in shipborne receivers but there is neither an IMO or IEC standard on how to process and implement SBAS signals in shipborne receivers. Most of recent maritime GNSS receiver models are SBAS compatible but present important differences in their performance since they are not certified according to any specific test standard. So, in order to ensure a safe and harmonised use of SBAS by all shipborne receivers, a new IEC 61108 standard for SBAS L1 receiver equipment is being developed.

IEC 61108 is a series of IEC standards for "Maritime navigation and radio-communication equipment and systems - Global navigation satellite systems (GNSS)". IEC has published International Standards for the following GNSS systems: *IEC 61108-1* [6] for GPS, *IEC 61108-2* [7] for GLONASS, *IEC 61108-3* [8] for Galileo, *IEC 61108-5* [9] for BeiDou and *IEC 61108-6* [10] for IRNSS. In addition, IEC has published International Standard *IEC 61108-4* [5] for DGPS and DGLONASS which are Differential Global Navigation Satellite System (DGNSS) enhancing the primary GNSS constellations (GPS and GLONASS). So, a new part within the IEC 61108 series is being developed for the SBAS L1 maritime receivers with reference *IEC 61108-7* [2].

Once the *IEC 61108-7* [2] is published, vessels will start equipping type-approval receivers using SBAS and RAIM to ensure a safe navigation in harbour entrances/approaches and coastal waters.

2.2 Content

The under development *IEC 61108-7* [2] standard addresses the use of SBAS L1 to provide augmentation to the GPS shipborne receiver. This standard, as done for all the standards belonging to the IEC 61108 series, is composed by a set of minimum performance requirements, method of testing and the required test results.

IEC 61108-7 includes the minimum performance for SBAS L1 maritime receivers to be obtained by the equipment under coverage of SBAS service in order to be compliant with the *IMO Resolution A.1046(27)* [1], describing operational requirements for ocean waters, coastal waters and harbour entrances/approaches. The requirements included in the standard define the specifications for accuracy, satellite acquisition, dynamic range, integrity, position update, interference conditions, equipment outputs, etc. In addition, it includes a high level procedure for SBAS L1 navigation computation to ensure that receivers correctly process and uses the SBAS data, the receiver output sentences to support SBAS L1 operation and bridge alert management compliant with *IEC 62923-1* [11] and *IEC 62923-2* [12].

Finally, to ensure that the receiver correctly implements the requirements a set of tests are also included in the standard describing the method of testing and the required test results. The receiver equipment (composed by receiver and antenna) shall perform and pass these tests in an accredited laboratory, which are oriented to the following functionalities:

- SBAS L1 receiver equipment
- Configuration
- Position output
- Equipment output
- Static accuracy and availability
- Static accuracy with angular movement of the antenna
- Dynamic accuracy
- Acquisition
- Sensitivity and dynamic range
- Effects on specific interfering signals
- Position update
- SBAS input and processing
- SBAS message processing
- SBAS GEO satellite selection and switching
- Navigational status indications
- Test for typical interference conditions
- Accuracy of COG and SOG
- Validity of COG and SOG information
- Output of UTC
- Validation material for tropospheric model

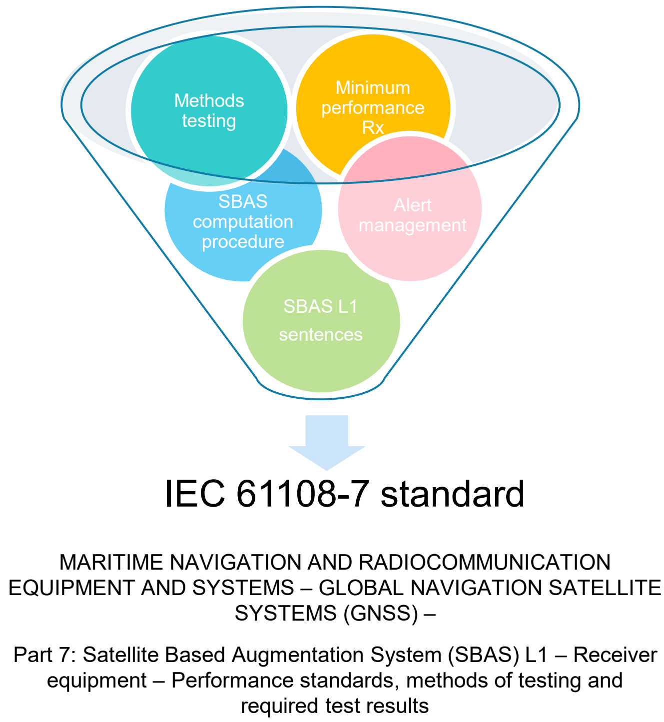

Figure 47: IEC 61108-7 content

It should be clarified that the current standard under development only covers the SBAS L1 systems augmenting GPS constellation. The future SBAS Dual-Frequency and Multi-Constellation (DFMC) services and other GNSS systems are out of scope of this version of the IEC 61108-7 standard (see section 4, future work)

2.3 Schedule

The standardisation process to produce the new standard IEC 61108-7 started on February 2021 when the New Work Item Proposal (NWIP) was submitted. The following ballot was a key milestone since it was required to pass the approval criteria in terms of participation and positive support from the national bodies with representation in IEC. The title proposed to the standard is "*Maritime navigation and radiocommunication equipment and systems - Global navigation satellite systems (GNSS) – Part 7: Satellite Based Augmentation Systems (SBAS) L1 – Receiver Equipment – Performance requirements and method of testing*". In order to support the development of the new standard two European initiatives were launched:

- First, the EU Agency for the Space Programme (EUSPA) and the European Commission (EC) launched the MARESS (MAritime Receiver SBAS Standardisation) project, where ESSP, BNAE, CEREMA and University Gustave Eiffel worked during 2021 and 2022 in the production of technical documentation to support the International Electrotechnical Commission (IEC) standardisation.
- Second, CEN, the European Standardisation Committee through its Technical Committee 5 dedicated to Space has created the Working Group 8 (CEN/CLC JTC5 WG8) of SBAS receiver performance for maritime applications in September 2020. In this group, MARESS project's outputs were presented to commonly agree on the final draft of IEC-61108 Part 7 for SBAS receiver equipment. In addition, each draft version generated by IEC TC80 has been reviewed by the members composing this group.

The NWIP was approved by the IEC TC80 in June 2021 and then, a new Project Team within IEC TC80 was created, the PT61108-7, to work on the development of the standard for SBAS L1 maritime equipment.

In November 2021 the first Working Draft, *IEC 61108-7 WD*, was presented at IEC TC80 PT61108-7 for discussion. After several WD versions, the PT61108-7 generated the first Committee Draft on July 2022, the *IEC 61108-7 CD*. The CD version is a draft version submitted to all IEC TC80 members, including those who participate actively in the IEC work and those who have observer status, for comment and approval

At the time of writing this paper, the last draft available is the *IEC 61108-7 CD2* (January 2023) which is being review for comments by the IEC TC80 members until 1st of April 2023.

The next step within the standardisation process is to generate the Committee Draft for Voting (CDV) in May 2023 which is the last stage at which technical comments can be taken into consideration. A ballot is then launched for members to vote the approval of the standard. This key milestone is expected to be by May 2023 and interested parties are welcome to participate to support the standard publication.

Finally, the last IEC stage is the Final Draft International Standard (FDIS) where, after the technical changes requested at the CDV have been incorporated; the vote to accept the publication of the standard is done. The objective of publication of the IEC 61108-7 is around the end of the 2023.

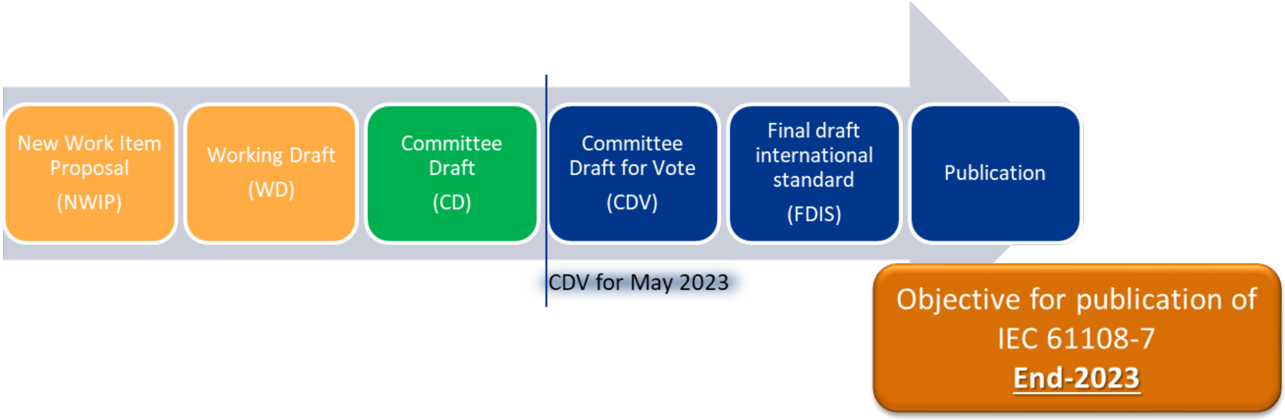

Figure 48: IEC status

3 EGNOS MARITIME SERVICE

EGNOS (European Geostationary Navigation Overlay Service) is the European Satellite Based Augmentation Service (SBAS) that provides services based on the Global Positioning System (GPS) signals as well as enhanced accuracy and integrity information. EGNOS currently supports three services: the Open Service freely available to the public in Europe, the Safety of Life Service for aviation safety-critical applications and EGNOS Data Access Service (EDAS).

EGNOS high level adoption roadmap for maritime is defined based on three steps:

1. Use of EGNOS corrections retransmitted via existing Aids to Navigation (AtoN).
2. Use EGNOS L1 Signal in Space (SiS) directly with adapted receivers (EGNOS L1 maritime service).
3. Use EGNOS DFMC with new Dual-Frequency receivers.

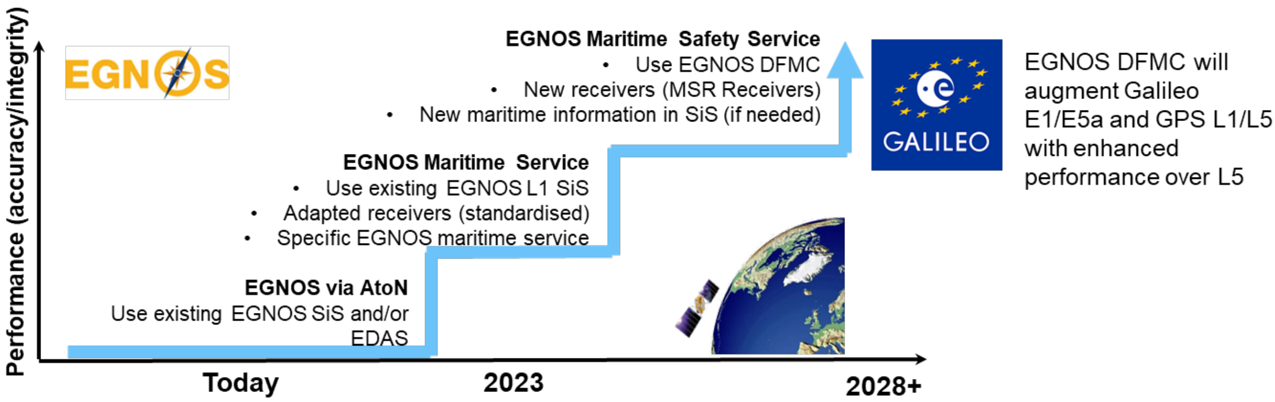

Figure 49: EGNOS maritime adoption planning

The European Commission, EC (EGNOS owner), the EU Agency for the Space Programme, EUSPA (EGNOS Services Programme Manager), the European Satellite Services Provider, ESSP (EGNOS service provider) and the European Space Agency, ESA (EGNOS design agency) are working in close collaboration to provide an EGNOS L1 maritime service by 2023 for "Harbour entrances/approaches and Coastal waters" and for "Ocean Waters" over Europe. The EGNOS L1 Maritime service aims at providing pseudo-range corrections, associated ranging integrity and alert information to GPS L1 signals to let shipborne receivers compute an enhanced navigation solution with respect to GPS standalone, meeting operational requirements included in the *IMO*

Resolution A.1046 (27) [1]. The service will provide as well performance monitoring reporting and provision of Maritime Safety Information (MSI).

EGNOS L1 performance (accuracy, availability, continuity, integrity, time to alarm, coverage) was already analysed in 2018 (ENG8-11.7 [13]) and 2019 (EGN9-2.1.17 [14]) concluding that EGNOS L1 is able to meet the operational requirements stated in International Maritime Organization (IMO) *Resolution A.1046 (27)* [1] for "Harbour entrances/approaches and Coastal waters" and for "Ocean Waters" over Europe. Assessment is ongoing to define the potential service area for the EGNOS L1 maritime service, which plans to cover most of European coast.

The service will provide GPS pseudorange corrections and alerts (system, satellite, iono) via signal-in-space, as well as performance monitoring reporting and provision of Maritime Safety Information (MSI).

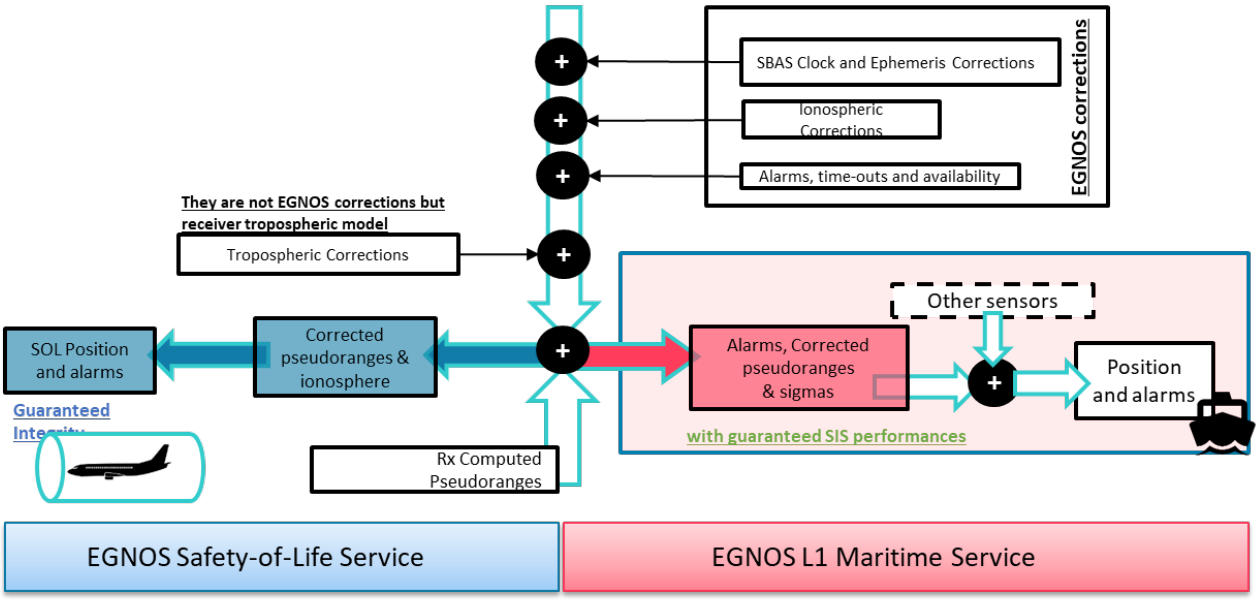

Figure 50: EGNOS safety of life service (left) and EGNOS maritime service (right)

4 CONCLUSIONS AND FUTURE WORK

EGNOS L1 maritime service is planned to be ready by end 2023 or beginning of 2024. Once the *IEC 61108-7* [2] is published, vessels will start equipping type-approval receivers using SBAS and RAIM to ensure a safe navigation in harbour entrances/approaches and coastal waters. The publication of the SBAS L1 shipborne receiver standard *IEC 61108-7* [2] is key for the harmonised and safe adoption of SBAS in the maritime domain.

IALA, in coordination with EUSPA/EC, together with EU Member States, Australia, China, New Zealand, ICS and the NI, co-sponsored the submission to IMO of a request for a new output for the development of minimum performance standards for Dual-Frequency Multi-constellation SBAS and Advanced-RAIM in shipborne radionavigation receivers. If the request is approved, IMO will develop the standard in 2024-25. After that, IEC will be approached to develop the standard to define the methods of testing, building as well on IEC-61108-7 for SBAS L1 and RAIM.

5 ACKNOWLEDGEMENTS

We would like to acknowledge the efforts done by EC and EUSPA to work at programme level for the next provision of EGNOS L1 maritime service.

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[3] IMO Resolution MSC.401 (95) performance standards for multi-system shipborne radio-navigation receivers.

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[11] IEC 62923-1: Maritime navigation and radiocommunication equipment and systems – Bridge alert management – Part 1: Operational and performance requirements, methods of testing and required results.

[12] IEC 62923-2: Maritime navigation and radiocommunication equipment and systems – Bridge alert management – Part 2: Alert and cluster identifiers and other additional features.

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AUTHOR BIOGRAPHY

Mr. Rodrigo González holds a M. Sc. Degree in Aeronautical Engineering from the Universidad Politécnica of Madrid (UPM). Since 2009, he has been working in the ESSP SAS providing support for the analysis and assessment of EGNOS performances. He has been in charge of different technical activities related mainly to support to in-service and major system evolutions of EGNOS programme. Finally, he is in charge of ESSP receiver laboratory and responsible of GNSS receiver platform configuration control as well as monitoring, analysing and reporting of GNSS receiver platform performance. In parallel, he has been participating in several H2020 projects, ESSP projects related with positioning in multimodal domains (aeronautical, maritime, railway, agriculture, drones) and in GNSS standardisation forums such as EUROCAE, RTCA and IEC. He is the main responsible of performing EGNOS data campaigns mainly in maritime domain and presenting their results in the corresponding GNSS events.

S114.1 Ensuring GNSS integrity in Brazil (006)

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ABSTRACT

This article provides an overview of the Global Navigation Satellite System (GNSS) and Differential Global Navigation System (DGNSS) infrastructure in Brazil, with a focus on their integrity. GNSS and DGNSS are essential tools for applications such as navigation, timing, and surveying, and ensuring their reliability and accuracy is crucial in critical applications such as aviation, maritime, and transportation. Brazil has made significant progress in developing its GNSS and DGNSS infrastructure, including the establishment of the Brazilian Satellite Navigation System (SISN) and the deployment of IALA Base Stations for maritime navigation. This article explores the current state of GNSS and DGNSS infrastructure in Brazil, measures being taken to improve their integrity, and the specific applications of GNSS and DGNSS in the country. It also discusses the regulatory frameworks and standards in place to ensure the safety and reliability of these systems in Brazil. The article concludes by emphasizing the importance of ensuring the reliability and accuracy of GNSS and DGNSS signals and data for critical applications in the country. KEYWORDS: Global Navigation Satellite System, Differential Global Navigation System, Maritime, IALA Base Stations, Integrity.

KEYWORDS: Global Navigation Satellite System, Maritime, IALA Base Stations, Integrity.

RESUMEN DEL ARTICULO

Este artículo proporciona una descripción general de la infraestructura del Sistema Global de Navegación por Satélite (GNSS) y del Sistema de Navegación por Satélite Global Diferencial (DGNSS) en Brasil, con un enfoque en su integridad. El GNSS y el DGNSS son herramientas esenciales para aplicaciones como navegación, cronometraje y levantamiento topográfico, y garantizar su confiabilidad y precisión es crucial en aplicaciones críticas como la aviación, la navegación marítima y el transporte. Brasil ha realizado avances significativos en el desarrollo de su infraestructura GNSS y DGNSS, incluida la creación del Sistema de Navegación por Satélite Brasileño (SISN) y el despliegue de estaciones base IALA para la navegación marítima. Este artículo explora el estado actual de la infraestructura GNSS y DGNSS en Brasil, las medidas que se están tomando para mejorar su integridad y las aplicaciones específicas de GNSS y DGNSS en el país. También se discuten los marcos regulatorios y las normas establecidas para garantizar la seguridad y confiabilidad de estos sistemas en Brasil. El artículo concluye enfatizando la importancia de garantizar la confiabilidad y precisión de las señales y datos GNSS y DGNSS para aplicaciones críticas en el país.

PALABRAS CLAVE: Sistema Global de Navegación por Satélite, Sistema de Navegación por Satélite Global Diferencial, Navegación Marítima, Estaciones Base IALA, Integridad.

RESUME DE L'ARTICLE

Cet article donne un aperçu de l'infrastructure du système de navigation par satellite global (GNSS) et du système de navigation par satellite global différentiel (DGNSS) au Brésil, en mettant l'accent sur leur intégrité. Le GNSS et le DGNSS sont des outils essentiels pour des applications telles que la navigation, le chronométrage et le levé topographique, et garantir leur fiabilité et leur précision est crucial dans des applications critiques telles que l'aviation, la navigation maritime et le transport. Le Brésil a réalisé des progrès significatifs dans le développement de son infrastructure GNSS et DGNSS, notamment avec la mise en place du système de navigation par satellite brésilien (SISN) et le déploiement de stations de base IALA pour la navigation maritime. Cet article explore l'état actuel de l'infrastructure GNSS et DGNSS au Brésil, les mesures prises pour améliorer leur intégrité et les applications spécifiques du GNSS et du DGNSS dans le pays. Il aborde également les cadres

réglementaires et les normes en place pour garantir la sécurité et la fiabilité de ces systèmes au Brésil. L'article conclut en soulignant l'importance de garantir la fiabilité et la précision des signaux et des données GNSS et DGNSS pour les applications critiques dans le pays.

MOTS-CLÉS: Système de navigation par satellite global, Système de navigation par satellite global différentiel, Navigation maritime, Stations de base IALA, Intégrité.

1 INTRODUCTION

Global Navigation Satellite Systems (GNSS) have become an integral part of modern life, enabling a vast range of applications such as navigation, timing, and surveying. However, ensuring the reliability and accuracy of GNSS systems is essential, especially in critical applications such as aviation, maritime, and transportation.

In Brazil, the use of GNSS technology is widespread, and the country has made significant progress in developing its GNSS infrastructure, including the establishment of the Brazilian Satellite Navigation System (SISN).

This article will focus on GNSS integrity in Brazil, discussing the challenges and opportunities that exist in ensuring the reliability of GNSS signals and data in the country. It will explore the current state of GNSS infrastructure in Brazil, including the development of SISN and its compatibility with other GNSS systems.

It will discuss the measures being taken to improve GNSS integrity in Brazil, such as the deployment of ground-based augmentation systems (GBAS) and the use of multi-constellation GNSS receivers. Furthermore, the article will examine the specific applications of GNSS in Brazil. The regulatory frameworks and standards in place to ensure the safety and reliability of GNSS systems in Brazil. Overall, this article aims to provide a comprehensive overview of GNSS integrity in Brazil, highlighting the challenges and opportunities in this field, and emphasizing the importance of ensuring the reliability and accuracy of GNSS signals and data for critical applications in the country.

2 BRAZILIAN’S GNSS AND DGNSS

Global Navigation Satellite System (GNSS) is a network of satellites and ground-based control stations that provide positioning, navigation, and timing (PNT) services to users around the world. The four well known constellation are US-Based Global Positioning System (GPS), Russian’s GLONASS, China’s Beidou and Europe’s Galileo.

GNSS integrity is critical for ensuring the reliability, availability, and accuracy of PNT services provided by GNSS. This is especially important in safety-critical applications such as aviation, maritime navigation, maritime dynamic positioning, and transportation, where even small errors in PNT information can lead to serious consequences. GNSS integrity is achieved by implementing measures to detect and mitigate errors, biases, and intentional or unintentional interference in GNSS signals.

These four constellations cover the territory of Brazil, however the signals are vulnerable to cuts depending on the intentions of the nations that own them. Brazil has made significant progress in developing its own GNSS system, includes a constellation of satellites called the Brazilian Regional Positioning Satellite and network of ground-based control stations. Currently consists of four operational satellites and one spare, with plans to launch additional satellites in the future. This project aims to provide PNT services for users in Brazil and adjacent countries, with a focus on applications such as transportation, agriculture, naval and security.

For Differential Global Navigation Satellite System(DGNSS), it’s integrity refers to the ability of the system to provide accurate and reliable positioning information, along with a measure of the confidence or trustworthiness of that information. This system uses a technique called differential correction, which compares the signal received from a GPS (Global Positioning System) satellite by a reference receiver at a known location with the signal received by a user receiver at an unknown location. The difference between

the two signals is used to calculate the error in the user receiver's position, which is then applied to correct the position information obtained from the GPS signals.
Integrity monitoring is an essential aspect of DGNSS, and it involves the detection and reporting of any errors or anomalies in the system that may affect the accuracy and reliability of the positioning information. There are several techniques used in DGNSS integrity monitoring, including:

1. Fault Detection and Exclusion (FDE): This technique involves detecting and excluding any satellite signals that exhibit abnormal behavior or characteristics, such as excessive noise, interference, or multipath.
2. Receiver Autonomous Integrity Monitoring (RAIM): This technique involves detecting and excluding any GPS satellite signals that are inconsistent with the expected geometry of the satellite constellation. RAIM uses statistical analysis to determine the confidence level of the positioning solution.
3. Signal-in-Space Monitoring (SIS): This technique involves monitoring the integrity of the GPS satellite signals as they are transmitted from the satellites to the user receivers. SIS provides a measure of the confidence level of the positioning solution based on the quality of the satellite signals.

The most common methods for transmitting DGNSS corrections are Satellite Broadcast:

1. Satellite broadcast is the most common method for transmitting DGNSS corrections. Corrections are transmitted from a ground station to a satellite, which then broadcasts the correction data to user receivers. The most well-known satellite-based correction systems are the GPS Satellite-Based Augmentation System (SBAS), such as the Wide Area Augmentation System (WAAS) in North America, the European Geostationary Navigation Overlay Service (EGNOS) in Europe, and the Multi-functional Satellite Augmentation System (MSAS) in Japan. Ground-Based Broadcast: Ground-based broadcast involves transmitting correction data from a ground station to user receivers using terrestrial radio or cellular networks.
2. Ground-based correction systems include the Ground-Based Augmentation System (GBAS), which is primarily used in aviation applications, and the Cellular-Based Augmentation System (CBAS), which is used in urban environments where satellite signals may be obstructed.
3. Internet: Internet-based correction systems involve transmitting correction data over the internet to user receivers. This method is commonly used for post-processing corrections, such as Differential Correction (DC) and Precise Point Positioning (PPP). The correction data is typically transmitted in a standard format, such as the RTCM (Radio Technical Commission for Maritime Services) or the CMR (Continuous Measurement Record) format.

Overall, the choice of communication method depends on several factors, including the application, the desired level of accuracy, and the availability of infrastructure. Satellite broadcast is the most common method for transmitting DGNSS corrections, but ground-based broadcast and internet-based methods are also widely used in various applications.

For differential GNSS integrity, public or private Brazil can count with:

1. SBAS Station "Sistema de Navegação Brasileiro", based on a network of ground-based monitoring stations and two geostationary satellites that broadcast correction messages to users equipped with SBAS-enabled receivers. The system is intended to improve the accuracy of positioning information for a range of applications, including aviation, transportation, surveying, and precision agriculture.

2. The “Rede Brasileira de Monitoramento Contínuo dos Sistemas GNSS”,RBMC, is a network of GNSS (Global Navigation Satellite System) stations in Brazil that are continuously operational. The Brazilian Institute of Geography and Statistics (IBGE) established it in 1996 with the goal of providing accurate and reliable geodetic and geocentric coordinates to support activities like land surveying, mapping, and navigation. The RBMC network consists of over 300 permanent stations located throughout Brazil

and outfitted with high-precision GNSS receivers and antennas that collect data 24 hours a day, seven days a week. The IBGE processes and analyses the data collected by the RBMC stations before making it available to the public via various means, including a web portal and FTP servers.

3. Brazilian Oil and Gas Companies has DGNSS solutions, a system that transmits differential corrections to GPS signals using Ultra High Frequency (UHF) radio signals, allowing for more precise positioning and navigation in the region. The UHF DGNSS signal is broadcast from a network of ground reference stations offshore and close to Offload operations, supports a variety of offshore activities, including oil and gas exploration, drilling, and production.
4. Private DGNSS signals are differential correction signals broadcast by private organizations or businesses as opposed to government agencies. Private DGNSS signals are used to improve the accuracy of GPS or other GNSS signals for specific applications like precision agriculture, surveying, and construction. A network of reference stations receives GPS or other GNSS signals and then transmits correction data to user equipment to generate private DGNSS signals. The correction data aids in the removal of errors introduced by atmospheric and other sources, resulting in more precise positioning data. Those systems have higher prices, depending of precision.
5. The IALA DGNSS (Differential Global Navigation Satellite System) stations in Brazil are part of the global network of stations that provide corrections to GPS (Global Positioning System) signals to improve the accuracy and reliability of navigation. The Brazilian Navy has a specialized unit called the Directorate of Hydrography and Navigation (DHN) that oversees the operation of the eleven IALA Station and other navigation infrastructure in the country.

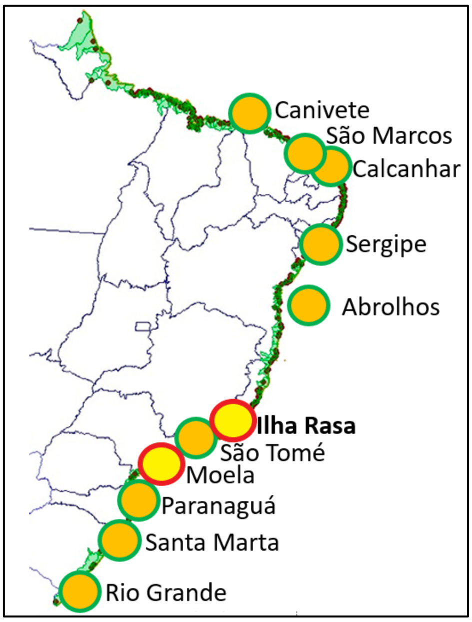

Figure 1: Actual IALA Stations in Brasil

The IALA stations in Brazil play a vital role in ensuring that marine navigation in the country is safe and efficient. They are a crucial component of the navigation infrastructure, offering essential navigation services to mariners and contributing to the development of the maritime sector in the area. At present, a project is underway to upgrade these stations, starting with Ilha Rasa and Moela Station. The goal of this initiative is to centralize all data in CAMR (Centro de Auxílios à Navegação Almirante Moraes Rego) through a Central Monitor network.

The system provides correction data to GPS and Glonass signals with a technique relies on a network of ground-based reference stations that receive signals from GPS and Glonass satellites. These reference stations then transmit correction data to the user's receiver, which utilizes the information to enhance the precision of the satellite signals.

Figure 2: Obsolete Iala Station - Left, Retrofitted Station -Center (Ilha Rasa Station), Retrofitted Moela Station – Right.

3 CONCLUSION

Ensuring that the Global Navigation Satellite Systems (GNSS) and Differential Global Navigation Satellite Systems (DGNSS) are reliable and accurate is vital for safe and efficient maritime navigation in Brazil. These systems, such as GPS, Glonass, Galileo, and Beidou, combined with DGNSS correction methods, provide precise positioning data for sailors.

To maintain the integrity of these navigation systems, the IALA stations in Brazil have a crucial role. The country is taking steps to enhance the safety and efficiency of maritime navigation in the region by implementing ongoing projects, including the upgrade of IALA stations with new technologies, and the centralization of information through a Central Monitor network.

In addition, the Kongsberg IALA System is a versatile solution that can adapt to various satellite navigation systems and correction methods, including Glonass, Galileo, and Beidou. The use of advanced technologies like this helps ensure the reliability and accuracy of GNSS and DGNSS in Brazil.

In conclusion, preserving the integrity of GNSS and DGNSS requires continuous efforts that involve advanced technologies, ongoing projects, and a commitment to safety and efficiency in maritime navigation. Brazil's investment in these initiatives serves to ensure the safety of mariners and promote the continued growth of the maritime sector in the region.

4 ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to Kongsberg for their valuable support and contribution to this article. Their expertise and innovative solutions in the field of marine navigation have greatly helped in enhancing our understanding of GNSS and DGNSS integrity in Brazil. We would like to thank the Kongsberg team for their assistance in providing technical information and insights that have enriched the content of this article. We appreciate their continued dedication to ensuring the safety and efficiency of maritime navigation and look forward to collaborating with them in the future.

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AUTHOR BIOGRAPHY

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Fernando Scoralick has a Bachelor's degree in Electrical Engineering and Telecommunications Engineering with MBA in Project Management and MBA in Data Science. Over 12 years' experience in the Naval industry. He was part of the first Kongsberg IALA Base Station installed in Brazil as a Sensor and Robotics Manager of Kongsberg Maritime. Actually, he is a Senior Automation Manager, with previous experience for many years in the Sensor and Robotics area. Started his career at Kongsberg as a Field Service Engineer in the Dynamic Positioning and Reference Systems areas.

S114.2 Status of the maritime highly accurate and resilient PNT policy in KOREA (019)

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ABSTRACT

ICT (Information and Communication Technology) and artificial intelligence that use PNT(Positioning, Navigation, Timing) information are deeply involved in our daily lives, driving innovation in various fields. These international technology trends are increasing the importance of accurate and reliable PNT information in many areas of society. In particular, in the maritime sector, PNT system that provides accurate and reliable location information is essential for autonomous vessels with AI technology to set safe routes and sail to their destinations. Currently, most Korean vessels rely on GNSS for navigation. However, maritime PNT systems that make vessels dependent on GNSS alone are highly vulnerable to intentional jamming. Therefore, applying new technologies such as autonomous vessels to the Korean maritime sector will be an achievable goal when more accurate and resilient PNT services are provided. In this paper, we introduced the current status of the Korean government's policy to provide highly accurate and resilient PNT services to the maritime sector by utilizing eLoran, MF R-Mode, GPS and the Korean Positioning System (KPS), and looked at the development and service schedule for each system.

It is written with the intention of helping IALA members set the direction of maritime PNT policy.

KEYWORDS: Maritime PNT, eLoran, POINT, R-Mode, KPS

1 INTRODUCTION

In 2019, Gartner, a leading IT research firm, published a list of 10 strategic technology trends, the first of which is "autonomous things". With the development of new technologies such as artificial intelligence and big data, various companies such as Tesla, Waymo, and GM have already secured a high level of autonomous vehicle technology through development competitions, and cars with these technologies are driving on the road. Automation and autonomous technologies have the potential to significantly improve efficiency and safety in a variety of industries, including transportation, logistics, manufacturing, and agriculture.

The demand for automation and autonomous systems will continue to grow across a wide range of industries due to a shortage of skilled labor in certain fields, research showing that the working-age population will decline, and the need to reduce production costs. In particular, Maritime Autonomous Surface Ships (MASS), which apply autonomous technology to the maritime sector, have the potential to reduce costs, improve productivity, and increase fuel efficiency by reducing human errors. The global market size of MASS is expected to expand rapidly, as shown in Figure 1.[1]

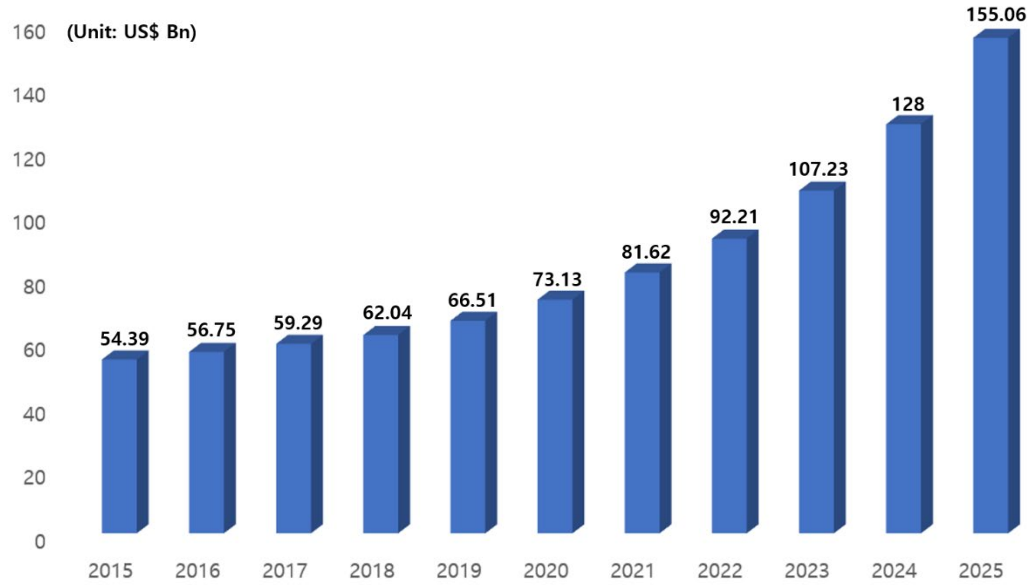

Figure 51: Global Market Forecast for Maritime Autonomous Surface Ships(2015~2025)

In January 2022, Japan announced the completion of the world's first demonstration test of MASS navigation systems for a large car ferry.[2] Mitsubishi Shipbuilding, a part of an industrial firm Mitsubishi Heavy Industries (MHI) Group, and marine transport company Shin Nihonkai Ferry successfully demonstrated a fully autonomous navigation system, on a 222-metre ferry, with autonomous port berthing and unberthing using turning and reversing movements and high-speed navigation. The Korean government has been actively progressing with the R&D project for MASS technology since 2020, and plans to complete the development of technologies such as intelligent navigation systems and engine automation systems by 2023 and begin demonstration and operational tests for two years from next year.

While MASS is an industry that will bring a revolution to the maritime sector, South Korea's geopolitical location has its own factor to consider. Since 2010, GNSS jamming has been causing problems for a variety of applications, including aircraft, ships, and mobile communication systems. Fishing vessels have also reportedly been affected by being unable to operate. If this happens in the future when MASS become common, it will cause even greater disruption to maritime traffic safety. Therefore, the Korean government is working to build a maritime PNT system that addresses these realistic issues.

In this paper, we propose the Korean government's policy to IALA members to build a highly accurate and resilient maritime PNT system, which is required by the automation and autonomy trends in the maritime sector internationally, and share the status of its implementation.

2 MARITIME PNT SYSTEM IN KOREA

Currently, the Korean Ministry of Oceans and Fisheries provides Loran-C and MF(Medium Frequency) DGNSS service for maritime traffic safety. Since these technologies are not capable of providing PNT services to the public with the performance required in the future maritime sector, a plan has been established to build a highly accurate and resilient maritime PNT system through the Korean Positioning System (KPS), eLoran, which significantly improves the performance of Loran-C, and MF R-Mode technology, which utilizes the existing MF DGNSS transmission infrastructure, as shown in Figure 2. The policy goal of the plan is to provide complementary national maritime PNT services by utilizing a combination of satellite and terrestrial transmission systems.

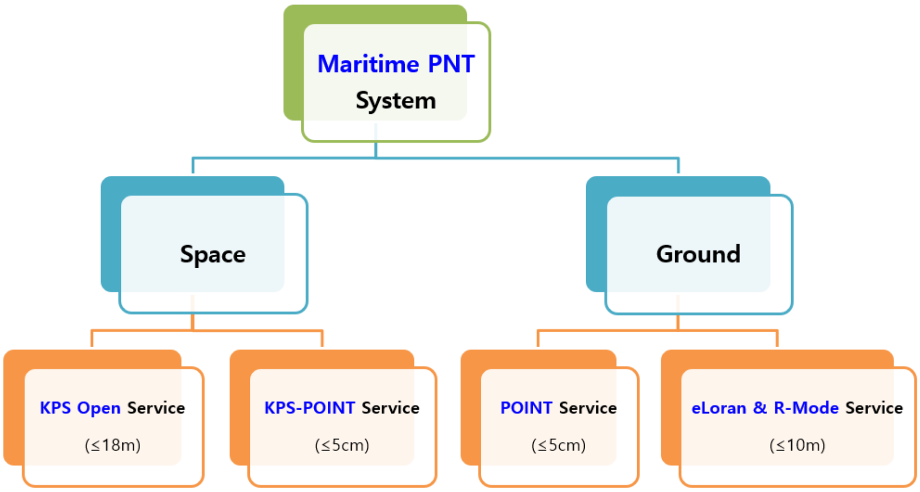

Figure 2. The Maritime PNT System Scheme in KOREA

2.1 eLoran Service

2.1.1 Status of the eLoran R&D project and service

eLoran(enhanced Long-range navigation) is a terrestrial-based navigation system that uses radio signals to provide accurate and reliable positioning information to vessels. It is considered a potential alternative system to the GNSS (Global Navigation Satellite System) when GNSS fails due to jamming and interference. After experiencing GNSS jamming, the Korean Ministry of Oceans and Fisheries continuously invested in R&D to build an eLoran system that can replace GNSS. As a result, eLoran R&D project was completed in 2020, and system's performance was verified through two years of demonstration on a testbed built at Incheon Port. An additional transmitting station required for navigation services was built on Sochung Island last year, as shown in Figure 3. Test signals have been transmitted over the Yellow Sea since the public pilot service began in January 2023.

Figure 3. eLoran station in Socheong

2.1.2 eLoran service plan

The Korean Ministry of Oceans and Fisheries plans to produce and distribute ASF correction maps required for eLoran navigation service by the first half of 2024 and declare eLoran an official service in the second half of that year. We also plan to build additional transmitting stations in Jeju and Ulleung by 2027 to expand the coverage of eLoran navigation service beyond the Yellow Sea, as shown in Figure 4.

Furthermore, the ministry will provide a test service for the UAM (Urban Air Mobility) demonstration project between Incheon International Airport and Seoul, which is being carried out by the Ministry of Land, Infrastructure and Transport. We aim to demonstrate the effectiveness and reliability of eLoran navigation service in the aviation industry.

Figure 4. eLoran Service Coverage in 2027

2.2 MF R-Mode Service

2.2.1 Status of the MF R-Mode R&D project

MF R-Mode (Ranging Mode) is a technology that transmits additional signals for positioning in the MF DGNSS frequency band, which is already widely used in the maritime domain, so that the vessel's receiver can calculate its position. It features a horizontal positioning accuracy of 10 meters or less, which is higher than the eLoran system, and that can be used by vessels even in the event of GNSS jamming like eLoran.

The Korean Ministry of Oceans and Fisheries has been carrying out the MF R-Mode R&D project since 2020, developing a reference timing unit, R-Mode signal and correction information generator, and receiver, and is currently in the process of verifying the performance of each part of the system through a testbed built in the area near Daesan Port in the Yellow Sea, as shown in Figure 5, in order to complete the development in September 2023.

Figure 5. MF R-Mode Testbed Configuration

2.2.2 MF R-Mode Service Plan

From October 2023, MF R-Mode test service will be provided in the area near Daesan Port in the Yellow Sea, and by 2026, eight MF DGNSS transmitting stations will be upgraded to MF R-Mode transmitting stations, and from 2027, navigation service will be launched along most of the coast of Korea. However, since the signals from the 12 MF R-Mode transmitting stations alone are insufficient to achieve the target performance of the MF R-Mode service, which requires a horizontal positioning accuracy of 10 meters or less, it is not possible to provide service to the entire coast of Korea due to the small coverage area. To address this limitation, a navigation service that combines eLoran signals, which offer wide signal coverage, with MF R-Mode signals is being planned.

2.3 POINT Service

2.3.1 Status of the POINT R&D project

According to the future GNSS requirements of the International Maritime Organization (IMO), which takes into account the era of MASS that we will experience in the future, a horizontal positioning accuracy of 10 cm or less is required for the automatic docking process. Therefore, Korea believes that the current DGNSS service with m-level horizontal positioning accuracy will not be suitable for the maritime environment where MASS will become common in the future, and conducted a planning study for the development of high-precision positioning service in 2015 to identify the need and demand for high-precision navigation services in Korea. Based on this study, the Precise Positioning and INTegrity monitoring (POINT) R&D project was launched in April 2020. The POINT service aims to generate cm-level augmentation information at the central processing center based on GPS raw measurements acquired from reference stations and provide it to maritime users sailing within 100 km of the Korean coastline. Currently, the augmentation information generation, integrity monitoring, and receiver technologies, developed so far are being tested on a testbed built at the Daesan port, as shown in Figure 6.

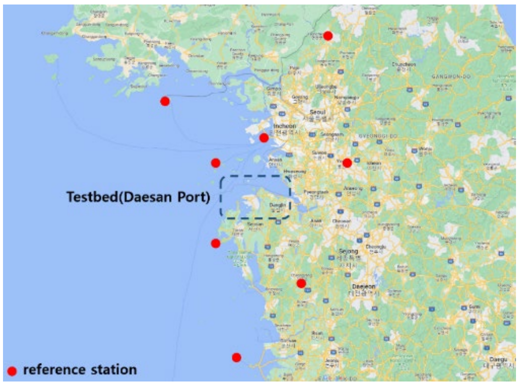

Figure 6. POINT Testbed Configuration

2.3.2 POINT Service (Phase 1) Plan

According to a plan announced by the Korean Ministry of Oceans and Fisheries, the R&D project for the POINT service will be completed by 2024. Starting in 2025, a pilot service for POINT will be provided to vessels sailing within 100 kilometers from the coastline using ground-based communication channels such as LTE-M to transmit GPS signal augmentation information at the centimeter level. Furthermore, after 2027, GLONASS and Galileo will be added to the list of constellations to be serviced.

2.4 Korean Positioning System (KPS)

2.4.1 Status of the KPS R&D project

We live in a world where technologies such as 5G, the Internet of Things (IoT), location-based services, and autonomous vehicles have become essential parts of our lives. Since most of these technologies require accurate Positioning, Navigation, and Timing (PNT) information to work properly, PNT has become critical not only in our daily lives but also in terms of national security. Our neighbouring countries, Russia, China, and Japan, have their own satellite navigation systems. However, Korea relies on foreign satellite navigation systems, such as the Global Positioning System (GPS) operated by the United States, to obtain PNT information. To address this problem, the Republic of Korea launched the R&D project for the Korean Global Positioning System (KPS) in 2022. The project is expected to be completed by 2035, and test service will be provided in 2036. Currently, the KPS system is being designed for each segment, which is divided into Space, Ground, and User.

2.4.2 POINT Service(Phase 2) Plan via KPS

As shown in Figure 7, the first KPS Inclined Geosynchronous Orbit (IGSO) satellite is scheduled to be launched in 2027. Following the launch, we plan to test and verify the performance of the POINT service (Phase 2) technology, which provides centimetre-level GPS augmentation information via satellite, and will also broadcast POINT service (Phase 2) test signals starting in 2030.

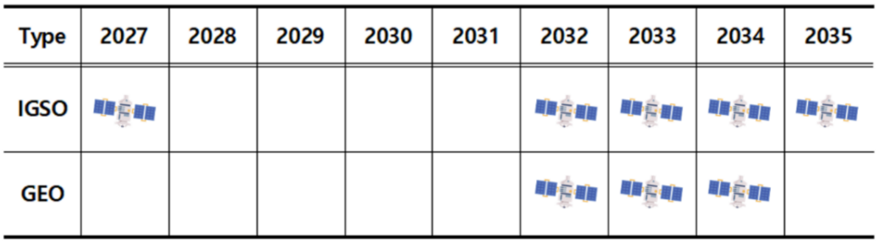

Figure 7. KPS Satellite Launch Plan[3]

3 CONCLUSION

As explained in the introduction, the rise of new technologies that rely on PNT information has made it increasingly important to build a highly accurate and resilient PNT system. This is especially critical from a national security and economic perspective, and is a necessary goal. To this end, the Korean Ministry of Oceans and Fisheries is pursuing a policy to build a Maritime PNT System, which combines satellite and terrestrial navigation systems. Since satellite navigation systems offer advantages in accuracy and terrestrial navigation systems offer advantages in resilience, it is appropriate to establish a national Maritime PNT System that allows the two systems to exist in a complementary relationship rather than main and backup relationship. In a country like Korea, where the introduction of new technologies is rapid and the risk of jamming is high, it is not too much to build a Maritime PNT System consisting of various PNT sources to enhance national competitiveness and strengthen the response to disasters by jamming or spoofing.

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S114.3 Development of Terrestrial Radio Navigation System of R.O.K for Maritime PNT (032)

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ABSTRACT

This paper consists of two main topics which are a results of eLoran testbed and status of R-Mode testbed development. First, a summary of eLoran testbed implementation and a test results under vessel at sea are presented. The performance evaluation results show the eLoran service can provide the within 20 m positioning accuracy. GNSS interference test results are also presented. A jamming and spoofing signal was considered during the test. The results show eLoran can provide safe PNT service without any affect by GNSS interference. Next, Korean R-Mode testbed system architecture and implementation results are presented. Korean R-Mode system considers MF DGNSS and VDES signal as a source to implement it. A differential R-Mode station for generating correction information and Integrity monitoring station are key component of Korean R-Mode.

KEYWORDS: terrestrial radio navigation, eLoran, R-Mode, DGNSS, VDES, GNSS backup

1 INTRODUCTION

The Republic of Korea (R.O.K.) is making efforts to set up a backup navigation system to provide resilient Position, Navigation and Timing (PNT) information to maritime users in case of GNSS emergency and to prepare for GNSS vulnerability. The eLoran testbed project, initiated by KRISO in 2016 with the support of the Ministry of Oceans and Fisheries, completed its technological development in December 2020, and its test services are being provided to two major ports (Incheon Port and Pyeongtaek Port) in the north-central region of the West Sea of Korea. The eLoran testbed project aims to achieve 20 m accuracy within the test harbour [1].

In the beginning of second quarter of 2020, another terrestrial based backup PNT project, developing Korean R-Mode testbed, was kicked-off. The goal of this project is to improve the positioning accuracy within 10 m to meet the requirement of IMO and IALA for harbour entrances and approach. The R-Mode testbed is located in Daesan port. The R-Mode service combined with eLoran is expected to support the safe navigation in Korean costal area [2].

2 ELORAN TESTBED DEVELOPMENT

The International Loran Association (ILA) defined the architecture of the eLoran system as shown on the left of Figure 1 [3]. The transmitting station broadcasts an eLoran signal synchronized with UTC to the user, and at this time, a Loran Data Channel (LDC) message is also broadcast. The LDC message includes time information and correction information (ASFs). The user receiver receives the signal from the transmitting station, obtains time information and corrections, and estimates its position by measuring a distance. At this time, the user receiver also applying ASF map on the pre-measured spatial error. Differential Loran reference station (dLoran) receives signals broadcast by a transmitting station near a user and estimates temporal corrections (ASFs) [4][5]. Then, the ASFs are transmitted through the network to the transmitting station via the control center.

The monitoring station receives the signal from the transmitting station, verifies the integrity of the eLoran system, and transmits the information to the control center. The control center performs system monitoring and control.

The right side of Figure 1 is the Korean eLoran testbed system configured based on the ILA definition [1]. It is mostly the same as the ILA eLoran system configuration, and in the eLoran testbed system, the dLoran station performs the function of the monitor site together. The transmitting system consists of three stations by adding a new eLoran transmitting station to the existing Loran-C transmitting stations located in Pohang and Gwangju. The new eLoran transmitting station has now moved to Socheong Island for better service and was located in Incheon at the time of research and development. Therefore, the results presented in this paper using the signal from the Incheon transmitting station. Pohang and Gwangju Loran-C transmitting stations upgraded to UTC time synchronized system for accurate synchronization between transmitting stations. The dLoran station is located near Incheon Port and Pyeongtaek Port, respectively, and the Control Station is located at the National Maritime PNT Office (NMPO) located in Okcheon. And, in order to achieve the target accuracy, ASF was measured at Incheon and Pyeongtaek ports, and ASF maps were created and inputted to the user receiver.

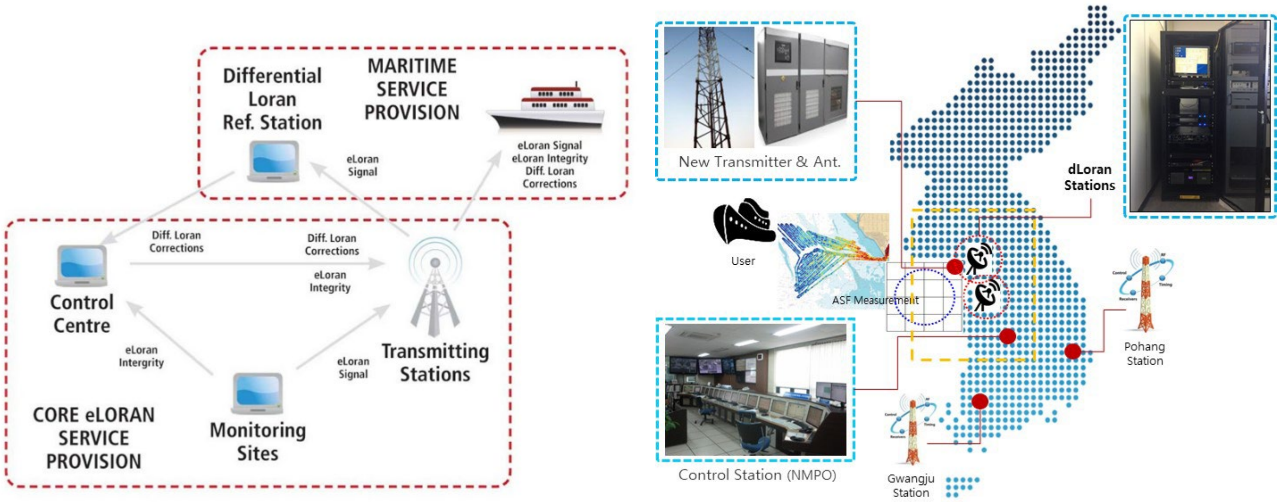

Figure 52: ILA eLoran system architecture (Left), Korean eLoran testbed configuration (Right)

3 ELORAN TESTBED PERFOMANCE EVALUATION

The eLoran performance evaluation test was conducted on two scenario. First, it was confirmed that eLoran was robust against GNSS interference. Second, the positioning accuracy of eLoran was confirmed. To test the accuracy performance, a static test at the dLoran station and a dynamic test using a vessel at sea were performed.

3.1 GNSS Interference Test

The GNSS interference test was conducted at Incheon Ara waterway. A GNSS receiver and an eLoran receiver were mounted on the vessel and the position was confirmed while moving along the waterway. And GNSS jamming and spoofing signals were applied using a simulator. The left side of Figure 2 is vessel's positioning result in the GNSS jamming environment, and the right side is the positioning result in the GNSS spoofing scenario. Blue is the GNSS receiver output, and red is the eLoran receiver output. When jamming occurs, the GNSS receiver does not provide vessel position and the eLoran receiver continuously provides the position. In the presence of spoofing, the GNSS receiver displays the position information of the vessel on the road, and the eLoran receiver stably provides the correct position along the water way.

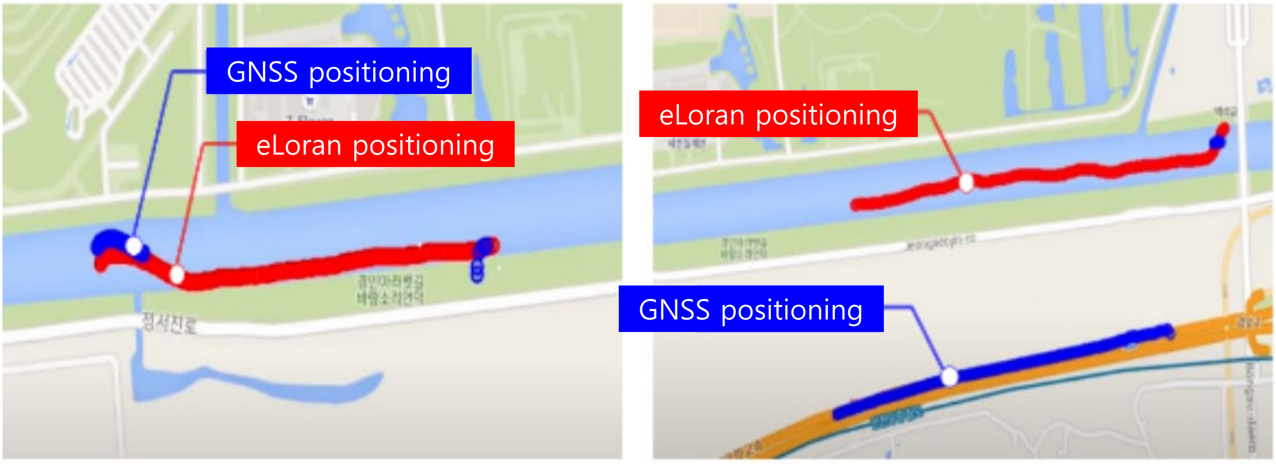

Figure 2: eLoran (Red) and GNSS (Blue) positioning results due to GNSS jamming (Left) and spoofing (Right)

3.2 Positioning Accuracy: Static

The static positioning accuracy test of eLoran was performed at the dLoran station located in Pyeongtaek. Two different antennas and receivers are installed at the dLoran station and there were used to short baseline test. The ASFs were generated in one receiver and applied to the other receiver [6]. Figure 3 is the eLoran static positioning result, showing 9.3 m (95%) accuracy when ASFs are applied.

3.3 Positioning Accuracy: Vessel Test

The eLoran dynamic positioning test was conducted near the Incheon Port. As shown on the left of Figure 4, GNSS and eLoran antenna and receiver were installed on the fishing boat, and the vessel was operated as shown on the right of Figure 4. ASFs were measured in advance, an ASF map was created, and it was input to the receiver. Figure 5 shows the horizontal positioning errors (HPE) which are difference between the position obtained by the GNSS receiver and the position obtained by the eLoran receiver. An accuracy of about 18.7 m (95%) was achieved using eLoran in the maritime environment.

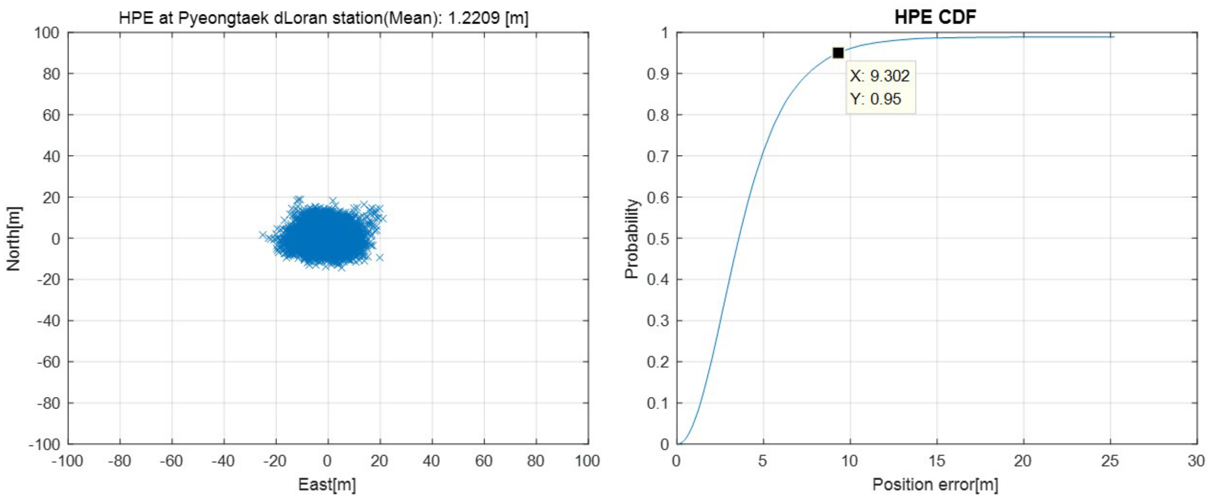

Figure 3: eLoran positioning results at Pyeontaek dLoran station

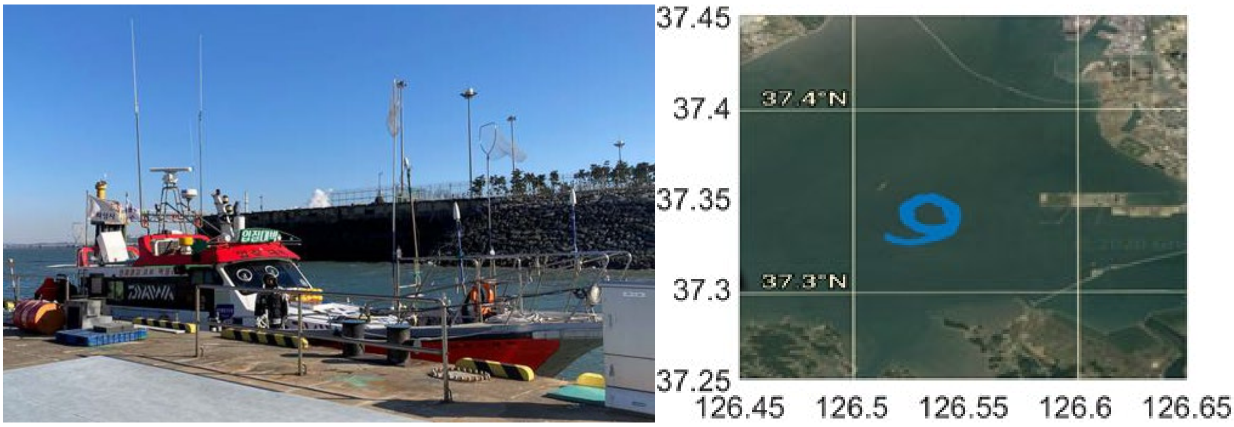

Figure 4: Vessel test environment

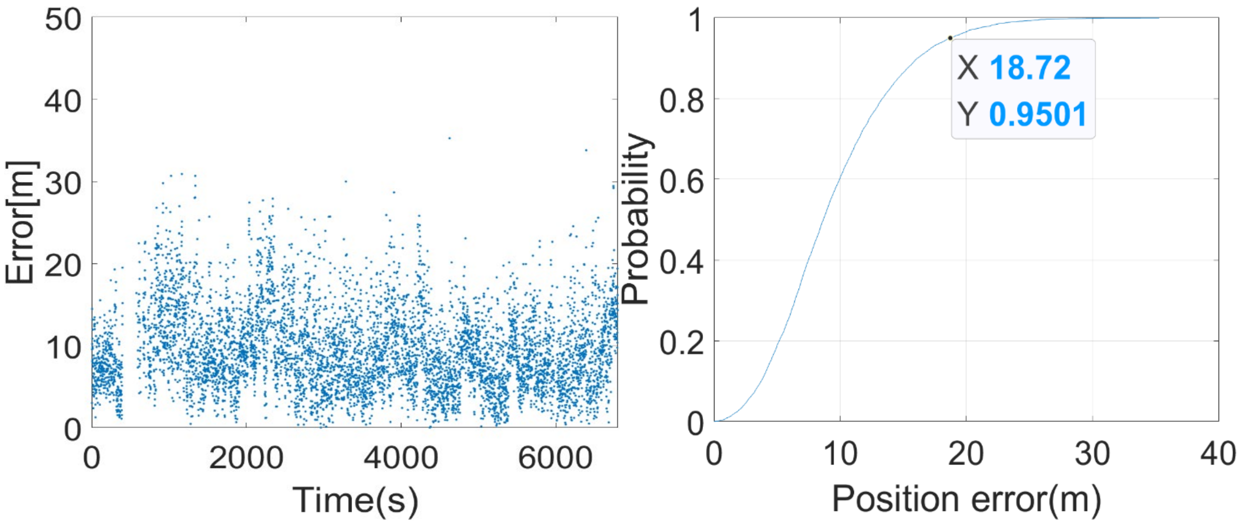

Figure 5: eLoran accuracy using vessel at Incheon harbour

4 KOREAN R-MODE TESTBED DEVELOPMENT

Terrestrial Ranging-Augmented, Complementary and Enhanced (TRACE) project, commenced the R-Mode testbed project of the Republic of Korea in April 2020 and will develop the core technology and demonstrate its performance in the test ports by September 2023 [2].

4.1 Testbed Configuration

The TRACE project plans to utilize the medium-frequency (MF) R-Mode, VDES R-Mode signal, and eLoran signal currently in service to achieve the project goals. Therefore, the testbed system will consist of a transmitting station for MF R-Mode signals, the VDES R-Mode signals, and eLoran signals and an integrated navigation receiver that receives and integrates each signal to determine its position. The integrated navigation receiver receives GNSS signals and terrestrial navigation signals. Furthermore, the system consists of a monitoring station for integrity information generation, a differential R-Mode reference station system for generating correction data to improve the positioning accuracy for MF R-Mode users, and an operating system to monitor and control the status of each system.

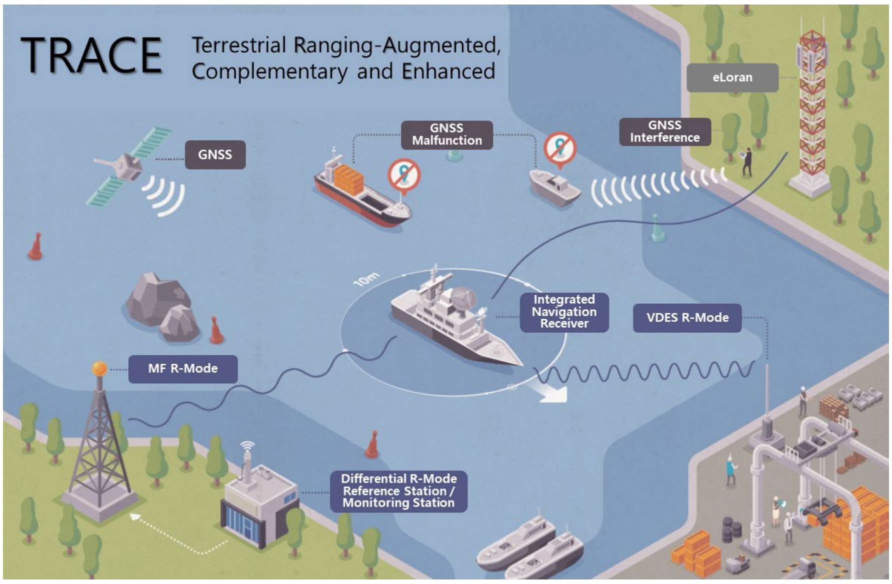

Figure 6: Korean R-Mode system

Figure 7 shows the testbed configuration. The Daesan Port located in the north-central region of the West Sea, Korea was selected as the testbed area for the actual performance, where eLoran signal reception is possible along with the signals of the MF R-Mode transmitting station. Therefore, the Socheong, Palmi, and Eocheong Island DGNSS marine reference stations and the Chungju DGNSS inland reference station was upgraded to MF R-Mode transmitting stations. The VDES R-Mode transmitting station was temporally installed at Humang AIS base stations, Nanjido, and Budo where it can complement the HDOP. The differential R-Mode reference station and the monitoring station was installed near the Daesan Port as shown in Figure 8.

The high level system architecture of Korean R-Mode test bed is shown in Figure 9. Differential R-Mode system (DRS) receives MF R-Mode signals and generates corrections for low and high CWs. R-Mode monitoring system (RMS) receives MF R-Mode corrections and feedback to DRS monitoring results. RMS monitors MF and VDES R-Mode signals and generates integrity information. VDES R-Mode Transmitting system (VRT) receives integrity information from RMS and sends it to users. MF R-Mode Transmitting system (MRT) receives MF integrity information, corrections and UDREs from RMS and generates R-Mode RTCM messages to send it to users. R-Mode Operation system (RMOS) monitors and controls each sub system.

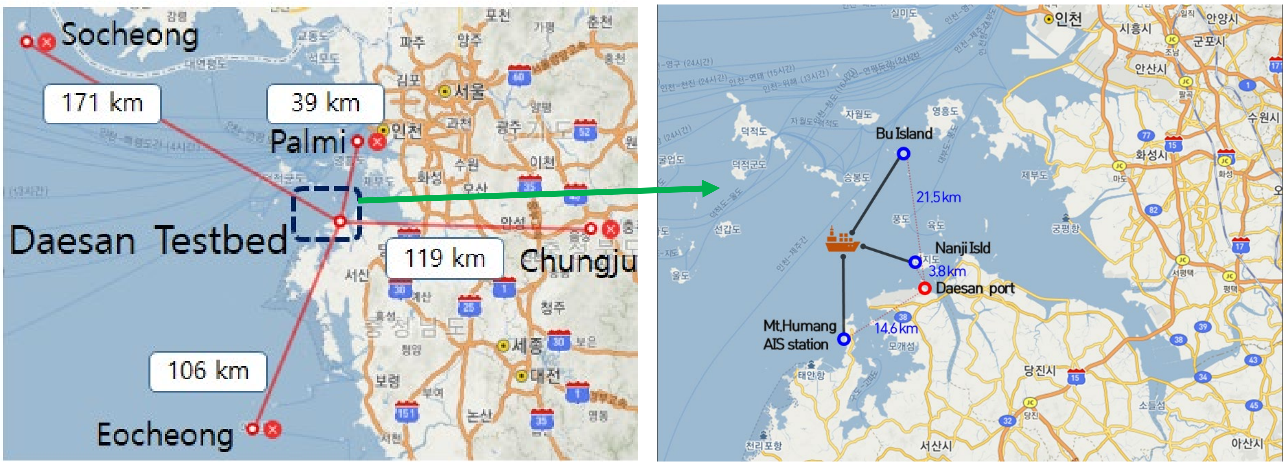

Figure 7: Korean R-Mode testbed configuration (Left: MF R-Mode, Right: VDES R-Mode)

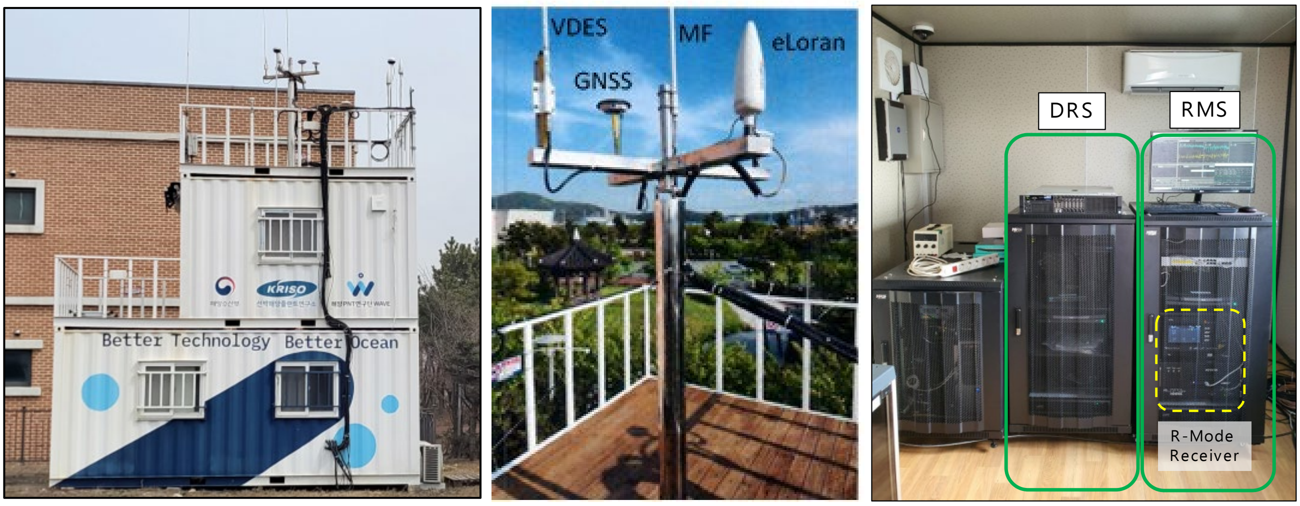

Figure 8: The differential R-Mode reference station and the monitoring station

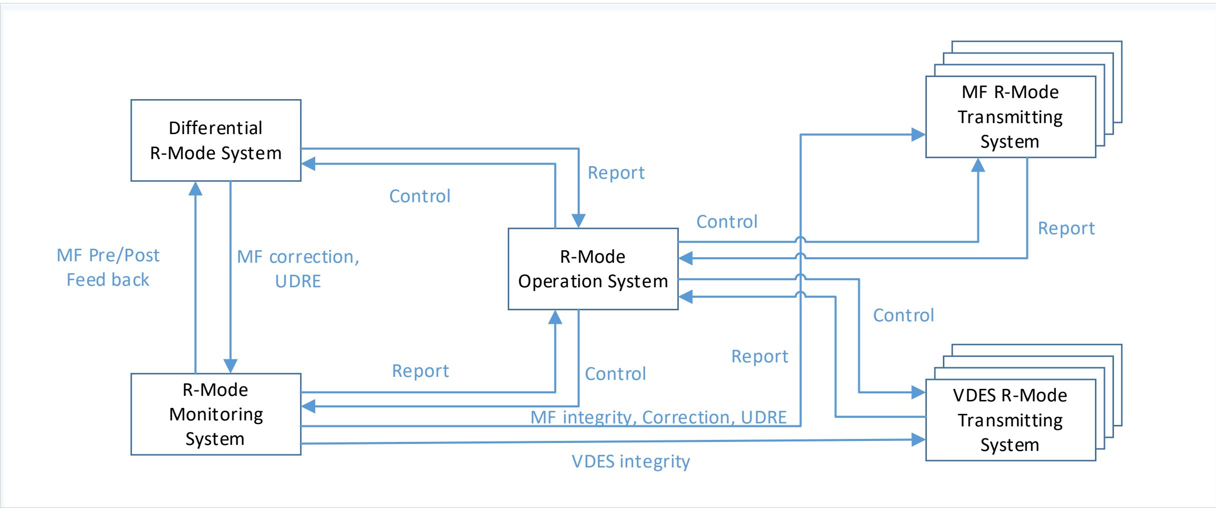

Figure 9: Korean R-Mode system architecture

4.2 MF R-Mode development

All MF R-Mode test bed transmitting stations are operating. Chungju inland station was first installed. It has been broadcasting MF R-Mode signal since June 2021. Eocheong maritime transmitting station is broadcasting signal from October 2021. Socheong and Palmi maritime stations have started to transmit each R-Mode signal since May and August 2022, respectively. The left side of Figure 10 shows Eocheong R-Mode transmitting station equipment. Korean R-Mode test bed is testing two options of CWs frequencies (250 Hz and 450 Hz) far from the MSK signal. Eocheong MF R-Mode signal spectrum set on 450 Hz is shown in the right side of Figure 10. Its monitoring status is shown in the left side of Figure 11. Korean DGNSS system is redundant. Thus, we installed an R-Mode system on the A side only. The B side has the original DGNSS to prevent the technical issue. Socheong station has R-Mode system installed on the B side [7][8][9].

The MF R-Mode receiver positioning results during 6 hours of daytime is shown in the right of Figure 11. We achieved about 7 m (95%) accuracy during daytime but large errors were existed during night due to sky wave.

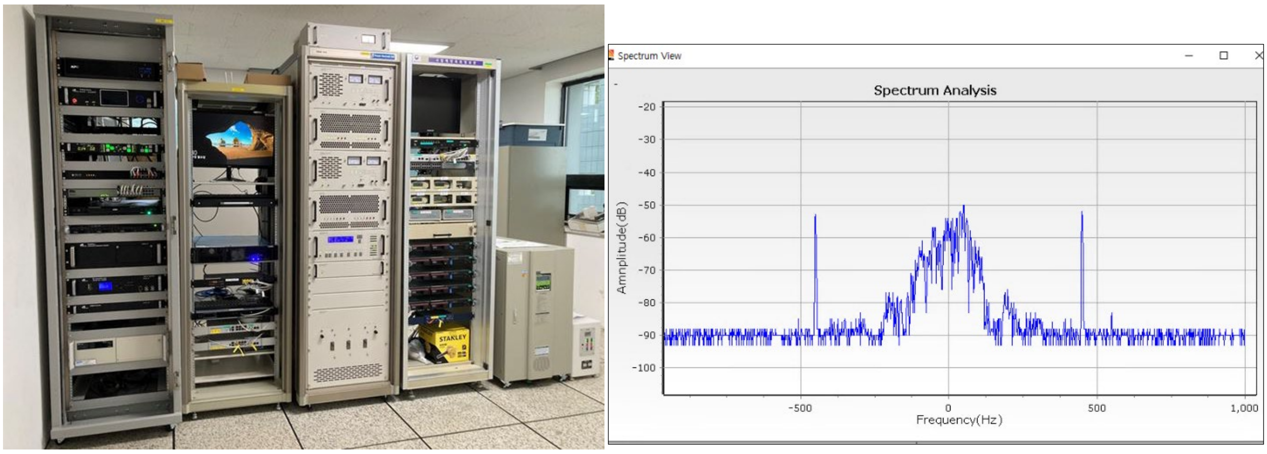

Figure 10: Eocheong MF R-Mode transmitting station equipment and signal spectrum

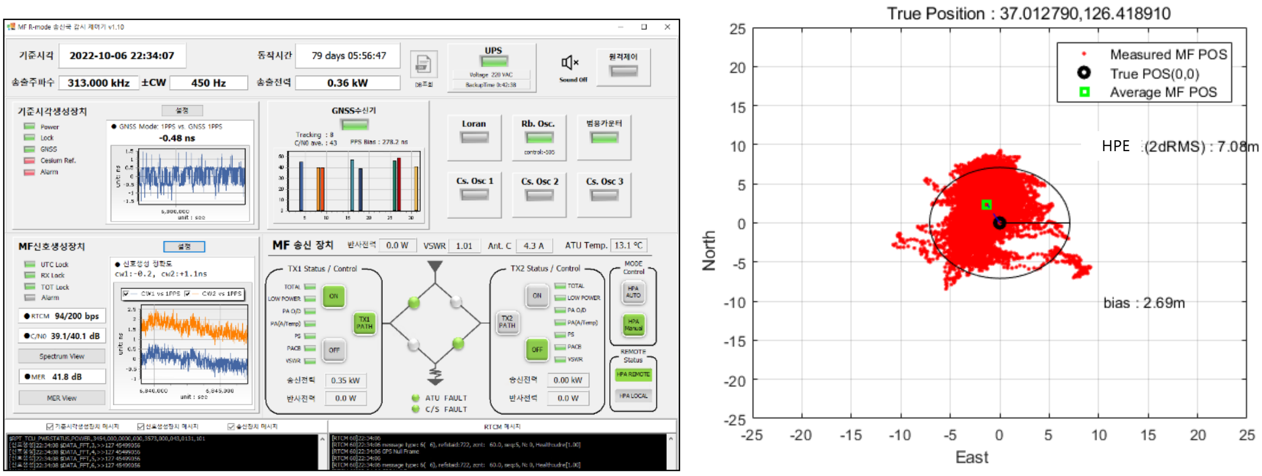

Figure 11: MF R-Mode transmitting station monitoring status at Eocheong (Left) and positioning results at RMS (Right)

5 CONCLUSION

In this paper, the current status of the terrestrial navigation system being developed in Korea was explained in preparation for GNSS vulnerabilities in the maritime domain. eLoran testbed was developed for the northern part of the West Sea, and eLoran test services are being provided near Incheon Port and Pyeongtaek PorPort. The eLoran testbed performance was analyzed in terms of accuracy and impact on GNSS interference. It was confirmed that positioning information could be stably acquired using eLoran even in GNSS jamming and spoofing environments. In addition, it was confirmed that positioning accuracy within 20 m (95%) could be obtained through marine experiments using vessel. Also, Korea is developing the R-Mode system to achieve the harbour entrance and approach accuracy required by IMO and IALA. To this end, we are developing MF R-Mode and VDES R-Mode technologies, and aiming to achieve 10 m (95%) accuracy by combining with eLoran. Static positioning using MF R-Mode signals can achieve accuracy within 10 m during the day, but a large error was confirmed during the night due to the effect of the sky wave. In the future, we plan to conduct accuracy improvement studies during the night through integration with VDES R-Mode and eLoran.

6 ACKNOWLEDGEMENTS

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SESSIONS 15 AND 115 - RADAR TECHNOLOGIES

S15.1 Radar absolute positioning (132)

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ABSTRACT

Traditionally, radar images are used to support relative positioning of a vessel with the range and bearing to the target calculated and displayed for the navigator. Many e-Navigation services will require the vessel's absolute location to provide context to the service or the information received/transmitted. In a world that is quickly recognising GNSS vulnerabilities and the need for resilient positioning, navigation and timing (PNT), radar for absolute positioning is a promising independent solution to GNSS.

This paper will outline the approach being developed by the General Lighthouse Authorities (GLA) of the UK and Ireland. It will explain the development of a radar absolute positioning approach that started with terrain matching, then considered radar image modelling and now provides a hybrid solution capable of obtaining the vessel's position to within 20m (95%), and can maintain that accuracy for several tens of minutes to an hour following the loss of GNSS. This technology is being developed and GRAD aims to improve on this performance. The paper reports on the system development and trials conducted to date.

KEYWORDS: Radar, SLAM, PNT, Resilience

1 INTRODUCTION

Global Navigation Satellite Systems (GNSS) are in use worldwide, and form the de-facto standard for positioning, navigation and timing systems. GNSS is accurate, reliable and available globally, free at the point of use. This has led to it becoming an integral part of most industries, adopted as a *silent utility* across almost all sectors, resulting in a large amount of industrial activity now being critically dependent on its functioning [1]. GNSS, in particular the American GPS, is used extensively in the maritime world, primarily for plotting the vessel's position on an electronic chart display (ECD) or ECDIS. It is also relied upon by other bridge equipment, such as reporting the vessel's position via AIS, and for timing purposes, such as for AIS transmission slots and digital selective calling (DSC). The advent of e-Navigation, integrated bridge systems and greater automation within the maritime sector will only increase the sector's dependency on GNSS further.

GNSS signals are very weak, vulnerable to obstruction, local radio interference or deliberate jamming. The General Lighthouse Authorities (GLA) have for a long time advocated adopting alternate, backup systems to mitigate the consequences of a potential loss of GNSS. The GLA Research & Development directorate (GRAD) has investigated a number of position fixing technologies which operate independently of satellite systems, including ship-borne equipment such as radar.

This paper provides a summary of our work, and the results of our investigations so far.

2 ABSOLUTE POSITION FIXING BY RADAR

SOLAS class vessels are required to equip radar in the X-band (9GHz) and, depending on size, also the S-band (3GHz) [2]. Marine radar is a valuable tool for navigation; maintaining situational awareness; and collision avoidance, particularly in reduced visibility. There also exist a number of ways to employ the ship's radar to determine the vessel's position, and to plot that position on a nautical chart [3]. A simple method is to pick several conspicuous landmarks such as headlands or radar reflective beacons, to take range and bearing measurements off the radar screen, and plot these on the chart to determine a position. This is relatively easy to do, but requires the navigator's time to determine the targets, to take measurements, and to transfer these to the chart. It is repetitive, and laborious, to do by hand. Easier, time-saving measures such as parallel indexing from the shore-line can help.

An automated process would relieve the navigator of much of this burden, but an automated system may struggle to unambiguously determine radar-conspicuous targets on the screen, and relate these to charted landmarks. GRAD has looked at a number of different methods to automatically employ radar data to determine the position of the vessel, these are described below:

2.1 e-RACON Positioning

An "e-RACON" is a device that operates almost identically to a conventional radar beacon, except it is able to send digitally encoded data in its Morse paint, to a suitably equipped New Technology (NT) radar. This information includes the precise surveyed latitude and longitude of the beacon.

By measuring the range and bearing to one or more e-RACONs, the radar can then determine its own position. The accuracy with which a radar can determine the range to a target is considerably better, usually a few meters [4], than its ability to determine the bearing angle. A bearing error of half a degree equates to a position uncertainty of almost 100 meters at six nautical miles from the beacon.

This potentially limits the capability of the process, since the radar requires simultaneous measurements to at least two e-RACONs for the best accuracy performance. The RACONs may only have a maximum visible range of about 10NM, which requires deploying at least two e-RACONS for every 10NM of coastline. The need to provide hardware with associated maintenance and management, led us to consider alternative approaches.

2.2 Radar Dead Reckoning by Image Matching

This is the basic process of performing dead-reckoning (DR) positioning by comparing the current image on the radar screen to a screen grab taken some time earlier at a known location. Indeed, this is not a new idea [5]. A correlation process is used to compare the two images, and this determines the best-fit offset (in terms of screen pixels) between the old and new radar images. This is then translated into a physical distance across the sea, and the ship's estimated position (EP) is updated accordingly.

Two significant aspects have been observed by GRAD when using this process:

1. The correlation to the reference image falls very rapidly as the ship sails away from the location the image was taken.
2. The error in the position solution computed by the image-matching process increases as the image correlation drops.

This process can fix the vessel's position to within an accuracy of about 20m, but only while the ship is within about half the radar range of the reference image. For example with a radar range setting of 6 Miles, if the ship loses its GPS position, image matching can provide an accurate Radar DR solution, but only for about the next 3 Miles of sailing. Depending on the speed of the vessel, this process may only be viable for a few minutes.

GRAD has investigated using more than one reference image for matching. Screen grabs can be taken regularly from the radar, and laid down as a "trail of breadcrumbs" to follow home. This is useful, especially if the vessel returns to an area where it has previously been, and allows accurate Radar DR to operate for an extended time without GPS. However, it can't help a vessel sailing into an area it has not previously visited. A solution to this is to pre-survey an area (e.g. a harbour approach) and publish a map of radar-conspicuous targets.

2.3 Conspicuity Mapping

A logical extension to the "trail of breadcrumbs" process is to pre-survey the harbour, gathering a large number of radar images, and to process these into a single, authoritative radar map of the region. This map consists of a large grid of pixels, covering the whole harbour area, with the value assigned to each pixel related to the strength and consistency of the radar returns seen at that location.

This process can be automated relatively easily: strong, reliable targets that appear across multiple images are given larger values in the map, weak or intermittent targets that were inconsistent across images given lower values.

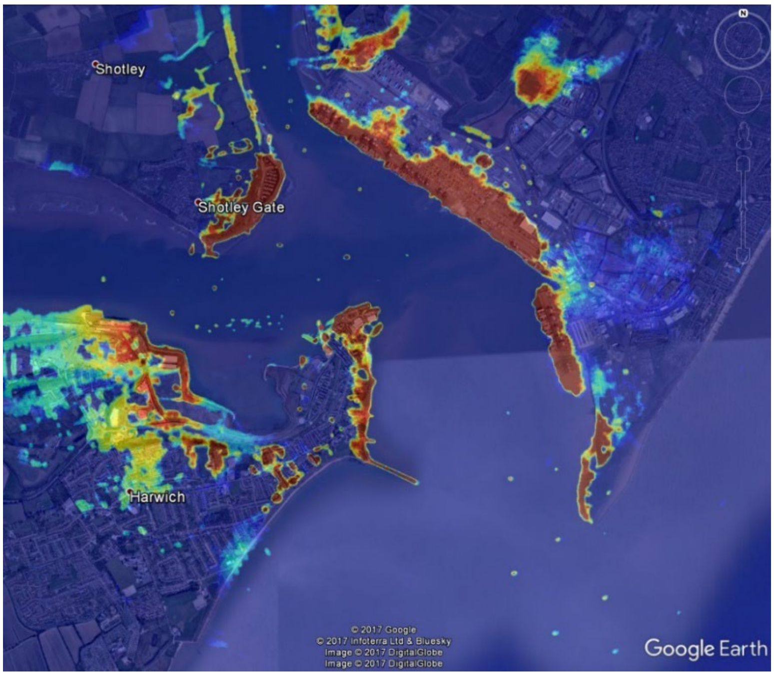

Figure 53 – Radar conspicuity map of Harwich and Felixstowe, derived from the ship's radar and overlaid onto Google Earth. Hotter colours represent stronger, more reliable targets.

Wherever the vessel is in this area, it can then match the image on its radar screen to the conspicuity map of the area. The same image-correlation process is used, and trials have shown that this allows the vessel to fix its position reliably within about 30m, and achieve 95% Accuracy performance of about 20m.

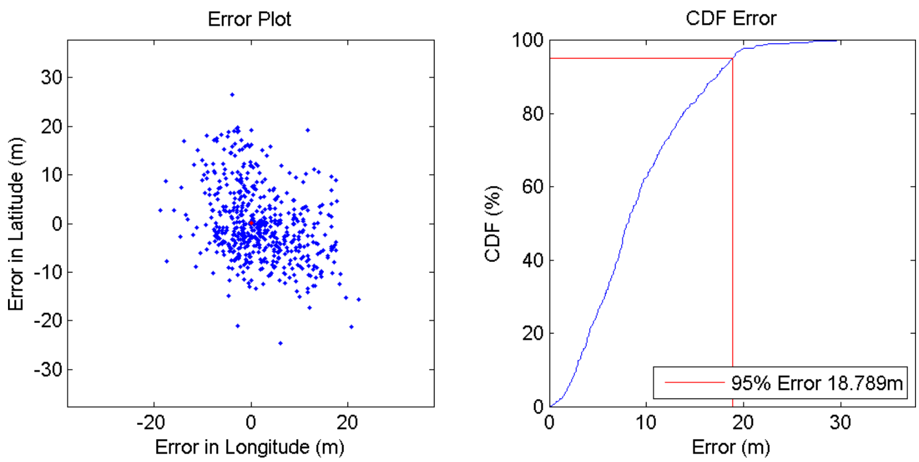

Figure 54 – Error scatter and CDF for position-fixing using image-matching to the above conspicuity map

2.4 Terrain Matching

There exist concerns that a radar conspicuity map measured by one vessel may not be usable by other vessels. Issues such as radar configuration; sensitivity; and the height of the antenna will mean different ships in the same area may see very different radar targets on their screens. It also takes a large amount of time and effort to survey a harbour, so GRAD has investigated using models of the terrain elevation to automate the process of determining radar conspicuity maps.

We have developed a process for generating simulated radar returns from the Digital Terrain Elevation Database (DTED), which is available for free at various resolutions, down to a post-spacing of about 30m. By employing a basic ray-tracing process and diffuse lighting model, GRAD can determine modelled radar conspicuity maps for any vessel configuration.

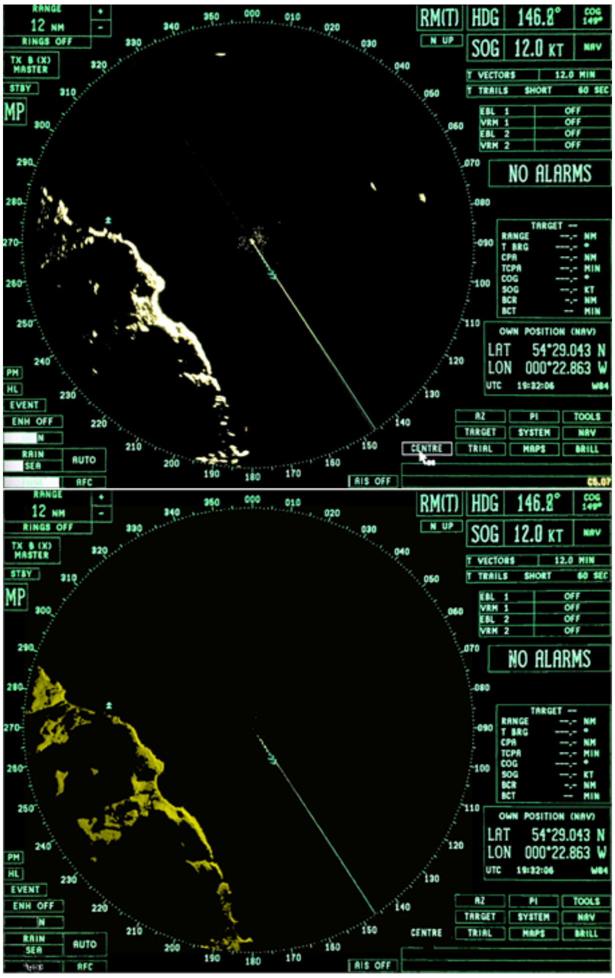

Figure 55 – Example Radar conspicuity generated from a terrain database. Real radar image captured from a vessel (above) and the same image with the radar returns replaced with simulated data (below).

To the human eye these simulated images do look quite realistic, and the process does work reasonably reliably. However, the absolute accuracy performance so far has been poor (~100m Accuracy, 95%). This is thought to be due to issues such as the quality of the terrain data; the accuracy of the datum used; and the absence of radar returns from man-made structures in the simulated maps. GRAD has paused our research into terrain-matching, pending the availability of better terrain data.

2.5 Simultaneous Location and Mapping (SLAM)

If the ship is able to build its own conspicuity map as it sails, then this alleviates us from the need to perform extensive surveys, and also solves the problem of whether the map is compatible between different ships' radar setups. However, this still leaves the problem of a vessel sailing into an area that it has not previously visited, and therefore does not have pre-existing conspicuity data to fall back on. The solution is Simultaneous Location and Mapping (SLAM) [6]. This allows the ship to continue building its conspicuity map, even if GPS is lost, by using the *radar-derived solution* as a ground-truth for mapping new radar conspicuous targets.

Our trials have shown it is possible to perform extended runs on Radar SLAM, even using only a single GPS-fixed image to start the process. GRAD has also investigated using the ship's own speed log and gyrocompass sensors to perform "traditional" dead reckoning, and has constructed a combined system-of-systems that integrates Radar and traditional DR.

This integration provides two useful pieces of information to the combined system:

1. The vessel's estimated position can be provided by traditional DR, so the map-matching process has a relatively accurate EP to begin with.
2. The inherent errors and biases in the speed log and gyro can be calibrated out by comparing the difference between the radar-derived navigation solution and the EP given by the DR process.

The result is that the error in the solution can be reliably constrained to within less than about 25m, even after sailing for several hours without GPS in previously un-surveyed areas.

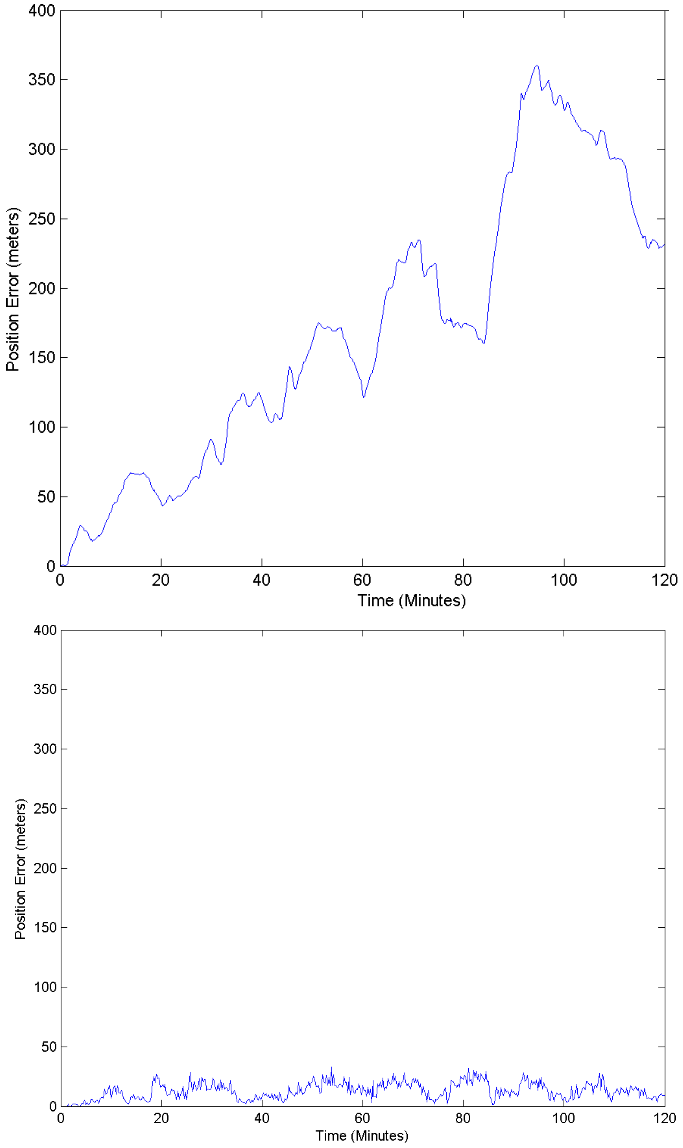

Figure 56 – Error growth over time using traditional dead reckoning (above) and when Radar SLAM is used to calibrate errors and biases in the DR sensors (below).

The combined system results in a 95% accuracy performance that has been shown to be reliably better than about 20m.

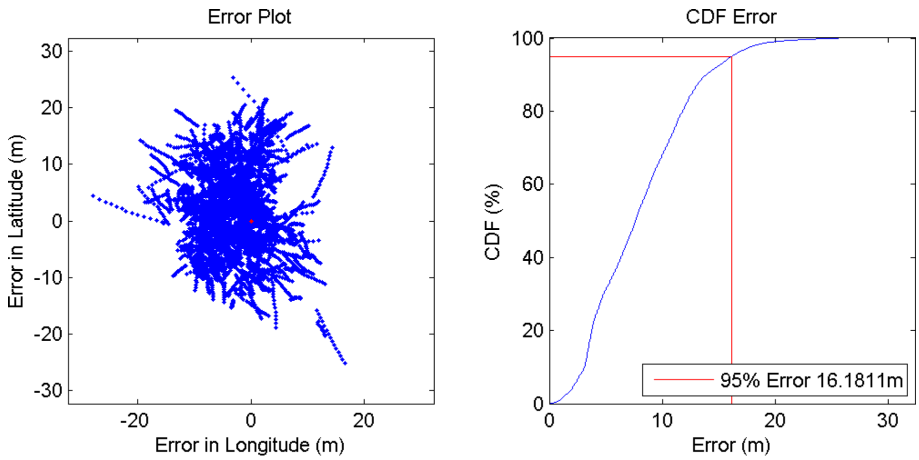

Figure 57 – Error vs. GPS for a combined radar SLAM and DR solution.

So far, this is the most accurate and reliable radar positioning GRAD has been able to achieve. Work is currently under way to get access to the raw data output from the radar itself, and to process this data directly in the radar SLAM algorithm. Use of a processed image captured from the radar screen is probably sub-optimal, as a number of artefacts have been added to the image to aid human interpretation, not least the overlay of other navigation information such as AIS targets. It is thought that an integrated system employing raw radar data, plus log-and-gyro DR should enable resilient position fixing in line with the 10m (95%) Accuracy requirement the IMO has set for electronic position fixing systems [7]. This is what our future research into the technology will investigate.

3 CONCLUSIONS

GRAD has investigated a number of different radar absolute positioning techniques, these are summarised in the table below.

It is envisaged that national maritime authorities may select a mixture of approaches, depending on the most appropriate approach for their waters. Installation of physical hardware, such as e-RACONs may offer a better result for areas of low lying coast with minimal radar features, while the SLAM and DR solution may perform better in areas with sufficient coastal radar returns.

Table 11 – Summary of Radar position-fixing methods investigated by GRAD

Method	Description	Performance	Notes
e-RACON	NT radar obtains range and bearing data from one or more RACONs	4m – 100m	Accuracy depends on how many RACONs are visible, and the crossing angle between them. Potentially a large number of e-RACONS will be needed.
Radar Dead Reckoning Single-image matching	The last radar image is associated with a GPS position, and is used as a reference. Positioning is by image-correlation.	~20m	Accuracy falls sharply as the vessel sails away from reference image and correlation falls. Limited to about half the range of the radar.
Multiple-image matching	Several GNSS-referenced images are laid down and used for image-matching.	<35m	Good for sailing in areas where the ship has already been, and left itself a trail of breadcrumbs to follow.
Conspicuity Mapping	A radar survey of an area is conducted to generate a single authoritative radar conspicuity map of the area. This is then used on the ship for image-matching.	<20m	Requires a lot of survey work. Conspicuity maps may not be compatible between different ships.
Terrain Matching	Uses a terrain database (DTED) to build the conspicuity map by a ray-tracing process.	<100m	Not currently viable for high accuracy positioning. May be improved with better terrain data and 3D models of man-made structures.
DR + SLAM	Integrated speed-log and gyro Dead Reckoning with Radar SLAM.	<20m	It may be possible to improve this technique further by accessing raw data from the radar. We are aiming for <10m Accuracy.

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He holds a Master's degree in Mathematics and Physics from the Durham University and a Master's degree in Navigation Technology from University of Nottingham. He spent time at sea as a navigation cadet with Trinity House before joining GRAD.

S15.2 Radar pulse deinterleaving with domain knowledge based clustering (095)

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ABSTRACT

New radar technologies present new challenges to Racons. Racons need to be more sensitive to pick up weaker radar signals while ignoring interference from stronger ones. The problem of recovering radar signals becomes even more difficult in crowded maritime areas where radar signals overlap with each other. To tackle this issue, we propose a new approach to deinterleave radar pulses based on domain knowledge. Our approach deinterleaves and recovers radar pulses in an unknown maritime environment in real-time without prior knowledge while providing a thorough interpretation of results The effectiveness it is demonstrated by simulations where the approach is tested through scenarios with different levels of radar density and compared to other algorithms. The obtained results show that our approach performs better than other algorithms regardless of the number of radar surrounding the Racon.

KEYWORDS: racons, radar signal, deinterleaving, machine learning, clustering, marine safety

RESUME DE L'ARTICLE

Les nouvelles technologies de radar présentent de nouveaux défis pour les Racons. Ces derniers se doivent d'être plus sensibles pour capter des impulsions de plus faibles puissances tout en ignorant les interférences dues aux impulsions de plus fortes puissances. Le problème de récupération des impulsions devient plus difficile dans les zones de forte densité de navires où les elles s'entrelacent les unes avec les autres. Pour résoudre ce problème, nous proposons une nouvelle approche pour le désentrelacement des impulsions radar basée sur des connaissances métiers. Notre approche désentrelace et récupère les impulsions dans un environnement maritime inconnu en temps réel sans connaissances préalables tout en fournissant une interprétation des résultats. Son efficacité est démontrée par des simulations où l'approche est testée à travers des scénarios avec différents niveaux de densité de radar et comparée à d'autres algorithmes. Les résultats obtenus montrent que notre approche fonctionne mieux que les autres algorithmes, quel que soit le nombre de radars entourant le Racon.

MOTS CLÉS : Racons, signaux radar, désentrelacement, apprentissage automatique, clustering, sécurité maritime

1 INTRODUCTION

Radar transponders known as Racons are marine aids to navigation devices operating in the 2.9-3.2 GHz and 9.3-9.5 GHz band. Racons transmit information to surrounding radars by simulating a return echo. Being safety-related systems, Racon's behaviour must be predictable [1], [2]. Moreover Racon's performance is assessed by its availability: IALA recommends an availability of at least 99.8% [3]. To meet this performance level many challenges arise.

On the one hand, new radar technologies such as Pulse Compression or Frequency Modulated Continuous Wave (FMCW) have emerged. Their radar signature is very different from previous radar technologies, and they emit signals with much less power. While conventional radars emit 25 kW pulses, pulse compression radars, and FMCW radars emit about 100 W and 100 mW, respectively. As a consequence, to meet IALA standards, Racons must be much more sensitive to detect these new technology radars. However, in doing so, the racons will be triggered by the side lobe of the high-power radars. It is therefore necessary to detect low-power emissions while suppressing side-lobe pulses.

On the other hand, it has been shown in [4] that in high radar density environments such as harbours, IALA standards are not met: not all trigger radars, even the most powerful ones, receive a response from Racons, but some receive several.

Thus to tackle this issue, an enhanced management of Racons' response distribution is necessary: Racons need to better understand which radars they have already replied to, while being sensitive enough to respond to low-power radars.

Identifying specific radar among interleaved pulses can be achieved in different ways. First it is possible, as in [5], to measure unintended modulations in the radar signature caused by manufacturing differences in order to obtain the radar fingerprint. Although it is suitable when only short pulses are detected and, cannot be implemented for Racons, which are confronted with various radar technologies with pulse widths ranging from tens of nanoseconds to milliseconds. Another approach is to extract some features of the detected pulse as the pulse's central frequency (f_c), the time of arrival (ToA), the pulse width (PW), the power (G), etc. to construct the Pulse Descriptor Word (PDW). Several approaches, based on PDW can be pursued:

i. Deinterleaving with deep learning
Authors in [6]–[8] use PDW information with deep learning to identify radars with signatures present in a given database. However, the models are trained on a fixed dataset, based on the features of today's radars. Then when the models will encounter radars not included in their training base, their behaviour will not be guaranteed. Also using Generative Adversarial Networks (GAN) to build a more general dataset, as in [9], is unsatisfying since generated synthetic data may not accurately represent the real world. Moreover, deep learning models' black-box nature does not confer the ability to interpret how results are obtained. The lack of transparency is problematic, particularly in such safety-critical applications, where it is essential to understand and certify the model's predictions. Since Racons require greater interpretability to justify their reliability, supervised deep learning is inconvenient for Racons applications.

ii. Deinterleaving with unsupervised machine learning algorithms
Unlike supervised deep learning, some unsupervised machine learning algorithms offer interpretable rules for their results. As an example, algorithms like K-Means, as in [10] are used to cluster radar pulses. Unfortunately it requires knowing in advance the number of clusters to process. Others unsupervised algorithms based on density-based clustering [11], Gaussian model [12], or nonparametric Bayesian model [13] have emerged and are able to identify radars. This paper presents an autonomous approach to deinterleave and identify the radar signal using a domain knowledge-based model that produces user-friendly decisions.

The remainder of this paper is organized as follows: section 2 begins with a description of how radar pulses are processed and introduces traditional deinterleaving strategies. Then our proposed approach is explained in section 0 while section 0 details the simulation process. Section 5 is dedicated to simulations and obtained results. Those results are discussed in section 6. At last, section 7 concludes the paper and presents future work.

2 CLUSTERING ALGORITHMS

In this section, we first present the data with which the algorithms will operate. Then we compare two clustering algorithms: Density-Based Spatial Clustering of Applications with Noise (DBSCAN) and Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN).

2.1 Data Description

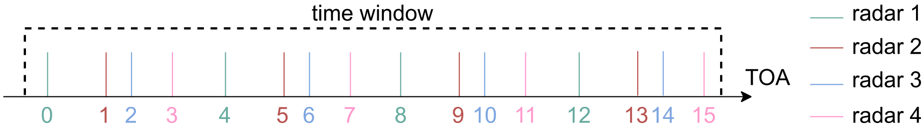

Figure 58: Pulses detected

The Racon extracts the features of pulses present in a given time window (Figure 1) thanks to a frequency discriminator circuit. Then for each detected pulse in the time window as in Figure 1, the Racon defines a pulse descriptor word (PDW) as follows:

$$PDW_{id} = [TOA, G, PW, f_f, f_m, f_b] \ (equation\ 1)$$

Where:

- *id* is the identification number of the PDW
- *ToA* is the time at which the pulse is detected in µs
- *G* is the level with which the pulse is detected in dBm
- *PW* is the pulse width in µs
- f_f, f_m and, f_b are, respectively, the frequency at which the pulse is detected, the frequency at half the pulse width and the end frequency in GHz. These frequency values are measured to determine the linear modulation type.

PDWs from pulses of the same radar have approximately the same set of features. Therefore, as illustrated in Figure 2, PDWs from pulses of the same radar are located in the same dense area. Thus, the study focuses on a density-based clustering algorithm. Figure 2 depicts the detected PDW of 5 different radars in the (G, f_f) plane. Among those radars, radars 0 and 2 are conventional radars, radar 1 is an FMCW radar, and radars 3 and 4 are pulse compression ones. Simulations made are more detailed in section 0.

2.2 Density-Based Spatial Clustering of Applications with Noise (DBSCAN)

DBSCAN is an unsupervised clustering algorithm that does not require prior knowledge of any dataset. It groups data that are located within the same dense area. In order to define a dense area surrounding a point, DBSCAN requires two parameters: the core distance ε and the minimum number of points *MinPts* within ε required to be considered as a core point.

As depicted in Figure 3, DBSCAN defines three kinds of data points to build clusters:

- The core point: a point that has at least MinPts points within ε
- The border point: a point reachable from a core point but which has fewer neighbours than MinPts within its core-distance ε
- The noise points are neither core points nor border points

DBSCAN starts by selecting an arbitrary point and finding all of the points within ε. If the number of points is greater than or equal to MinPts, the point is considered as a core point, a new cluster is formed, and all of the points within the ε are added to the cluster. The algorithm then repeats the process for all of the core points in the created cluster until all added are border point. If a point is not within ε of any core point, then it is classified as a noise point and ignored. In our use case, DBSCAN clusters PDWs in the same dense area with the given, *MinPts* and ε parameters.

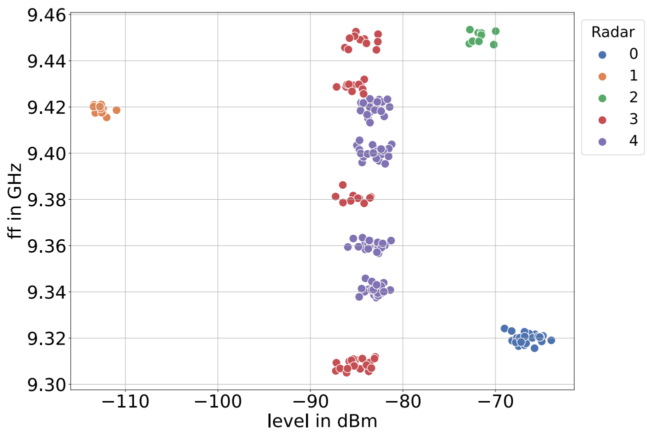

Figure 59: PDW representation in the (G, f_f) plan

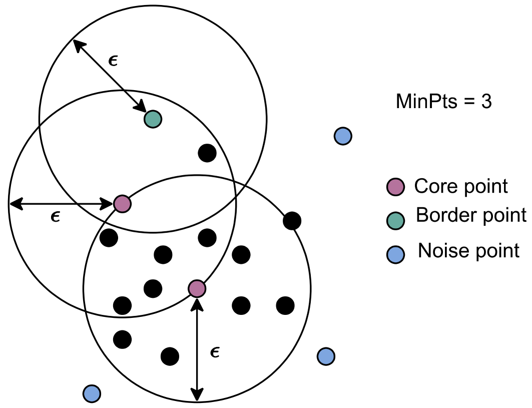

Figure 60: Description of DBSCAN algorithm

2.3 Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN)

Nevertheless, a core-distance ε for DBSCAN can be hard to tune: if too small, everything will be considered as noise; if too large different clusters will be merged together and even noise could be considered as a cluster. To tackle this issue, HDBSCAN, uses hierarchical density to cluster data. It relies on the Mutual Reachibility Distance (MRD) between points to cluster data. The MRD is evaluated between two points. It gets the maximum distance between the core distance of both points and their mutual distance. HDBSCAN requires two parameters: MinPts which as for DBSCAN is the minimum number of points in its neighbourhood to be considered as a core point and MinClusterSize the minimum size of a cluster. A stability criterion is used to keep only the cluster of higher density [11]. Table 1 summarises the advantages and disadvantages of these two approaches.

To sum up, setting ε and *MinPts* values for DBSCAN clustering is challenging and is usually done empirically. HDBSCAN deals with this issue through its hierarchical clustering. It uses a stability criterion to extract the clusters. Also to evaluate the distance between PDWs, both of those algorithms standardize the data in order to use the Euclidean distance.

3 PROPOSED APPROACH

Our proposed approach deals with the challenge of setting the clusters, without standardizing the data, with parameters relying solely on domain knowledge. In order to propose an interpretable and efficient solution, we propose a binary similarity criterion based on domain knowledge approximating the role of the ε value in DBSCAN. This binary similarity criterion $\varepsilon_{features}$, is defined as follows:

$$\varepsilon_{features} = [c_G \quad c_{PW} \quad c_{ff} \quad c_{fm} \quad c_{fb}]$$

Where:

- c_G the Racon sensitivity measuring the level with which the pulse is detected in dBm
- c_{PW} the Racon sensitivity measuring the pulse width in µs
- c_{ff}, c_{fm}, and c_{fb} the Racon sensitivity measuring the different frequencies in GHz

The values of $\varepsilon_{features}$ are set according to the Racon's sensitivity. They are therefore completely predictable. Once those thresholds are set, they are used to evaluate the similarity between PDWs. Two PDWs are considered similar when the differences between their respective features are lower than their respective thresholds defined in $\varepsilon_{features}$. Our approach is referred as *DBSCAN racon* in the rest of the paper.

Table 1: Advantages and disadvantages of DBSCAN and HDBSCAN clustering algorithms

	DBSCAN	HDBSCAN
Advantages	• Does not require to specify cluster number • Has a notion of noise • Results are easy to interpret • Complexity of o(nlog(n)) with n the number of PDW [14]	• Does not require to specify cluster number • Has a notion of noise • Deals with clusters of varying density • Complexity of o(nlog(n)) with n the number of PDW [15]
Disadvantages	• Sensitive to the chosen ε value • Data has to be standardize	• Data has to be standardized • Requires many more steps than DBSCAN and thus increases its computation time • The stability criterion is fixed through unsupervised techniques and thus cannot be monitored.

4 SIMULATION DESCRIPTION

Since labeled real data were not accessible, simulations are used to demonstrate the effectiveness of the approach.

4.1 Data generation

A simulator has been developed to generate PDWs from pulse radars, compressed pulse radars, and FMCW radars. Pulse radar and FMCW radar emit pulses (Figure 4) with a fixed pulse repetition frequency (PRI), while compressed pulse radar emits a batch of different pulses (Figure 5) with a staggered PRI. Based on the International Maritime Organisation standards for civil maritime radars emissions [16], technical report [17], datasheets [18]–[24] and AMG Microwave expertise, data generation rules have been set and are presented in Table 2. Only pulses from the main lobe are generated, Gaussian noise is added to the PDWs' measurements, and sea clutter is not considered [24]. In the simulation, radar pulses are in the form of PDW, as defined in equation (1). The technical report allowed us to construct ranges of values for each PDW's feature. A random error is added to each of them. These errors follow a normal distribution with a standard deviation specific to each feature.

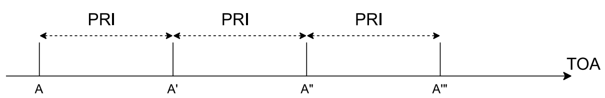

Figure 61: Emission from a pulse radar or a FMCW radar

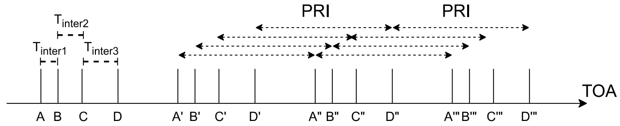

Figure 62: Emission from a compressed pulse radar

4.2 Scenario setup

To ensure the presence of interleaved radar signals in the time window, simulations are done over a time window of 30 ms. This time window corresponds to the duration of a main lobe in the sight of Racons. Simulations with 2 to 90 radars in the time window are performed. Each time window configuration is simulated 100 times. Radars are either pulse radars, FMCW radars or pulse compression radars. Our approach is compared with DBSCAN's configuration with different value of ε. Standardization has been done on the input data of the DBSCAN and HDBSCAN algorithms.

Table 2: Data generation criteria

Criteria	Condition
Feature invariance criteria	A civilian radar always transmits pulses or batch of pulses with the same features
Level invariance criteria	Pulses emitted by the same radar are detected with an equivalent power
PRI criteria	There is a constant time difference between two pulses with the same features from the same radar
Inter-pulse criteria	There is a minimum and a maximum time between two consecutive pulses of a staggered PRI radar
Pulse redundancy criteria	Pulses emitted by radar will be detected several times by the Racon

4.3 Evaluation metrics

Since the reconstruction of the Racon's environment is unsupervised, metrics related to classification cannot be used as in [25]. Therefore, we use the homogeneity scores, the completeness scores, and the Rand index as in [26], [27] to evaluate our unsupervised model. Homogeneity will measure the similarity of radar emitter between the PDW clustered together. Completeness will measure the success of the algorithm in clustering all PDW coming from the same radar together. They both use Shannon's entropy. Let C and K be, respectively, the ground truth cluster and the predicted clusters after aggregation. Homogeneity and completeness are defined in equations (2) and (3). A homogeneity score of 1 indicates that cluster K contains only PDWs from one radar. A completeness score of 1 indicates that all the PDW of cluster C are included in cluster K.

$$homogeneity = 1 - \frac{H(C|K)}{H(C)}\ (equation\ 2) \qquad completeness = 1 - \frac{H(K|C)}{H(K)}\ (equation\ 3)$$

Regarding the Rand index score, denoted by RI, it assesses the similarity between the created clusters and the ground truth. It is also equal to the rate of correct decisions made by our algorithms. Let TP and TN be, respectively, the number of true positives and the number of true negatives. FP and FN are the number of false positives and the number of false negatives. Formally, the Rand index score is defined as follows:

$$RI = \frac{TP + TN}{TP + FP + FN + TN}\ (equation\ 4)$$

5 SIMULATION RESULTS

According to metrics defined in 4.3, Figure 6 shows simulation results of various clustering algorithms for different numbers of radars in a 30 ms time window. As depicted in Figure 6.a, most algorithms have a completeness score higher than 90% no matter how many radars are in the time window. The DBSCAN algorithm with an ε of 0.2 has the lowest completeness score as it creates a cluster with fewer pulses, which are therefore less complete but more homogeneous. That is not the case with an ε of 0.1, since all pulses are considered noise and form a unique cluster. Consequently, the created created cluster is complete but not homogeneous. As illustrated in Figure 6.b, algorithms with larger ε are less homogeneous as the time window gets increasingly crowded: since they create larger clusters containing pulses with distinct features. As a result, they are less homogeneous. Then Figure 6.c shows a performance collapse in the Rand index for most algorithms when there are more than 10 radars in the time window. Only the DBSCAN racon algorithm as a Rand index of more than 70% when there is more than 20 radar in the time window.

Finally, the DBSCAN racon exceeds the performance of HDBSCAN and DBSCAN algorithms with fix ε. Its homogeneity score is higher than 90% when there are less than 20 radars in the time window. HDBSCAN and DBSCAN algorithms with a fix ε may have a higher completeness score, but their Rand index are always lower than 70% and collapse when there are more than 20 radars.

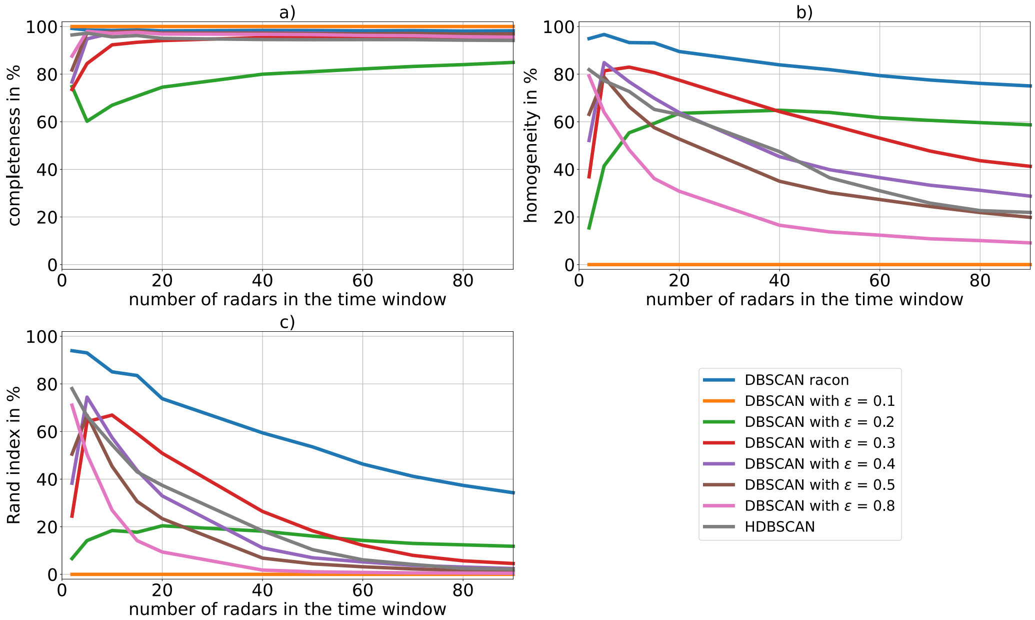

Figure 63: Simulations results for different metrics: a) Completeness, b) Homogeneity, and c) Rand Index

6 DISCUSSION

DBSCAN racon can cluster pulses according to their features. It autonomously distinguishes between pulses with different features. In the simulation, since the time window was crowded, only the main lobes of the radars were presented. Indeed, a side lobe has the same characteristics as a main lobe but is detected with much less power. Therefore, the side lobes can be considered, at this stage, as additional radars. Thus to suppress side lobes, it would be possible to determine the mean features of the created clusters and remove those with less power.

However, the current approach is limited in its ability to reconstruct the signature of every radar technology. For instance, while conventional radar have signatures with a single type of feature configuration, pulse compression radar and FMCW radar signatures change according to the area scanned by the radar. As a result, the created clusters only contain pulses with a single type of feature configuration, which means that pulses from a conventional radar will be represented by one cluster, whereas pulses from a pulse compression radar or an FMCW radar will be represented by several clusters. To reconstruct the radar signature of pulse compression radar and FMCW radar, a more detailed study of the Time of Arrival (ToA) is necessary. Indeed, despite the fact that pulses from the same batch may have different features, their ToA on the Racon is relatively close.

Once this is completed, the remains issue of radar from the same manufacturers' reference range remains. If several radars from the same manufacturers' reference range in the Racon's environment, their detected pulses will be contained in the same clusters. Therefore one cluster may represent multiple radars having identical features. To address this issue, another kind of in-depth study on the ToA has to be done. Pulses emitted by the same radar will be contained in the same cluster. However pulses are emitted with a periodic pattern. This pattern has to be found in the created cluster to differentiate pulses with the same features but coming from different radars.

7 CONCLUSION

In this article, radar pulses are detected and deinterleaved with a clustering algorithm based on domain knowledge in an interpretable and explainable way without any training stage. When less than 20 pulses signature is detected in a time window of 30 ms, homogeneity and completeness scores of more than 90% and a Rand index of 70% are achieved. The approach is able to deinterleaved radar pulses.

Also, since the proposed approach builds as many clusters as there are sets of pulse features, it is possible to extract from the created clusters the signature of conventional radar. As far as pulse compression radar and FMCW radar, because they emit pulses with a different signature, they are represented by several clusters. Therefore more work has to be done to obtain their full signature.

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AUTHOR BIOGRAPHY

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S15.3 Development and application of "NT" Racon (039)

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ABSTRACT

With the continuous development of radar solid-state transmitter technology, Solid state radar navigation is gradually used by ships. However, due to the Convention, regulations, technology, price and other reasons, many ships still use magnetron radar, which makes the new technology (“NT”) radar and magnetron radar co-exist in a certain period of time in the future. Racon needs to adapt to the development of radar technology.

A new Racon has been developed in China, which can respond to both new radar system and traditional radar systems. But the launch mechanism of magnetron radar is different from that of Solid-state Radar. Even solid-state radar has solid-state pulse system and solid-state continuous wave radar. What is the performance of the newly developed Racon? This paper presents the actual test results of response and sidelobe suppression of different radars system in several scenes. The test results show that for radars with different working mechanisms and performance parameters, the range and sidelobe suppression effect of Racon in X / S band are also different, which leads to our thinking and suggestions on the use of Racon and continuous improvement of products. It is suggested that IALA should further discuss this and coordinate it in IMO, ITU and IEC as appropriate.

(No paper submitted)

AUTHOR BIOGRAPHY

Jianyun Yang has a bachelor’s degree in Automatic control. Since 1987 Her entire career has been in engineering, designing and researching of aids to navigation. She has been engaged in the design of navigation aids products in Shanghai Navigation Aids Factory for 14 years, and then engaged in the design and aids to navigation engineering System in CCCC Shanghai Waterway Engineering Design and Consulting Co., Ltd for 22 years. Jianyun Yang is a member of national working groups dealing with development and standardization of integrated AtoN systems. She is focused on product designand product development of marine aids to navigation (including racons) as well as providing complex marine aids to navigation projects proposals and technical support. Jianyun’s participation in large-scale projects such as Yangtze Estuary Deepwater Channel Regulation Project, Yangshan Port Project, Hong Kong-Zhuhai-Macao Bridge Project, etc., won the gold medal of China's national design.

S15.4 Modern Racons for use with Modern Solid-state Radars (158)

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ABSTRACT

Modern solid-state radars use modulation techniques that can confuse existing racons, especially in busy areas. There is a need for the development of modern racons that can work with modern solid-state radars and improve performance in busy areas.

In addition, the reliance of on Global Navigation Satellite Systems (GNSS) and their vulnerabilities are well known. The need for GNSS independent positioning capability is also widely recognized and there is an opportunity to use modernized radar and racons in this regard.

A system known as Enhanced Radar Positioning System (ERPS) uses specially designed racons (eRacons) with specially designed radars (eRadars) to allow radars to automatically calculate their absolute position. In this system, eRacons provide their surveyed absolute position encoded on their response signals to eRadars, which use these signals, along with measured range and bearing, to calculate their own vessels' absolute positions. The system is independent from GNSS. This system is simple to implement on modern radars and racons and should be included in any modern racon discussion.

This paper discusses the need for standardization of racon and radar features that are needed to allow the further development of ERPS and modern racons. Standardization is needed to assure the future use of racons.

KEYWORDS: racon, radar, ERPS, resilient PNT

1 INTRODUCTION

At some point in time, the type of racons installed today will no longer be usable. Eventually, modern marine radars will replace the traditional magnetron radars in common use today. This paper focuses on radars and racons in the 9400 MHz band, as they are most useful for close-in, port, harbour, berthing and inland waterway operations. Radars and racons in the 3000 MHz band have similar issues and solutions but are not discussed specifically. A modern radar is one that uses a solid-state transmitter, modulated to give best performance[1]. The purpose of this paper is to offer a way forward for continued use of racons.

Every evolution and change in technology has the potential to introduce new challenges and issues, over and above those it resolves. Some technical challenges are introduced in Section 2, while

Section 3 discusses regulatory issues, including the International Maritime Organization (IMO) call for more resilience in Positioning, Navigation and Timing (PNT) systems and how radars and racons contribute to higher resilience.

Section 4 discusses using radar for automatic absolute positioning. Two systems are introduced, Enhanced Racon Positioning System (ERPS) and radar terrain matching.

2 TECHNICAL CHALLENGES

This section illustrates technical challenges in three areas:

- racon side lobe suppression – this is an important racon feature to help prevent false triggering of the racon and confusing radar displays; racons are useless without this feature

[1] Compare to traditional radar with magnetron vacuum tube transmitter and pulse modulation.

- range limitations using solid-state radars – such transmitters operate at lower transmitted power than traditional magnetron transmitters which reduces the detection range of the racon
- modulation used by modern radars – current racons expect pulse modulation and there are no set standards for the modulation employed

2.1 Racon Side Lobe Suppression

Side Lobe Suppression (SLS) is a required feature for racons. The term "side lobe" refers to any signal lobe of a non-ideal radar antenna that is not the "main lobe". The main lobe signal is used by the radar for ranging. The purpose of SLS is to prevent the racon from transmitting to any signal but the main lobe from the radar antenna. The reason it is needed is the combination of powerful radar transmitter, non-ideal radar antenna and sensitive racon receiver can result in a signal that the racon can respond to when the radar antenna is pointing away from the racon. In some cases of close-in operation, a racon without SLS can respond to nearly every pulse of the radar[2].

SLS works by measuring the signal strength of the transmission from a radar and only responding to the most powerful received signals from that radar. Individual radars are identified by various methods, including frequency, pulse width and radar antenna sweep period.

Figure 1 shows radar signals captured during an interval of time. There appear to be three radars operating here. The more obvious is the radar with an antenna period of about 2.6 seconds and peak amplitude about -34 dBm. There also appears to be two other radars – one at a period of about 2 seconds with amplitude of about -30 dBm, the other at about 4.5 seconds period and -23 dBm amplitude. In this case, SLS would block the 2.6 and 2 second period radars because the 4.5 second period radar has a higher amplitude.

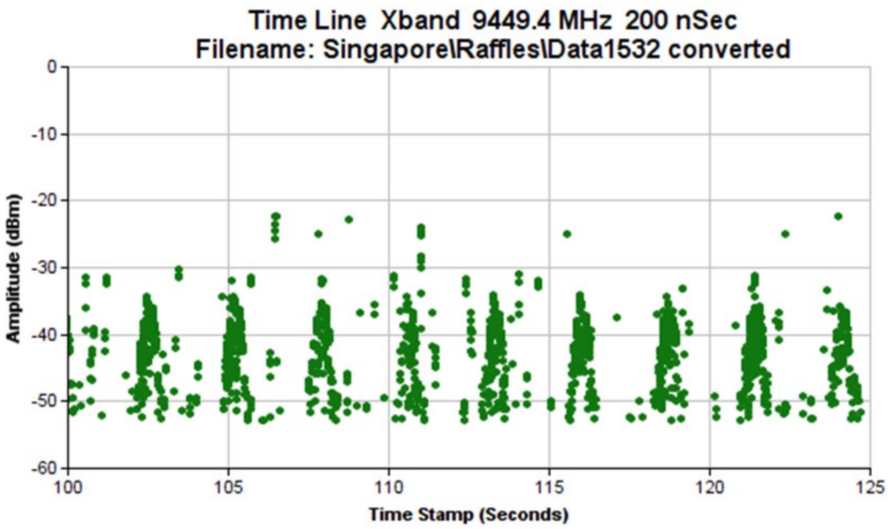

Figure 64 Radar Signals over an Interval of Time

2.1.1 Radars in Busy Harbours

There has been anecdotal evidence of poor performance of racons in busy harbours. Some radars see racons intermittently or not at all. This was studied in the port of Singapore in 2017. Please see "On Racons in Busy

[2] A racon without SLS is more of a radar jammer than a useful aid to navigation.

Harbours" [1]. Radar traffic was monitored by measuring radar pulse frequency and pulse width along with a time stamp. Figures 1, 2 and 3 are taken from the Singapore study report. The study showed that most problems are related to SLS and are caused by many radars transmitting at the same frequency. This was not unexpected, knowing that many radar magnetron devices are manufactured to the same frequency. Figure 2 shows a map of radar frequencies and pulse widths over for an interval of time. The clumping of radar frequencies is apparent.

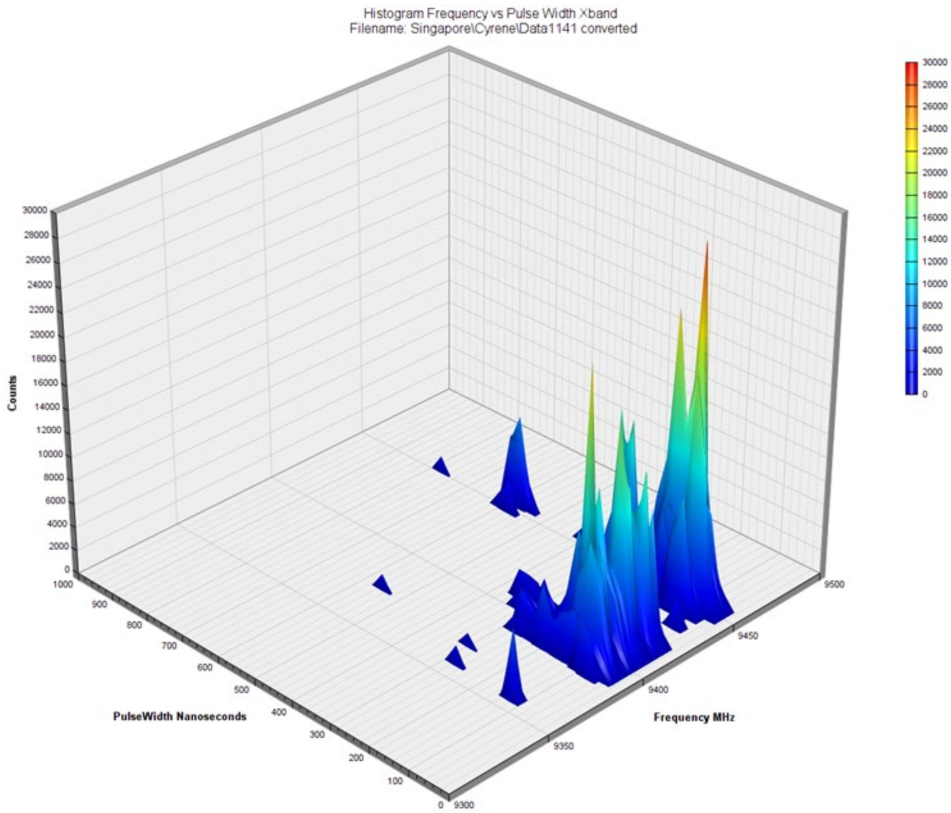

Figure 65 3-D Histogram of Radar Frequencies

Figure 3 shows a slice through Figure 2 at one pulse width.

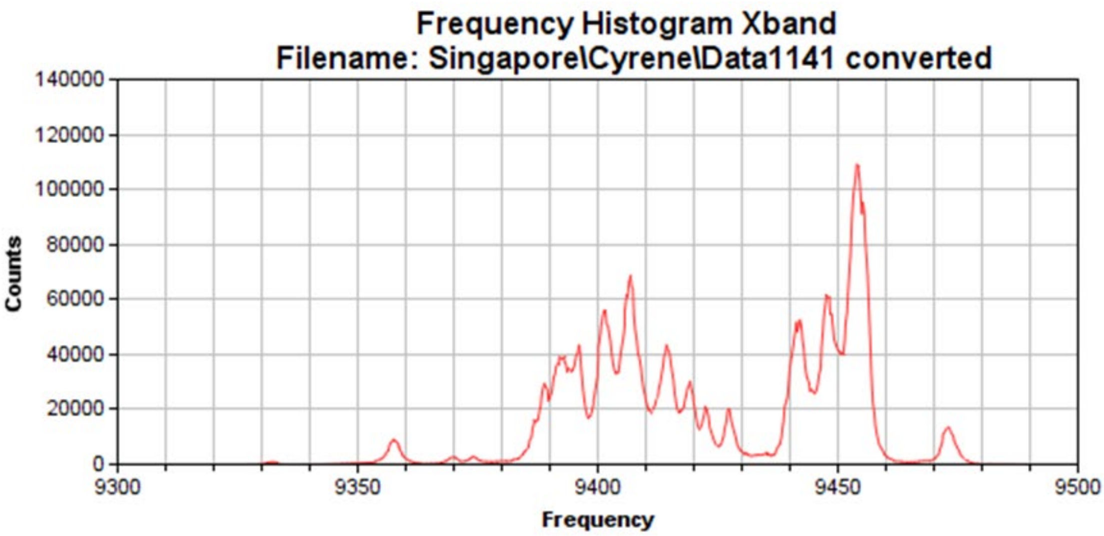

Figure 66 Frequency Histogram at One Pulse Width

These figures show that many racons are broadcasting on the same frequency, which means that while one vessel's radar may trigger the racon, other vessels with a radar that looks similar in the radio frequency domain, do not trigger the racon, and therefore do not get the use of that AtoN.

2.1.2 Gets Worse with Solid-State Radars

Most magnetrons are delivered to a radar manufacturer at a specified nominal frequency, with many using the same design. The manufacturer may have bought tens of thousands at the same nominal frequency which are installed in radars all over the world. The frequency peak shown in the figure above has been verified by Furuno to be the frequency they specify. SLS works, though poorly, because manufacturing tolerances spreads the actual frequency of the magnetron so that they are not all on the exact same frequency.

Consider that solid-state transmitters can be set to an exact frequency. The worst case is all radars, from all manufacturers, are set to the same frequency. In a busy harbour (or anywhere there are multiple radars operating) only one radar will be serviced by the racon due to SLS. The solution is for the manufacturers to set each radar transmitter to a different frequency.

2.1.3 The 9400 MHz Band

IMO "*Resolution MC/192(79) Adoption of the Revised Performance Standards for Radars*" [2] and International Telecommunication Union (ITU) "*Recommendation ITU-R M.824-4*" [3] recognize the full marine radar band to range from 9200 to 9500MHz. The addition to the band of 9200 to 9300 MHz was made many years ago. To the authors' knowledge, there are no marine radars operating in 9200 MHz part of the band. Likewise, the authors know of no racon servicing the 9200 MHz part of the band. Radar and racon manufacturers need to agree on whether to use the full band, or not.

2.2 Range Limitations Using Solid-State Radars

Solid-state radars transmit at lower power than magnetron radars. This reduces the signal strength at the racon antenna, which reduces the detection range of the racon. The actual reduction can be quite a large value, but the practical result may not be that bad.

In 2009 the General Lighthouse Authorities of UK and Ireland (GLA) conducted a trial onboard the Irish Lights vessel Granuaile comparing the performance of a solid-state radar to a magnetron radar. The trial report, "*Second Racon Trials with NT Radar*" [4] concluded that the solid-state radar did have a reduced range, as expected. The GLA data indicate that:

1) Range reduction severely limits the usability of racons for land fall; range is reduced to less than radio horizon
2) In port and harbour operation, radio horizon is quite close, especially when racons are mounted to buoys; detection range for racons with lower receiver sensitivity may be less than radio horizon; detection range for racons with higher receiver sensitivity may be as far as radio horizon

One conclusion is that racons with higher receiver sensitivity can perform adequately with solid-state radars in port and harbour operations.

2.3 Radar Modulation

There are no standards for the modulation that radars can use. Each manufacturer may choose the modulation they think best and have no desire to publish details of their intellectual property. This is a difficult environment for racon manufacturers.

One racon manufacturer appears to have reverse engineered the modulation from at least one radar and claims to respond to that and similar radars. There was a trial sponsored by China Maritime Safety Administration [5] with a different manufacturer that showed a racon working with a modern radar.

However, these solutions are in precarious positions, dependent on the whims of the radar manufacturers. What works today, may not work tomorrow. Clearly, some form of standardisation is required to ensure interoperability between the different racon and radar manufacturers.

2.4 The Way Forward – Standardisation

The move to solid-state radar technology has the potential to limit the performance of racons. There needs to be a coordinated approach to future radar operating conditions. The authors suggest radar and racon manufacturers initially take a voluntary approach to managing the spectrum. Contact between IALA and Comité International Radio-Maritime (CIRM) levels has been initiated. To recap, the following are basic issues to address:

1) Frequency usage – at what frequencies within the band will radars operate; what diversity in transmission frequency can be provided
2) How to signal racon – what modulations should racons expect
3) How racons should respond – what modulations should racons use

3 REGULATORY ISSUES

3.1 Resilient PNT

GNSS has been widely recognised as the primary Position, Navigation and Timing (PNT) data source. However, its vulnerabilities, which could lead to GNSS outage or provision of erroneous PNT information and make GNSS dependent navigation systems unable to provide the expected performance, have been identified. IMO, in its "MSC.1/Circ.1595 *eNavigation Strategy Implementation Plan"* [6] identified and captured the risk as one of the Risk Control Options (RCO 5) "Improved reliability and resilience of on-board PNT systems". To achieve resilience in PNT service provision, it is necessary to put in place a back-up or fall-back arrangements utilising alternative techniques that do not share the failure modes of GNSS. In the case of GNSS outage or malfunction, the alternative system can provide PNT services.

Radar has traditionally been used as a resilient relative positioning system. When used with fixed, known absolute position targets, a fair absolute position solution for a vessel can be manually calculated. The use of racons can aid the radar operator in the identification of fixed targets.

IALA "*Recommendation R1017 Resilient Position Navigation and Timing (PNT)*" [7] and "*Recommendation R0129 GNSS Vulnerability and Mitigation Measures*" [8] discuss resilient PNT.

3.2 IMO Carriage Requirements

IMO "*Resolution MSC.192(79) Revised Recommendation on Performance Standards for Radar Equipment*" require 9400 MHz radars to trigger and display racons, search and rescue transponders (SART) and radar target enhancers (RTE) [3]. With currently installed racons, modern radars might be unusable to satisfy this requirement because of modulation incompatibilities.

[3] SARTs and RTEs may have similar issues as racons. They are not discussed in this paper.

3.3 Radar and Racon Standards

There are no existing radar and racon interoperability standards. IMO "*Resolution A.615(15) Radar Beacons and Transponders*" [9] and *ITU-R M.824-4* are recommendations on what should happen, not how it should be done. The path to modern racons will require radar and racon standards to ensure interoperability. Modulation standards are needed to *allow* and *enable* interoperability.

3.4 Where to Start?

In 2021 IALA held a workshop to discuss Enhanced Radar Positioning Systems (ERPS is discussed in Chapter 4). Please see "*Workshop Report IALA Workshop on Enhanced Radar Positioning System Standardization*" [10]; many of the suggestions from the workshop regarding standardisation apply directly to the problems of modern racons.

4 AUTOMATIC RADAR ABSOLUTE POSITIONING SYSTEMS

As stated earlier in section 3.1, radar data can be used by a navigator to manually calculate the absolute position of the vessel. This is not a difficult calculation, but tedious and error prone to do manually. And the solution may be out of date before it can be used. Having the radar do the calculation automatically is an attractive and somewhat obvious solution. But a radar lacks absolute position references, which must be provided by some other party.

A system known as Enhanced Radar Positioning System (ERPS) uses specially designed racons (eRacons) with specially designed radars (eRadars) to allow radars to automatically calculate their absolute position. The system is independent from GNSS and can be considered as a resilient PNT solution per IMO. ERPS is a backup to GNSS. Please see IALA "*Guideline G1147 The Use of Enhanced Radar Positioning Systems*" [11]. This system is simple to implement on modern radars and racons and should be included in any modern racon discussion.

ERPS has been developed over many years and through several collaborative projects, including EU EfficienSea and ACCSEAS programs. These projects, along with additional development sponsored by the Maritime and Port Authority of Singapore, have demonstrated the concept works and that performance with accuracies of 27 meters can be achieved, recognising that this is affected by geometry and the number of eRacons in view.

It is interesting to note that ERPS does not require a modern radar as defined above. Any radar with digital or software defined receiver can be modified to use EPRS.

4.1 Description

ERPS is rather simple in concept and execution. eRacons provide their surveyed absolute position encoded on their response signals to eRadar interrogations, eRadars use these signals, along with their own measured range and bearing, to calculate their own vessels' absolute positions. At least two eRacons are needed to get position solution.

If the eRadar can also use the vessel's heading (compass), position solutions can be calculated using only one eRacon. Figure 4 illustrates ERPS:

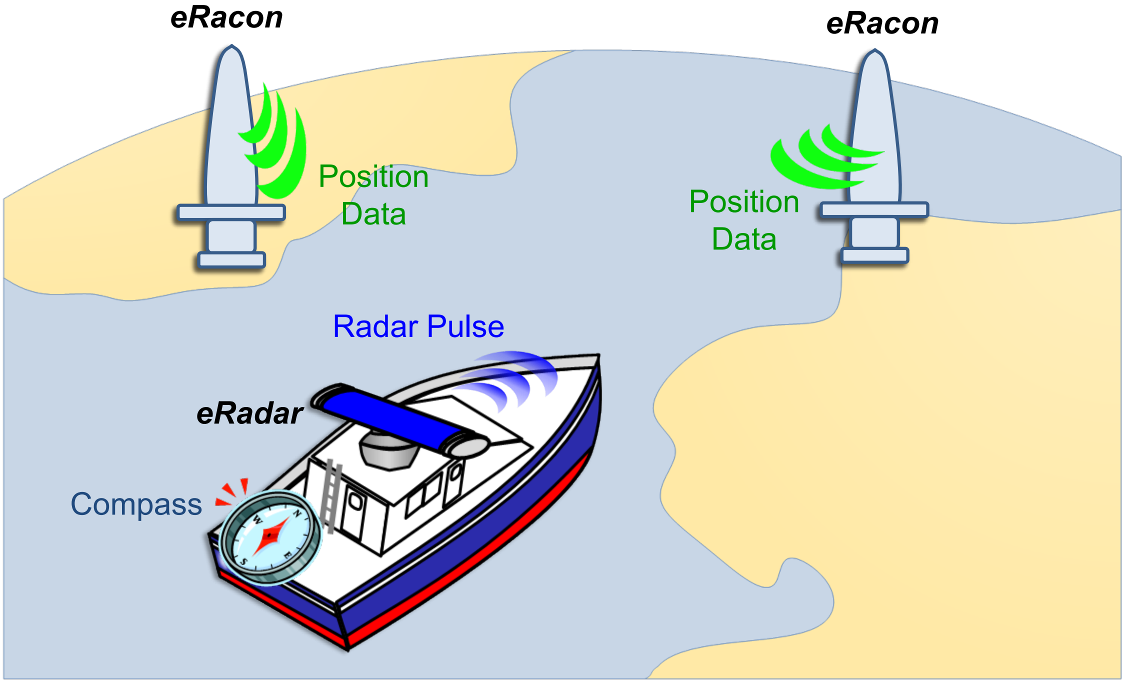

Figure 67 Enhanced Radar Positioning System

4.2 Map Matching

Terrain Matching is an alternative approach to absolute position determination using radar data. There are a number of potential approaches as discussed in [12], but the general concept is that the radar matches measured terrain features to a database of features and calculates absolute positions. This technique is a candidate for resilient positioning.

Although the technique does not necessarily require racons, racons can be included in terrain features databases and may be required where there are insufficient radar returns, for example in areas of low-lying coastline.

The two approaches are compatible and could be considered within the same standardisation process.

4.3 Regulatory Issues – Resilient PNT

The IMO, during the development of its e-Navigation SIP, recognised the need for resilient Positioning, Navigation and Timing. Vessels generally obtain their absolute positions from Global Navigation Satellite Systems (GNSS) which have known common vulnerabilities, and as such, the IMO support the use of multiple, dissimilar systems.

At the same time, radar is mandatory carriage on larger vessels and is typically fitted to most craft. Therefore, making use of this evolving technology is advantageous to the overall business case and supports its introduction.

Recognising that the ERPS concept may evolve further and has the potential to include the use of computational advances such as terrain database matching, the use of radar to support resilient PNT at sea is a beneficial and optimistic development.

4.4 Adoption

Adoption requires support from the radar and racon manufacturers.

Much standardization work needs to be done. IMO MSC.192(79) specifically allows radars to use other signals from racons. ITU radar performance M.824-4 may need to be updated. Other ITU radio regulations and documents may need to change to allow racons to transmit location information.

The IALA Workshop on ERPS mentioned in Section 3.4 was a good start at identifying the work to do.

5 CONCLUSIONS

The vessel's radar is a significant navigation aid, its evolution path to solid-state technology brings potential benefits through reduced power and the ability to provide data encoding to support resilient PNT, but there's a need to standardize the approach, to aid system interoperability and performance, and to support efficient management of the spectrum.

Automatic position determination is very attractive and seems to be easily added to radars and racons.

The authors invite IALA to hold a second ERPS workshop to further the work on modern racons. Attendance of radar and racon manufacturers would be extremely beneficial.

6 ACKNOWLEDMENTS

The authors wish to acknowledge Liu Chunhai for his review of this paper and acknowledge the many others who have contributed ideas and suggestions over the years.

The authors also wish to acknowledge the contributions of the Danish Maritime Administration, the General Lighthouse Authorities of United Kingdom and Ireland, the Maritime and Port Authority of Singapore, Furuno Electric and Tideland Signal to the extensive work done to develop ERPS.

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AUTHOR BIOGRAPHY

Paul Mueller earned his Bachelor's degree in Physics from Ithaca College in 1978. Since then, his entire career has involved engineering. He has designed electronic scientific and industrial instrumentation and control systems, including an automobile tire testing (tire abusing) machine, a golf swing analyzer and variable speed AC motor drives. He also designs marine aids to navigation, including remote monitoring systems, racons, optics, and structures in marine environments. Many may know Paul from his 30 years at Tideland Signal. Currently, he is the Chief Engineer for both Orion Maritime Systems, Singapore and Half-PI Electronic Product

Development, Texas, USA. The latter he co-owns with his spouse Dawn (Managing Director). Paul serves on the board of directors for the Arc of Spring Branch – Memorial, a membership organization providing social growth and athletic opportunities for people with intellectual and developmental disabilities. He also volunteers with Special Olympics and enjoys woodworking.

S15.5 Passive radar reflectors for use on AtoNs: Theoretical basics and ways for application oriented selection of a suitable radar reflector (141)

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ABSTRACT

In the 1970's, intensive investigations were carried out by several waterways- and shipping administrations in the field of radar reflectors used on AtoNs. At the 10th Conference of IALA, held in Tokyo in 1980, the German Federal Waterways- and Shipping Administration presented the results of the investigations. Thereafter, helpful, mostly technical reports were published that included specifications of radar reflectors as well as methods to calculate basic parameters, e.g. the maximum range of detection. For about 40 years, this work formed the design and use of radar reflectors on AtoNs. However, this great work was limited by the technical possibilities of the time. Not all questions could be answered and new questions were raised, for example, how to use radar reflectors inside a plastic buoy. Today, new, powerful technologies are available, especially in the field of numerical simulation of electromagnetic fields and waves. This opens up the possibility of taking a different, "modern" look at radar reflectors. What has not changed after so many years of using radar reflectors on AtoNs is the need for their use. They are still indispensable for supporting the navigation of ships with radar. The use of radar reflectors increases the probability of radar detection of an object by increasing the intensity of the backscattered radar wave and makes the reflection properties reproducible and measurable. The correct selection and evaluation of a radar reflector for an AtoN is often a difficult task. In addition to the radar-relevant properties, mechanical, design and operational aspects should be taken into account. From a global perspective, many different radar reflectors are used in the field of AtoNs. During the preparation of an IALA guideline on radar reflectors in the past working period of the ENG Committee, the most frequently used different types were identified. Their reflection properties and applications were investigated, evaluated and clearly worked out.

The presentation shows the necessary steps for the selection, dimensioning and evaluation of suitable radar reflectors for AtoNs. Furthermore, it describes

- applicable international requirements and standards;
- theoretical basics of radar waves and their reflection;
- task, function and parameters of radar reflectors;
- basics for the design of the reflection behaviour;
- possibilities for range calculations and applicable examples;
- measurement methods of reflection properties and their on-site verification;
- simulation procedures as well as their practical use;
- effects of surrounding materials, e. g. plastic; and
- an overview of radar reflectors used in practice including their properties.

Also non-radar specific requirements such as environmental conditions, construction and installation methods and maintenance requirements are presented.

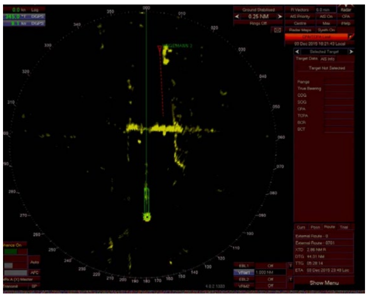
KEYWORDS: RADAR, AtoN, reflection pattern, range, simulation, measurement, selection

1 INTRODUCTION

1.1 Navigational Radar

Radar is the abbreviation for = Radio Detection and Ranging. Navigational radar equipment plays an important role for the safe navigation of vessels.

- It provides reliable, safety related traffic information.
- It enables the surveillance of the traffic situation around the vessel, including
  - Landmarks,
  - Other vessels and
  - Marine Aids to Navigation (AtoN).



It has the capability to detect objects even in poor visibility conditions such as

- Darkness,
- Fog and, with some restrictions,
- Even in heavy precipitation, snow or hail.

<u>The big advantage is, that it can detect objects which are not equipped with radar systems themselves.</u>

1.2 Radar Reflectors: Task and Function

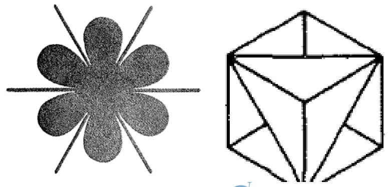
The probability of detection of an object by radar is highly dependent on the magnitude of the reflected radar wave. Not all objects reflect with the same intensity. The reflection behaviour depends on the geometry, dimension, material properties and surface roughness. Large structures, such as big vessels, typically made of steel, are well suited for detection by radar (metal = good conductor). Other objects, especially when made of non-metallic materials such as plastic, do not reflect the radar wave as well.

Radar reflectors are optimized to reflect the incident radar wave back to the radar with the highest possible intensity. They have a defined reflection behaviour over a certain range of spatial angles.

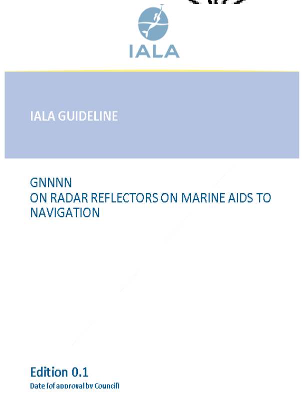
By equipping AtoN with radar reflectors, the radar reflectivity properties become consistent, measurable and comparable.

2 THE NEW IALA GUIDELINE ON PASSIVE RADAR REFLECTORS

During the 10th IALA Conference in Tokyo in 1980, the results of intensive research of IALA on passive radar reflectors for AtoN were presented.



After that, many technical reports on radar reflectors were published, but a coherent work of IALA on the selection and dimensioning of radar reflectors, according to current technical possibilities, was missing.



Based on an intensive worldwide inventory of AtoN radar reflectors and the latest technical simulation and calculation methods, a new IALA guideline has been developed. It contents:

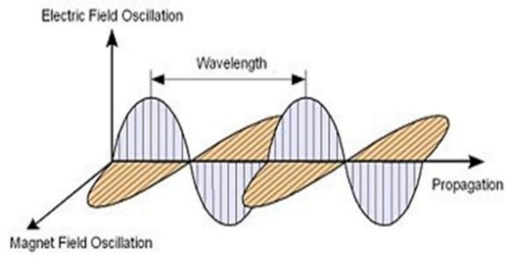
The basic knowledge for understanding radar reflectors

Necessary steps for the not always easy selection and dimensioning of suitable radar reflectors

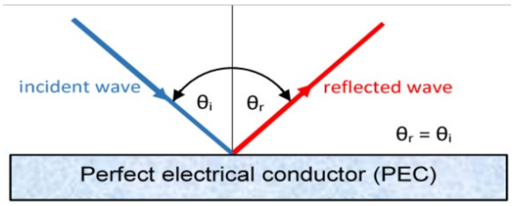
Mechanical, design and operational aspects

2.1 Theoretical basics of Radar Wave

A radar wave is an electromagnetic wave with an electric and a magnetic field component. In free space, these two field vectors are perpendicular to each other. The radar wave propagation is orthogonal to both field components with a velocity close to the speed of light. The propagation in free space follows quasi-optical laws.



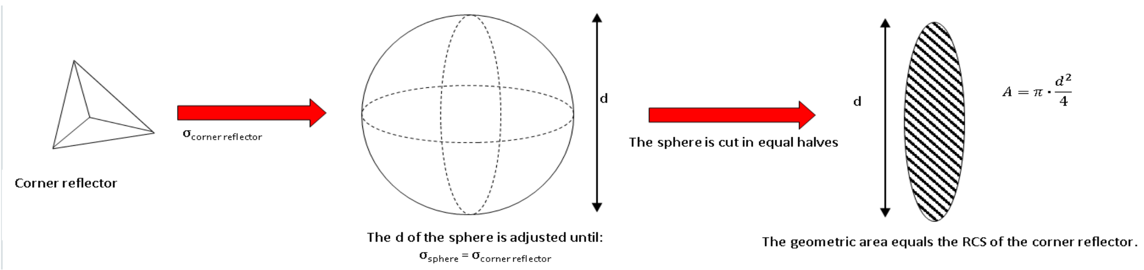
When the radar wave hits a metallic conductive object, the entire electromagnetic wave is reflected. The angle of incidence is equal to the angle of reflection.



There are several other effects that influence the propagation of electromagnetic waves, such as diffraction, refraction and diffuse reflection.

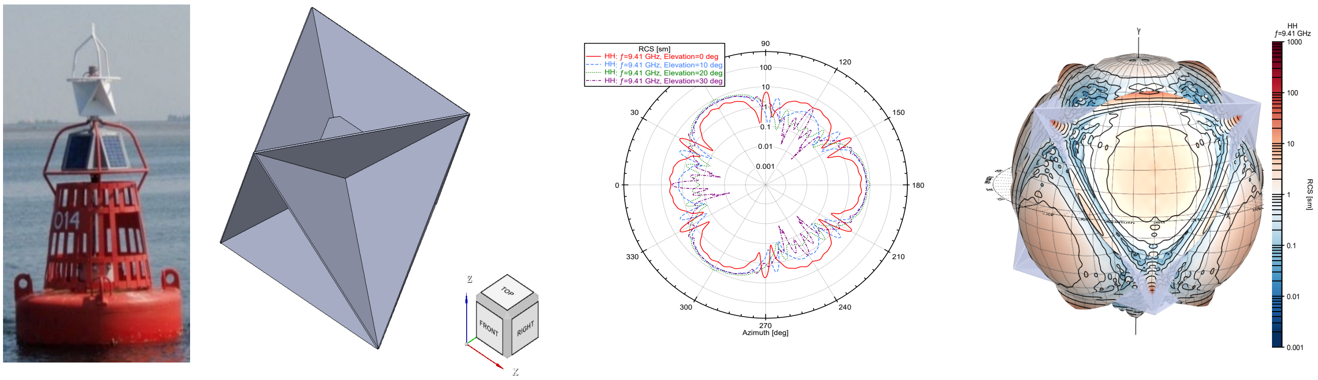
2.2 Radar Cross Section (RCS)

The intensity of the echo, scattered back to the source of the wave (i.e. the radar), is expressed by the radar cross section (RCS). RCS is the projected area of a metal sphere which, if it would replace the reflecting object, would backscatter the same power to the radar. Size, shape and especially orientation of an object have a deep impact on its RCS. Hence, an object has not only one RCS, it has a RCS for any spatial direction. Based on the RCS value, the range of the radar reflection can be calculated.



2.3 Simulation of the RCS pattern

Modern simulation tools can simulate the RCS pattern for each spatial angle. Input data are 3D models of the shapes. Time-consuming and expensive measurements on real objects can thus be omitted. The development of radar reflectors including the verification of their reflection behaviour can be accelerated. Simulations were also used for the new guideline: Almost all illustrations of the reflection behaviour of different radar reflectors were done via CST MICROWAVE STUDIO.



2.4 RCS pattern of simple objects

Simple shapes produce a radar echo which is not really suitable as a radar reflector in practice.

Metal sheet:

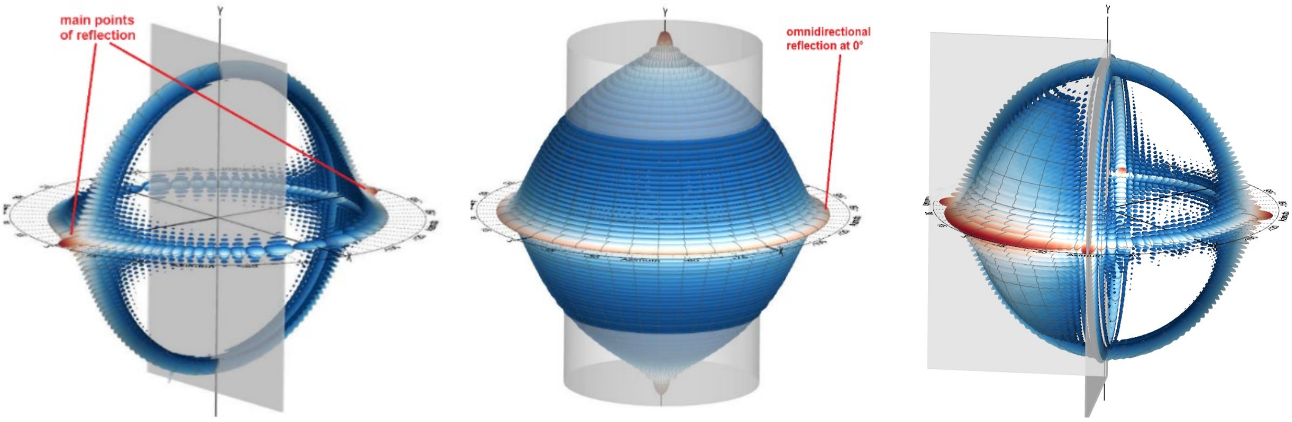
- High reflection
- But only in two small spatial angles

Cylinder:

- Perfect omnidirectional reflection
- But only an elevation of 0 °

Bent metal sheet:

- High reflection in a spatial angle of ≈ 30 °
- But only at 0 ° elevation



2.5 RCS pattern of complex structures

On more complex shapes, radar reflection occurs on the various components of the object, e.g.

- Surfaces
- Cylindrical shapes
- Edges
- Corners, etc.

The reflected radar waves are superimposed, resulting in a more or less undefined and strongly direction-dependent reflection behaviour. Therefore, objects that are not specifically designed for the reflection of radar waves are only suitable as radar reflectors to a limited extent in practice.

Here, the installation of a radar reflector with defined reflection properties is usually recommended.

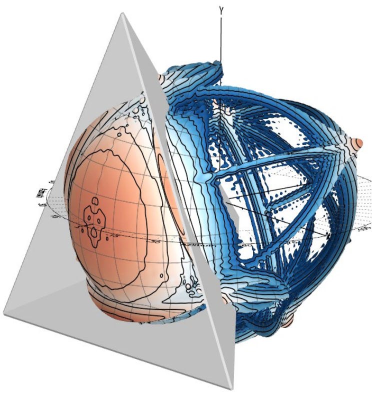
2.6 Radar reflector for one reflection direction

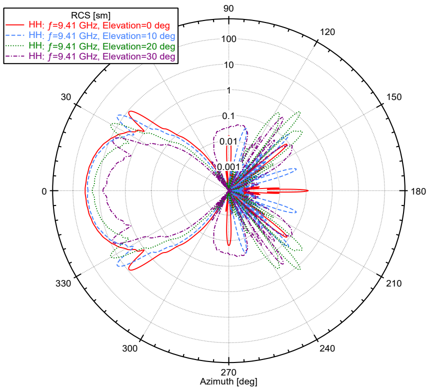
The central component of all radar reflectors is the corner reflector (in different shapes). Its reflection principle is based on the triple mirror. It has 3 reflecting surfaces at an angle of 90° to each other. The incident radiation is returned almost exactly to the sender of the radiation. It can directly be used as radar reflector for just 1 reflection direction (for example, to mark pylons of a bridge).

A simplified RCS calculation is:

$$\text{RCS} \approx \frac{4\pi \cdot a^4}{3 \cdot \lambda^2}$$

$\pi \approx 3.14159$
a = inner length (m)
λ = wavelength (m)



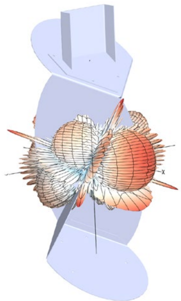


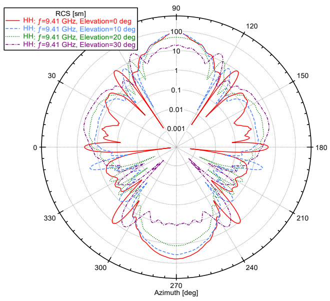
2.7 Multidirectional and omnidirectional radar reflectors

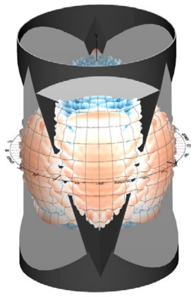
For reflections in several directions, a multiple arrangement of individual corner reflectors is usually chosen. The corner reflectors are combined in such a way that the superimposition of their reflections results in the desired overall reflection behaviour.

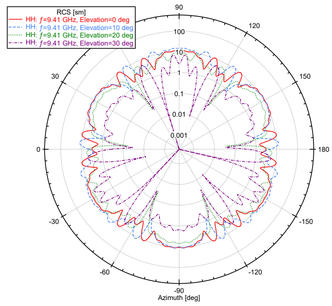
The design and calculation of the final reflection pattern is complicated due to positive and negative superimpositions, phase shifts, etc.

The guideline contains an overview of the most commonly used radar reflectors worldwide. For all of them, the preferred application was identified and their RCS pattern was simulated.









2 main reflection directions, 2 corners

Omnidirectional reflection, 6 corners

2.8 Effects of surrounding materials, e. g. plastic

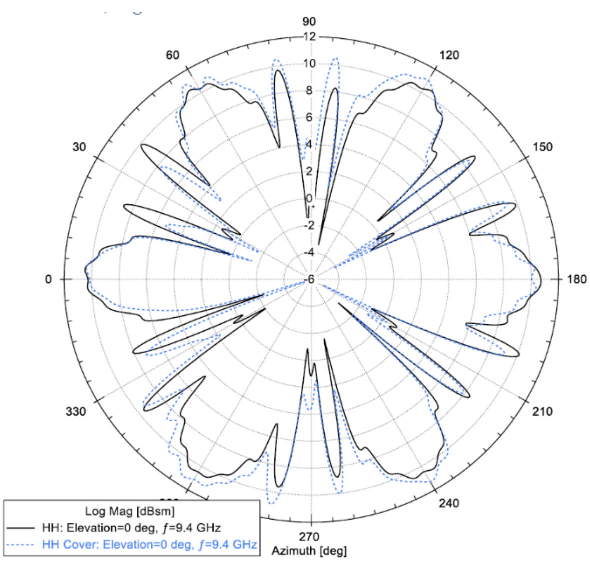
To assess the effects of a plastic cover in reality, laboratory measurements were carried out (SR6 radar reflector, 330 mm diameter).

To be as realistic as possible, a cut-out from a commercially available plastic buoy was used (diameter 400 mm, wall thickness 12 mm). The polyethylene was solid coloured.

The measurements show that the plastic cover only has a minor impact on the reflection behaviour in this arrangement.

Measurement results (linear scale):

- Without plastic cover (black solid line)
- With plastic cover (blue dashed line)



2.9 Range Calculation

The radar equation can be used for the calculation of the theoretical radar range under ideal conditions in free space:

$$R_{max} = \sqrt[4]{\frac{P_t G_t G_r \sigma \lambda^2 F_t^2 F_r^2}{(4\pi)^3 P_r}}$$

Pt	= transmitted signal power (W)
Gt	= transmitting antenna gain
Gr	= receiving antenna gain
σ	= RCS, radar cross section (m2)
λ	= wavelength (m)
Ft	= pattern propagation factor for transmitting antenna
Fr	= pattern propagation factor for target to receiving antenna
π	≈ 3.14159, mathematical constant
Pr	= received signal power (W)

In practice, the maximum range is influenced by many additional parameters. Software-based simulation tools (for example CARPET) can take further parameters into account for the range calculation.

2.10 Range calculation / International requirements and standards

For easy range estimations the guideline contains a table showing maximum ranges depending on:

- Different RCS values
- Different antenna heights
- The radar band

The input parameters of the CARPET simulation were set in such a way that they come as close as possible to reality.

IMO defines regulations for shipborne equipment, but not for AtoN radar reflectors. However, IMO Resolution MSC.192 (79) assumes a certain performance (in terms of a RCS value) of radar reflectors on AtoN (ship antenna height 15 m, buoy height 3.5 m)

	Buoy RCS	Min.Detection Range
X-band	10 m²	4.9 NM
S-band	1 m²	3.6 NM

Table 8 Typical achievable maximum radar ranges

Shipborne radar antenna height	Target height	X-band		S-band
		RCS	Detection range	Detection range
5 m	1.0 m	10 m²	3.7 NM	2.9 NM
		50 m²	4.2 NM	3.5 NM
		300 m²	4.9 NM	4.1 NM
		1000 m²	5.3 NM	4.6 NM
	3.5 m	10 m²	4.5 NM	3.5 NM
		50 m²	5.2 NM	4.1 NM
		300 m²	5.9 NM	4.9 NM
		1000 m²	6.4 NM	5.5 NM
	7.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	5.8 NM	4.9 NM
		300 m²	6.6 NM	5.8 NM
		1000 m²	7.2 NM	6.5 NM
10 m	1.0 m	10 m²	4.8 NM	3.7 NM
		50 m²	5.5 NM	4.4 NM
		300 m²	6.2 NM	5.2 NM
		1000 m²	6.7 NM	5.7 NM
	3.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	6.4 NM	5.1 NM
		300 m²	7.2 NM	6.0 NM
		1000 m²	7.8 NM	6.6 NM
	7.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	7.4 NM	5.6 NM
		300 m²	8.4 NM	6.9 NM
		1000 m²	9.1 NM	7.6 NM
15 m	1.0 m	10 m²	5.0 NM	3.7 NM
		50 m²	6.5 NM	5.3 NM
		300 m²	7.3 NM	6.1 NM
		1000 m²	7.8 NM	6.7 NM
	3.5 m	10 m²	5.0 NM	3.7 NM
		50 m²	7.4 NM	5.6 NM

2.11 Non-radar specific requirements: environmental conditions, construction and installation methods

Radar reflectors are manufactured from good electric conductivity materials, in practice aluminium and mild steel/stainless steel. Even a very thin layer of metal can make an object highly radar reflective: Plastic material with a metallized surface or with a metallized nylon mesh embedded has good results.

Tight tolerances are important, otherwise the reflected wave will not be reflected exactly in the direction of incidence.

Reflector diameter	Maximum angular tolerance	Maximum flatness tolerance
0.5 m	± 1°	≤ 1 mm
1 m	± 0.5°	≤ 2 mm

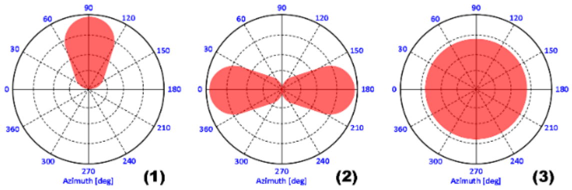
Manufacturing processes include bending and welding of sheet metal. It is also possible to attach individual corner reflectors to a supporting structure.

In some cases, the radar reflector is part of the daymark of an AtoN or fully integrated into the buoy body. The materials must be of sufficient strength and quality: Consider conditions of stress due to sea states, vibration, humidity and change of temperature in the marine environment.

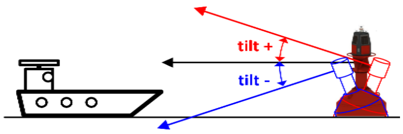



2.12 Using the new IALA guideline for finding an appropriate radar reflector for a particular application

- The user should develop a rough understanding of radar waves and their reflection (sections 4, 5, 6).
- Determine the desired horizontal reflection pattern: one (1), two (2) or more, omnidirectional (3)



- Note the required vertical reflection angle: for example the maximum tilt angle of buoys
- Make a pre-selection of potentially suitable radar reflectors (section 7.4 and ANNEX A)



- Consider environmental conditions, installation possibilities and maintenance (sections 12,13,14,15)
- Determine the required RCS based on the required range, the antenna height on the vessel and the mounting height of the radar reflector on the AtoN (section 8, table 8).
- Final radar reflector requirements:
- For simple corner reflectors, the size can be easily calculated based on the required RCS.
- For more complex reflectors, the reflection properties should either already be available, simulated on the basis of initial designs or measured on the basis of samples.
- ANNEX A contents examples of simulated radar reflectors, ANNEX C shows an example for designing a radar reflector for buoys.

AUTHOR BIOGRAPHY

54 years old, married, one child, education as radio electronics technician, studying telecommunication engineering, worked as development engineer and product manager, since 2003 working at Federal Waterways and Shipping Administration, Germany. Member of the IALA ENG Committee since 2014, Vice Chair of Working Group 2

S115.1 New generation racon in an increasingly autonomous world (184)

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ABSTRACT

Since the invention of radar in 1935, radar technology has been constantly updated. However, racon's technology develops relatively slower since early 1980s. The conventional racon cannot respond to New Technology (NT) solid-state radars, and cannot meet the requirements of the new era of shipping autonomy. This paper elaborates on the technical route and experimental results of the new generation racon. The application of the new generation racon will open the door for NT solid-state navigation radar, and support the standardization of eRadar / eRacon positioning system (ERPS).

KEYWORDS: radar, racon, autonomy, ERPS

1 RADAR AND RACON

1.1 Radar and its history

The harsh and rapidly changing climate at sea, accompanied by invisible underwater obstructions such as reefs, make huge risks for navigation. In order to ensure the navigation safety of ships, our ancients began to set up some visual aids to navigation to guide ships to avoid risks and ensure navigation safety. However, visual aids to navigation such as lighthouses and buoys etc. are highly susceptible to the weather. In the event of poor visibility such as fog, the visual range of these aids to navigation equipment or facilities will become very short or even invisible, which greatly increasing the risk of navigation. In order to solve the problem, marine radars were put into operation.

Radar, an abbreviation of Radio Detection and Ranging, uses the reflected electromagnetic waves of the target to achieve detection, positioning, tracking, imaging and identification of the target. In World War I, Britain urgently needed a device that could detect German aircraft in the air, which led to the creation of radar. In 1935, the famous British physicist Watson Watt invented a device that can both emit radio waves and receive reflected waves, which can detect the movement of aircraft at a long distance. This was the world's first radar [1]. During World War II, radar technology developed extremely rapidly due to military needs. Britain and the United States developed centimetre-wave sea-to-sea radar. After the war, in order to ensure the safety of navigation, radar technology was widely used on merchant ships.

In 1960, the Intergovernmental Maritime Consultative Organization (IMCO), which was renamed the International Maritime Organization (IMO) in 1982, held the 1960 SOLAS Conference in London, and first raised the issue of using radar to avoid ship collisions [2]. The SOLAS Convention of 1974 further made it a mandatory requirement for ships to be equipped with radar.

1.2 Racon and its history

Racon, also known as radar beacon, is an important radio aids to navigation device. It can return a signal containing Morse code to respond to the navigation radar electromagnetic wave, the frequency of which is the same or similar to that of the navigation radar signal, so that it can be received by the radar and displayed on the navigation radar screen as a Morse code composed of lines, points, and spaces. This prominent signal can better provide a reference for ship positioning and navigation.

The origin of racon can be traced back to the Identification Friend or Foe (IFF) system developed and used by the Royal Air Force during World War II. The basic principle of this system is that a ground radar transmitter broadcasts a radio signal to the aircraft, and the aircraft is equipped with a transponder that can respond to the signal. This is the earliest radar beacon.

Since the 1950s, racon has been gradually applied in the field of shipping. In 1979, the International Maritime Organization (IMO) adopted Resolution A.423 (XI) RADAR BEACONS AND TRANSPONDERS, which for the first time stipulated the technical requirements of racon. Since then, racon has become the standard equipment for ship navigation, widely used to display land, inconspicuous coastline, new hazards, turning points, and so on. In 1987, the International Maritime Organization (IMO) issued the standard document for racon, Resolution A.615 (15) RADAR BEACONS AND TRANSPONDERS, which updated the technical and operational requirements of racon and added the requirements for Morse code display.

1.3 Comparison of development processes

Table 1 – development processes of radar and racon

TIME	1935	WW II	1960	1971	1970s	1980s	Latest
Radar	First radar	Widely used in military applications, centimetre wave sea radar emerged	IMCO proposed using radar to avoid collision, marine radar widely used	A.222 (VII) specifies the technical and operational requirements for navigation radar	Solid state phased array radar appeared	IMO continuously upgraded its radar requirements in 30 years ： A.278(VII), A.477 (XII), MSC.64(67), A.820(19), A.823(19)	2004: MSC.192 (79): In order to introduce new solid-state radar technology, S-band navigation radars are allowed not to support racon
Racon		First racon			1979: A.423 (XI): Specifies the technical and operational requirements of racon with sweep frequency operation mode	In 1987 A.615 (15) stipulates Morse code requirements and frequency agility mode	No significant upgrade for racon

2 THE PROBLEMS EXISTING IN TRADITIONAL RADAR AND RACON, AND THE DEVELOPMENT TREND IN THE ERA OF AUTONOMOUS SHIPPING

Due to the long transmission distance and strong penetration ability of the radio signals from the radar and racon, the navigation risk in poor visibility situations is effectively reduced. Decades of application have proven that radar and racon are very valuable navigational aids. However, with the development of shipping, the defects of conventional radar and racon have gradually emerged.

2.1 Disadvantages of traditional radar

Traditional radar or magnetron radar emits narrowband signals (typically 9375 MHz and 9410 MHz) through vacuum microwave tubes for target detection. This narrowband signal is easily identified, imitated, and interfered with due to its single frequency and immutable nature. If complex waveform FM signals can be used and transmitted, the radar's anti-interference ability will be greatly improved.

Therefore, in the 1960s, because of the military need for anti-interference, and with the popularization of electronic computers, microprocessors, microwave integrated circuits, and large-scale digital integrated circuits, phased array radars emerged in the 1960s. In the 1970s, many new systems and new technology radars, such as solid-state phased array radars and pulse Doppler radars, were successively developed.

Solid state radar is a new technology radar that uses a combination of high-power transistors, transistors and frequency multipliers to form a microwave source instead of a high-power microwave tube oscillator (magnetron). It can generate complex FM signals through computer control, which can transmit up to 4-6 different frequency and different waveforms of signals.

On the other hand, the time width of solid-state radar signals is also much larger than that of magnetron radar signals. Conventional magnetron radar signals typically have a time width of nanoseconds to about 1 μs while about 100 μs for pulse compression solid state radar. The continuous wave solid-state radar signal has a time width of more than 1ms, which is more than 100 times that of traditional magnetron radar. With pulse compressing technology, it can greatly improve the resolution of the radar.

The performance comparison between the NT solid-state radar and the magnetron radar is as follows:

Table 2 - performance comparison between the NT solid-state radar and the magnetron radar

Radar type	**Megnetron radar**	**NT Solid state radar**
Signal	Narrow frequency band	FM
Life	6000 hours	Maintenance free
Peak power	High（3-30 KW）	Lower (10-500 W)
Emitting	Magnetron	Transistor
Signal width	Around 0.05-1.2μs	Around 0.05μs-1ms
Resolution	Lower	High
Safety	High Radiation	Low Radiation
Start	Preheating needed	Instant

Due to the above advantages, solid-state radar began to be accepted and applied in the industry. By the end of the 20th century, solid-state radar was also widely used in military, meteorological, aviation, slope, bird watching, and other fields.

2.2 Disadvantages of conventional racon

At the same time, due to the limitations of its working mode and performance, the conventional racon also poses risks to coastal states to fulfill their obligations to ensure navigation safety.

In August 2017, the Maritime and Port Authority of Singapore organized relevant radar and racon manufacturers to carry out evaluation experiments on enhanced radar and enhanced Racon (eRadar/eRacon) at Singapore ports. The purpose is to assess the working conditions of eRadar and eRacon in a busy port with numerous radar signals from passing ships. They installed three conventional frequency-agile Racon. However, at the beginning of the experiment, there was a situation where the radar could not receive the eRacon's responses [3].

The situation experienced by the Singapore experiment shows that the conventional racon cannot meet the requirements of busy ports. The reason is caused by the “comparative judgment” response mode of conventional racon. One is that the "comparison and judgment" mode treats signals with the same or even similar frequency sent by different radars as the same radar signals, so that only the radar with strongest signals is replied to, while ignoring the weaker radars; The second is that the “receive -compare and judge – reply” method requires a long processing time, and during this period, it cannot accept signals from other radars. Therefore, when the port is busy and there are too many ships, conventional racon cannot respond to concurrent radar signals.

2.3 Development trend of autonomous shipping

Global autonomous technology has achieved rapid development in unmanned vehicles, aircraft, and ships. In particular, with the development of technology and the continuous improvement of intelligence, autonomous ships have been widely used in surveying and mapping, environmental protection, marine transportation, scientific investigation, monitoring, rescue, as well as military mine clearance, anti-submarine, patrol, and other fields.

The production and sales of autonomous ships in China have maintained growth. In 2021, the demand for autonomous ships in China was 1895, and the output was 1982. It is estimated that the demand for autonomous ships in China will be 2130 and the output will be 2250 in 2022 [4]. In 2021, the scale of China's civil autonomous ships market was 630 million yuan, with a year-on-year increase of 90.91%.

From February 26 to March 1, 2022, the 204TEU container ship “SUZAKU” successfully conducted an autonomous navigation test on the round-trip route from Tokyo Port to Matsuzaka Port to Tokyo Port, covering a total distance of 790 kilometers.

Also in 2022, Ocean Infinity, the world's leading autonomous underwater robot operator, continued to expand its fleet, subscribing to another six 85-meter-long multifunctional autonomous navigation ships, bringing its remotely operated fleet to 23 [5].

Considering the unmanned characteristics of autonomous ships, while energy conservation and emission reduction have become the mainstream in the world, the development of the global shipping industry towards low-carbon direction has become the consensus of the international community, placing higher requirements on the energy efficiency and reliability of onboard equipment. The traditional magnetron radar with short service life, high equipment failure rate, and high energy consumption is doomed to be unable to adapt to the needs of unmanned ships in the autonomous era. Therefore, the new technology solid-state radar, with its technical advantages, will definitely become the first choice for future unmanned ships.

2.4 Market Overview and Problems of NT Solid State Radar

Region	Africa	Middle East	Asia Pacific	China	India	Latin America	North America	Eastern Europe	Western Europe	World
2022 Fleet										
Narrowbody	430	505	1,690	3,142	478	997	4,062	1047	2,884	15,235
Widebody	142	624	1,021	505	39	143	1,314	155	896	4,839
Regional jet	164	54	205	159	5	218	1,834	269	367	3,275
Turboprop	307	28	631	0	83	197	552	110	321	2,229
TOTAL	**1043**	**1,211**	**3,547**	**3,806**	**605**	**1,555**	**7,762**	**1,581**	**4,468**	**25,578**

Figure 1 – Aviation fleet in 2022

Source: Aviation Week Intelligence Network’s Fleet Discovery, Oliver Wyman analysis

According to the research report data from Oliver Wyman in February 2022, the global commercial fleet in service began to grow in 2021 after contracting by 18% in response to the COVID-19 pandemic in 2020. The number of aircraft has expanded by 2800, reaching 25500 in early 2022 [6].

Table 2.4 Ownership of the world fleet, ranked by carrying capacity in dead-weight tons, 2021

	Country or territory of ownership	Number of vessels			Deadweight tonnage				
		National flag	Foreign flag	Total	National flag	Foreign flag	Total	Foreign flag as a percentage of total	Total as a percentage of world
1	Greece	642	4 063	4 705	58 067 003	315 350 152	373 417 155	84.45%	17.64%
2	China	4 887	2 431	7 318	105 657 323	138 898 420	244 555 743	56.80%	11.56%
3	Japan	914	3 115	4 029	35 107 223	206 741 103	241 848 326	85.48%	11.43%
4	Singapore	1 459	1 384	2 843	73 258 302	65 805 758	139 064 059	47.32%	6.57%
5	China, Hong Kong SAR	886	878	1 764	72 367 151	31 851 549	104 218 700	30.56%	4.92%
6	Germany	198	2 197	2 395	7 437 473	78 759 307	86 196 779	91.37%	4.07%
7	Republic of Korea	787	854	1 641	15 096 916	70 995 920	86 092 836	82.46%	4.07%
8	Norway	387	1 655	2 042	1 899 017	62 144 480	64 043 497	97.03%	3.03%
9	Bermuda	13	540	553	300 925	63 733 226	64 034 151	99.53%	3.03%
10	United Kingdom (excl. Channel Islands)	309	1 014	1 323	7 160 493	46 524 174	53 684 667	86.66%	2.54%
11	United States of America (incl. Puerto Rico but excluding Virgin Islands)	790	1 020	1 810	10 395 172	44 576 019	54 971 191	81.09%	2.60%
12	Taiwan Province of China	147	867	1 014	6 998 235	46 284 542	53 282 777	86.87%	2.52%
13	Monaco	0	478	478	0	43 426 478	43 426 478	100.00%	2.05%
14	Denmark	26	902	928	47 415	42 185 673	42 233 088	99.89%	2.00%
15	Belgium	108	249	357	8 974 783	21 969 171	30 943 954	71.00%	1.46%
16	Turkey	429	1 112	1 541	5 994 812	21 970 706	27 965 518	78.56%	1.32%
17	Indonesia	2 232	89	2 321	24 139 035	2 704 715	26 843 751	10.08%	1.27%
18	Switzerland	18	396	414	928 432	25 794 797	26 723 229	96.53%	1.26%
19	India	875	195	1 070	16 396 087	10 013 434	26 409 521	37.92%	1.25%
20	United Arab Emirates	119	941	1 060	525 959	24 431 420	24 957 380	97.89%	1.18%
21	Russian Federation	1 464	322	1 786	9 184 626	14 682 694	23 867 320	61.52%	1.13%
22	Iran (Islamic Republic of)	246	8	254	18 898 257	352 889	19 251 146	1.83%	0.91%
23	Netherlands	692	515	1 207	5 577 088	13 185 003	18 762 090	70.27%	0.89%
24	Saudi Arabia	151	111	262	13 397 363	3 422 203	16 819 566	20.35%	0.79%
25	Italy	481	170	651	10 296 714	5 900 509	16 197 223	36.43%	0.77%
26	Brazil	292	91	383	4 735 593	9 120 015	13 855 608	65.82%	0.65%
27	France, metropolitan	98	327	425	1 592 919	12 004 098	13 597 017	88.28%	0.64%
28	Viet Nam	929	166	1 095	9 491 311	3 043 458	12 534 769	24.28%	0.59%
29	Cyprus	134	177	311	5 166 089	7 174 723	12 340 812	58.14%	0.58%
30	Canada	210	164	374	2 569 373	7 212 024	9 781 397	73.73%	0.46%
31	Oman	5	58	63	5 704	8 926 419	8 932 123	99.94%	0.42%
32	Malaysia	456	163	619	6 587 734	2 158 859	8 746 592	24.68%	0.41%
33	Qatar	57	69	126	1 123 717	6 145 431	7 269 149	84.54%	0.34%
34	Nigeria	198	73	271	3 517 645	3 429 887	6 947 532	49.37%	0.33%
35	Sweden	90	208	298	1 004 333	5 448 524	6 452 857	84.44%	0.30%
	Subtotal, top 35 shipowners	**20 729**	**27 002**	**47 731**	**543 900 223**	**1 466 373 485**	**2 010 273 707**	**72.94%**	**94.99%**
	Rest of the world unknown	*3 096*	*3 146*	*6 242*	*37 011 088*	*69 116 093*	*106 127 181*	*65.13%*	*5.01%*
	World	**23 825**	**30 148**	**53 973**	**580 911 310**	**1 535 489 578**	**2 116 400 888**	**72.55%**	**100.00%**

Figure 2: Ownership of the world fleet,2021

Source: UNCTAD calculations, based on data from Clarksons Research

According to the statistics of the United Nations Conference on Trade and Development (UNCTAD), the number of ships with a gross tonnage of 1000 or more reached 53973 globally in 2021. It is more than twice the number of aircraft used in civil aviation worldwide [7].

However, in the case of significant differences in number between aircrafts and ships, the utilization rates of NT solid-state radars are exactly the opposite. According to the data statistics of the data research service provider Knowledge Based Value (KBV) in 2020, the global market share of solid-state radar by end user is shown in the figure below, ranking first for military purposes, second for meteorological monitoring, and third for aviation. The market share in the maritime field is too small to be listed, and KBV research predicts that the market share will maintain the same pattern in the future [8].

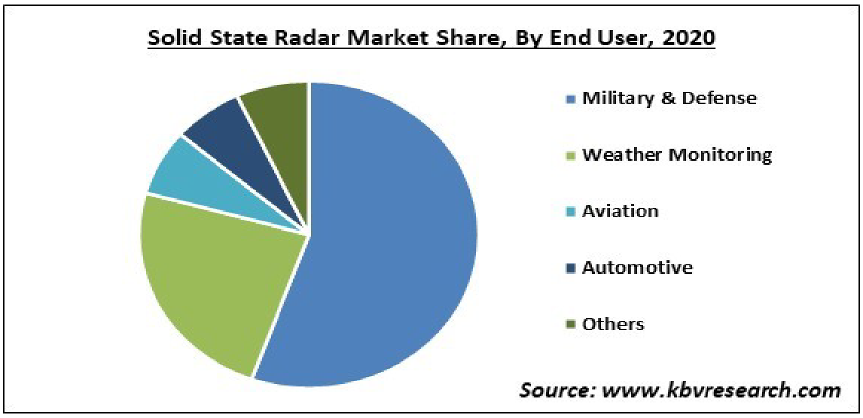

Figure 3: Solid State Radar Market Share

Source: www.kbvresearch.com

It can be seen that although the performance of NT solid-state radars has been recognized by the industry in many fields, but in the navigation field, especially X-band (9Ghz) navigation radars, due to the operating mode of NT solid-state radars, they cannot be popularized in this field.

3 FACTORS THAT LIMITED NT SOLID-STATE RADARS BEEN USED ON SHIPS

There are many factors that hinder the application of solid-state radar technology used onboard, such as technical and economic costs, but the conventional racon is also one of the reasons which cannot be ignored.

3.1 Technical level - the Reason why conventional racon cannot be triggered

We can study at the sides of racon and radar separately. At the racon side, the conventional racon uses the “receive - compare and judge – reply” response mode. Because the “compare judge” can only judge the fixed narrowband signals of the magnetron radar, it is unable to judge the long-time wide frequency modulation signal of the new technology solid-state radar. As a result, conventional racon cannot be triggered by the new technology solid-state radar.

At the solid-state radar end, the narrowband signals will be filtered out as clutter by the new technology solid-state radar due to echo processing mechanisms and pulse compression processing. Conventional racon can only transmit narrowband signals. Therefore, the response signals of the conventional racon will also be filtered by the new technology solid-state radar. In other words, conventional racon cannot respond to the new technology solid-state radar.

3.2 International Regulation

3.2.1 SOLAS

Chapter V of the International Convention for Safety of Life at Sea (SOLAS) stipulates that:

“2.3 All ships of 300 gross tonnage and upwards and passenger ships irrespective of size shall, in addition to meeting the requirements of paragraph 2.2, be fitted with:

.1 an echo-sounding device, or other electronic means, to measure and display the available depth of water;

.2 a 9 GHz radar, or other means, to determine and display the range and bearing of radar transponders and of other surface craft, obstructions, buoys, shorelines and navigational marks to assist in navigation and in collision avoidance.” [9]

Article 2.7 of Chapter V of the International Convention for Safety of Life at Sea (SOLAS) stipulates that all ships with a gross tonnage of 3000 or more should be equipped with an X-band (9GHz) radar, followed by a 3 GHz radar or, where considered appropriate by the Administration, a second 9 GHz radar [10].

3.3 IMO Resolution A.615(15)

In addition to the SOALS Convention, ANNEX 2 of the IMO Resolution A.615 (15) RADAR BEACONS AND TRANSPONDERS, adopted by the International Maritime Organization (IMO) on November 19, 1987, also clearly stipulates that:

“2.1 Radar beacons designed to operate on a wavelength of 3 cm should be capable of being interrogated by any navigational radar equipment operating on any frequency between 9,320 MHz and 9,500 MHz and respond within this frequency band” [11].

In practical operation, NT solid-state radars, especially X-band solid-state radars, do not meet the requirements of the above international standards due to their inability to trigger conventional racon. As a result, new technology solid-state radars, especially X-band solid-state radars, have not yet been certified by the classification society, resulting in the inability of 3cm (X band) solid-state navigation radars to be installed and used on SOLAS ships.

3.4 IMO Resolution MSC192(79)

However, IMO has also recognized the advantages of NT solid-state radar and is attempting to give new technology radar more space in terms of rules.

In the Resolution MSC 192 (79) ADOPTION OF THE REVISED PERFORMANCE FOR RADAR EQUIPMENT issued by IMO in 2004, the requirement that S-band navigation radar must trigger racon was cancelled, but the requirement that X-band navigation radar must trigger racon was still maintained [12]. Although restrictions on new technology solid-state radars have been relaxed to a certain extent, previous market data have proven that new technology solid-state navigation radars have still not been able to obtain wider applications.

However, the author believes that from the perspective of IMO and navigation safety, given that the current racon is still the mainstream and important aids to navigation equipment, it is necessary to maintain the existing IMO standards for shipborne navigation radars to be able to trigger racon, and it is correct not to further deregulation. The shipping industry should consider starting from the shore side and considering the application of a new generation of racon that can respond to both traditional radars and NT solid-state radars. On the one hand, it solves the limitations of new technology upgrades, and on the other hand, it helps the coastal states to better implement their obligation of ensuring navigation safety.

4 TECHNICAL SOLUTIONS AND TESTS OF NEW GENERAL RACON

4.1 Technical Solutions

The traditional manufacturers in Europe and the United States, are aware of the need to upgrade traditional racon technology, and have conducted research for many years. China has also started research on a new generation of racon since 2017. Although various options have been considered and tested, no progress has been made. Later, technicians took inspiration from parrots in the biological world. Although parrots cannot understand human speech, they can repeat what people say. In other words, racon does not need to “understand (i.e., compare and judge)” the “speech (i.e., FM signal)” of each new technology radar. As long as it can repeat the “speech (i.e., response signal)” of the radar, the radar can naturally “understand (receive)”.

Therefore, a new type of digital full-bandwidth direct-forwarding racon system has been proposed.

A digital full-bandwidth direct-forwarding racon system comprises: an antenna system including a receiving antenna and a transmitting antenna, a radio-frequency transceiver module including radio-frequency receiving link and a radio-frequency transmitting link, and a baseband processing module including ADC acquisition module, an FPGA processing module and a DAC module;

The radio-frequency receiving link and the radio-frequency transmitting link share a local oscillator module, and the radio-frequency receiving link is configured to convert a radio-frequency signal output by the receiving antenna into an intermediate-frequency signal and output the intermediate-frequency signal to the ADC acquisition module of the baseband processing module; the radio-frequency transmitting link is configured to convert an intermediate-frequency signal output by the DAC module of the baseband processing module into a radio-frequency signal and output the radio-frequency signal to the transmitting antenna;

The ADC acquisition module converts a radio-frequency analog signal output by a radio-frequency receiver into a digital signal and sends the digital signal to an FPGA processing module; the DAC module converts a digital signal output by the FPGA processing module into an analog signal and sends the analog signal to an intermediate-frequency analog input interface of a radio-frequency transmitter; and the FPGA processing module is configured to realize orthogonal down-conversion processing of data acquired by ADC, envelope detection, Morse encoding modulation and orthogonal up-conversion processing. The specific workflow is as follows.

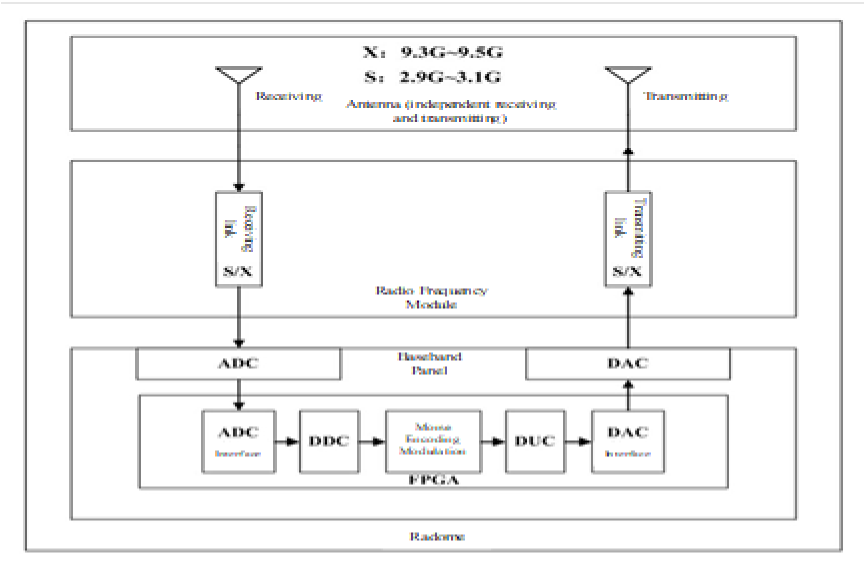

Figure 4: New Generation Racon Technical Route Diagram

This technical idea achieved a breakthrough in the 2021 sea trial. The test was conducted at the Fujian Minjiang River estuary in March 2021. Experimental equipment includes new technology pulse compression solid-state radar, FM continuous wave solid-state radar, and a new generation of racon. As a result of the experiment, the pulse compression radar and racon achieved a response distance of 10 kilometres [13].

After adjustment and improvement, the test was conducted again in Hangzhou Bay on October 26, 2022. The test results exceeded the practical response range of 10 nautical miles.

4.2 Tests

Test location: Hangzhou Bay. Hangzhou Bay, located in the south of Shanghai, is a trumpet shaped bay. Hangzhou Bay has a wide sea area, ranging from a few kilometres to 98 kilometres in the east. The world’s biggest container port - Yangshan Port is in the east of Hangzhou Bay (Figure 5).

Figure 5: Hangzhou Bay Test Sites

Test environment: On the day of the test, it was cloudy in the morning, and at around 3pm, the wind increased and began to rain slightly.

Test hardware: Test equipment includes pulse compression solid-state radar HALO-3, new technology racon, test vessel, computer, and other auxiliary test equipment.

The new technology pulse compression solid-state radar (HALO-3) was placed on the top of a residential building (Figure 6) on the shore of Fengxian Bay in Shanghai, about 19.01 kilometers away from racon and about 58 meters high; The new generation of racon was placed on the ladder which was on the crosswalk at the ferry terminal of Dajinshan Island in Hangzhou Bay, about 6 meters above the sea level (Figure 7).

Experimental results show that the Morse code "N" was clearly visible on the display screen of the solid-state radar (Figure 8). The new generation racon has broken through the response distance of 10 nautical miles (18.52 kilometers).

Figure 6: Solid State Radar

Figure 7: New Generation Racon

Figure 8: Solid State Radar Screen Display

The signal peak power of the HALO-3 new technology solid-state radar is only 25W, and the antenna is 3 feet long, making it one of the smallest pulse compression radar. Generally, the power of solid-state radar is around 100-200W. If a solid-state radar with higher power is selected and the racon is installed at a higher location, the response distance can be longer.

4.3 Lesson learned

The response technology of digital full-bandwidth direct-forwarding adopted by the new generation of racon replaces the traditional “receive -compare and judge – reply” response mode of conventional racon. The process of identifying radar signals is omitted, and the received signals are "recorded" and "played back" just like a tape recorder, allowing the new generation racon to respond to any waveform and any frequency modulated radars, including traditional magnetron radar narrowband signals and any new technology radar operating within a specified frequency band. Because the new generation of racon can simultaneously record various radar signals like a tape recorder and forward them together, the new generation of racon can simultaneously respond to multiple radars. This solves the previously described problems of conventional racon not responding in busy ports encountered during the test in Singapore.

5 SUMMARY AND PROSPECT

In addition to its unique technical advantages, the NT solid-state navigation radar also features energy conservation, environmental protection, maintenance-free, and long service life. This is in line with the goals of low-carbon and sustainable development advocated by the United Nations, but it cannot be applied because it cannot trigger conventional racon or the trigger distance cannot meet practical requirements. Therefore, the launch of a new generation racon will solve the obstacles encountered at the racon side and have a positive role in promoting the upgrading of navigation radars in the global navigation field. At the same time, it will also solve the problem that conventional racon cannot respond to concurrent signals from multiple radars, and can further improve the ability of coastal states to ensure the safety of navigation within their jurisdiction.

Furthermore, the new generation racon can also load other functions, such as enhanced radar positioning (ERPS) in conjunction with enhanced radar. IALA has been committed to the standardization of ERPS for many years [14]. In order for ERPS to meet practical requirements, it is necessary to use new technology solid-state radars, and to use new technology solid-state radars, it is necessary to enable a new generation of racon. Therefore, the new generation racon will also be one of the key equipment of the ERPS system.

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SESSIONS 16 AND 116 – AIS AND VDES

S16.1 Research on AIS VDL Integrity Monitoring (073)

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ABSTRACT

As the application of AIS becomes increasingly widespread, the types of AIS messages, services, and equipment, as well as the number of users, are rapidly growing. At the same time, the inherent vulnerabilities of AIS have gradually become apparent, drawing the attention of IALA members. This paper analyzes the vulnerability risks of AIS VDL and discusses real-time AIS VDL integrity monitoring methods in the context of AIS channel protection. Moreover, it introduces the application case of VDL integrity monitoring technology by the China Maritime Safety Administration and its effectiveness in maritime law enforcement. Finally, the paper looks ahead to the future monitoring needs of VDES VDL.

KEYWORDS: AIS; VDL; integrity; big data

1 INTRODUCTION

With the development of the global shipping industry, the Automatic Identification System (AIS) has become an indispensable key technology in modern maritime operations. AIS provides navigation, safety information, and other relevant services for ships through VHF Data Link (VDL). Along with the increasing popularity of AIS applications, the continuous growth of AIS message types, services, and equipment types, as well as the number of users, have collectively driven the widespread application and technological advancements of the AIS. However, the accompanying AIS VDL load issues have become increasingly severe, and the vulnerability of AIS VDL has gradually emerged, posing potential threats to the safety of navigation and effective communication where crew members are reliant on AIS increasingly.

This paper aims to analyze the causes of AIS VDL vulnerabilities and investigate the practical technologies of AIS VDL integrity monitoring to deal with the AIS VDL vulnerability. Furthermore, this paper presents the effectiveness of implementing VDL integrity monitoring. It plays a crucial role in maintaining stable and reliable AIS communication services, regardless of the increasing workload and various influences on VDL integrity.

2 FACTORS AFFECTING AIS VDL INTEGRITY

In order to reduce technical complexity, fully utilize channel bandwidth, and facilitate the global promotion, the AIS protocol has to make a compromise for VDL security initially. As the expanding application of AIS, its VDL vulnerability is gradually raising more concern and can be summarized into four main aspects.

2.1 Signal Domain

AIS VDL communicates using the VHF frequency band, which may be subject to unintentional or malicious interference due to overloaded VDL. This interference may lead to interruptions, errors, or delays in information exchange. Factors affecting AIS VDL integrity in the signal domain are given as follows.

(a) Interference from non-AIS services. Out-of-band emissions originate from non-AIS applications, particularly from other VHF devices, which may interfere with AIS communication.

(b) Interference from AIS devices. It mainly includes jitter caused by AIS message transmissions, aliasing distortion on account of the transmission not adhering to slots, and interference to distant devices caused by excessive transmission power.

(c) Malicious interference in the AIS band. It can shorten the AIS transmission distance, increase the packet error rate, and even prevent data transmission.

(d) GNSS Interference. It can cause shipborne AIS devices to fail positioning or have abnormal positioning results, thereby reducing the credibility of the latitude and longitude fields in the AIS dynamic data. In recent years, to prevent the possible risks caused by drones, facilities storing dangerous goods, such as coastal oil depots, have used drone defense devices with GNSS interference functions, which have also interfered with the GNSS positioning of ships in some areas, causing errors or abnormalities in AIS dynamic data.

(e) Slot overload. A large number of messages transmission can cause slot overload. Currently, the AIS VDL load in China's coastal waters ranges from 10-40%, with peak loads reaching up to 60%. In extreme cases, AIS safety and information exchange capabilities will be compromised.

2.2 Protocol Domain

According to AIS standards and recommendations, all AIS devices have specific requirements in terms of transceiver parameters, multiple access scheme, working mode, slot selection, and transmission intervals. Suppose a device is not designed strictly according to the standards or has design defects. In that case, it may lead to abnormal slot access, channel selection, transmission intervals, etc., resulting in conflicts, message errors, resource waste, or congestion. Issues at the AIS protocol level mainly include the following parts.

(a) Devices do not fully comply with the VDL multiple access protocol. Some AIS devices do not strictly follow the slot reservation and release protocol when accessing the VDL, resulting in increased slot conflicts and packet error rates. In recent years, the emergence of numerous AIS equipment for fishing mask using the burst mode has intensified slot conflicts on the VDL. Ships often need to be closer to each other to recognize one another, and the increased packet error rate also reduces the real-time capability of ship dynamic messages.

(b) Transmission intervals that do not comply with protocol requirements. Devices using transmission intervals shorter than the protocol requirements can lead to an increase in the number of slots occupied, thereby causing excessive consumption of VDL resources.

(c) Devices have incomplete protocol support. For example, AIS devices do not support ACK for binary addressing messages, or give no response to interrogation, assignment, or VDL management messages. In that case, it can result in abnormal communication between devices, and AIS shore-side cannot completely manage the devices.

2.3 Data Domain

Due to the transparency of AIS data, the messages transmitted over VDL may be subject to tampering or forgery, affecting system operation, navigation decisions, and ship traffic management. The main issues at the data level of AIS include the following parts.

(a) False AIS targets. Some modified AIS stations can simulate AIS messages according to the AIS message format and generate a large number of AIS targets. It occupies AIS slot resources and may cause AIS targets confusion.

(b) Unauthorized messages. AIS is able to send specific information, such as safety-related messages, hydrometeorological messages, DGNSS broadcast binary messages, etc. The transmission of these messages must be authorized to provide reliable information to crews. However, AIS lacks a verification mechanism for these messages. Therefore, unauthorized AIS messages can lead to confusion or even misleading.

(c) Unauthorized signaling. AIS base stations use AIS messages 16, 20, 22, and 23 to manage the VDL. The competent authorities should authorize the broadcasting of signaling. Unauthorized signaling can lead to disorder in AIS resource allocation and slot access.

(d) Undefined messages. Although the latest recommendation defines only 27 types of messages, some devices use private protocols with message number greater than 27. It leads to slot occupation and may cause conflicts with future applications.

2.4 Operational Domain

Incorrect configuration and installation of AIS devices may result in abnormal messages and erroneous or incomplete information transmission. The main issues in the AIS operational domain include the following parts.

(a) Incorrect static data and voyage-related information have been entered. The most common operational anomalies are incorrect inputs of MMSI, static, and voyage-related information, which can lead to abnormal vessel identification and cause confusion and misinformation.

(b) Device malfunctions due to incorrect parameter configuration. Incorrectly configured device parameters, such as transmission channels and power, can result in messages not being transmitted correctly. China Maritime Safety Administration has discovered cases where satellite AIS channels on some shipborne devices were set to channels 87B/88B, preventing the proper transmission of satellite AIS messages.

(c) Device malfunctions due to incorrect installation. Some ships have not correctly installed their GNSS antennas and VHF antennas, leading to dynamic information being set to default or radiated power failing to reach nominal value.

(d) Equipment aging. The aging of equipment can lead to a decrease in the transmission power or a reduction in the receiving sensitivity of AIS transceivers. Additionally, the aging of the feeder line can also have an impact on the transmission and reception performance of AIS devices.

(e) Failure to turn on AIS devices as required. When AIS devices do not start according to the requirements of the maritime authorities, it results in their inability to be identified by other vessels. Ships involved in smuggling activities often turn off the transmission of their AIS devices to evade regulation.

(f) Multiple AIS devices installed on a single vessel. Some ships operating beyond regulated sailing areas or engaging in smuggling activities may be equipped with multiple AIS devices, allowing them to switch between identities.

3 METHOD OF AIS VDL INTEGRITY MONITORING

Taking into account the vulnerability of AIS and the need to protect AIS VDL, China Maritime Safety Administration initiated an AIS VDL integrity monitoring project in 2019. This project relies on AIS raw data, dedicated monitoring equipment, and ship database to detect the status of AIS VDL and promptly identify and discover anomalies. The AIS raw data provide VDM, VDO, VSI, and FSR data with Tagblocks, obtaining channel conditions in AIS VDL. Dedicated monitoring devices enable the tracking of AIS signal frequency deviation and jitter. The ship database enables comparisons with ship static data to identify error static information.

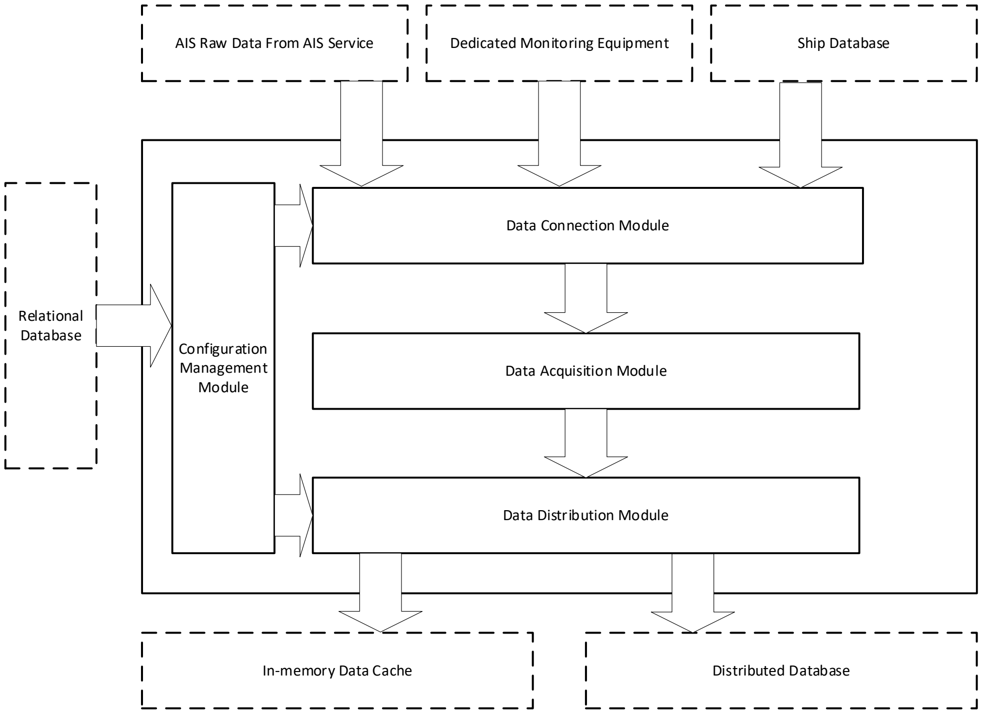

Figure 1: AIS VDL Integrity Monitoring Logical Architecture

This project utilizes a distributed database for fast data storage and establishes an in-memory cache to achieve real-time analysis and rapid data processing.

The system realizes the AIS VDL monitoring and the abnormal identification through the following multiple parallel services.

(a) VDL status monitoring. The crucial indicators of VDL integrity, such as channel load, reserved slots ratio, target count, channel balance, etc., are dynamically monitored through an integrity assessment model.

(b) Dynamic data conformance monitoring. Conformance checks are performed on Message 1, 2, 3, 18, and 19 to detect any anomalies or default values and use auxiliary methods such as value rationality checks. Concurrently, continuous detection of frequency deviation and time-domain jitter of dynamic messages is conducted to identify abnormal messages and targets.

(c) Static data conformance monitoring. Messages 5, 19, and 24 are monitored, including fields such as MMSI, ship name, call sign, IMO number, type of ship, dimensions, etc. Targets with abnormal information are identified by comparing with the ship database and conducting rationality checks. Whitelist and blacklist mechanisms are added to the processing flow. Ships with expected detection results are entered into the whitelist, avoiding repeated detection during a period to reduce the computational load for information matching.

(d) SOTDMA(Self-Organizing Time Division Multiple Access) protocol conformance monitoring. By analyzing the device's multi-address access behavior, the system checks its conformance with the SOTDMA protocol during continuous operation stages, including slot selection, slots reservation, and the consistency between transmission and reserved slots.

(e) ITDMA(Increment Time Division Multiple Access) Protocol conformance monitoring. By analyzing the device's multi-address access behavior, the system checks the conformance of the ITDMA protocol during the first frame stage and when changing the transmission interval, including slot selection, consistency between slot increment and subsequent ITDMA slots usage, consistency between slot keeping and the next frame's slots usage.

(f) Dynamic messages transmission interval conformance monitoring. For Class A equipment, Messages 1, 2, and 3 have broadcast intervals that vary according to the vessel's navigation status, speed, and course changing. For Class B vessels, Messages 18 and 19 have transmission intervals that vary according to the vessel's speed. The message transmission intervals can be calculated by analyzing the vessel's dynamic messages, thus determining whether the target vessel's broadcast intervals under different states comply with the ITU-R M.1371-5 recommendation.

(g) Identification of AIS devices with duplicate identities. Most AIS devices with duplicate MMSIs can be identified by analyzing the differences in static data. If the AIS static data of two targets is identical, the rationality of adjacent track point locations can help identify vessels with duplicate identities and separate their tracks.

(h) Detection of vessels with multi-device. In cases where a vessel is equipped with multiple AIS devices, protocol detection is used to identify the vessel with the same MMSI. Additionally, track correlation check can be used to identify devices with inconsistent static data on the same vessel.

(i) Identification of target loss authenticity. By analyzing the multi-address access characteristics of AIS devices during the first frame stage, vessels that previously turned off their AIS devices can be identified.

(j) Identification of false ship stations. False AIS targets can be identified based on the received signal strength of devices and the rationality of the relative positions of receiving stations and vessels.

(k) AtoN device detection. Conformance checks are performed on Message 21, including device availability, MMSI compliance, transmission interval, and the consistency between slots reservation and the slots actually used.

(l) Identification of unauthorized base stations. Unauthorized AIS base stations are identified through the base station profiles as well as base station reports and VDL management messages from shore-based AIS service.

(m) Safety-related broadcast message detection. By examining the characteristics of the binary data field, safety-related messages that do not meet the standard requirements are identified.

(n) Undefined message monitoring. Message number beyond 27 should be identified.

VDL anomalies can be monitored and identified using the above detection methods, supporting daily AIS management and maritime law enforcement.

4 IMPLEMENTATION AND APPLICATION OF AIS VDL MONITORING

China MSA fully completed the AIS VDL integrity monitoring project in 2021. The AIS VDL integrity monitoring system is designed based on a microservices architecture. It divides into 18 microservices according to services' function. It is composed of a big data foundation platform and a basic backend database. Data from 610 AIS base stations, 3 dedicated monitoring equipment, and the ship database are all integrated in this system. The overall system structure is illustrated below.

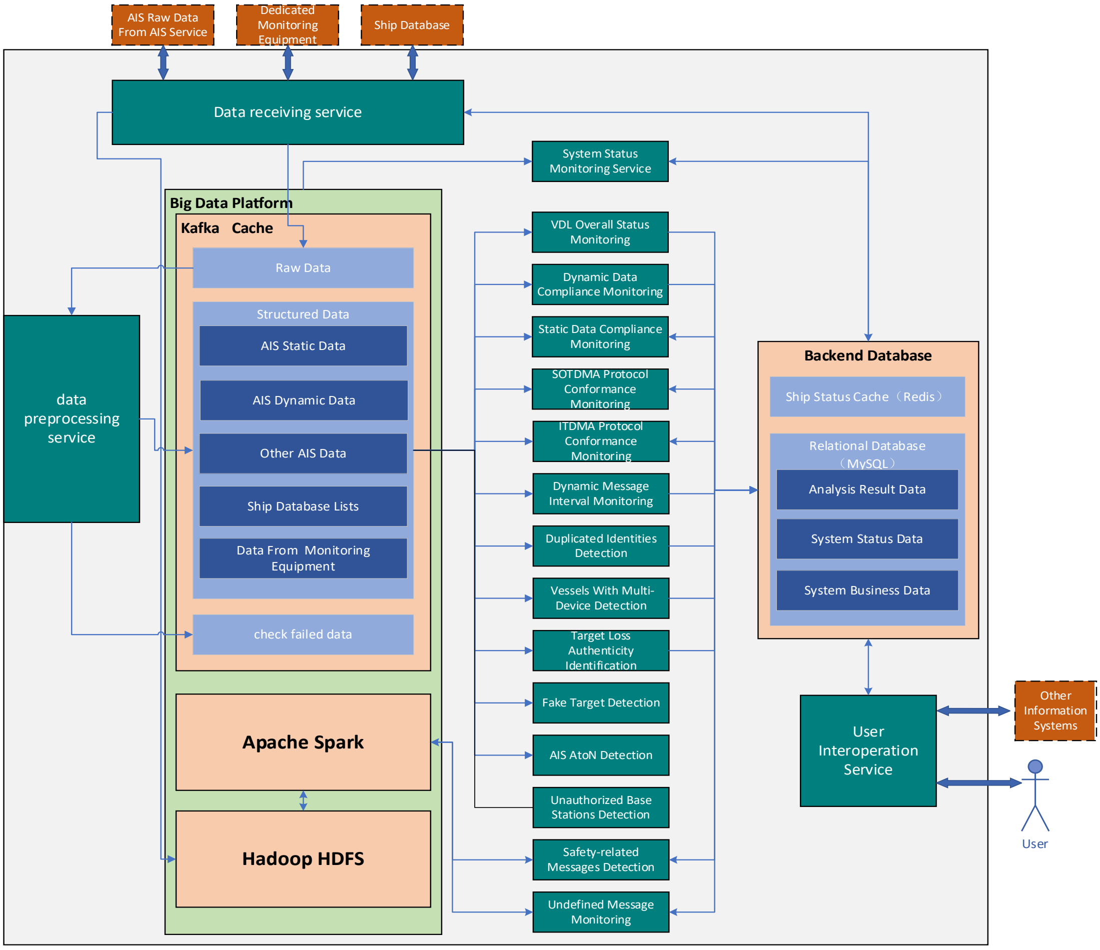

Figure 2: Overall system architecture

The overall system architecture is designed according to data status based on a big data platform. The received data enters the big data platform, where it is cached in Kafka and stored in HDFS. It then undergoes data transformation and computation through various microservices, and the final monitoring results are output to the basic backend database, which presents the results to users through user interaction services. Additionally, the system provides convenient API interfaces for data applications and secondary development, enabling the export of analytical results to other information platforms.

In terms of the computing platform, the system has deployed three real-time computing nodes. Each node is equipped with two Intel Xeon Platinum 8168 processors, 48 cores and 96 threads, 384GB of memory, and 20TB of available disk space to meet the needs of real-time AIS data online analysis and storage.

Besides that, the system has deployed one extra historical data computing node to meet the needs of massive AIS historical data analysis. Its configuration is two Intel Xeon Gold 6226R processors, totaling 32 cores and 64 threads, 768GB of memory and 96TB of available disk space.

The system mainly implements the following functions.

4.1 AIS VDL Status Overview

The system provides an overview of the core AIS VDL indicators, including slot occupancy rate, slot reservation ratio, channel balance, AIS target count, etc. It is easier for administrators to understand the AIS VDL operational status visually.

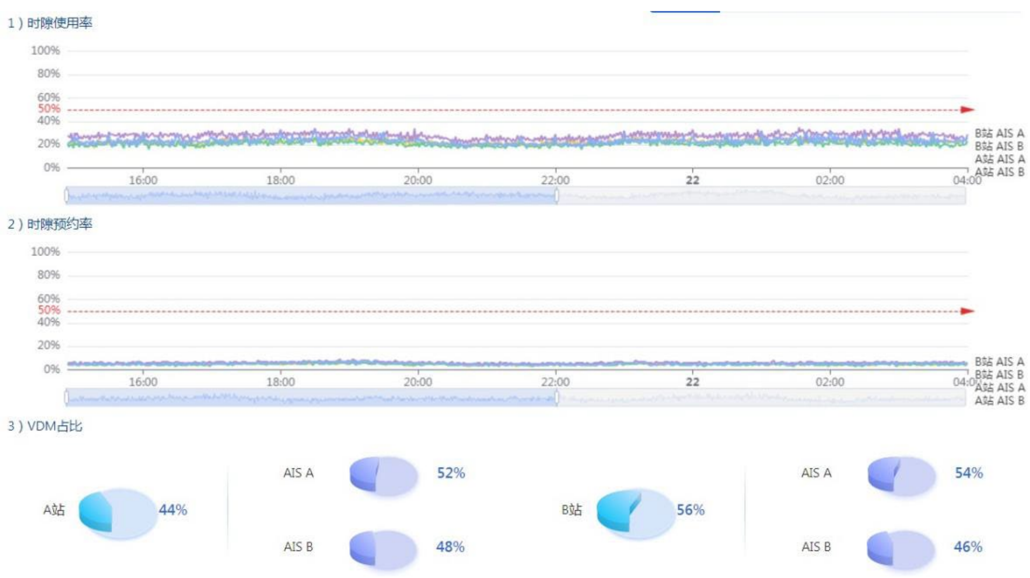

Figure 3: Overview of AIS VDL

4.2 AIS Static Data Compliance Identification and Calibration

The system identifies abnormal vessels based on fields such as MMSI, ship name, call sign, IMO number, type of ship, and dimensions. Ships are classified and displayed using a whitelist and blacklist mechanism. Furthermore, the system automatically matches erroneous fields to the ship database for calibration and output, making it convenient for users to reference. As shown in Figure 4, when the system identifies a vessel with a missing ship type and abnormal dimensions, it automatically adds it to the blacklist, and its icon is highlighted in bright red on the nautical chart. Detailed information of the identified issues can be accessed through a pop-up dialog box, which directs to a page providing the correct ship information for administrators' reference.

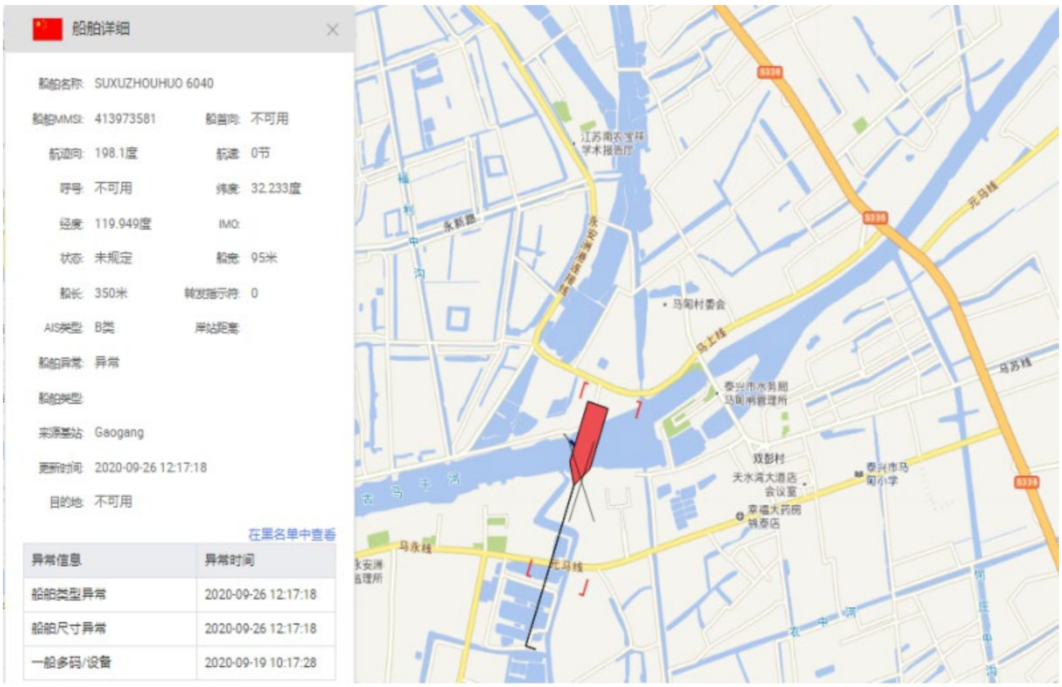

Figure 4: Identification of vessels with incorrectly static data

4.3 AIS Dynamic Data Conformance Identification

As shown in Figure 5, the AIS vessel dynamic data conformance identification service evaluates the compliance of fields such as latitude and longitude, speed, course, and timestamps for vessels, identifying anomalies and pinpointing the corresponding ships.

MMSI	船名(报文)	船名(数据库)	AIS类型	报文类型	异常类型	异常信息
412473060	YUEXINGSHUN 678		A类船台	1号	GPS定位无效异常	经纬度数据为空或默认值
412365772	SURUYUYANG18680		B类船台	18号	GPS定位无效异常	经纬度数据为空或默认值
700060025	不可用		B类船台	18号	GPS定位无效异常	经纬度数据为空或默认值
636019953	CROMARTY SENTINEL		A类船台	1号	GPS定位无效异常	经纬度数据为空或默认值
413265350	RUN HAI DA 5	润海达5	A类船台	1号	GPS定位无效异常	经纬度数据为空或默认值
413554090	JIN_SHUANG_LONG_1	金双龙1	A类船台	1号	GPS定位无效异常	经纬度数据为空或默认值
412522411	QIONGDANZHOU31023		B类船台	18号	GPS定位无效异常	经纬度数据为空或默认值
412352651	SUQIYU02258		B类船台	18号	GPS定位无效异常	经纬度数据为空或默认值

Figure 5: Ships with GPS positioning failure

4.4 AIS Protocol Compliance Identification

Based on the ITU-R M.1371-5 recommendation, the system identifies shipborne AIS device transmission behavior, including SOTDMA protocol compliance, ITDMA protocol compliance, and broadcasting interval protocol compliance. As shown in Figure 6, the system identifies a vessel exhibiting inconsistency between its SOTDMA slot reservation and actual transmission slot, exceeding the acceptable threshold for slot jitter. It is automatically added into the blacklist and highlighted on the interface. We can see which parameters of the shipborne AIS messages do not meet the requirements of the recommendation in the detailed information interface.

Figure 6: Identification of protocol inconsistent devices

4.5 Vessel Validity Identification and Monitoring

This function is used to identify deceptive behavior. It can achieve locking onto vessels with duplicate MMSIs, identification of deviation between voyage information and dynamic data, intelligent recognition of vessels with multiple AIS transponders, and determining instances when the AIS device power has been manually turned off. As shown in Figure 7, the system locks onto a vessel whose receiving base station and reported position cannot form radio communication. In Figure 8, the system identifies and separates the tracks of vessels with duplicate MMSI numbers.

Figure 7: Identification of ships with fake positions

Figure 8: Identification of targets with duplicate MMSI

4.6 Identification of Non-compliant AIS Devices

By analyzing signal characteristics and information features, non-compliant AIS devices, such as fishing mask AIS targets, can be identified. The AIS VDL integrity monitoring system supports marking and output of abnormal targets, helping maritime authorities distinguish between vessel and fishing mask devices. Figure 9 shows the fishing mask AIS targets near Tianjin Port identified by the system on October 14, 2020.

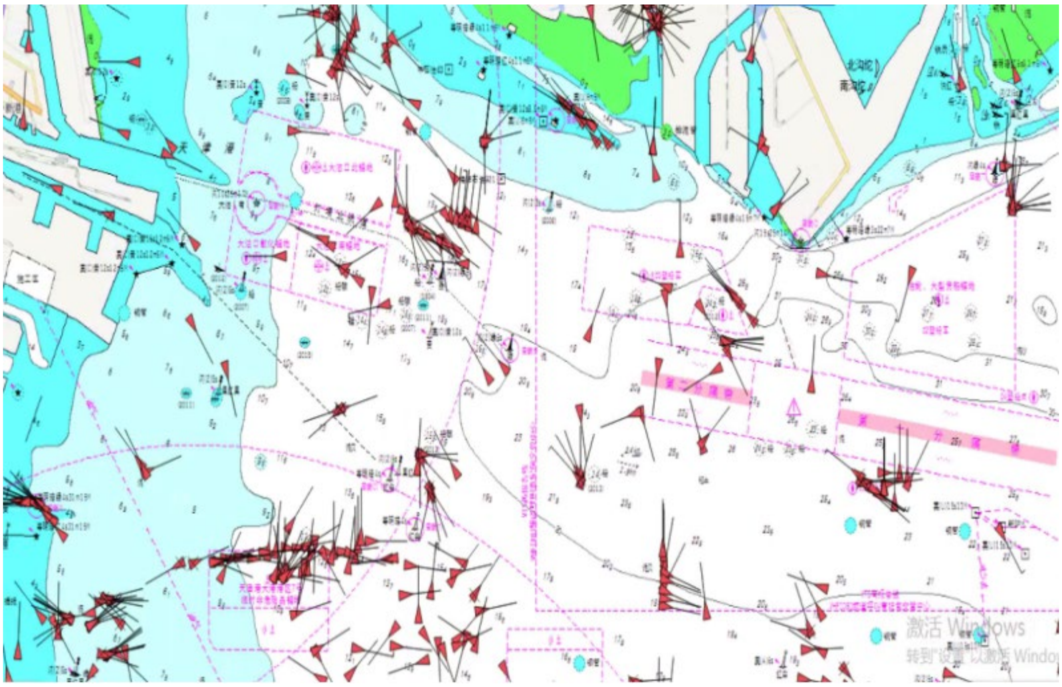

Figure 9: Identification of fishing mask AIS targets near Tianjin Port

4.7 AIS Base Station Monitoring and Identification

AIS VDL integrity monitoring system realizes monitoring and identification functions for base stations, which can be used not only for the management of base stations owned by the China Maritime Safety Administration but also for identifying unauthorized AIS base stations. As shown in Figure 10, we identified an unauthorized base station that reserved a large number of slots through Message 20 but did not use them. The location carried by the base station reports was also false, inconsistent with the receiving base station. In subsequent law enforcement actions, the base station was located through radio direction finding and ultimately shut down.

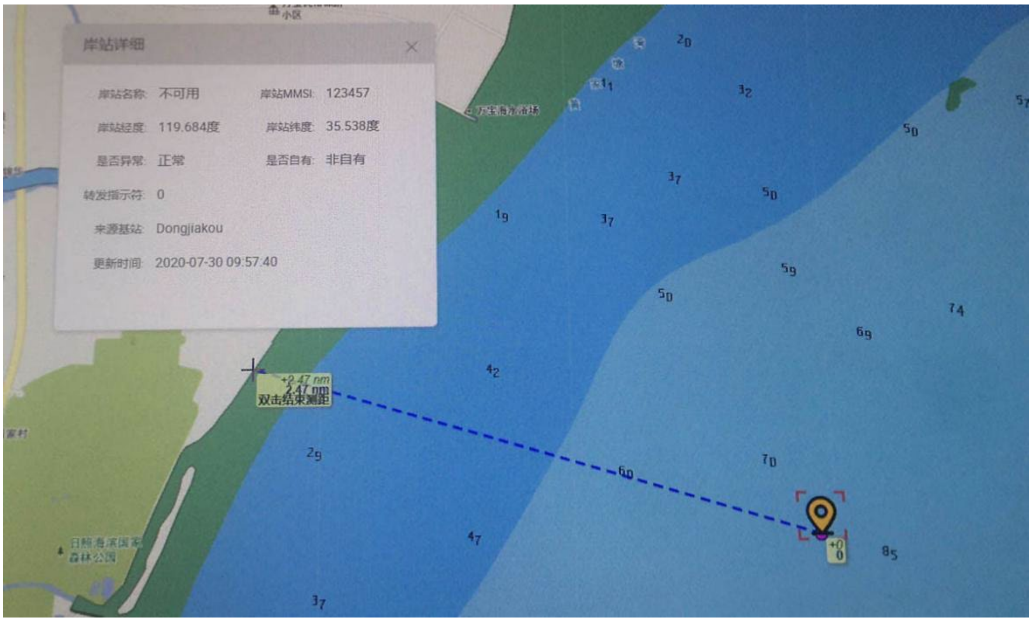

Figure 10: Identification of abnormal AIS base station targets

4.8 AIS AtoN Monitoring

By identifying message type 21 from accessed AIS national data, it is feasible to monitor the performance of AIS AtoN and detect any anomalies. As illustrated in Figure 11, the system identified an AIS AtoN near a port in the Bohai Bay that did not transmit according to FATDMA slot allocation.

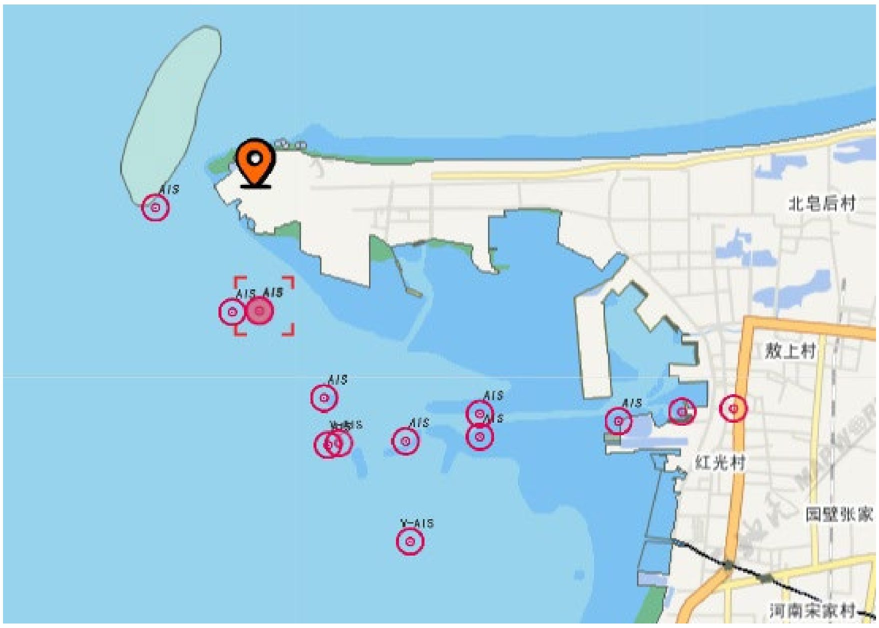

Figure 11: AIS AtoN with Abnormal Working Status

5 AIS VDL MONITORING ACHIEVEMENTS IN LAW ENFORCEMENT

Since June 2020, China Maritime Safety Administration has deployed a lightweight law enforcement app service on Webchat, utilizing the API of the AIS VDL integrity monitoring system. This app provides law enforcement personnel with information on vessels with AIS anomalies, as shown in Figure 12.

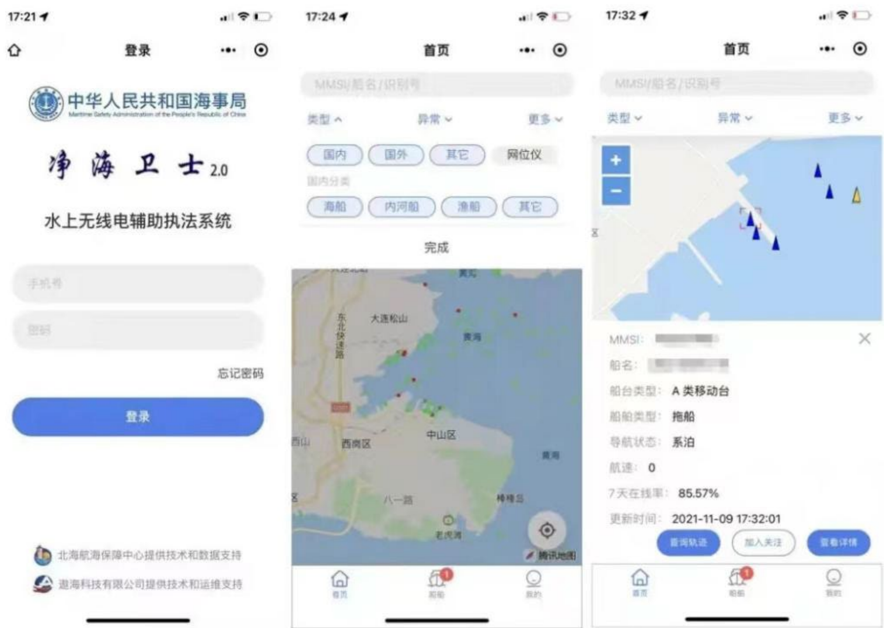

Figure 12: Lightweight law enforcement application on Webchat

Since implementing the AIS VDL integrity monitoring system, it has processed over 600 billion real-time AIS data entries and 1.2 trillion historical AIS data entries. The system has identified a total of 12,850 abnormal targets. This information is directly pushed to frontline maritime law enforcement personnel, providing information support for law enforcement actions and significantly reducing the proportion of abnormal AIS devices along the Chinese coast.

As shown in Figure 13, the proportion of targets with abnormal AIS static data has significantly decreased, dropping from 10.56% in May 2020 to 0.77% in October 2021. As shown in Figure 14, the proportion of AIS targets with duplicate identities also shows an overall downward trend, decreasing from 0.16% to around 0.03%.

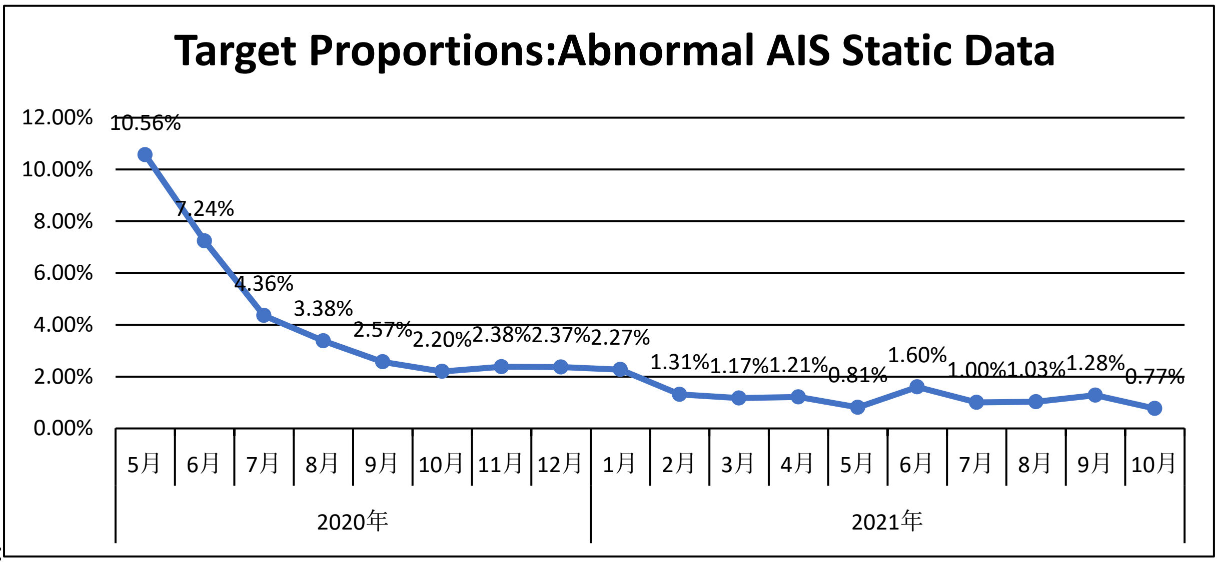

Figure 13: Proportion of targets with abnormal AIS static data

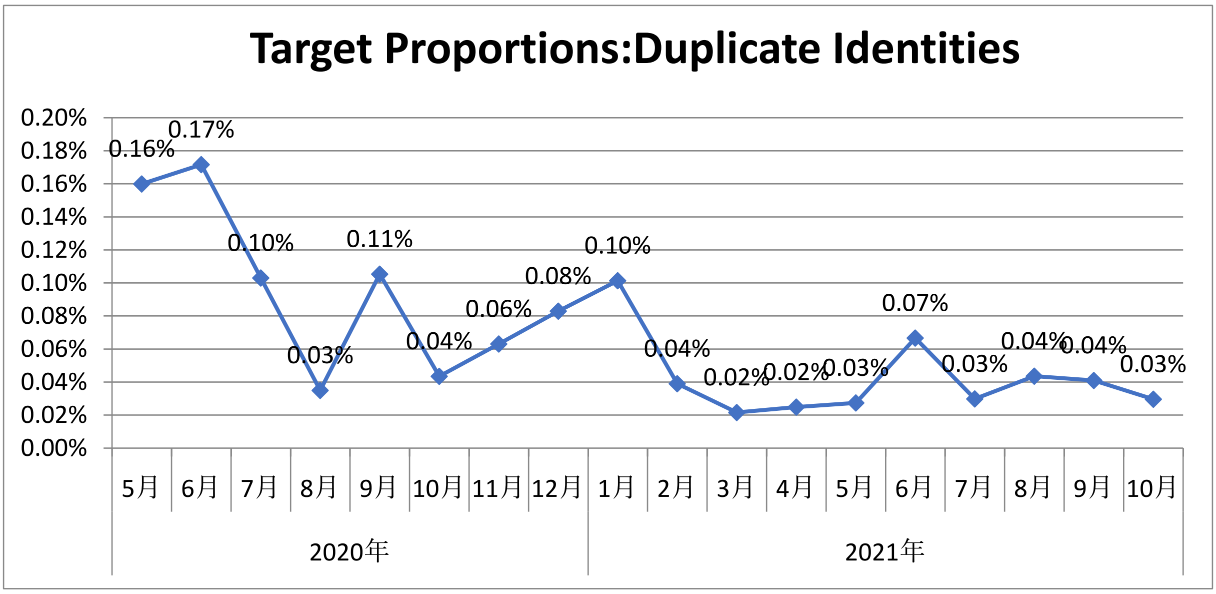

Figure 14: Proportion of targets with duplicate identities

6 CONCLUSION AND PROSPECT

Currently, the protection of AIS VDL has reached a consensus among the international maritime community. In Resolution MSC.140(78), the IMO recognizes the urgent need to ensure the integrity of VDL and recommends that national governments adopt necessary protective measures. IALA R0124 also strongly suggests that designated national authorities take responsibility for managing AIS VDL. The authorities are responsible for collecting AIS data from AIS shore-based systems, and monitoring and protecting VDL. The research and implementation of AIS VDL integrity monitoring presented in this paper demonstrate that effective VDL integrity monitoring can substantially support AIS management and maritime law enforcement. Ultimately, it enhances AIS's operational efficiency and maintains a safe and orderly maritime environment.

In the future, the study and system development of AIS VDL integrity monitoring holds significant potential for further advancement. It includes the integration of new data sources, the application of cutting-edge algorithms, and the development of additional features to bolster system capabilities. Moreover, as AIS is currently evolving towards VDES and given the higher reliability requirements for VDES communications, the monitoring, and protection of future VDES VDL are prerequisites for guaranteeing its effective support for future maritime services. It calls for the industry to concurrently advance VDES applications and promote research and rule-making in VDES VDL monitoring, thereby achieving comprehensive integrity monitoring capabilities during the construction and application phases of VDES.

AUTHOR BIOGRAPHY

Yao Gaole is a senior engineer, specializing in the research and application of digital navigation. He joined the National AIS Centre in 2009 as one of its earliest members. For over 10 years, he has involved in eight AIS construction projects dedicated to improving the operational reliability and application efficiency of Chinese AIS system. He is also responsible for several projects on e-Navigation, VDES and R-mode, as well as developing testbeds and carrying out related verification. Meanwhile, Yao has participated in nine IALA committee sessions, contributing five inputs as a lead author.

S16.2 Authentification in Maritime Communication (133)

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ABSTRACT

The threat of cyber-attacks is increasing over time and there are a number of guidance documents available to support the mariner in identifying and minimising such threats. However, traditionally, maritime safety information (MSI) and maritime Aids to Navigation (AtoN) information are transmitted in open, well publicised, formats and generally taken as being true when received by the mariner. It is well known that mariners are encouraged to not rely on one piece of information, however the risk remains that in a world of software defined radios and downloadable software, that bored teenagers or unscrupulous actors could provide false information to mariners with relative ease, with the result of potentially leading vessels into danger.

This paper looks at the introduction of authentication into maritime communications, it considers how MSI and AtoN information could be protected, considering what information is reasonable to protect and reviewing approaches. It reports the work in this area undertaken by the General Lighthouse Authorities of the UK and Ireland (GLA) to assess the risks associated with different AtoNs, the development and trial of authentication to support virtual AtoNs, and explores how the maritime connectivity platform could help bring authentication into use.

This paper also reports on a live 'over the air' demonstration of an authenticated Virtual AtoN made using authenticated Automatic Identification System (AIS) broadcasts. This we believe is a world first. The technique used is shown to be fully backwards compatible with existing AIS standards and the mariners existing use of AIS.

KEYWORDS: AIS, Authentication, AtoN, VDES, Cyber-Security, Spoofing

1 INTRODUCTION

Over recent years the maritime industry has become increasingly aware of the damage caused by cyber-attacks. Groups such as the International Maritime Organization (IMO) and the UK Department for Transport have warned that the industry is increasingly the target of dedicated, professional cyber-attack [1] [2]. Some successful cyber-attacks have interfered with port operations and vessel control systems and have led to equipment damage, economic loss and loss of reputation. More serious cyber-attacks have the potential to cause a loss of life at sea.

The IMO has therefore taken steps requiring vessel operators to address cyber-security through resolution 'MSC.428(98)' [3] and cyber-security guidelines have been published by various maritime industry bodies intended to assist compliance with MSC.428(98). These include guidance from the Baltic and International Maritime Council [4] and technical standards published by the International Electrotechnical Commission [5].

Whilst these standards aim to improve the security of maritime *systems*, most maritime *communications,* including maritime communications relating to safe navigation, are broadcast openly without any means of authentication. As these communications are unauthenticated, they are vulnerable to spoofing (effectively a form of cyber-attack). Such spoofing attacks are becoming increasingly easy to conduct and have the potential for serious consequences, including the potential to lead a ship into harm. Consequently, steps must be taken to routinely authenticate maritime communications.

This paper describes an approach developed by the authors to authenticate maritime communications in a secure and backwards compatible manner through the use of Public Key Cryptography (PKC). Presented for the first time are successful 'over the air' trials in which the authors broadcast an authenticated AIS Virtual Aid to Navigation (VAtoN) using this technique.

2 DANGER OF SPOOFING ATTACKS

Whilst wired communications links offer a small degree of protection from their being intercepted and/or spoofed by an unauthorised third party, radio communications are inherently vulnerable to such attacks.

Although the interception of radio messages may be prevented by encrypting them (using a secret code to obscure the message contents) encryption is seldom appropriate for maritime messages relating to safe navigation. Such messages must be broadcast openly and 'in the clear' so they may be understood by all vessels, shore stations and other interested parties. However, these messages would benefit from being authenticated to prevent them being spoofed by a malicious actor, thereby providing the user with assurances they are genuine.

Broadcasting spoofed messages is increasingly easy. The availability of cheap software defined radios (SDR) now greatly simplifies the ability for any individual to intercept data and transmit potentially malicious data throughout the radio spectrum. This makes previously difficult to access communications services, such as maritime VHF radio and the Automatic Identification System (AIS) easily accessible to cyber-criminals. Furthermore, open-source software is easily available for use with SDR that allows relatively unskilled actors to spoof Global Positioning System (GPS) and AIS broadcasts [6] [7]. It is suggested that as such software develops and hardware becomes ever cheaper, spoofing many types of radio messages will become within the ability of even the most unskilled actor.

Given the above, it is recommended that steps are taken to begin authenticating all maritime communications as a matter of ordinary routine, though it is acknowledged this will be challenging and is unlikely to be accomplished in the near term. Nonetheless, priority should be given to authenticating those message types likely to cause the most harm if spoofed, and ensuring that any new systems under development incorporate an authentication mechanism as standard.

The mariner will routinely take in data from multiple sources, such as from the ships AIS receiver and radar systems as well as visually, and is encouraged not to rely on a single piece of information; thereby providing a degree of protection from spoofing. However some messages, such as Differential Global Navigation Satellite System (DGNSS) corrections sent via AIS (known as AIS 'Message 17') and AIS Virtual AtoN[4] broadcasts (that use AIS 'Message 21'), cannot be verified by another means and in these circumstances, the mariner is forced to rely on a single source of information. This is further compounded as the mariner will not normally know the legitimate position from which these messages are broadcast, meaning radio direction finding techniques are useless in helping determine the message is from a genuine actor. It follows that spoofing messages such as these presents an attractive target for cyber-attacks and priority should be given to providing them with a means of authentication.

3 APPROACH TO AUTHENTICATION

The authors have previously published work describing their approach to authenticating maritime communications, and more specifically authenticating AIS communications, using Public Key Cryptography (PKC) [8] [9]. Whilst the reader is directed towards these references for a complete description of the technique, an overview is provided here for completeness as follows:

PKC is a widely used technology, described in detail by the authors in [10]. PKC makes use of public and private 'keys', essentially mathematical codes. The message sender uses a private key (kept secret and known only to them) to digitally sign data transmissions. Any recipient may then use a corresponding and openly available

[4] A Virtual AtoN (VAtoN) has no physical presence but is instead displayed electronically on an Electronic Chart Display and Information System (ECDIS).

public key to verify the digital signature to confirm authenticity. Such digital signatures prove that transmissions are authentic and originate from the vessel or entity they purport to be from and not a malicious third party.

The PKC use of separate public and private keys provides an enormous advantage over other cryptographic techniques as users do not need to meet beforehand to agree on a common shared secret key (such as a shared secret password); something which is clearly impractical for most maritime use cases.

The authors' method for authenticating AIS messages using a PKC digital signature is described in Figure 1 (adapted from a figure first shown in [8]). In this example, an AIS base station broadcasts an 'ordinary' Virtual AtoN using AIS Message 21. This is then followed by a digital signature contained within a second 'follow on' AIS message, namely an AIS 'Message 8' or AIS binary message broadcast.

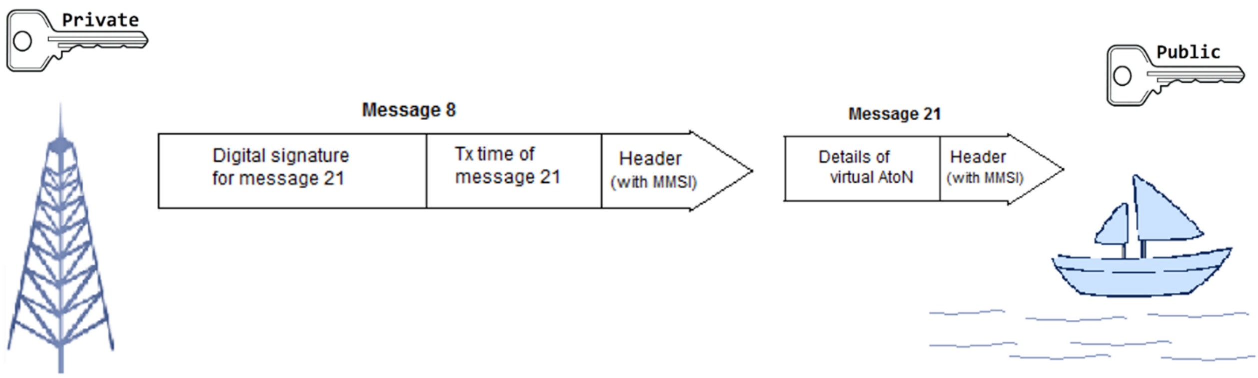

Figure 68: Representation of a Virtual AtoN (Message 21) broadcast, followed by a broadcast containing a digital signature (Message 8).

The first AIS Message 21 is a standard AIS message which will be received by any AIS-equipped vessel within range, thereby displaying the Virtual AtoN on the vessel's bridge in the ordinary manner. However, vessels so equipped, and in possession of the AIS base station public key certificate, may optionally use digital signature contained within the 'follow on' AIS Message 8 to confirm the authenticity of the previous Message 21, thereby confirming the Virtual AtoN was broadcast by the AIS base station and not an imposter. The inclusion of the 'Tx time of message 21' (i.e. the broadcast time of the Virtual AtoN message) in the Message 8 broadcast helps the recipient determine the correct Data Message (i.e. the correct Message 21) to which the signature applies [8]. This is an important consideration, given that a user will normally be in receipt of multiple AIS messages from many different sources to which the signature could apply.

Whilst the above example relates solely to AIS, the technique of carrying the digital signature in a separate follow on message (thereby leaving the Data Message uncorrupted and so retaining backwards compatibility) is quite flexible and may be used to authenticate a variety of communication types. Work by the authors has extended the same technique to authenticating messages sent via the VHF Data Exchange System (VDES) [8] and has extended to carrying signature messages used to sign AIS messages in VDES message space, thereby avoiding any additional loading on the crowded AIS channels [9].

In using PKC, various algorithms are available offering differing levels of speed and security. The preferred option chosen by the authors, and used in the demonstration described in the following section, is the Elliptic Curve Digital Signature Algorithm (ECDSA) using a 256 bit key size. This combination offers a robust degree of security whilst producing digital signatures just 512 bits in size and therefore small enough to fit within the limited message space available [8].

A potential difficulty with PKC relates to 'key management'. In particular, users must be certain that the Public Keys they have been given belong to the entity (such as an AIS base station) that they purport to be from and not an imposter. The topic of key management will not be addressed by this paper, though it is noted that the authors preferred approach is to make use of the Maritime Identity Registry (MIR) component of the Maritime Connectivity Platform (MCP) [9] [11].

4 LIVE DEMONSTRATION

To conduct broadcast trials, a licence was obtained from the UK spectrum regulator, OFCOM, allowing the use of AIS and VDES frequencies within designated UK waters for experimental purposes on a non-interference basis.

The demonstration was conducted in March 2022 and elected to broadcast an authenticated Virtual AtoN. So as not to cause confusion to nearby vessels, the Virtual AtoN was programmed to appear in a designated GLA buoy testing ground, known as the 'Cork Hole'. ECDSA public and private keys were first generated and issued, using the MIR, to the 'GRAD' AIS base station and to 'THV Alert', a General Lighthouse Authorities (GLA) ship. The Virtual AtoN and the signature message were then broadcast from the base station and received using equipment installed aboard THV Alert. This is represented in Figure 2.

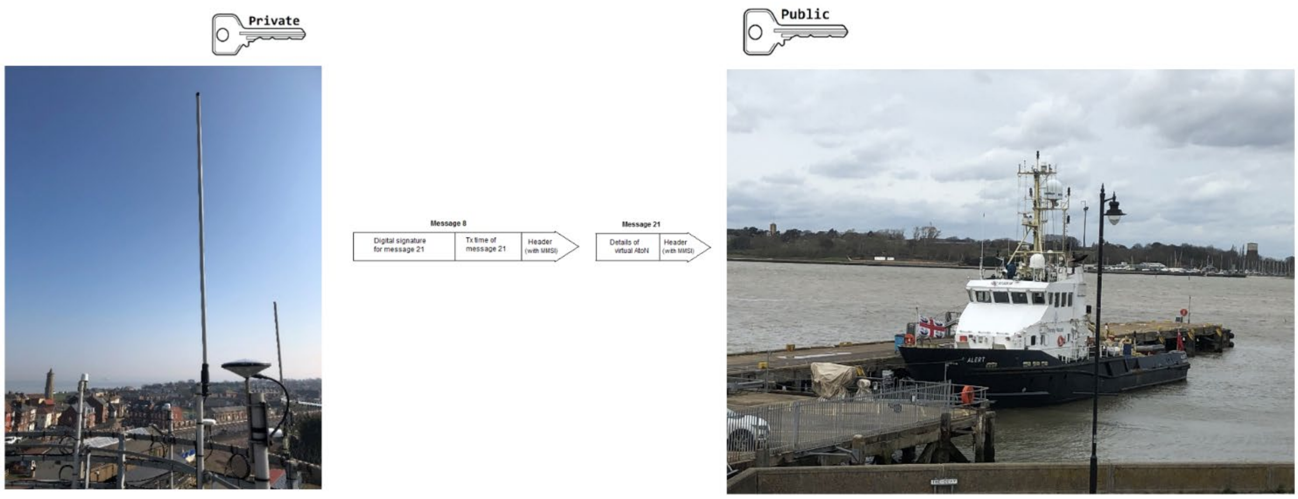

Figure 69: Trials involved the broadcast of a Virtual AtoN (using AIS Message 21) and an associated digital signature (using AIS Message 8) from the GRAD AIS base station (left) to a GLA ship, THV Alert (right).

Figure 3 shows a schematic representation of the equipment setup. On the left is the equipment used to broadcast the AIS messages, namely a VDES 1000 unit connected to a local laptop computer. On the right is the equipment used aboard THV Alert to receive and decode the messages.

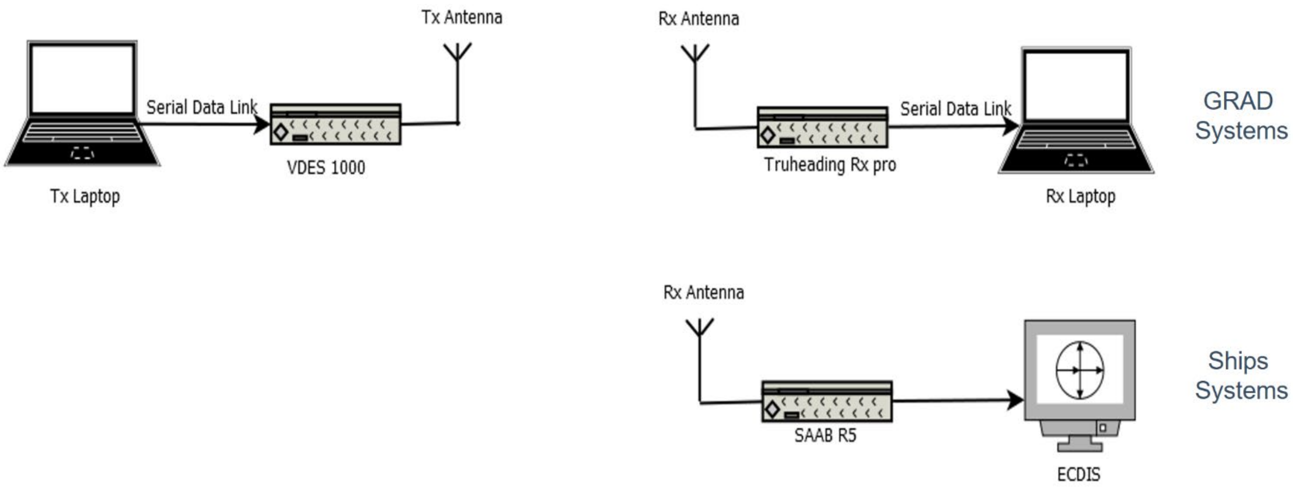

Figure 70: Schematic representation of the transmitter hardware (left) and equipment used to receive the messages installed on the ship (right).

It can be seen that two sets of equipment were installed aboard the ship. On the top is the experimental GRAD system. This uses a Truheading Rx Pro AIS receiver, passing data from this receiver into a laptop computer for further processing. On the bottom is the ship's 'ordinary' AIS equipment, namely a SAAB R5 AIS transceiver, passing data to the ship's Electronic Chart Display and Information System (ECDIS).

Figure 4 shows images taken from aboard THV Alert and shows the outcome of a demonstration in which an authenticated Virtual AtoN with the name 'Cork Hole Test' was broadcast from the GRAD AIS base station.

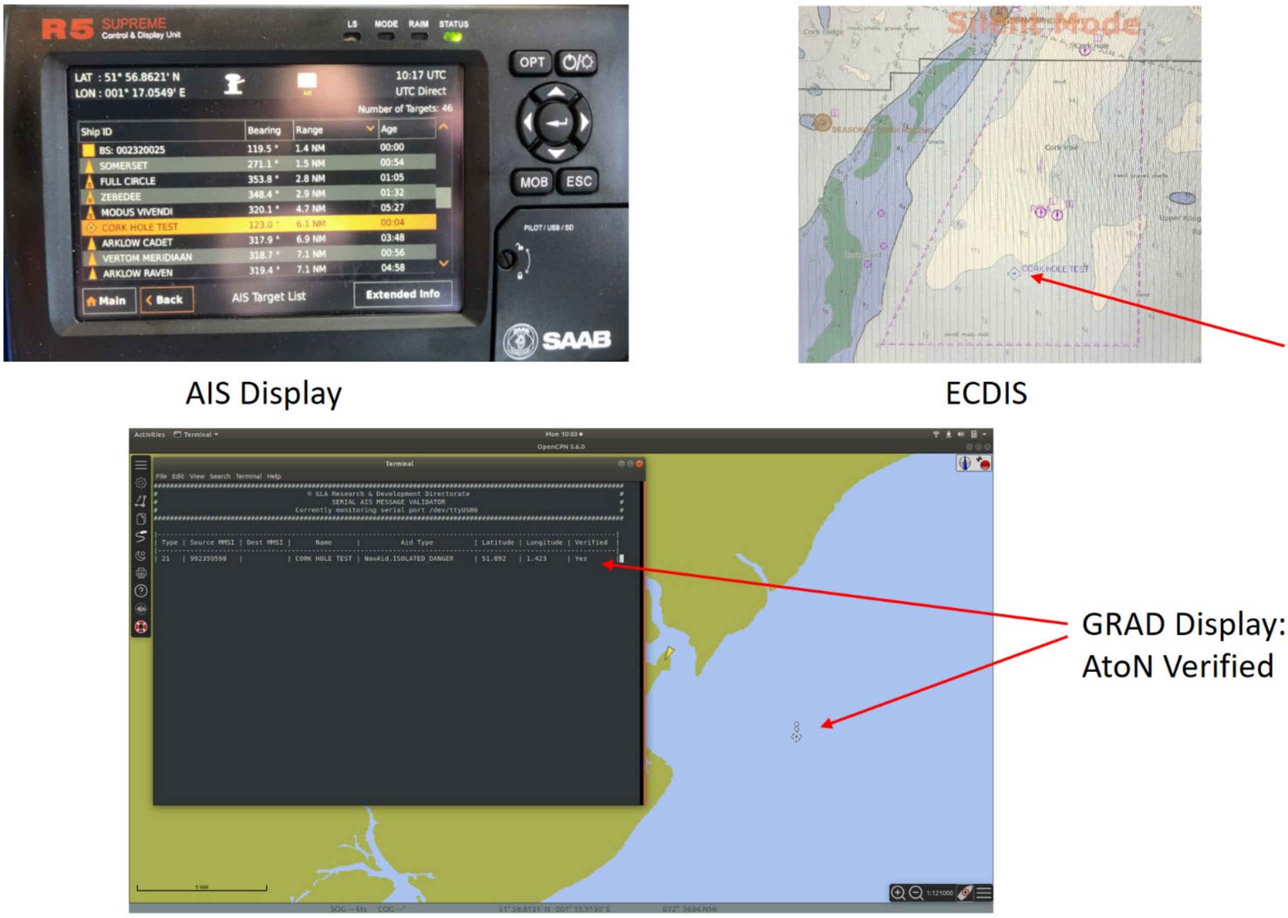

Figure 71: Authenticated AIS Virtual AtoN, as seen aboard THV Alert.

To the top of Figure 4 are shown photographs of THV Alerts AIS display and ECDIS screen. On both of these displays the Virtual AtoN, ‘Cork Hole Test’, appears correctly in its designated position. This demonstrates that the VAtoN appears on the ship’s bridge displays in the ordinary manner and that the system is backwards compatible.

At the bottom of Figure 4 is a screenshot from the GRAD laptop. The laptop processes both the VAtoN message (Message 21) and the follow on signature message (Message 8) that was ignored by THV Alert’s AIS transceiver and ECDIS. By using the follow on signature message, the GRAD laptop is able to verify the message as genuine (the word ‘Yes’ appears in the verified column on the text display) and the Virtual AtoN is plotted on the laptop’s chart display.

The above steps were then repeated, this time broadcasting a Virtual AtoN that had been deliberately spoofed, signed using a key belonging to an unauthorised third party, and given the name ‘Cork Hole Spoof’. Figure 5 shows images taken from aboard THV Alert showing the outcome of this demonstration.

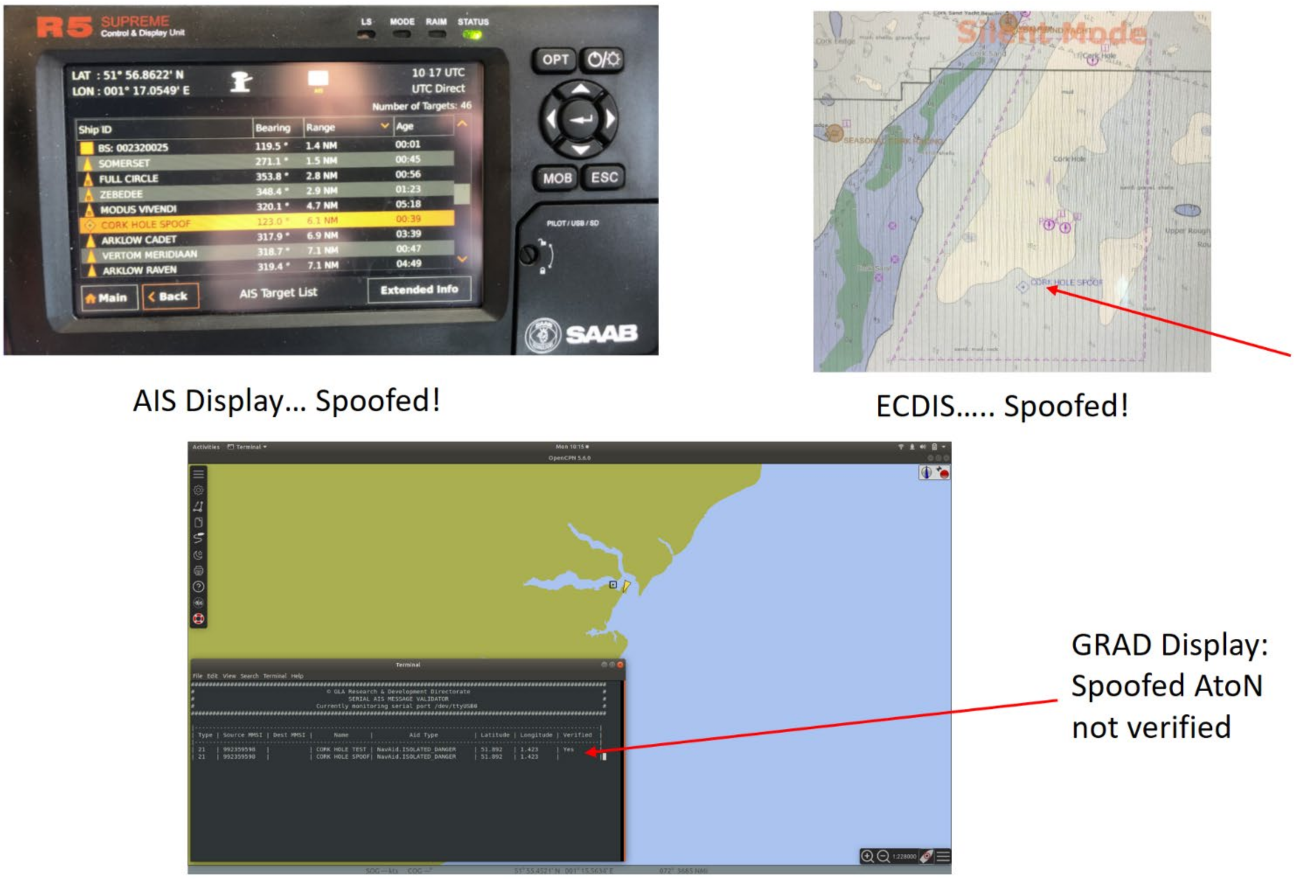

Figure 72: Spoofed AIS Virtual AtoN, as seen aboard THV Alert.

To the top of Figure 5 are shown photographs of THV Alert's AIS display and ECDIS screen. On both of these displays the spoofed Virtual AtoN, 'Cork Hole Spoof' appears, thereby showing the vulnerability of the ships 'ordinary' systems to spoofing.

At the bottom of Figure 5 is a screenshot from the GRAD laptop. This processes the VAtoN message (Message 21) and the follow on signature message (Message 8) and detects that the signature does not match or is otherwise corrupted. The Message 21 is therefore not verified (the verified column text display is blank) and consequently, the Virtual AtoN is not plotted on the laptop's chart display.

Whilst the above shows the technique to be practical, it is noted that the above is a 'proof of concept' demonstration and that further work will be needed in order to integrate the display of authenticated data onto the ECDIS in an intuitive manner.

5 CONCLUSION

The spoofing of radio communications is becoming ever easier and it is vital sensitive maritime communications systems are authenticated to secure them against spoofing. Without a means of authentication, such systems may eventually be regarded as unsafe to use.

Presented is a practical method of authenticating maritime communications using Public Key Cryptography (PKC). Also presented is the outcome of a demonstration in which an AIS Virtual AtoN was authenticated using PKC 'over the air' in what we believe is a first. The technique used is shown to retain backwards compatibility with the mariners' existing use of AIS.

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AUTHOR BIOGRAPHY

Gareth Wimpenny is a research and innovation engineer with the General Lighthouse Authorities of the UK and Ireland. His work is principally focused on maritime communications and e-Navigation. Specific areas of research have included work on the VHF Data Exchange System (VDES), GNSS vulnerabilities and maritime cyber-security; particularly the securing and authentication of e Navigation communications.

S16.3 VDES R-Mode (130)

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ABSTRACT

R-Mode is the concept of adding a timing signal to existing maritime infrastructure. While the original approach considered marine radiobeacons and AIS base stations, it was quickly recognized that the VHF Data Exchange System (VDES) is a better candidate due to the additional bandwidth and stage of development.

This paper reports on work of the General Lighthouse Authorities of the UK and Ireland in support of VDES R-Mode. It introduces the in-house modelling capability and explains how it was employed to investigate several system configuration options, modelling the operational impact and performance of different numbers of base stations in view and with different clock configurations. Such a model can be used to support VDES and AIS R-Mode system planning as well as identifying potential usable regions and expected performance.

Furthermore, this paper provides an overview of a novel concept of a VDES R-Mode transponder. A lightweight, reduced-functionality VDES base station designed to be autonomous and installed offshore. A simple system that may be used to enhance positional accuracy in regions with limited base stations along a coastline, where a signal from further out to sea could make all the difference to the mariner.

KEYWORDS: VDES, R-Mode, coverage prediction, positioning accuracy

1 INTRODUCTION

Maritime navigation relies heavily on Global Navigation Satellite Systems (GNSS) to obtain accurate positioning, navigation and timing (PNT) information worldwide. However, GNSS services are vulnerable to threats such as radio frequency interference, jamming, spoofing and satellite or constellation-wide failures [1]. These threats have the potential to compromise the safety and efficiency of maritime operations, as demonstrated by a 2017 study by London Economics [2]. The study estimated that a five-day GNSS outage would result in a loss of £5.2bn to the wider UK economy, with the maritime sector accounting for approximately 21% of the loss.

Given the potential impact of disruptions to GNSS services, there is a need to develop and implement alternative PNT sensors and systems capable of mitigating their effects. One promising approach is ranging off maritime radio communication transmissions in the Medium-Frequency (MF) and Very High Frequency (VHF) bands, commonly known as 'Ranging Mode' (R-Mode). This paper focuses on the VHF variant of R-Mode.

The concept of R-Mode was first introduced in a 2008 paper by the German Federal Waterways and Shipping Administration (WSV) [3], which identified the Automatic Identification System (AIS) as a potential candidate technology for R-Mode. The European Union-funded 'Accessibility for Shipping, Efficiency Advantages and Sustainability' (ACCSEAS) project conducted an initial feasibility study of AIS R-Mode, exploring four potential approaches based on different ranging waveform options. All options assumed that R-Mode transmissions would be accurately synchronized to a common timescale to support passive (pseudo)ranging, as is done in GNSS. The study recommended using the standard AIS waveform for ranging [4].

Further research into AIS R-Mode was conducted by the Dalian Maritime University (DMU) in China, resulting in the development of a prototype positioning system, including a real-time propagation correction subsystem [5]–[8].

Recently, investigations have expanded to include the next-generation evolution of AIS – the VHF Data Exchange System (VDES). VDES aims to safeguard the core functions of AIS while providing enhanced, globally standardized data exchange capabilities supporting maritime digitalisation, in line with the International Maritime Organization's (IMO) concept of e-Navigation [9], [10].

A previous publication by the authors has shown that VDES transmissions offer significantly improved ranging performance compared to AIS, with statistical performance bounds on the ranging error established for all radio waveforms proposed for use in terrestrial VDES communications [11]. The analysis was extended to the satellite components of VDES in a further publication by the authors [12].

The feasibility of a combined terrestrial and satellite VDES R-Mode service concept was examined by the European Space Agency (ESA) funded 'Augmenting GNSS to Prevent Loss of Service' (ANGELOS) project [13], while another ESA-funded project, 'Maritime Resilience and Integrity in Navigation' (MarRINav), considered VDES R-Mode as a component of a Resilient PNT 'system of systems' designed to meet the needs of maritime shipping in the UK [14].

The R-Mode Baltic project and its follow-up, R-Mode Baltic 2, established an MF/VDES R-Mode testbed in the Baltic Sea region, undertaking various activities such as designing novel ranging waveforms for VDES R-Mode and conducting related performance analyses [15].

This paper reports on work conducted by the General Lighthouse Authorities of the UK and Ireland (GLA) to support the development of VDES R-Mode. The paper is structured as follows: Section 2 provides an overview of the requirements for VDES R-Mode, its architecture and signal design as envisaged by IALA. Section 3 describes a coverage and performance modelling capability developed by the GLA. In Section 4, the feasibility of establishing a VDES R-Mode service in the waters surrounding the UK and Ireland is examined. Sections 5 and 6 discuss the remaining technical challenges facing VDES R-Mode and outline potential solutions, while Section 7 summarizes the conclusions.

2 VDES R-MODE OVERVIEW

2.1 Stakeholder's Requirements

R-Mode operates by measuring the time of flight, or Time of Arrival (TOA), of radio signals to estimate the distance between the user and multiple transmitting stations with known positions. With sufficient stations available, the user's position can be determined by multilateration. The desired characteristics of VDES R-Mode were documented in a series of IALA working papers [16]–[20], with key requirements and design goals outlined below.

The VDES R-Mode system shall output *signal observables* and *navigation data* to enable an external *PNT Data Processor* to determine the user's position with the required accuracy, integrity, availability, continuity and at the required fix rate, as specified in IALA Recommendation R-129, 'GNSS Vulnerability and Mitigation Measures' [1]. The relevant required navigation performance parameters are summarized in Table 1 below.

The system shall support navigation in coastal waters, ideally covering as much of a state's Exclusive Economic Zone as possible, as well as navigation in port approaches, restricted waters and inland waterways.

All transmissions originating from a VDES R-Mode system shall be synchronized to a common time scale traceable to UTC.

The system shall operate in accordance with ITU Radio Regulations, Article 28, 'Radiodetermination services', and allow integration within Multi-system Shipborne Radionavigation Receivers (MSR) compliant with IMO Resolution MSC.401(95) [21].

Where R-Mode observables are used with measurements from other ranging systems, such as eLoran, to form a tightly-coupled integrated position solution, the system should accept a local clock signal so that the measurements from all systems used can be referenced to a common time scale. This eliminates the need to determine inter-system clock biases, thus reducing the number of observables required to produce a position solution.

The system should use no more than 8% of the VDES time slots[5] available on any given VDES frequency channel and should allow an unlimited number of vessels to make ranging measurements simultaneously.

Additionally, the system should be designed to consider cyber-attacks, including jamming and spoofing, so that such events can be detected and their effects mitigated.

Table 12 Minimum performance requirements for general navigation as per IALA R-129 – backup system.

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

To better understand the role of VDES R-Mode within the realm of PNT systems, it is helpful to consider the different categories of alternative PNT systems defined in IALA Recommendation R-129. These categories include:

(i) *redundant systems*, which provide the same functionality as GNSS and allow for seamless transition with no change in procedures;

(ii) *backup systems*, which ensure continuation of the navigation application, but not necessarily with the full functionality of GNSS; and

(iii) *contingency systems*, which allow for safe completion of a manoeuvre, but may not be adequate for long-term use.

Additionally, a fourth category can be defined for systems that can mitigate the impact of a GNSS disruption at the user's location but may be susceptible to GNSS disruption at the site(s) of the system's infrastructure. Such systems are referred to as (iv) *mitigation systems* [22].

VDES R-Mode systems can be configured as any of the latter three categories (ii-iv), depending on the transmission synchronization approach used and the available budget. Due to design constraints, such as using land-based transmitters and a relatively narrow signal bandwidth, the fully redundant system category (i) is not considered achievable for R-Mode technology. Different stakeholders may choose a different approach depending on the perceived level of risk from GNSS malfunction. For instance, the R-Mode Baltic project viewed R-Mode as a contingency system with a holdover capability of at least 2 hours, whereas the IALA ARM Committee suggests that R-Mode, of any variety, should be considered as a backup to GNSS, providing essentially infinite holdover capability.

2.2 System Architecture

IALA has played an important role in harmonizing the development of R-Mode technologies, with the present agreement on the architecture and detailed technical characteristics of the VDES variant described in IALA Guideline G1158, 'VDES R-Mode' [23]. However, it is important to note that this work is still in progress, and there are several technical challenges and uncertainties remaining, as discussed in Section 5. Therefore, the final design remains open at this stage.

[5] VDES uses Time Division Multiple Access (TDMA) with 2250 time slots established every 60 seconds.

The baseline system architecture includes a network of R-Mode enabled VDES Base Stations and Monitor Stations, shipborne VDES R-Mode Sensors/Transceivers and one or more Monitoring, Control and Security Centre(s). Each component is considered in turn.

The *Base Stations* transmit accurately timed ranging signals and navigation data, as described in more detail in Section 2.3. They are equipped with high-stability clocks that are kept synchronized to a common time scale using either GNSS or other means independent of GNSS, such as two-way satellite frequency and time transfer or optical fibre time transfer technologies. If synchronization is lost, the Base Station clock will drift at a rate dependent on its frequency stability (which is commensurate to its cost), until it is no longer considered usable for ranging. The holdover times for a 10-meter equivalent ranging error are in the order of minutes for an oven-controlled crystal oscillator (OCXO) clock, hours for a Rubidium clock, and days when a Caesium clock is used [24].

The Base Stations will primarily be land-based, reusing as much of the existing AIS and future VDES shore-side infrastructure as possible. However, some off-shore stations may also be required to ensure good geometry for positioning, as discussed further in this paper.

The shipborne *VDES R-Mode Sensor* measures the timing and other parameters of the received R-Mode signals and outputs the signal observables, along with the navigation data, to a PNT Data Processor, which may be part of the IMO MSR mentioned previously or another system. It is assumed that the shipborne equipment is receive-only (passive) and uses a relatively low-cost, likely crystal-based, clock. Consequently, signals from at least three stations need to be received to allow the PNT Data Processor to solve for the user's latitude, longitude and the local clock bias. This navigation technique will be referred to here as 'passive (one-way) *pseudoranging* with three or more signals'.

The *Monitor Stations* perform a critical function in ensuring the integrity of the positioning system. They assess the system's capability to compute a position solution based on R-Mode signals received off air, detect system faults, and communicate alerts to the Monitoring, Control & Security Centre for subsequent action.

The Monitor Stations can also serve as differential reference stations, producing real-time corrections that R-Mode Sensors can use to correct for signal propagation delays, which can vary depending on environmental factors. By doing so, they help maintain the positioning accuracy to the user requirement. These corrections can be disseminated to the users via a relevant VDES Base Station or another communication channel with guaranteed latency. The need for real-time differential corrections is currently one of the design unknowns in VDES R-Mode, as discussed in Section 5.2.

The *Monitoring, Control & Security Centre* plays a critical role in the system's operation and management, overseeing the system 24 hours a day. Its responsibilities include maintaining the system's synchronization within agreed tolerances, monitoring the status of technical installations at the Base Station and Monitor Station sites and initiating corrective action if out-of-tolerance conditions are detected. The Centre is also responsible for configuring remote equipment and software, as well as providing cryptographic services to the other system components.

In addition to the core components mentioned above, there may be other system components, such as dedicated wide-area networks and time transfer infrastructure, GNSS interference monitors, e-navigation data centres and maintenance centres.

2.3 Signal Design

2.3.1 VDES Communications Waveforms

The technical characteristics of VDES are described in Recommendation ITU-R M.2092 [25]. VDES comprises three subsystems, each optimized for different use cases. These subsystems include the original AIS and two new technological concepts known as 'Application Specific Message' (VDES ASM)[6] and 'VHF Data Exchange' (VDE). The subsystems use different frequency channels and radio waveforms, as described below. While each subsystem has both terrestrial and satellite components, this section will only focus on the terrestrial VDES components.

AIS uses two simplex (single-frequency) channels with a 25 kHz bandwidth in the upper section of the maritime mobile VHF band, known as AIS 1 and AIS 2. The second VDES subsystem, VDES ASM, operates on two 25 kHz-bandwidth channels adjacent to AIS 1 and AIS 2. The terrestrial component of VDE (VDE-TER) uses two blocks of spectrum, each 100 kHz in bandwidth, located in the lower and upper sections of the maritime mobile VHF band, with a separation of 4.6 MHz between them. VDE-TER can be configured for either simplex or duplex (dual-frequency) operation.

Access to the VDES channels is coordinated using Time Division Multiple Access (TDMA) techniques. The longest unit of time used in the VDES TDMA hierarchy is referred to as a *frame*. A new frame is established every minute and is uniformly divided into 2250 *time slots*.

VDES transmissions can occupy a varying number of time slots and use a range of channel bandwidths, modulations and Forward Error Correction (FEC) rates. For example, the AIS uses transmission bursts 1 to 5 time slots in duration. The channel bandwidth and modulation are fixed in AIS, and FEC is not used. On the other hand, the terrestrial VDES ASM component uses transmissions 1, 2 or 3 time slots in duration and FEC rates of 1 (no FEC) or ¾, giving rise to six transmission configurations, referred to as '*Link IDs*'.

The VDES specification further defines three Link IDs for terrestrial VDE data transmission, with an additional six marked as optional. The three Link IDs currently recommended for use in VDE-TER allow channel bandwidths of either 25 kHz or 100 kHz and support the use of an adaptive modulation and coding scheme, enabling reliable and efficient communication under a wide range of channel conditions. All VDE-TER Link IDs use single-slot transmissions.

The VDES communications waveforms introduced above provide the foundation for the design of the VDES R-Mode waveforms. The R-Mode signal consists of two components: the *Ranging Signal* and the *Navigation Data Signal*, detailed in the following two subsections.

2.3.2 R-Mode Ranging Signal

The Ranging Signal has been specifically designed to facilitate precise measurement of the signal's TOA by correlating the received signal with a locally generated replica. The TOA measurements are then converted into (pseudo)ranges[7] for use in positioning. The ranging precision achievable at a particular Carrier-Power-to-Noise-Density Ratio, C/N_0, (or Signal-to-Noise Ratio, SNR), is primarily dependent on the shape of the signal's autocorrelation function and the transmission duration. The former is a function of the signal's bandwidth, along with the modulation type and symbol sequence employed.

Previous research by the authors has shown that single-slot VDE-TER waveforms with a 100 kHz-bandwidth provide superior ranging performance over the narrower-bandwidth VDES waveforms, including 5-slot AIS transmissions [11]. Consequently, the IALA Guideline G1158 [23] recommends a 100 kHz-bandwidth VDE-TER waveform (specifically, Link ID 37) for ranging purposes.

The VDES specification [25] defines four Link IDs (namely, Link ID 35 to 38) that facilitate the use of custom symbol sequences optimized for ranging. These Link IDs bypass the CRC[8] and FEC operations otherwise

[6] Not to be confused with AIS Application Specific Messages (AIS ASM).
[7] The term 'pseudorange' is used rather than 'range', owing to the inherent bias in the measurements caused by the R-Mode Sensor's clock not being synchronized with the system time. As the clock bias is unknown a priori, it needs to be obtained as part of the position solution or by other means.
[8] Cyclic Redundancy Check

performed by the VDES transceiver, which could alter the sequence and its correlation properties (and therefore the ranging accuracy).

References [12], [26] show that the use of repetitive or, in the extreme, alternating symbol patterns results in higher ranging precision at mid-to-high SNR (or at closer range), whereas pseudorandom (noise-like) patterns perform better in low-SNR conditions. By concatenating alternating symbol sequences with pseudorandom ones, it is possible to minimise the ranging error across a given range of SNRs by controlling the ratio of the number of alternating to pseudorandom sequence symbols used. The actual number of alternating symbols used expressed as a fraction of the total length of the ranging sequence is referred to as the 'γ factor' in IALA G1158 and is communicated to users via the Navigation Data Signal.

VDES Base Stations send Ranging Signal transmissions at regular intervals of 1-2 seconds in accordance with the 'fix interval' user requirements stated in Table 1.

2.3.3 R-Mode Navigation Data Signal

The Navigation Data Signal carries supporting data necessary for the PNT Data Processor to acquire a position solution and accurate time. This includes Base Station Identity (up to 16 stations within a system can be defined), R-Mode System Time corresponding to the beginning of the current VDES frame, R-Mode System Time to UTC conversion, Base Station clock and equipment delay corrections, signal health status, Base Station transmitting antenna coordinates and the 'γ factor' introduced in the preceding subsection.

The Navigation Data is transmitted once per minute, in turn, by all Base Stations in a system. To ensure maximum coverage, a robust VDE-TER waveform with a bandwidth of 25 kHz (namely, Link ID 11) is used.

The current design of the Navigation Data Signal allows a PNT Data Processor to "cold-start" within 16 minutes (or less if the system consists of fewer than 16 Base Stations).

In general, for a given station to be considered usable for ranging, both the Navigation Data Signal and the Ranging Signal must be received. As a result, the user must be located within the data coverage of at least three VDES R-Mode Base Stations to be able to produce a VDES R-Mode position fix.

3 COVERAGE AND PERFORMANCE PREDICTION

The GLA Research & Development Directorate (GRAD) has developed a software tool that can provide valuable insights into the coverage and performance achievable by the VDES R-Mode system. The tool draws on a state-of-the-art radio wave propagation model provided by ITU-R, a high-resolution terrain elevation database produced by the European Commission's Copernicus programme, data from a radio noise survey performed on-board GLA vessels and other intellectual property developed in-house. It has been used to produce the coverage and performance plots included in this paper and to support studies conducted as part of the MarRINav and R-Mode Baltic projects.

This section provides a high-level overview of the methods employed within the GRAD tool. For additional detail the reader is referred to the report [27].

3.1 User Settings

The coverage prediction tool provides a broad range of user-configurable options and parameters, including the geographical area of interest, maximum distance for path loss calculations, spatial resolution of the output data arrays and various parameters related to the Ranging Signal and Navigation Data Signal waveforms, as well as Base Station and R-Mode Sensor parameters. These settings can be adjusted via a human-readable configuration file.

A separate spreadsheet is used to store Base Station site-specific data, such as transmitting antenna coordinates, antenna gain, transmitter power and cable losses. This spreadsheet also enables users to select sites for inclusion in the coverage analysis conveniently.

To keep a record of the exact system configuration used, copies of both files are stored along with the coverage plots produced.

3.2 Received Signal Power

The power of the VDES signal received from a Base Station at a given location is dependent on several factors, including the transmitter power, transmitting antenna gain, feeder loss, directivity of the receiving antenna and path loss. The path loss, which is affected by antenna heights and separation, terrain elevation profile, the climate and atmospheric conditions, is estimated using a propagation model described in Recommendation ITU-R P.2001-3 [28].

To calculate the path loss, a certain number of radials are traced from each Base Station and the ITU-R model is applied to all points along each radial. The values at points not lying directly on a radial are obtained by interpolation.

The ITU-R model comprises four sub-models that account for propagation by diffraction, tropospheric ducting, tropospheric scattering and propagation via the sporadic-E layer of the ionosphere. Nevertheless, in the present application, the contribution of the sporadic E layer can be deemed insignificant.

For ranging, only signal components that propagate near the Earth's surface are considered useful. Signal components that arrive via higher layers of the atmosphere are subject to additional propagation delay and can act as a form of multipath interference, potentially distorting the range measurements. Therefore, when calculating the path loss and received power for (the desired component of) the Ranging Signal, the GRAD tool uses only the first sub-model of the ITU-R propagation model (i.e. propagation by diffraction).

In contrast, it is anticipated that all three major propagation modes identified previously (i.e. diffraction, ducting and tropospheric scattering) would contribute to the receiver's capability to demodulate and decode VDES communication signals. Thus, when calculating the received signal power for the Navigation Data Signal, the GRAD tool employs the corresponding three sub-models of the ITU-R model. The outputs obtained from each sub-model are combined to produce a single path loss figure, as described in Recommendation [5].

The ITU-R model predicts the path loss not exceeded for a given percentage of an average year. In this paper, we use the path loss not exceeded for 99.67% of the time when calculating the power of the Navigation Data Signal, consistent with the 99% availability requirement for the R-Mode system overall[9]. Choosing a 99.67% figure provides a conservative confidence bound on the station's usable range, meaning that 99.67% of the time, the range will be greater than stated. This is conservative but in keeping with the 99% system availability requirement.

The Ranging Signal is characterized using the mean received power rather than a power guaranteed for a certain percentage of time.

Terrain profile data required as input to the ITU-R model is obtained from the EU-DEM digital elevation model, which covers most of Europe with a horizontal resolution of 25 m.

Climatic parameters, such as the expected change in refractivity in the lower layers of the atmosphere, the mean rain height, surface water-vapour density and others are obtained for each location of interest by bi-linear interpolation from data files sourced from ITU-R.

3.3 Station Coverage

As previously mentioned, the current signal design limits the usability of each Base Station to its data coverage area. The GRAD tool models this area as the geographic region where the predicted C/N_0 of the Navigation Data Signal is greater or equal to the decoding threshold for the Link ID 11 VDE-TER waveform. To calculate

[9] Assuming that the system requires at least three stations to be simultaneously available within an area to be considered available, and that station outages are statistically independent, the station availability must be at least $\sqrt[3]{0.99} \approx 0.9967$.

the C/N_0 array for each Base Station, the tool subtracts[10] the assumed noise power spectral density level, N_0, from the corresponding received signal power array produced in the previous step. The noise level used in this paper is based on equipment manufacturer data and external noise measurements carried out on GLA' vessels.

3.4 Ranging Error

In a multipath-free propagation channel with additive white noise, the achievable ranging accuracy depends primarily on the spectral (or correlation) characteristics of the ranging waveform used and the C/N_0 of the received signal. The literature provides various theoretical lower bounds on the estimation error, including the Cramér-Rao Bound (CRB), Modified Cramér-Rao Bound (MCRB) or the Ziv-Zakai Bound (ZZB). The GRAD tool uses the ZZB technique [26], [29] to estimate the ranging accuracy, which has the advantage of providing a tighter (more realistic) lower bound in the low C/N_0 region compared to other methods. It is assumed that the Ranging Signal uses VDES Link ID 37 and is modulated with a pseudorandom (Gold-code) symbol sequence as described in IALA G1158; the alternating symbol sequence is not used, i.e. the 'γ factor' is assumed to be 0.

A constant term of 3 meters (one-sigma) is added to the ranging error budget to account for achievable transmitter synchronization accuracy of 10 nanoseconds (one-sigma).

The ranging error model is applied to each C/N_0 array produced in the preceding step to create a new set of arrays that represent the predicted ranging error in an area around each Base Station.

3.5 Positioning Accuracy

It is assumed that the PNT Data Processor calculates the position by using the Weighted Least Squares (WLS) method to solve a system of linearized (pseudo)range observation equations. The position error is then estimated at each point of a grid covering the area of interest as follows.

A geometry matrix and a weighting matrix are formed and used to calculate the covariance matrix of the position solution coordinates. The geometry matrix contains unit vectors pointing from the current position within the area of interest to the available Base Stations. The weighting matrix is chosen to be the inverse of the estimated covariance matrix of the (pseudo)range measurements, which contains the ranging error estimates for each station in view determined previously. Using the covariance matrix of the solution coordinates, the semi-minor and semi-major axes of the one-sigma position error ellipse are calculated, and the Harre approximation [30] is used to estimate the 95th-percentile horizontal position error (R95).

4 CASE STUDY

In this section, we use the GRAD coverage prediction tool to evaluate the feasibility of a VDES R-Mode system spanning the UK and Ireland. We make the following assumptions: all of the 119 existing AIS Base Stations[11] in the UK and Ireland are converted to VDES stations with R-Mode functionality, the Base Station VHF antenna height is 25 m above terrain, the Base Station transmitter power is 12.5 W, omnidirectional antennas with a gain of 0 dBd are used and the receiving antenna height is 10 m above the Earth's surface. As per the baseline system architecture, we assume that a position solution requires pseudorange measurements from at least three Base Stations.

The predicted positioning accuracy coverage for the UK/Irish VDES R-Mode system is shown in Figure 1. Our results indicate that the system is unable to meet the 10 m (R95) accuracy requirement for port approach, with the exception of a few patchy areas on the West and North coast of Scotland and along the coast of Northern Ireland. The coverage area at the 100 m (R95) accuracy level required for coastal navigation is

[10] Assuming that logarithmic units are used.

[11] This includes AIS Base Stations operated by the GLA, Irish Coast Guard and the UK Maritime and Coastguard Agency, as well as AIS Coast Stations used within the Trinity House Virtual AtoN system.

significantly larger but still inadequate, with significant gaps existing along much of the coast of England and Wales.

In conclusion, based on the above assumptions, it can be inferred that the mere conversion of existing UK and Irish AIS Base Stations to VDES and the addition of the R-Mode capability is insufficient to provide satisfactory coverage around the UK and Irish coastline.

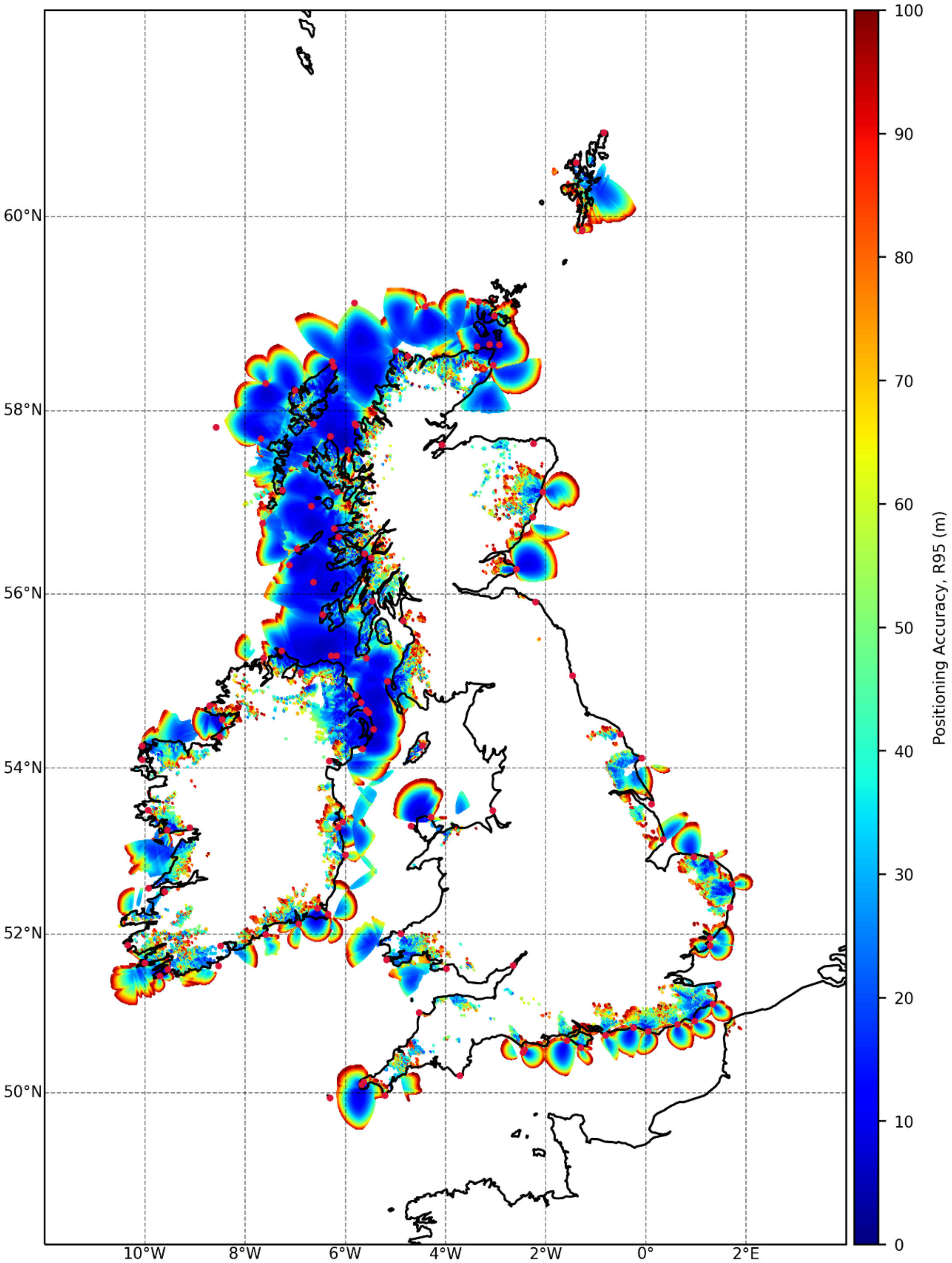

Figure 73: Estimated VDES R-Mode accuracy coverage assuming the upgrade of all currently existing AIS Base Stations in the UK and Ireland to VDES R-Mode, using positioning with three or more pseudoranges and considering a multipath-free propagation channel.

5 REMAINING TECHNICAL CHALLENGES AND DEVELOPMENT UNKNOWNS

5.1 Insufficient Stations and/or Station Geometry

The baseline VDES R-Mode architecture, based on IALA Guideline G1158, faces two primary challenges that limit its ability to provide adequate accuracy coverage in the waters surrounding the UK and Ireland. Firstly, the architecture requires at least three VDES R-Mode Base Stations to be in view, but modelling shows that only a relatively small fraction of the region will be covered with three or more VDES signals.

Secondly, as with any terrestrial pseudoranging system, the user ideally needs to receive signals from stations equally spaced in azimuth around their location. When the stations are clustered to one side of the user, the positioning accuracy degrades rapidly. Given the nature of the UK and Irish coastline, the ideal geometry is not going to be available in most maritime locations, unless additional stations are deployed offshore.

5.2 Multipath Propagation and Effects of Changing Environmental Conditions

Multipath propagation is a phenomenon that occurs when a signal reaches a receiver as a sum of composite signals with different delays, carrier phases and amplitudes due to diffraction, refraction, scattering and/or reflection. In ranging systems, the delayed signal components can affect the TOA measurements, giving rise to ranging and ultimately positioning errors. Because of the relatively narrow bandwidth of VDES R-Mode transmissions, multipath components are usually not resolvable and can cause significant measurement errors.

In the maritime environment, multipath can occur due to reflections from land masses and objects on land, such as buildings, port infrastructure or stacks of shipping containers. However, multipath can also arise from atmospheric anomalies, such as tropospheric ducting and scattering, as discussed in Section 3.2.

VDES channel sounding measurements conducted by the GLA [31] and the Japan Radio Company [32] suggest that the VDES channels can exhibit RMS delay spread in excess of 10 µs (equivalent to 3 km in range). AIS R-Mode experiments carried out over a 9 km baseline in China indicate peak-to-peak diurnal variability in signal propagation delay measurements of up to 2.5 µs (equivalent to 750 m) [7]. The R-Mode Baltic 2 project conducted a measurement campaign to investigate the long-term stability of VDES R-Mode signals [33]. Test signals were sent over a sea-water path between two stations in the Gulf of Gdansk, separated by 20 km, with data collected over 24 days in summer and autumn 2021. The results showed significant diurnal and seasonal variability in the estimated signal propagation delay, with daily RMS ranging errors of 25-50 m in the summer and 50-140 m in the autumn. Some correlation between increased ranging error and rainfall and occurrences of suspected tropospheric ducting was observed.

Analysis of the data collected by the R-Mode Baltic 2 project suggests that the ranging error can significantly be reduced by applying real-time (hourly) corrections. However, more experiments are required to determine the rate of spatial decorrelation of such corrections and hence the required density of differential reference stations.

As demonstrated by the discussion above, multipath propagation can be expected to have a significant impact on the accuracy of R-Mode positioning. Initial steps towards developing a model for the multipath-induced error were taken by GRAD in report [27]. The initial model seems to be consistent with the experimental results reported in the literature; however, further work is required to fully validate it.

5.3 Non-line-of-sight Propagation

Non-line-of-sight (NLOS) propagation can lead to increased ranging error in areas where the signal travels over land or where it encounters significant obstructions[12] along the line of sight between the transmitter and receiver. Correction maps are used in some terrestrial positioning systems, for example eLoran, to mitigate

[12] obstructions with dimensions comparable to or greater than the wavelength of the VDES R-Mode carrier

the effects of additional propagation delays due to land mass. It is unclear at this stage whether VDES R-Mode will require such maps or to what extent these effects can be corrected.

Results of VDES R-Mode positioning trials performed by the German Aerospace Centre (DLR) on Lake Ammer in Bavaria demonstrate the impact that even a small ship can have on positioning performance. During the trial, the horizontal position error grew from around 10 m to approximately 60 m when a ship temporarily obstructed the line of sight to one of the transmitter sites [34]. With all signals coming from just above the horizon, a terrestrial system is more likely to experience errors caused by obstructions than a satellite system where most signals arrive from higher up in the sky.

5.4 Other

There are several additional challenges that must be addressed in the implementation of VDES R-Mode. One such challenge is the development of an affordable and scalable Base Station synchronization technique that can support potentially hundreds of stations within a given region. This is a critical requirement for ensuring accurate and reliable positioning information across a wide area.

Integration with other systems on-board vessels is another important consideration. VDES R-Mode must be able to operate seamlessly with existing navigation systems and other on-board equipment.

Finally, cyber-security is a significant concern that must be addressed. In particular, it is essential to protect VDES R-Mode signals against spoofing, as VHF transmissions are generally easier to spoof than low-frequency or medium-frequency signals that require large antennas for effective radiation. Robust security measures must be implemented to ensure that VDES R-Mode signals are not compromised, and that they can be relied upon for accurate and trustworthy positioning information.

6 POTENTIAL SOLUTIONS

6.1 Additional Stations

6.1.1 Land-based Stations

This section examines the possibility of improving the coverage and performance of VDES R-Mode by installing additional Base Stations at strategic locations on land. Although this example focuses on the Dover Strait, the principles outlined are applicable to other areas around the coastline of the UK and Ireland where good performance is necessary.

The coverage plot for the baseline configuration, as shown in Figure 1, indicates that despite the relatively high density of Base Stations in the area, a vessel steaming through the Dover Strait would experience significant variation in accuracy, ranging from better than 100 meters to much worse than 100 meters. This is because the stations all lie to one side of the vessel.

Figure 2 demonstrates the improvement that can be achieved when three new VDES R-Mode stations are introduced on the other side of the Channel in France, namely at the Gris-Nez Lighthouse and the Ports of Calais and Dunkirk. The new stations have extended the coverage contour someway across their respective locations, and the system is now predicted to cover the entire Dover-Calais ferry route. These results confirm the principle that, in a pseudoranging system, good positioning performance requires the user to be surrounded by stations.

The figure also suggests that the set of stations deployed in this example likely represents the best that can be achieved with land-based VDES R-Mode alone in this region. This is because the UK and French coastlines diverge from each other, and adding more stations along the French coast is unlikely to improve coverage further. This is particularly evident in the eastern part of the region, where the additional station at Dunkirk has little effect on the coverage contour due to the range limitations of the VDES R-Mode signal and poor geometry of the three stations (Gris Nez, Calais and Dunkirk) that are available in that area.

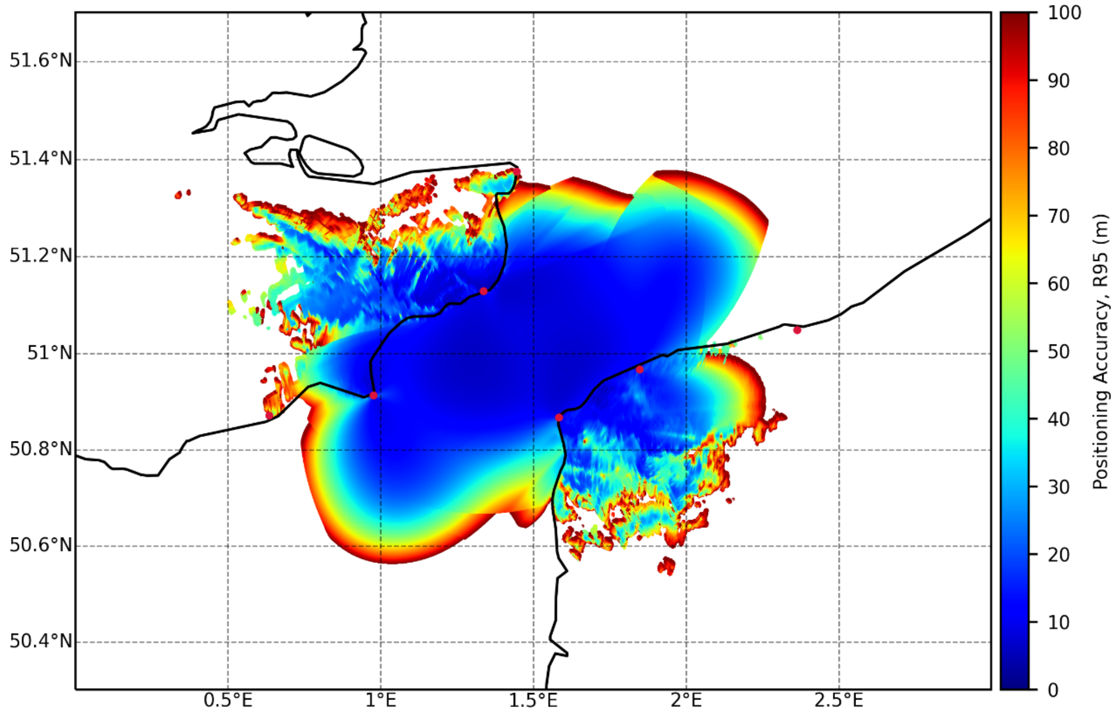

Figure 74: Estimated VDES R-Mode accuracy in the Dover Strait with four stations in the UK (East to West: Fairlight, Dungeness, Dover, North Foreland) and three new stations in France (Gris Nez, Calais, Dunkirk), using positioning with three or more pseudoranges and assuming a multipath-free propagation channel.

6.1.2 Offshore Stations

An additional improvement in coverage could be achieved by siting stations on offshore platforms such as windfarm substations and oil platforms. To this end, GRAD has been exploring the feasibility of a low-cost, low-profile *VDES R-Mode Transponder* that could be strategically located within the intended service area to complement existing signals from land-based R-Mode Base Stations. The Transponder is envisaged to operate in conjunction with a full-fledged VDES R-Mode Base Station (referred to here as the 'Master Station') but would not require the full Base Station capability itself.

As the deployment locations would be offshore, the Transponder should be designed to minimize the logistical inconveniences associated with providing power, communications and synchronization to the station. Ideally, the Transponder would be solar-powered, support remote monitoring and control via a secure VDES data link and allow for clock synchronization with the Master Station's clock by performing two-way VDES R-Mode measurements. This latter concept of two-way *self-synchronization* could be extended to all stations within a regional VDES R-Mode system, which could result in significant infrastructure cost savings.

6.1.3 Space-borne Stations

While the primary focus of this paper is on improving terrestrial VDES R-Mode infrastructure, it is worth noting that augmenting this infrastructure with space-borne stations is also a possibility. Readers interested in this concept are encouraged to consult references [35], [36] and the ongoing ESA-funded 'Independent Critical Navigation' (ICING) and 'VDES-R Advanced User Technologies for Alternative PNT' (VAUTAP) projects.

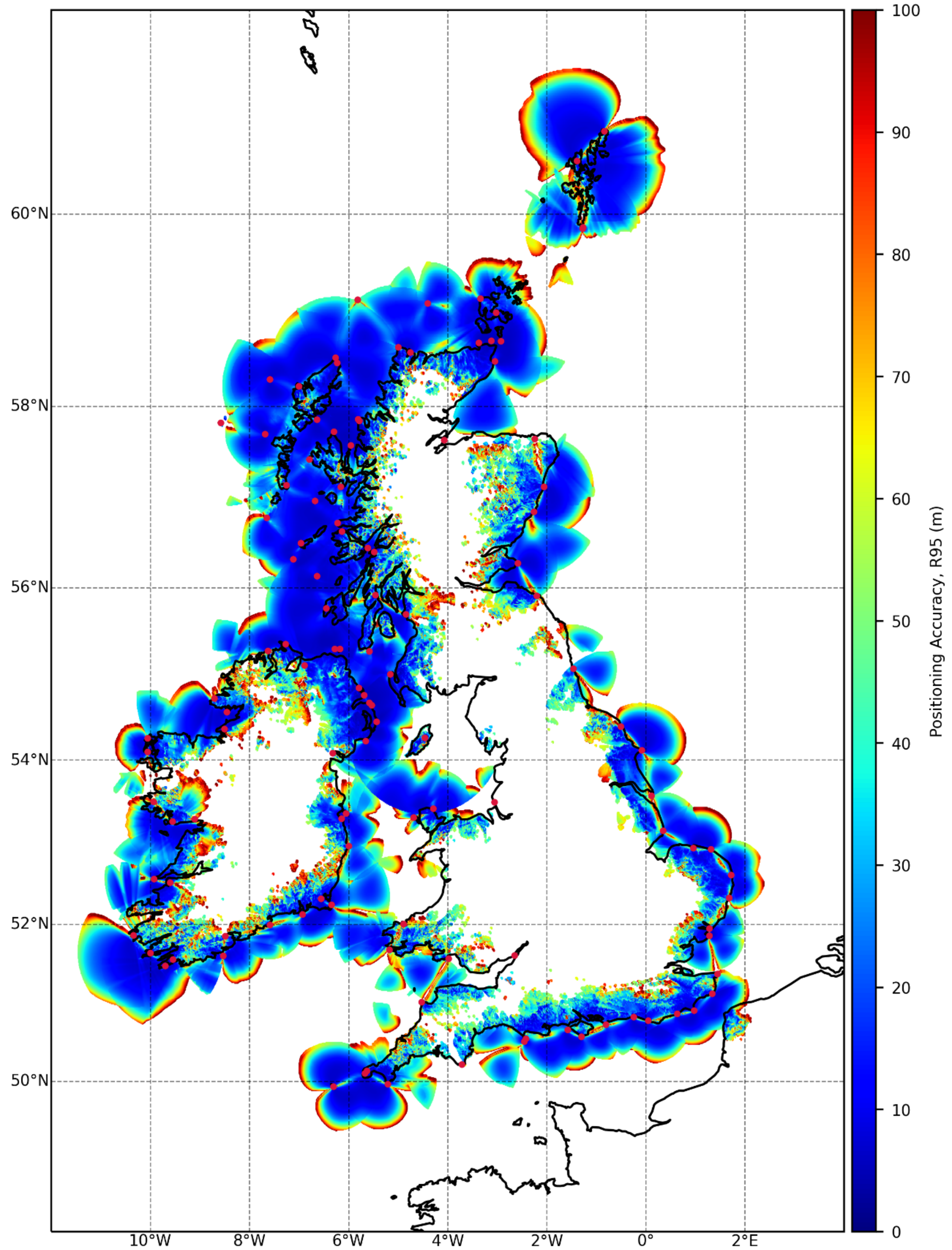

Figure 75: Estimated VDES R-Mode accuracy coverage assuming the upgrade of all currently existing AIS Base Stations in the UK and Ireland to VDES R-Mode, using positioning with two or more "true" ranges and considering a multipath-free propagation channel.

6.2 High-stability On-board Clock

One approach to overcome the need for offshore R-Mode stations may be to use a high-stability clock (such as a high-quality OCXO or Rubidium one) on-board the vessel. This clock could be synchronized to the R-Mode System Time using GNSS, when available, or via occasional two-way VDES timing measurements (independent of GNSS). Depending on the type used, the clock could provide a hold-over of perhaps a few tens of minutes to a couple of hours. With this approach, the system could perform *"true" ranging*, as opposed to pseudoranging.

By eliminating the need to solve for the local clock bias as part of the position solution, a position fix could be obtained using signals from only two stations instead of three, resulting in a larger coverage area. Furthermore, the optimum geometry for two range measurements is achieved when the lines of sight to the two stations (or the two corresponding circular lines of position) subtend 90°, while with three ranges available, the optimum geometry occurs when the lines of sight are separated by either 120° or 60°. The system could thus provide adequate positioning performance at sea using only land-based stations, unlike pseudoranging systems that require the user to be surrounded by stations.

Figure 3 illustrates the effect of this approach on coverage and performance. The plot in Figure 3 assumes the same 119 Base Station sites are used as considered previously in Section 3, but operating in true ranging mode with two or more signals used at each location. It can be observed that coverage is significantly improved compared to the baseline configuration shown in Figure 1. Although gaps in coverage remain along the coast of England and Wales, they could now be closed by installing only land-based stations.

However, using only two range measurements can result in potentially dangerous position ambiguity, as two circular lines of position will intersect in two places. This ambiguity could be resolved using a combination of prior knowledge of position (for example, the last available GNSS fix or the previous R-Mode fix) and knowledge of the maximum distance travelable between position updates, or input from dead-reckoning sensors.

6.3 Integration with Other PNT Systems and Sensors

To further improve coverage and performance, it is possible to take advantage of signals from other (pseudo)ranging systems. For instance, in the report [27], an extended version of the GRAD tool was used to model the coverage of a combined VDES/MF R-Mode system in the Baltic Sea region. Due to the relatively long usable range of the MF R-Mode stations, significant enhancements in predicted coverage were realized by introducing a small number of MF stations. However, it should be noted that the waveforms currently used in MF R-Mode do not permit reliable carrier phase ambiguity resolution and are susceptible to substantial measurement errors at night because of unresolved sky-wave interference.

Similarly, modelling conducted by the MarRINav project demonstrated how a smaller number of VDES R-Mode stations could fill gaps in coverage of a UK-wide eLoran system consisting of six transmitting stations [24].

The integration of measurements from radionavigation systems such as eLoran, various R-Mode variants and GNSS can be accomplished using the IMO MSR architecture [21]. Additionally, the MarRINav project has proposed integrating VDES R-Mode with other navigation techniques, including radar absolute positioning and Dead Reckoning (DR) based on a Doppler or correlation velocity log, gyrocompass and inertial sensors. According to the MarRINav architecture, the PNT output would be sourced from the DR subsystem, which would be calibrated by the various positioning systems, including GNSS or whatever mix of alternative systems is available when GNSS is degraded [24]. This approach exceeds the scope of the MSR but is deemed consistent with the associated Guidelines on PNT Data Processing [37].

6.4 Advanced Signal Design and Signal Processing Algorithms

The following paragraphs propose several enhancements to the R-Mode Signal structure and processing approach that have the potential to improve coverage and performance.

Noting that VDE-TER uses two blocks of spectrum 4.6 MHz apart (see Section 2.3), there is potential to provide Ranging Signals in both blocks. While this approach is novel and raises several questions, the potential for such '*meta-signals*' has already been demonstrated for GNSS [38]. Estimation theory suggests that combining the lower and upper VDE-TER bands for ranging purposes could bring significant performance improvements, and the wider signal bandwidth could also contribute to better multipath resolvability. It is worth noting that the transmissions in the two bands may not necessarily need to be simultaneous, as long as they are accurately synchronized with each other to form a single, deterministic, wideband waveform.

To further improve positioning performance, R-Mode (pseudo)ranges could be combined with Doppler frequency measurements in a Kalman filter, as demonstrated in reference [36].

The design of the Navigation Data Signal currently requires that the user be located within the "data" coverage area of at least three R-Mode stations to produce a position solution. Redesigning the Navigation Data Signal to allow all necessary data for positioning to be obtained from any single station could greatly improve coverage. This is because the Ranging Signal is modulated with a known symbol sequence and consequently can be used at much longer ranges than the Navigation Data Signal.

Finally, using signal Direction of Arrival (DOA) measurements in addition to ranges could significantly improve coverage, as a position solution could be obtained using only one station. However, this would require an antenna array to be installed on the vessel, and the position accuracy at locations where only a single station is available would likely be significantly poorer than in the areas where (pseudo)ranging can be used.

6.5 Signal Authentication

A potential solution for securing VDES R-Mode signals was outlined by DLR researchers in reference [39]. The proposed approach uses the Timed Efficient Stream Loss-tolerant Authentication (TESLA) protocol to protect the Navigation Data Signal, while the Ranging Signal is secured by introducing multiple ranging sequences and only disclosing in the secure Navigation Data message which specific sequences were transmitted. If the ranging sequences detected by the receiver do not match those identified in the authenticated Navigation Data message, the user knows they have been spoofed. Although this solution is considered a promising approach and deserves further investigation, it should be noted that the method is protected by a patent.

7 CONCLUSIONS

The risk of disruptions to GNSS services necessitates the development and implementation of alternative PNT sensors and systems to mitigate their impact. VDES R-Mode is a promising candidate system currently being considered by IALA. VDES R-Mode can be configured as a mitigation, contingency or backup system, offering different levels of resilience and holdover capability, as per IALA's classification of alternative PNT systems.

GRAD has developed a software tool that can provide valuable insights into the coverage and performance achievable using different configurations of the VDES R-Mode system. IALA's baseline architecture for VDES R-Mode assumes that the system will operate by pseudoranging with three or more signals used at each location. Our modelling indicates that standalone VDES R-Mode based on the IALA baseline architecture and the use of only existing AIS Base Station sites is not a viable option for most of the UK and Ireland due to insufficient stations or poor station geometry.

Improvements in coverage and performance can be achieved by deploying additional R-Mode stations at strategic locations. For example, it may be of mutual benefit for the UK and France to deploy stations on both sides of the Channel. The combination of just four stations in the UK and three stations in France is predicted to provide satisfactory positioning accuracy for the whole of the Dover Strait, including the approaches to the Port of Dover and Calais. Additional improvements in coverage could be achieved by siting stations on offshore platforms, such as windfarm substations and oil platforms, and by augmenting the terrestrial infrastructure with space-borne R-Mode stations.

Alternatively, using a high-stability clock on-board vessels could enable positioning by ranging with two or more signals used at each location. Although this approach could provide satisfactory coverage along most of the coastline of the UK and Ireland, users would need to be mindful of the inherent position ambiguity that arises when only two range measurements are used and increased user equipment cost.

VDES R-Mode could also be considered as a component in an integrated PNT system of systems, combining multiple short, medium, and long-range positioning systems and techniques, such as radar absolute positioning, MF R-Mode, and eLoran, with Dead Reckoning. Such architecture could provide a resilient PNT solution in situations where none of the constituent technologies alone can.

Areas for further research include the use of both VDE-TER frequency bands for ranging to support the meta-signals approach, the use of Doppler frequency and/or signal DOA measurements in positioning, the design of a more efficient Navigation Data Signal structure to reduce the number of signals that need to be demodulated simultaneously and the use of the TESLA protocol for R-Mode signal authentication.

Overall, our findings suggest that VDES R-Mode has the potential to be a valuable component of a resilient and robust PNT system.

8 REFERENCES

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Dr Jan Šafář is a Research & Innovation Engineer with the General Lighthouse Authorities of the United Kingdom and Ireland. Jan has over 15 years’ experience as a researcher in the radio navigation and communications field, working in the areas of Global Navigation Satellite Systems and augmentations, alternative positioning, navigation and timing systems and e-navigation communications. He is a member of the Royal Institute of Navigation, U.S. Institute of Navigation and several international working groups, including the Digital Communication Systems Working Group within the IALA e-Navigation Committee and the IEC AIS Working Group. He has been closely involved with the development and international standardisation of the VHF Data Exchange System (VDES), including its R-Mode component.

S16.4 VDES-R advanced user technologies for alternative PNT (118)

Martin Bransby, Telespazio, Head of Navigation, United Kingdom

ABSTRACT

Global Navigation Satellite Systems (GNSS) have become the primary marine aid-to-navigation and source of Position, Navigation and Timing (PNT) information. Yet, all GNSS are vulnerable to natural interference, deliberate and accidental jamming and spoofing. Maritime trials, and trial in other domains, have demonstrated that degraded GNSS produce hazardously misleading information and erroneous vessel positions without an alarm being raised. As ships' systems become increasingly digital, with the introduction of a wide range of supporting services and the emergence of autonomous vessels, PNT accuracy, integrity, continuity, and availability become increasingly critical. Projects have shown that a System-of-Systems approach to the provision of PNT for maritime and other critical infrastructure is preferable to provide resiliency. National Governments, Inter-Governmental Organizations and Multi-National bodies now recognize this System-of-Systems approach.

Having a System-of-Systems approach requires that systems other than GNSS be utilized to provide resiliency. One such system is the Very High Frequency Data Exchange System (VDES). VDES is a new maritime radio communication system in development by the international maritime community, with the principal objectives, to:

- Safeguard existing Automatic Identification System (AIS) core functions, such as ship-to-shore and ship-to-ship position reporting, preventing future AIS overload; and
- Enhance maritime communication applications, based on robust and efficient digital data transmission with wider bandwidth than the AIS.

However, at the same time, the international maritime community has been investigating the potential use of these VDES communication signals transmitted from shore-based stations for positioning—a concept commonly referred to as 'ranging mode', or R-Mode. VDES R-Mode is still at a relatively low Technology Readiness Level and much of the standardization required for such System-of-Systems components are not yet in place, giving developers the opportunity to develop better waveforms, techniques, components and concepts to provide truly resilient PNT. The VAUTAP project will utilise the strong alliance and experience of our Consortium to investigate, consolidate and develop new algorithms, waveforms, software and hardware, to evolve VDES R-Mode closer to an operational and viable component of a resilient PNT System-of-Systems.

(No paper submitted)

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Martin Bransby is the Head of Navigation at Telespazio UK. He is accountable for delivering Telespazio's research, innovation and product development programme in resilient position, navigation & timing, focussing on a multi-layered, multi-systems approach to PNT provision as a service, whilst delivering the company's PNT strategy and direction. He is a Chartered Engineer, Fellow and Council member of the Royal Institute of Navigation, an Associate Fellow of the Nautical Institute. He also holds memberships of the Institute of Engineering & Technology, and the US Institute of Navigation.

S16.5 Implementation of a satellite VDES system with open interfaces (175)

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ABSTRACT

The VHF Data Exchange System (VDES) as the natural evolution of AIS, also called "AIS 2.0", is full of opportunities to broaden the use of digital services in the maritime domain. After WRC-15 and WRC-19 has given the maritime world frequencies to create this new digital exchange system, we now have the obligation to use the frequencies for maximum utilization.

Several new ship and shore equipment already today is made compatible with VDES, and satellite networks are being built to support the internationally standardized exchange of digital information between maritime users and shore services to improve sustainability, economics, and safety of operations at sea. IALA committees through their work currently support the definition of guidelines on how maritime services in the context of e-Navigation may be realized using the mechanisms of the Maritime Connectivity Platform and VDES.

In this report, the implementation of a satellite VDES system, utilizing the Maritime Connectivity Platform trust system and open interfaces is shown. The report gives insight into how satellite VDES can be used to transport secure bidirectional services between the sea and shore while using the well-established mechanisms of the Maritime Connectivity Platform to provide trust between the communication partners.

KEYWORDS: VDES, Satellite, e-Navigation, MCP, Secure, VHF

1 INTRODUCTION

VHF Data Exchange (VDES) is the natural evolution of AIS. Therefore, it also is called "AIS 2.0".

VDES includes:

- AIS as we know it,
- 2 dedicated 25kHz channels for short messages transporting ASM,
- 200 kHz dedicated to terrestrial high rate VHF Data Exchange, and the secondary satellite VDE service, and
- 100 kHz dedicated for high rate satellite VHF Data Exchange.

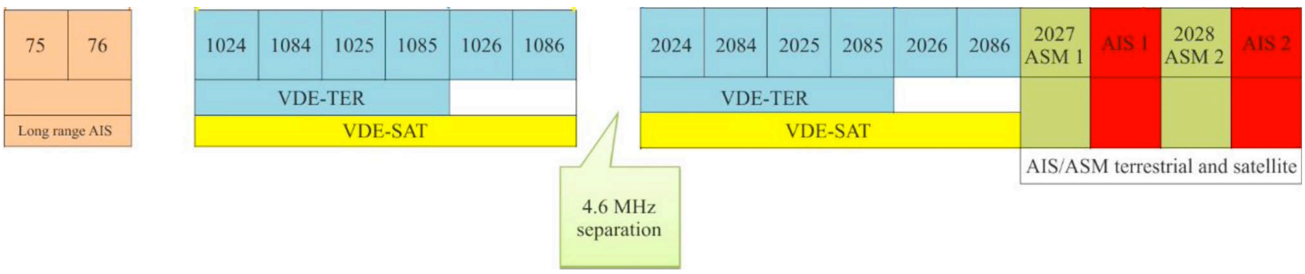

Figure 76 VDES Frequency usage, satellite frequencies indicated in yellow, whereof 100kHz are shared with terrestrial VDE.

VDES mainly consists of ship, shore, and satellite equipment. Aids to Navigation, like buoys, lighthouses and other infrastructure can also be equipped with VDES, e.g. for monitoring of functionality of a remote light house. For simplicity, these applications of VDES will be seen as "ship" equipment here.

On the ship side, the well-known AIS will become VDES compatible, as equipment producers today prepare their AIS products for VDES already [4]. For ship installations, changes are only minimal, as the VHF AIS antenna can be reused also for a VDES compatible AIS, and connections to ECDIS, GNSS and other ship communication/navigation equipment just will remain as they are already standardized today.

AIS Shore equipment is currently being made VDES compatible [5], as many equipment producers today already prepare their AIS shore base station products to contain all VDES functions.

The satellite VHF Data Exchange, or short VDE-SAT, while not requiring more than replacing the old AIS with a new VDES compatible AIS on board of the ship, it requires a new satellite infrastructure, that has not been existing before VDES. Due to its nature defined in [2], it requires the satellites to fly at about 500-600 km over earth's surface, these satellites are orbiting earth at a speed that makes them appear move quickly over the sky. Communication with one satellite can be maintained from a ship for a few minutes to exchange data, then the ship must wait for the next satellite or terrestrial connectivity before being able to exchange further data.

A high number of satellites allows more frequent visits and will make services more available to the mariners.

However, operators of VDE satellites today:

- launch only low numbers of satellites to keep cost and risk at a controllable level,
- use the satellites only for their own services and customers over small areas of the globe.

If the collected resources of all operators would be made usable by open interface standards, this would enable:

- service providers to disseminate their service using all available operators, or
- agreements between operators, and
- sharing of VDE satellites between operators, and
- offering the use of multiple VDE Satellite networks to service providers by each operator.

leading to:

- much improved usage of the available satellite resources,
- increased value from the invested capital and materials,
- improved global service availability for early services and VDE-SAT users.

This paper is introducing possible ways and current activities on the way to solving the political and technical necessities to facilitate sharing of VDE satellites between operators and service providers.

2 THE VDE-SAT SYSTEM

2.1 Low Earth Orbit

VDE Satellite transmissions happen on the VHF band, having a wavelength of roughly 1.9 meters.

$$\lambda = \frac{c}{f} \approx \frac{3 * 10^8 \frac{m}{s}}{160 * 10^6 \frac{1}{s}} \approx 1.9m (1)$$

The satellite antenna for the VDE signal needs to concentrate the radio signal to a certain region over earth, to operate efficiently and to avoid exceeding the maximum allowed signal strength reaching the surface of the earth [3].

The higher the satellites fly over the surface over the earth, the more of the signal gets lost in space, which can be compensated by high gain antennas.

However, antenna constructions giving high gain become very quickly large in size, and require complicated deployment mechanisms that are difficult to build and carry on satellites, which give us today a sweet spot between 500-600km, as indicated in [3].

2.2 Coverage

At 500-600km altitude over earth's surface, a VDE satellite is moving at a given speed to keep its orbit. This speed is given by the Keplerian laws, resulting in one full orbit around the earth being approximately 90 minutes.
At the given altitude, that results in a visible time of the satellite of up to 14 minutes from a given ship transceiver position at earth. However, as the satellite points it's antenna towards a certain region, the ship cannot be absolutely sure to get service during the whole time.
The coverage area of a VDE Satellite is greatly dependent on the pointing angle, as the figure below tries to illustrate for a 550km altitude satellite with a reference antenna, transmitting at maximum allowed power:

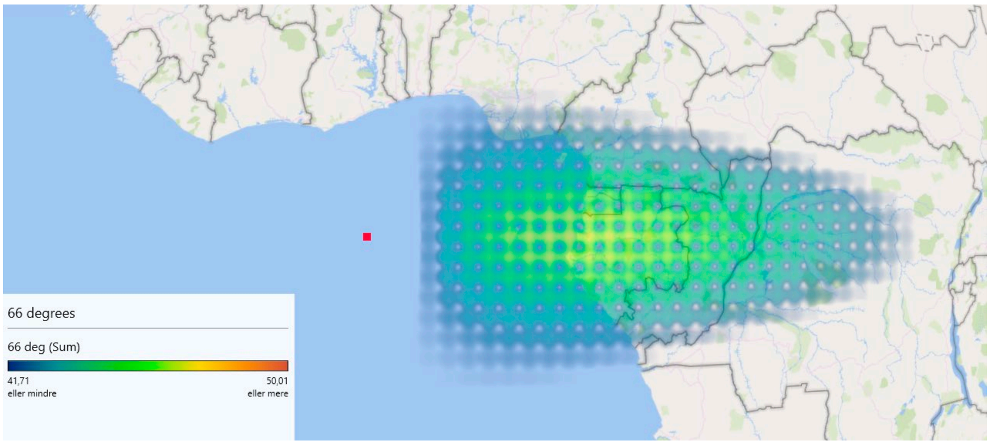

Figure 77: Simulated VDE satellite coverage area using limb pointing as described in [2, 3] pointing eastwards from the satellite position (red dot to the left of the indicated coverage area).

In Figure 2, the usable coverage area for a higher rate communication ([2] SAT-MCS-0.50-3) would be leading to approximately 1000 x 500 km of size for a given point in time.

2.3 Forms of communication

2.3.1 Satellite – Ship, Ship – Satellite

The VDE satellite system provides following forms of communication between satellite and mobile devices, such as ships or AtoN, etc:

- Broadcast messages from one VDE satellite to all ships in the coverage area
- Direct messages from one VDE satellite to one ship
- Direct messages from one ship to one VDE satellite

The transport of data happens in form of messages. For direct messages, retransmission of parts of a message is possible in case the receiver did not properly read a part, i.e. due to a own AIS transmission. All transmissions are protected by forward error correction.
Broadcast messages can be retransmitted by the satellite repetitively in order to:

- reach more receiving ships as the satellite passes over earth, and
- increase the chance that receiving ships can recover from single parts of a message that were not properly received.

2.3.2 Satellite – Ground, Ground – Satellite

For the satellite to be able to:

- route ship messages from ships to shore,
- shore messages to ships,
- update broadcast data in the satellite to be repeatedly sent over the targeted service areas, and
- being monitored and controlled from the ground control center,

it needs to have a backhauling communication link that is realized through other means than VDES [6]. S-band radios are a typical way to handle that need, including the satellite telemetry and commanding.

Backhauling today is mostly performed through ground stations that track the satellite for the visible time of up to 14 minutes per pass. Many ground stations would be required to keep contact with the satellite at all time. Consequentially, there are times where the operator and the shore services have no contact with the satellite, and it has to operate autonomously.

2.4 Store and Forward

For VDE satellite systems where the backhauling link is not permanently available, the satellite may either:

(a) only be used over the areas where a ground station connectivity is available, to provide a real time link between ship and service providers at shore, or
(b) perform store and forward of the messages to forward them when it is possible to either ground station/shore services or ships.

Store and forward is the same concept as used by mail delivery, electronical mail and real-world physical mail. It introduces delays that depend on:

- The number of ground stations available to communicate with the satellite,
- the time until a ship is seen by the satellite again, to deliver a message, and
- the ability of the satellite system to optimize the routing of messages to the next possible satellite by using the known location and capabilities of the ship before having contact with the actual ship.

Store and forward can be implemented in many ways, one possible way is to use the concept of the Maritime Messaging System, introduced by the EfficienSea2 project [7], and further developed by the Maritime Connectivity Consortium MCC [8], and introduced in IALA Guideline G1117 [9].

A store and forward based system can cope with unstable or changing types of connectivity. However, it also can provide near real-time appearance, where the connectivity is robust. Thereby the store and forward based approach allows to get the best of any connectivity.

The here proposed open interface architecture will use store and forward to maximize the use cases, while minimizing the complexity.

2.5 Interfaces of a VDE-SAT system

A typical VDE-SAT network architecture is shown in Figure 3. In this example, a network operator has 4 satellites, 2 ground stations, one gateway and 2 service providers. Figure 3 shows the connection state of the system at a certain point of time, where satellite 2 and 3 have a backhaul connection to the VDE satellite network gateway through a ground station each, to exchange telemetric, command, and service data between the gateway and the satellites. All data exchange is typically performed over proprietarily chosen protocols, which may or may not be standardized or open.

Most importantly, interface S1 to the service providers is proprietary, as there is no standard for that interface, yet.

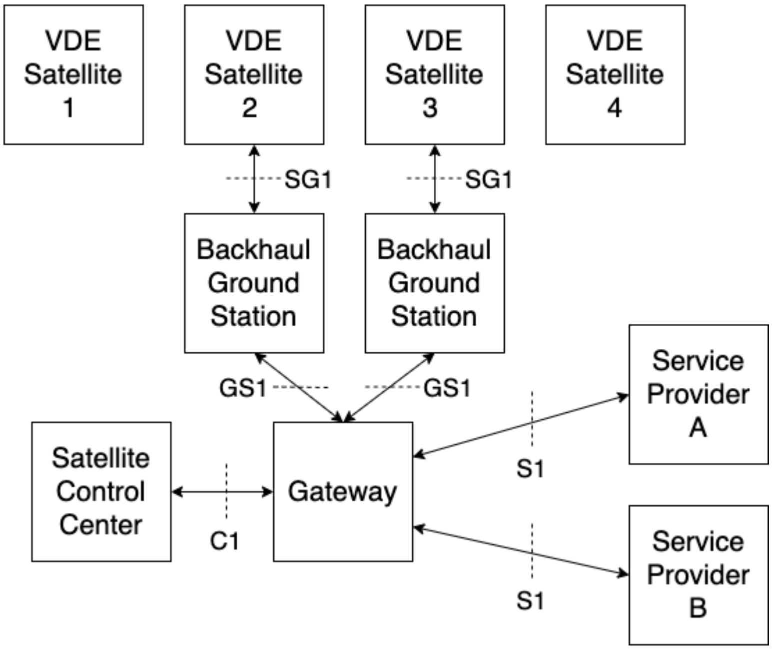

Figure 78: A typical VDE Satellite system implementation using proprietary interfaces.

2.6 Proprietary Interfaces

Even if sharing satellite capacity with other operators, the operator of a VDE satellite is expected to protect:

- the value of the satellites in space,
- any proprietary design of the satellite or payloads that gives that operator a competitive advantage,
- the strategy of which areas to cover exclusively or when to offer spare capacity to other operators,
- all telemetric information about the health and operational limits of the satellite that might give competitors an advantage,
- the ability to run telecommands towards the satellite bus.

Operators are therefore not expected to share the Ground Station interface (GS1 in Figure 3), the Satellite to Ground interface (SG1 in Figure 3), or the Control interface (C1 in Figure 3), as it would give others the full control over their satellite.

These interfaces are considered highly protected and proprietary for the responsible operator of a satellite.

2.7 Open Roaming Interface

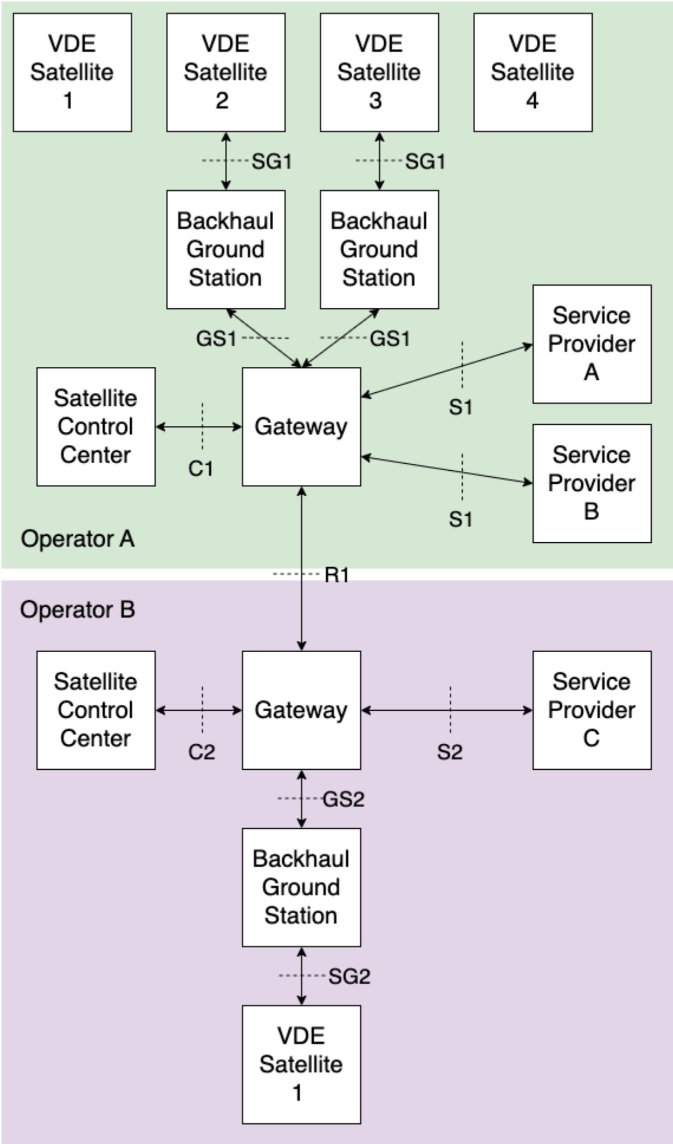

Figure 79: Example of 2 satellite operator networks A and B, with network sharing. The ships are omitted to keep the illustration less complex.

To share capacity of a satellite, the operators need to share information in order to being able to take decisions. While some information might be predictable a long time in advance, other information might be dependent on short term data.

For example, the amount of traffic operator A has to transmit over region X has an impact on the depth of discharge of the satellite batteries, determining the remaining amount of power that can be offered to operator B to be used over region Y. This situation is changing when regions X and Y transit from night to daylight, where charging is possible to a higher degree than during night.

Therefore, a Roaming interface (R1 in Figure 4) is introduced which needs to be implemented by both operators.

This interface would make available:

- an estimate of when a message of a certain size could be delivered to a certain MMSI or area,
- at which cost,
- and when it would be necessary to deliver the message to the gateway;
- furthermore, at what cost the other operator could receive messages for a certain service destination.

Consequentially, by using Roaming interface R1, VDE satellite network operator A could offer its customers, namely service provider A and B:

- more frequent broadcasts over certain service areas, and
- higher capacity to transport more broadcast and direct message data,

by selectively using VDE satellite network operator B's satellites.

The same applies for network operator B.

Both operators would benefit directly and are protected against outages of their networks by the other operators' networks availability for such cases.

The here proposed roaming interface allows operators to selectively cooperate and transport each other's services without the knowledge of the service or customers, just by sharing the bare ability to send and receive via VDE satellite channels.

Contracts will have to be made between the operators to:

- cover cost for each other's roaming traffic,
- cover customer's concerns for privacy and metadata information keeping,
- align on security requirements for each other's ground to satellite links and involved infrastructure.

Customers will need to agree that their metadata can be visible to operators other that the main operator. For publicly available broadcast data, that should be of less concern. For more private data, the use the Maritime Messaging Service could be encouraged.

2.8 Open Routing Interface

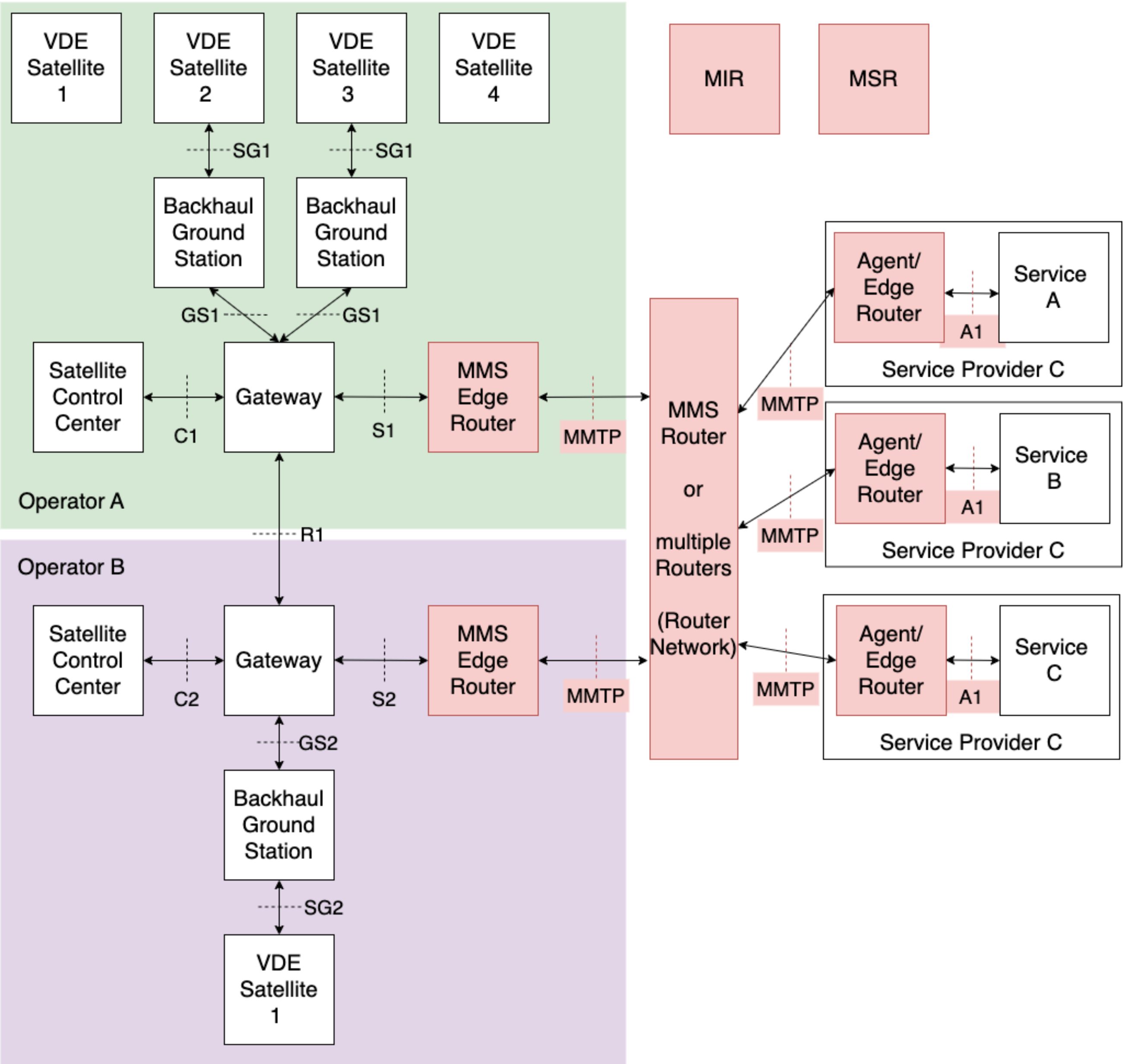

Figure 80: Open Routing using the Maritime Messaging Service. All red blocks are standardized functions and interfaces that are provided by the Maritime Messaging Service standard.

While the previous chapter introduced the Routing interface R1, making it possible for operators to share resources on the lower level, the Maritime Messaging Service will add more sharing possibilities.

The Maritime Messaging Service was first metioned in [7], the Maritime Connectivity Consoritum has since proceeded to define its architecture and functions. The architecture was introduced recently in the newest edition of [9].

At first glance, Figure 5 shows a more complex architecture, however all red blocks are standardized and foreseen to be open source implementations. The MMS Router is the central engine that handles routing of messages, is distributed as a router network to address trust and security concerns.

Trust between all participants, the Services A to C, the Edge Routers and Routers, is enabled through the already known Maritime Identity Registry (MIR), provided by the Maritime Connectivity Platform.

Transport of all messages happens through the Maritime Messaging Transport Protocol (MMTP), carrying all necessary information.

The Service Application interface A1, is expected to be a library interface to the MMS Agent, which shall be available in several programming languages.

However, A1 can also have variants that allow the use of SECOM [10] to interface with existing SECOM services, that are emerging many paces right now.

The basic concept of the MMS is subscription to Maritime Resource Names from the ship side (not shown in Figure 5). Example subscriptions in MMS can be:

(a) to a subject like "Weather bulletin Greenland South",
(b) to messages addressed to "my ships message application", or
(c) messages from Service A, B or C, etc.

Based on subscriptions managed by the Edge Routers, the Routers store and forward messages when connections to ships are as seen. This can happen either through Network Operator A or Operator B network. Given, either the ship or the service have an agreement with both Network Operators, messages can be roamed between the two.

The MMS is currently still under standardization. More details on the MMS are expected to be published by IALA, Maritime Connectivity Consortium and RTCM.

With the MMS, a more flexible setup for generic transport of messages over VDE satellite was shown. The MMS Router Network will also be connected to ships via IP connections, such as mobile internet, LTE-M, BGAN, Iridium, etc. As the store and forward mechanism is used in MMS, it is compatible with heterogeneous, constantly changing and unreliable connectivity, while providing simple interfaces for the Service and Ship end points.

3 CONCLUSION

Two methods for using open interfaces in VDE Satellite to share resources have been introduced. While the Roaming Interface R1 does not strictly require standardization. The MMS requires standardization, happening at the Maritime Connectivity Consortium, and is planned to intermediary become a RTCM standard, to finally become an IEC standard later.

Both methods "Roaming Interface" and "MMS" will benefit from participation of operators and ship equipment producers early in the standardization phase.

4 ACKNOWLEDGEMENTS

The author thanks for the excellent collaboration at IALA and the Maritime Connectivity Consortium. The freedom to concentrate on work, instead of heavy procedures, in both of these two organizations, leads to a lot of beneficial work that finally ends in international standards to the benefit of the mariners worldwide.

Thanks also to the VDES Alliance for its efforts to arrange inter-operability testing, which is not in scope for any other standard or organization, ensuring that equipment can function together out in the waters.The VDES Alliance might be potential platform to standardize the inter-satellite operator Roaming Interface R1.

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AUTHOR BIOGRAPHY

Stefan Pielmeier was born in Nürnberg, Germany in 1972 and received his Master of Electrical Engineering from University of Erlangen-Nürnberg in 1997.During his formal education at the University, he created several small series power and receiver amplifiers for radio amateurs, supporting his interests in technology and a sailplane pilot's license. In 1997 Stefan Pielmeier joined Ericsson Eurolab Deutschland GmbH in Nürnberg developing embedded software for the first generation mobile 3G base stations later as a system architect.

In 2003, at Texas Instruments Villeneuve-Loubet, France he took the role of project leader for 2.5G mobile chipsets and in 2005 changed to be the continuous integration responsible at the Aalborg, Denmark site. In 2007 Stefan Pielmeier changed to Telenor Denmark, bringing the data core network components to support 4G. From 2010-2018, he managed the software development of the maritime MF/HF and VHF radios AIS, GNSS and NAVTEX for Thrane & Thrane A/S in Aalborg, known as the SAILOR Radios.

Since 2014, Stefan is actively participating in the standardisation of the new maritime digital communication standard VHF Data Exchange, since April 2019 as chairman for the IALA eNav communications working group. Since July 2019, Stefan is CTO for the first commercial danish satellite network operator Sternula, delivering the VDE-SAT service to the maritime community, founded by his partner Lars Moltsen and himself. Stefan represents Denmark for VDES related topics in ITU WRC, ITU WP5B, IEC and IMO, and is proud member of RTCM.

S116.1 AIS Network in Papua New Guinea (001)

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ABSTRACT

The National Maritime Safety Authority (NMSA) of Papua New Guinea (PNG), through the Asian Development Bank funded Maritime and Waterways Safety Project (MWSP), sought to develop a nation-wide maritime monitoring and surveillance system to improve maritime safety, reduce environmental risk related to shipping, and to increase domain awareness throughout its coastal waters.

At the advent of the MWSP project, there was a very limited operational network of infrastructure through which NMSA could monitor shipping in PNG territorial waters. The need to establish such a system was responded to through the 'Automatic Identification System (AIS) Coastal Network Extension and Base Station Installation' project.

Awarded through an international bidding process in 2019, the project was successfully carried out by Vissim AS, of Norway, and M-NAV Solutions, the nominated in-country specialist sub-contractor. A total of fifteen new AIS Coastal Stations were successfully designed, installed and commissioned at strategic locations around PNG, and integrated through a communication network to display data at a centralised Vessel Monitoring Centre (VMC), located at NMSA headquarters in Port Moresby, vastly increasing the NMSA's capacity to carry out monitoring and surveillance of shipping in its territorial waters.

At completion of the project, an upgrade and rehabilitation of two Coastal Monitoring Stations was undertaken by the contractor, providing Vessel Traffic Service capabilities and enhanced monitoring in two critical locations, including the Jomard Passage Particularly Sensitive Sea Area (PSSA). Data from both sites was integrated into the VMC centralized monitoring systems, allowing the NMSA to detect vessels by both radar and CCTV, to monitor local meteorological conditions and provide the ability to communicate remotely via VHF radio.

KEYWORDS: Coastal Monitoring, AIS Monitoring, Coastal VTS, Papua New Guinea, Maritime Safety, Jomard Passage, Radar, Coastal VHF

1 INTRODUCTION

The National Maritime Safety Authority (NMSA) of Papua New Guinea (PNG), through the Asian Development Bank (ADB) funded Maritime and Waterways Safety Project (MWSP), sought to develop a nation-wide maritime monitoring and surveillance system to improve maritime safety, reduce environmental risk related to shipping, and to increase domain awareness throughout its coastal waters.

With over 600 islands spanning a total sea area of 3.1 million square kilometres and 65% of its population residing in in coastal areas, PNG relies heavily on its network of coastal shipping services. Passenger and cargo services allow citizens to access health, education and other services essential for inclusive growth [1].

Local shipping routes are shown in Figure 1, with the thickness of the lines indicating corresponding traffic volumes.

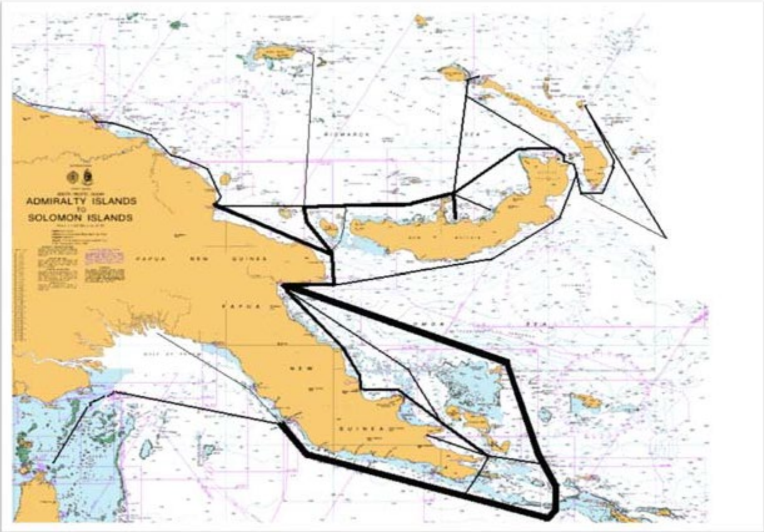

Figure 81: Local Shipping Routes [2]

Likewise, due to its geographical location, there is a network of well-established, heavily trafficked international shipping lanes between Asia and Australasia passing through PNG’s coastal waters. Shipping through these lanes consist of both vessels on international transit and international cross-over operators.

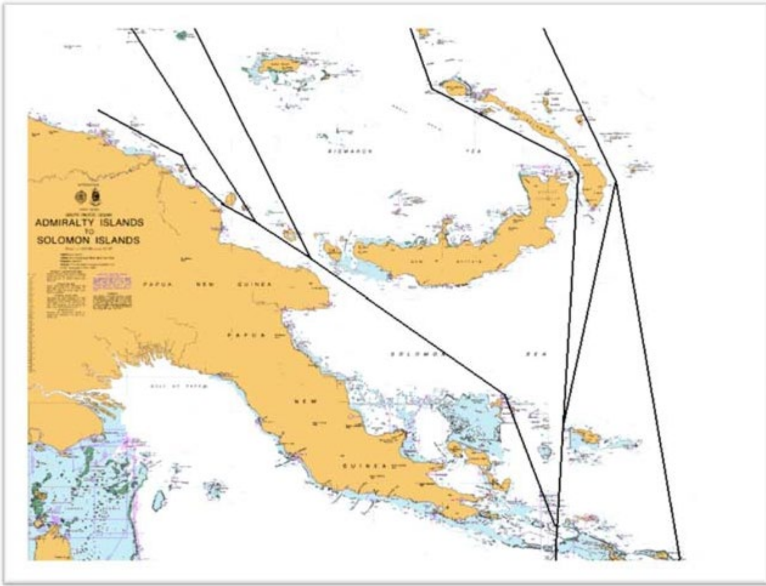

Figure 82: International shipping routes [2]

The complexity and volume of shipping is further complicated by the presence of shipping lanes in pristine marine environments, which presents significant risk to the marine environment unless hazards are well marked and there is a capacity to monitor and respond to potential incidents. This is especially evident in areas like the Jomard Entrance, which is a navigable strait in the Milne Bay Province, where the convergence of north and south bound international shipping poses considerable risk of impact on the marine environment. The level of risk in that location prompted PNG to successfully lobby for the area to be designated a Particularly Sensitive Sea Area (PSSA) by the International Maritime Organization (IMO), one of only seventeen (17) worldwide.

In 2008/09 NMSA took the first steps in establishing an AIS network, comprising five base stations in Port Moresby, Alotau, Lae, Madang and Rabaul [2]. The distribution of those AIS stations throughout established ports provided coverage of about 35% of PNG waters. In consideration of ever-increasing traffic, the NMSA planned to extend coverage to about 75%, enabling the authority to better monitor traffic in territorial waters and to react faster and more efficiently at any incidents or emergencies [2].

At the advent of the MWSP project there was a very limited operational network of infrastructure through which NMSA could monitor shipping through PNG coastal waters. Coastal stations previously installed were no longer serviceable due to a number of contributing factors. The need to re-introduce such a system was responded to through the 'Automatic Identification System (AIS) Coastal Network Extension and Base Station Installation' project, which provided the scope for the replacement and installation of a series of new AIS coastal stations in strategic locations around PNG.

The competitive international bidding process for this contract commenced in December 2018, and after the official evaluation and procurement process, was officially awarded to Vissim AS, of Norway, in June 2019. M-NAV Solutions was engaged as the in-country sub-contractor responsible for assistance with design, logistics and local installation. The contract was signed in September 2019, at which time the design process commenced.

2 THE PNG AUTOMATIC IDENTIFICATION SYSTEM (AIS) PROJECT

The scope of the contract required Vissim and M-NAV to design, install and commission a series of fifteen (15) AIS Coastal Stations in locations around PNG's coastlines. These AIS Coastal Stations were to be designed to suit the operating conditions in remote, aggressive marine environments and to collect AIS signals from vessels within range, and reliably transmit that data to a central Vessel Monitoring Centre (VMC) to be established at NMSA headquarters in Port Moresby.

Vissim partnered with M-NAV Solutions, a specialist Aids to Navigation (AtoN) product and service provider, who have extensive experience in remote site works and the design and operation of AtoN in the Asia-Pacific Region, including PNG.

The complex requirements of the project and the remoteness of the coastal station sites presented several unique technical challenges that could not be met by off-the-shelf equipment. As such, Vissim and M-NAV developed a concept design for an AIS Coastal Station system to meet these challenges and ensure equipment performed in difficult and remote environments with a high level of reliability. Some of the key issues were the;

- Extreme remoteness and difficulty of access for many of the sites,
- Lack of a reliable power supply to power and operate the electronics with a high level of availability, and;
- Tropical conditions, particularly the high heat and humidity, in which the electrical equipment would need to operate.

These issues were addressed in the selection of a modular, lightweight, durable telecommunications enclosure for housing of the AIS base station and other electronics. The modular nature of the enclosure allowed for transport to difficult-to-access sites by helicopter and for ease of installation on site.

A fully autonomous power supply, incorporating solar panels and an internal battery bank, was designed based on providing a minimum of 10 days autonomy, ensuring that the coastal stations would continue to operate even during extended periods of inclement weather or low sunlight.

The enclosures were also designed to allow cooling through efficient natural airflow and ventilation, avoiding the use of power-hungry air-conditioning whilst still ensuring operating temperatures inside the cabinet were optimally maintained.

An innovative method of ground mounting was also incorporated, using specially engineered ground anchors to ensure the coastal station could be installed with a high level of stability, regardless of the ground conditions. This allowed Vissim and M-NAV to avoid the use of concrete foundations, which would have required mobilization of a large volume of materials to site and increased the risk of environmental impact.

Figure 83: AIS Coastal Station Enclosure

Figure 84: AIS Coastal Station Enclosure

Installation of the fifteen (15) AIS Coastal Stations was successfully completed over a 7-month period between March and September 2020.

Communication links between the remote sites and the VMC were critical, and the majority of sites were connected to the national Telikom system, allowing for transmission of data through a country-wide network leased by the NMSA. AIS Coastal Stations were co-located on Telikom sites, with enclosures ground-mounted adjacent to Telikom structures, and VHF antennas installed at the top of the towers for maximum elevation and coverage.

For sites where Telikom networks were not available, Broadband Global Area Network (BGAN) satellite terminals were used, to provide high-performance, reliable connectivity.

Figure 85: AIS Coastal Station Enclosures (Battery Array and AIS Base Station)

Figure 86: AIS Coastal Station Enclosure; BGAN Terminal and VHF Antenna

After completion of site installations, the VMC was installed and commissioned. Networks were configured for the reliable transmission and receipt of data from all remote AIS Coastal Stations into the VMC servers, where it was received, processed and made available for intuitive display on the Vissim VTMS software platform.

A dedicated server room was used for the controlled storage of the redundant servers, power distribution system and a rack mounted UPS system designed to provide several hours of back-up power in the event of power failures. The central VMC room was designed to incorporate two (2) operator work stations and one (1) supervisor work station. Each work station consisted of three (3) LED display screens and a PC networked to the AIS servers. A multi-screen LED wall was also installed, consisting of eight (8) 50” LED screens, providing a geographical overview of PNG coastal waters, displaying all AIS targets within range of coastal stations. This large multi-screened wall display provides operators a snapshot of vessel traffic activity throughout the country, allowing them to check locations or vessels in more detail at their operator stations when needed.

Figure 87: Vessel Monitoring Centre (VMC) Installation

At the completion of the project, the NMSA had system whereby they could monitor shipping on a 24/7 basis, both domestic and international, through the majority of PNG's coastal waters, with data collated from the network of remote AIS Coastal Stations, from a central monitoring location at NMSA headquarters. This provided a significant increase in the NMSA's capacity to carry out monitoring and surveillance, which increased the understanding of activity within PNG's coastal waters (both real-time and historical), vastly improving maritime safety, search and rescue and incident response, and protection of the marine environment. Access to real time information and historical data also allowed inter-agency and inter-departmental cooperation with other sectors of the PNG government, to provide additional support for defence, security, customs, maritime border awareness, fisheries surveillance and law and order.

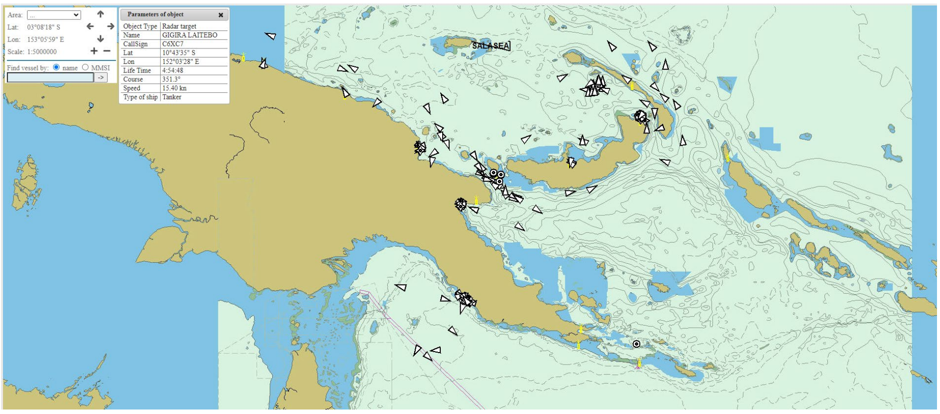

Figure 88: AIS Targets Showing on System Traffic Display Web Server

The focus on using fit-for-purpose enclosures, where robust, high quality marine electronics could be operated in stable, controlled conditions, powered by autonomous renewable power supplies, ensured the system was reliable and would operate with high availability levels.

The success of the project and the enhanced capacity it provided in delivery of their mandate of the management of maritime safety, prompted NMSA to look at the possibility of upgrading other critical infrastructure and integrating it into the same system, namely the Tuam Island and Jomard Island Coastal Monitoring Stations (CMS).

3 THE PNG COASTAL MONITORING STATION (CMS) UPGRADE PROJECT

The original Tuam and Jomard Island CMS sites were installed by the NMSA in 2014 – 2015. The CMS locations were chosen due to their proximity to major international shipping routes in PNG waters.

Tuam Island is located in Morobe Province, on the east side of the Vitiaz Strait, which is a heavily trafficked shipping lane for both domestic and international shipping.

The location of the CMS at Jomard Island was particularly important, as the Jomard Entrance is a critical convergence point for vessel traffic through PNG waters, to and from Asia and Australia. The designation by the International Maritime Organization (IMO) of the Jomard Entrance as a Particularly Sensitive Sea Area (PSSA) made the requirement for monitoring and traffic management even more critical. The IMO define a PSSA as a "an area that needs special protection through action by IMO because of its significance for recognized ecological or socio-economic or scientific reasons and which may be vulnerable to damage by international maritime activities". The designation of the Jomard Entrance as a PSSA allowed PNG, via an IMO mandate, to introduce mandatory ship routing measures as a means of controlling and regulating traffic on both the northern and southern approaches.

However, the effectiveness of such measures is restricted to the level of compliance by vessels, and the Jomard Island CMS provided the most effective means of monitoring vessels and gathering data with which to pursue vessels that do not comply.

The original sites were equipped with a number of data acquisition technologies, including radars, AIS base stations, CCTV cameras and weather stations. Communication links were established through installation of large satellite dishes on site, facilitating transmission of the data to a monitoring centre at NMSA headquarters in Port Moresby. Due to the remote nature of the sites, the system was designed to be powered by solar and battery systems, with some supplemental power supplied by wind turbines.

The sites were successfully installed and operated as required for an extended period. The concept proved successful, however the technical trade-offs required to meet the site related challenges meant some operational issues were experienced.

These included the need to choose very low power consumption radars with limited radar performance across the entire spectrum, providing some limitations to range and target identification and tracking and the need to use very low-resolution CCTVs to meet the size restrictions of the satellite link.

The sites operated for several years, but due to maintenance difficulties, the age of power supplies, and issues identifying a suitable satellite communication provider, the sites eventually stopped operating.

The success of the concept however, provided an opportunity for NMSA for improvement and upgrading. Advancements in the technology that the CMS sites initially used had been significant, providing the possibility for better performance, lower power consumption and smaller communication links.

As such, during the implementation phase of the PNG AIS project, NMSA requested Vissim and M-NAV to explore the possibility of rehabilitating and upgrading the CMS sites. This process eventually led to a formal direct contracting to Vissim and their subcontractor, M-NAV Solutions, for the design, supply and installation of the Tuam and Jomard Island CMS upgrades.

The complex requirements of the project, the range of sensors needed and the extremely remote and difficult-to-access natures of the sites presented serious technical challenges that required an experienced approach to the site design. Some of the key issues were;

- Extreme remoteness and difficulty of access for many of the sites and the need to manually carry all equipment to site,
- Lack of a reliable power supply to power and operate the electronics with a high level of availability.
- Tropical conditions, particularly the high heat and humidity, in which the electrical equipment would need to operate, and;
- Selection of an economic and appropriately sized method of satellite transmission for large amounts of data.

These issues were similar to those experienced and successfully addressed in the PNG AIS project and as such a similar approach was taken – by installing equipment and power supplies in modular, lightweight, durable telecommunications enclosures. Due to the amount of equipment to be utilised on the CMS sites, a different selection of cabinet sizes was chosen. The modular nature of the enclosure allowed for manual handling and transport between vessels, the shoreline, and transport to site.

The power consumption of the CMS systems was calculated to be approximately thirty (30) times more than the AIS Coastal Stations and the power supply was designed based on an analysis of historical wind and solar irradiation data. An autonomous hybrid power supply was designed, incorporating both solar panels and a wind turbine powering a large internal battery bank. The system was designed with enough autonomy to ensure the sites would operate reliably even during extended periods of inclement weather or low sunlight.

The enclosures were designed to allow cooling through efficient natural airflow and ventilation, with fans placed in optimum locations to ensure circulation and regulation of temperatures inside the cabinet.

The actual rehabilitation phase site works commenced in November 2021 and were complete after four (4) weeks. NMSA and the Vissim / M-NAV installation team were based aboard a liveaboard survey vessel for the duration of the site works, with over fifteen (15) tonnes of equipment stored and transported on three different vessels.

All equipment was manually transferred from vessel to shore and local communities and resource owners were engaged to assist with transportation of the equipment to site.

Communication links between the CMS sites and the VMC were critical, with satellite communication the only option. The provision of the final satellite communications was outside the scope of the Vissim contract and were installed separately by a contractor engaged directly by NMSA. Site layout required careful consideration and the CMS enclosures were installed in locations to optimize solar gain and to avoid shading, yet close enough to the structures where the VHF antennas, weather stations, CCTV and radars were installed on the top platforms. Locations also took into consideration the position of the satellite dish foundation and the required cable runs.

Whilst site works were completed in 2021, delays in the procurement of the satellite communications meant that the satellite links were not commissioned until March 2022. Once links were established, the final configurations and calibration of the sites and the VMC were undertaken.

The existing servers were reconfigured with additional software modules, now providing NMSA operators a suite of new monitoring and identification methods at both Tuam and Jomard, including:

- The viewing and interrogation of all AIS targets,
- Viewing of radar targets, which the software platform automatically integrates with visible AIS targets,
- Visual identification and tracking of vessels through the Jomard Passage, via the CCTV,
- Real-time information on weather conditions, including wind speed, temperature, humidity, precipitation, air pressure and visibility,

- VHF radio capabilities, including the ability to scan and monitor a range of VHF channels, and to communicate directly with vessels, and;
- The ability to remotely monitor the status of the site power supplies, including solar charging levels, battery voltages and equipment power consumption.

Integration of the CMS data into the existing VMC resulted in a major enhancement of the NMSA’s ability to monitor and carry out surveillance in PNG waters, and in particular, vessel activity in two (2) new locations where the complexity and volume of vessel traffic creates significant risk.

In the case of the Jomard Entrance, it also allowed the NMSA to study whether vessels were complying with the mandatory routing measures stipulated by the IMO as part of their designation of the area as a PSSA. Access to data provided the means by which the NMSA could further lobby the IMO for additional protection measures if they were deemed needed.

The data from the CMS sites also increased cross-agency and government departmental cooperation in protection of PNG’s sovereign interests in the maritime domain.

Furthermore, the flexibility of the system allows for the addition and integration of additional sites which will allow the NMSA to focus on installing infrastructure in locations where a lack of coverage is identified or the level or risk identifies that additional monitoring, surveillance and response is required.

The overall design, particularly the site enclosures and choice of high-quality equipment, can be easily adapted to meet any technical requirements or site conditions, and forms the basis of a system that can be operated remotely, cleanly and reliably from a central location.

Figure 89: CMS Enclosures

Figure 90: CMS Power Supply Enclosures

Figure 91: Radar Installation

Figure 92: CCTV (Jomard Island)

Figure 93: Tuam Island CMS Site

Figure 94: Jomard Island CMS Site

4 CONCLUSION

In a region where maritime transport is so critical, the need for systems to improve maritime safety, for marine surveillance and monitoring or for better management of shipping, is undeniably important.

The capabilities, performance and reliability of those systems should be based on a carefully managed design process, which takes into account all factors that will impact both performance and reliability.

The actual capabilities of systems should firstly be designed to respond to the end-user's requirements. Whilst those requirements are often understood by governments and/or their designated safety authorities, there are still several key issues that should be considered in early-stage system design. These include domestic or inter island shipping patterns, an analysis of international shipping lanes, an assessment of the presence of pristine environments, natural or man-made navigational hazards and the risk of environmental impact that is associated with shipping activities. A review of the history of shipping related incidents and consideration of inclement weather patterns and natural disasters and the impact they have on maritime safety is also critical.

The above process allows identification of the core elements of a suitable system, including a concept layout, the identification of locations for a central monitoring / control centre and selection of the core technologies that are required.

This then allows for a more detailed design process. The Asia-Pacific region poses numerous unique challenges that can impact the performance and suitability of these systems. Extreme remoteness and geographical layout can affect range and performance of monitoring technologies and propagation modelling should be carried out based on actual conditions, in order to identify the extent of coverage. Heat and humidity also present a major danger to the operation of remote sites and marine electronics, which is not always understood by manufacturers and suppliers.

Equipment must be carefully chosen based on its operating parameters, and as can be seen by the PNG AIS and CMS Projects, the enclosures or method of storage have to be carefully selected to ensure operating temperatures are maintained, humidity is controlled and that there is a stable, reliable power supply that has been designed to suit the site conditions. Modern satellite communications provide numerous options for the transmission of data, and the most suitable can be chosen once the system design and layout is established.

This is the process by which the NMSA's MWSP projects were implemented, with the end result being a highly reliable, functional, country-wide monitoring and surveillance system that is administered and managed from a central location at the NMSA's headquarters.

5 ACKNOWLEDGEMENTS

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AUTHOR BIOGRAPHY

Adam Hay has worked in the AtoN and maritime safety industry for the last 18 years, predominantly in the Asia Pacific region. During that time, he was involved in the design, installation, maintenance and management of remote AtoN and maritime surveillance infrastructure and in assisting in the building of regional capacity.

Adam is now Director of M-NAV Solutions, an AtoN and IALA Industrial Member based in the Australia, the Philippines and Hong Kong. In 2021, Adam also co-founded Inovaton Limited to develop, design, and manufacture innovative products for the maritime safety and maritime surveillance industries.

Adam has had extensive involvement in IALA activities, acting as Chairman of Working Group 2 in the IALA Engineering and Sustainability Committee (ENG) for 2014 - 2018. He has also attained the IALA Master of Marine Aids to Navigation Management qualification.

S116.2 Practical experience with greenfield AIS base stations in a remote, challenging and vulnerable Arctic (122)

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ABSTRACT

Svalbard is an archipelago in the Arctic, North of Norway, stretching from approximately 76° to 81° North. In later years, there has been a large increase in ship traffic around the Islands. The increase relates to a combination of tourism and fishery. The area is remote and challenging from several operational perspectives, such as search and rescue, oil-spill recovery and environmental protection. AIS will help monitor and manage maritime traffic around Svalbard, while dealing with hazards like extreme cold and powerful gales in addition to darkness during long winters. The Norwegian Coastal Administration (NCA) has established an AIS network on the archipelago, delivered by KONGSBERG. Several locations have been equipped with Greenfield AIS technology, developed by KONGSBERG. In addition to technical operational challenges, the installation and maintenance of the AIS base stations has also posed challenges in this remote and extremely weather exposed area.

KEYWORDS: AIS, Base Station, Arctic, IMO e-navigation, Maritim ITS, Greenfield

1 INTRODUCTION

The presentation starts out with explaining the need for traffic monitoring capability in the Svalbard archipelago. There are many stakeholders and factors to consider when operating in this isolated, exposed and vulnerable environment. Furthermore, the presentation highlights important considerations needed to satisfy operational needs. AIS is a mature technology. The challenges mainly relate to achieve a green footprint, supply of power, battery, communication links, installation, and maintenance in a harsh and remote environment.

2 THE AIS ENVIRONMENT

AIS (Automatic Identification System) Norway, operated by the Norwegian Coastal Administration (NCA), provides a continuous overview of ship traffic along the Norwegian coast. Information from on-board AIS mobile stations providing vessel identity, position, speed, and course, is received by 70 base stations along the coast, and by four AIS satellites. The satellites circle the earth in polar orbits, providing good coverage of the northern areas. However, due to a limited number of satellites , each spending a short time over the primary monitoring area, they only provide intermittent coverage. In contrast, terrestrial AIS base stations provide a near real time continuous traffic overview.

The Svalbard archipelago is composed of tall mountains, glaciers, beaches, deep fjords and a diverse wildlife of birds, marine mammals, and polar bears. Around 20-30 cruise vessels/passenger vessels, taking a maximum of 250 passengers, are on a regular basis operating in the area, typically on a voyage circling the main island that takes 7-9 days. In addition, there are 30 larger cruise vessels and a high number of smaller passenger vessels calling at the port of Longyearbyen yearly. The season stretches from May-September. In addition, we are seeing a large increase in the number of visits by leisure crafts. These vessels tend to circle the Archipelago as well. Fishery is also increasing. The Snow crab is moving westwards and is approaching the south tip of the archipelago, whilst the cod is the major fishery on the west and south side. Shrimp fishery is a big industry, especially in the northern part.

Figure 95 A shrimp trawler grounded on the north side of Svalbard at the end of 2018

The real time AIS data collected from the AIS network on Svalbard provides valuable information about the movement of fishing vessels. This data is valuable for statistical purposes. The Coast Guard is using the data in their daily operations for more efficient inspections. AIS data can also be used in case of disputes related to illegal fishing.

In case of accidents, the MRCC will immediately be able to track the distressed vessel and identify any vessels in the area that may be able to assist. The MRCC has access to information of capabilities of the relevant vessels' capabilities, such as rescue materials on board, towing capacity, medical capabilities and size, which will be important, especially if the distressed vessel is large and has many passengers on board.

The development and implementation of Greenfield AIS stations on Svalbard is partly based on experience from the Arctic mainland of Norway. Its development has involved several stakeholders and experts on arctic conditions. Some locations have benefited from the use of existing infrastructure, but due to the increase in traffic, it was also decided to expand the coverage on Svalbard beyond sites with existing power and communication network. It might sound simple just to install some base stations, however, this decision caused some quite extraordinary challenges.

The setting was as follows;

- the base station power consumption is below 10W on average in standard operation.
- the temperature easily fall below -30°C, which is a problem for charging batteries,
- batteries are expensive and a large supply isrequired,
- solar panels can be used effectively from April-September; however, the rest of the year is too dark for them to function properly,
- there are heavy winds and much snow and rain,
- close to the sea there are curious polar bears,
- up in the mountains there are large birdlife habitats,
- at elevation higher than 400 meters icing poses a challenge for technical equipment,
- the vast areas are only accessible by helicopter,
- there was a need for a solution to harvest and store excess power, from other sources than solar cell panels.

The solution was a self-contained base station with the battery capacity of around four months. The batteries from SAFT are chargeable down to -25°C. Power is produced from three high and slim solar panels mounted around the mast and a wind turbine with silicone coated blades that makes it less vulnerable to icing. As the sun is above the horizon 24/7 in the summer months, the power production is good, and the slim shape makes it less exposed to heavy wind. The stations are mainly located below the cloud level. No guywires are used to avoid negative effects on birdlife. In general, the station has a low footprint and earns its name, Greenfield AIS base station.

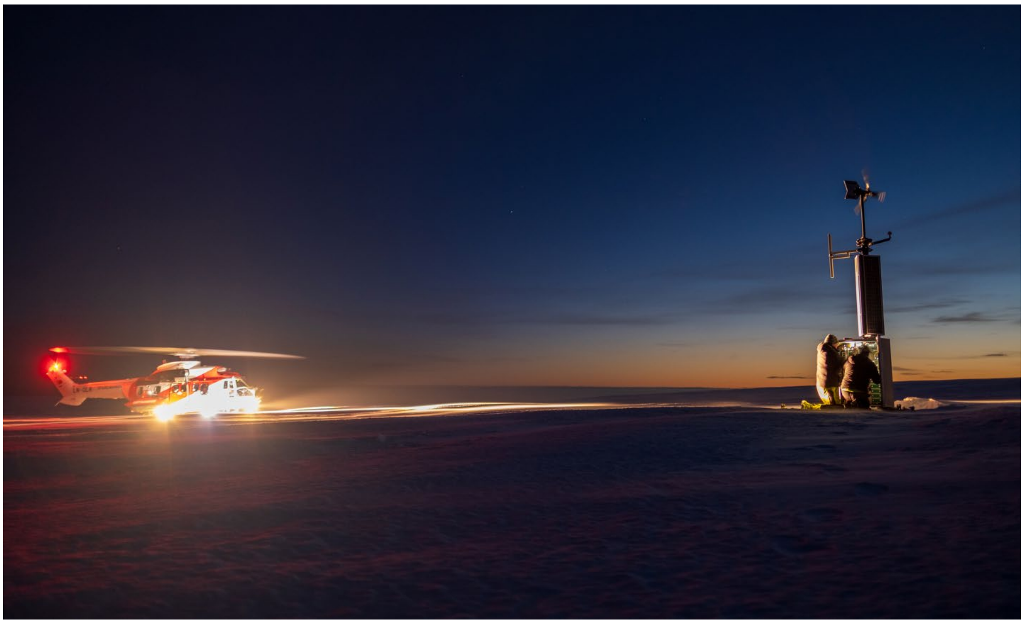

Figure 96 Installation of AIS GFS on Svalbard

The Greenfield AIS base stations are located around the main island as well as on Hopen and Bjørnøya. Data is transferred from station to station while utilizing the repeating functionality of a base station and the third channel (Ch C). Data enters the network after being received by a base station with network access. The Greenfield AIS stations are hence independent on satellite communication, which is an advantage considering the reduced satellite coverage and power consuming equipment. The area between Svalbard, Bjørnøya, Hopen and the mainland is now covered by terrestrial AIS. The highest stations have continuous coverage of around 80-90 Nm.

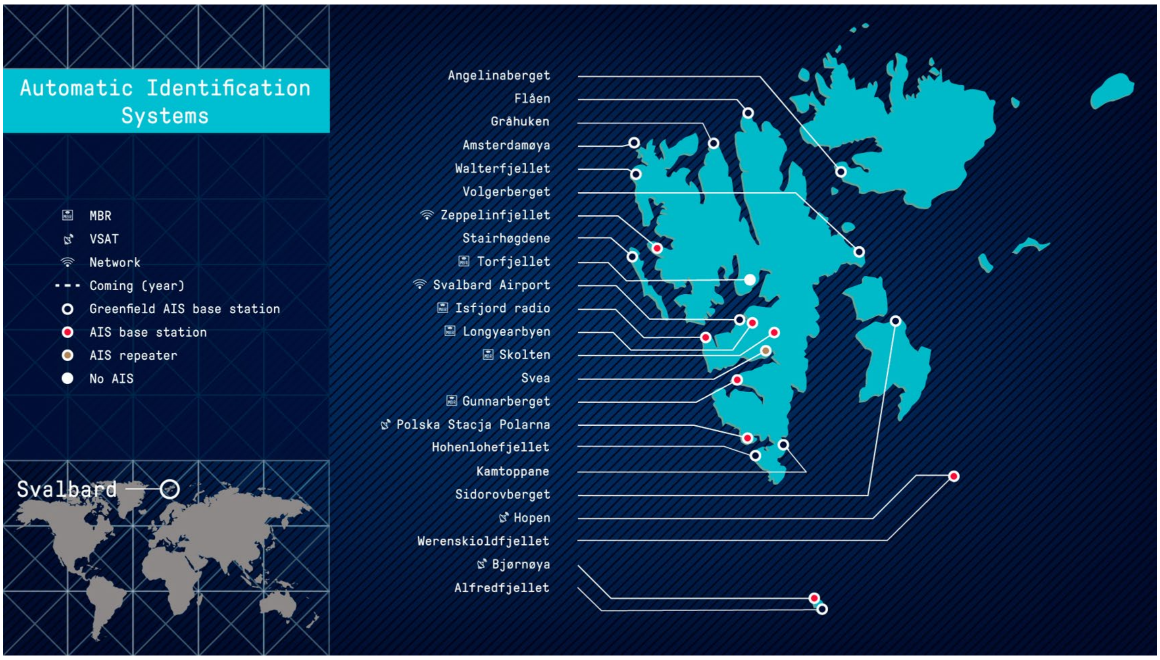

Figure 97 AIS Greenfield coverage. Blue = GFS, Red = standard AIS base station

We have gained valuable experience during the installation process and some years of operation:;

- Originally, the plan was to bring the base stations in parts to the site. It turned out to be more efficient to preassemble it completely, except for the turbine, and flying it out to the site by helicopter.
- It is important that the batteries can be charged at low temperatures. The selected SAFT batteries were the fourth type of batteries tested.
- Excessive power needs to be "boiled" away. An "oven" is therefore used outside when the batteries are full. This is handled by the regulator. The turbine used produces more power (500W) than documented (400W), resulting in a need for a larger oven and a reduced turbine diameter.
- A vertical turbine was tested initially (20W), but due high operating winds it did not work and was very vulnerable for icing.
- The VT10 turbine (pictures) has started to show weak bearing. This is probably due to vibrations in the mast. In 2023, the NCA plans to test a new type of turbine.
- All edges have been rounded and enclosed to prevent polar bears from climbing the base stations. One site had a visit where a panel was ripped off and its enclosed cables chewed on. A new profile that will close the gap between panels completely will be mounted.


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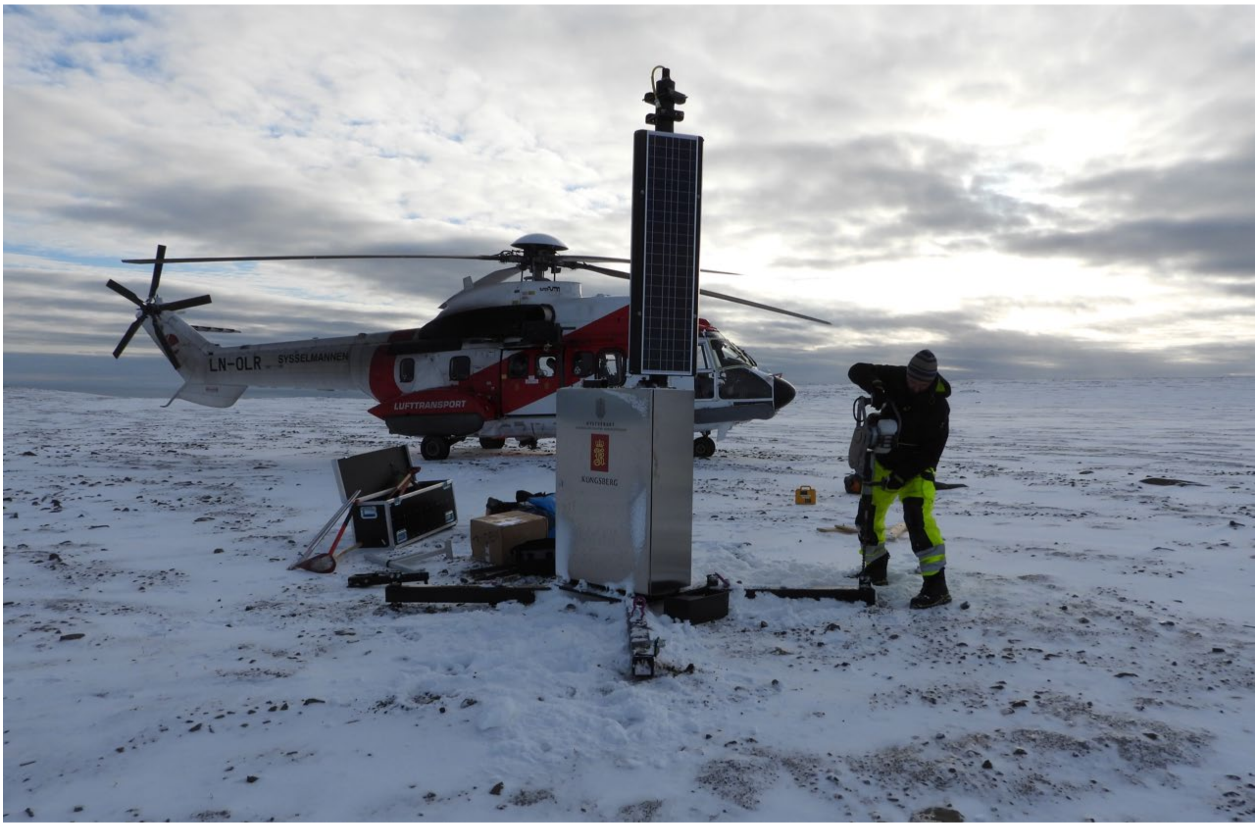
LN-OLR
SYSSELMANNEN
LUFTTRANSPORT
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3 CONCLUSION

- AIS greenfield stations (GFS) have increased the vessel monitoring capability in the Svalbard archipelago.
- Good planning is essential to ensure success.
- Installation must be carefully planned in locations where we can gain the most experience from weather and climatic conditions.
- The equipment must be able to operate autonomously and without supervision throughout long winter periods.
- GFS is leaving a green footprint compared to alternative solutions.

AUTHOR BIOGRAPHY

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S116.3 Navigating our way to the future with Virtual AtoN (149)

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ABSTRACT

This paper describes how the recent efforts to bring up to date IALA Guideline G1081 and IALA Recommendation O-143 on the Provision of Virtual Aids to Navigation has impacted the inclusion of virtual AtoN into marine navigational services and how it may impact the future of navigation. The updates to these documents have been based on testing in multiple countries, and this shared knowledge has made possible guidance that better reflects current knowledge of the technology, the risks and limitations of virtual AtoN and their potential applications.

KEYWORDS: Virtual, Aids to Navigation, AtoN, technology, navigation

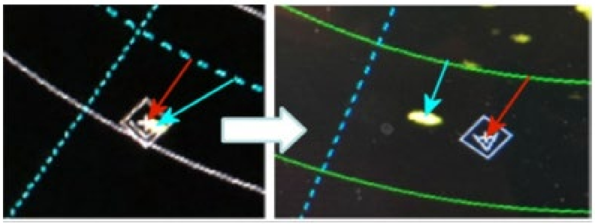
Mariners have been using a variety of instruments from their toolbox to safely navigate around the world for centuries. Many of the tools in use are dependent on what aids to navigation authorities can physically provide. The advent of the Automatic Identification System (AIS) has allowed national authorities and mariners to think outside the box and make use of Virtual Aids to Navigation (AtoN) to mark both objects and non-objects significant to navigation, allowing for an enhancement to safety and efficiency in navigation. Although AIS is the technology that has driven the development of this new tool, authorities are now able to look towards the future to other means of communication that will be able to provide the same benefits to navigators. As the use of Virtual AtoN has increased worldwide, it has become essential for AtoN authorities, mariners and equipment manufacturers to be informed on the value and uses of Virtual AtoN, along with the limitations and inherent risks involved, so as to be able to more safely execute the basic tasks of navigation, verify their position, determine a safe course to steer, and avoid dangers. In order to achieve this goal, international collaboration was necessary, as countries came together to share their experiences in the use of Virtual AtoN, resulting in a robust yet flexible guideline and recommendation, G1081 and R0143, on the Provision of Virtual Aids to Navigation.

1 FROM 2013 TO 2021

The original guideline on the Provision of Virtual Aids to Navigation was published in 2013 when countries first started thinking about the use of AIS for purposes other than collision avoidance. It has become clear that it is time to update shared information to reflect new findings and knowledge in order to allow for the implementation of technology in a harmonized and standardized way, a key concept of e-navigation. This collaborative effort in sharing perspectives has allowed for a larger body of knowledge than existed previously. In Canada, this has allowed for the development of national best practices. The IALA guideline has been instrumental in helping the Canadian Coast Guard to develop a structure for mandated and external use of Virtual AtoN, including directives, operational procedures, and risk analyses.

Initially, permanent usage of Virtual AtoN was limited in the 2013 guideline, however, as knowledge about the technology has increased, new ideas and beneficial applications have emerged. Although caution is still recommended to prevent misuse, a comprehensive risk assessment and consultations may lead AtoN authorities to consider more usages for Virtual AtoN. This is outlined in the expanded Annex A of the guidelines, Application of Virtual Aids to Navigation.

Trials and feedback from mariners have been instrumental in defining some of the benefits and limitations of this technology. For example, the use of Virtual AtoN by Canadian marine pilots led to the development of a new body of knowledge on some of the potential risks involved with using virtual AIS AtoN in confined waterways, such as position offset and triggering of ECDIS alarms by AIS AtoN. A new section was also added on the use of virtual AtoN for marking restricted areas.



Source: Corporation des Pilotes St Laurent, Canada

Figure 1 Example of offset appearance of Virtual AIS AtoN symbol

Increased knowledge of offset also allowed for more situational awareness, and visual information, on errors in GNSS position and the use of virtual AIS AtoN in evaluating shipborne equipment-related errors, information that is significant to marine pilots boarding foreign commercial vessels. An example of that effect is shown in the diagram below:

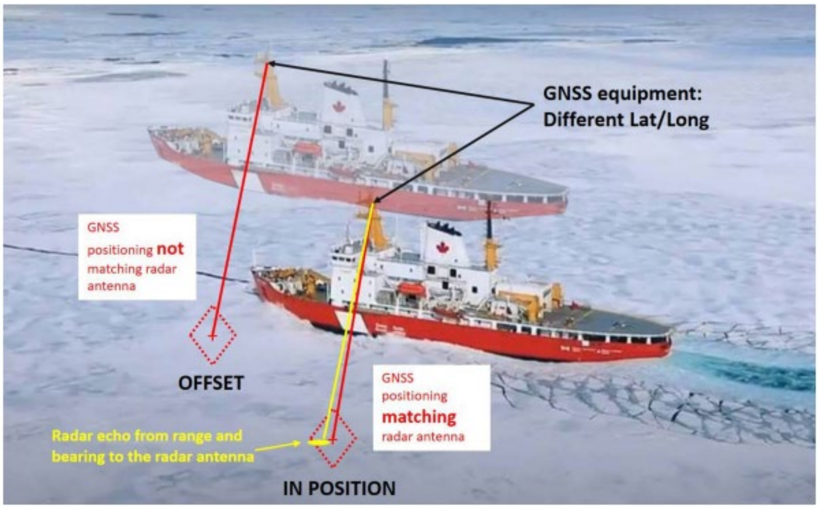


Figure 2 Example of effect of delayed GNSS antenna position on display of Virtual AIS AtoN symbol

The international collaboration allowed for sharing of information on things such as how a Virtual AtoN is displayed on shipborne equipment and has highlighted the issue of display inconsistencies between different systems. Making mariners aware that different display possibilities exist is an important educational piece and allows competent authorities to build trust in the tools they are providing.

During tests with virtual AIS AtoN by the competent authorities in Sweden in 2019, the following results emerged in the various systems:

Source: Swedish Maritime Administration and Swedish Transport Agency

Figure 3 Variation of imagery due to software and type of ECDIS equipment or mobile application

The tests conducted have provided valuable insights, emphasizing the need for continued testing.. Although a great deal of progress has been made with standardization, there is still work to be done to ensure that all required bridge equipment is capable of the same portrayal. Despite these inconsistencies in portrayal, concurrent work on other international publications has allowed for additional symbology information to be made available to mariners and equipment manufacturers, enabling more standardization in portrayal. For example, updates to documents such as IMO SN/Circ.243/Rev.2 Annex 2[5], IEC 62288, and the ECDIS Performance Standard have enabled increased guidance on navigation-related symbols, including Virtual AIS AtoN. Symbology for a missing AtoN was included in the Virtual AtoN guidelines, to clearly identify an absent charted physical AtoN. Although not available on all displays and testing with this symbol is still ongoing in Canada, this has the potential to provide a significant piece of information to mariners.

Source: Corporation des pilotes du Bas St-Laurent, Canada

Figure 4 Missing virtual AIS AtoN symbol versus display on ECDIS

Research into the naming of Virtual AtoN revealed large inconsistencies in how national authorities were identifying them, leading to confusion for mariners. As a result of collaboration on the guidelines, a set of guiding principles to assist national authorities in naming virtual AtoNs was provided, considering factors such as the use of a short name, respecting the IALA Maritime Buoyage System (MBS) conventions, avoiding repetition of other information already available in other parts of the AtoN Message 21.

Virtual AIS AtoN has been demonstrated to be a very suitable tool to use when mariners need to be quickly warned of new obstacles, which was successfully used by Danish and Swedish competent authorities during the gas leak in the southern Baltic Sea in September 2022. This marks a significant advancement in notifying mariners of immediate dangers that was not previously available..

Source: Seapilot

Figure 5 Virtual AIS AtoN for marking *of risk area in the event of a gas leak in the southern Baltic Sea in 2022*

The guidelines allow us to also consider the use of virtual AtoN for marking restricted areas. As the protection of our oceans becomes more and more important globally, virtual AtoN can be considered as an appropriate marking for a sustainable environment, as it allows for minimal environmental impact in sensitive areas such as Marine Protected Areas (MPA), either as a complement or an alternative to regular physical aids to navigation. Although at first glance this type of marking may not be appropriate in areas of heavy traffic, it has proven very useful in particular cases. For marking a temporary and variable area like this, AIS Application Specific Messages (AIS-ASM) could be used, however, virtual AtoN are considered more practical in real situations. This is because most systems can display virtual AtoN, while the proficiency to display AIS-ASM is not mandatory and only a few systems currently support it..

Source: Swedish Transport Agency (TSFS 2019:12)

Figure 6 AtoN and pictogram marking of MPA

2 CONCLUSION

The development of a more resilient guideline for Virtual AtoN provision has also led to the publication of Recommendations on the Provision of Virtual AtoN (R0143). To reiterate, this allows AtoN authorities, as well as mariners, to better understand and use Virtual AtoN in safe navigation. This in turn leads to protection of the marine environment and increased efficiencies in shipping while protecting the marine environment. Through these recommendations, AtoN authorities can manage user expectations, and users can better understand the potential applications of Virtual AtoN. The many examples cited from various countries also help the end users understand what they see on their shipborne displays and how to use it to their navigational advantage. Additionally, it allows for national authorities to develop their own operational procedures while respecting the basic principles of harmonization and standardization, essential elements of our digital future. Although there is still work remaining to overcome discrepancies between various systems and inconsistent portrayal, resulting in an imbalance of information available to mariners, the knowledge gained and shared provides a solid and resilient basis to chart the way forward together.

3 ACKNOWLEDGEMENTS

The authors would like to acknowledge the work and dedication of Mr. Yves Jacques, a retired employee of the Canadian Coast Guard, and the great contributions he made in Canada, and internationally, towards a greater understanding of the use of Virtual AtoN. This paper would not have been possible without his collaboration.

4 REFERENCES

[1] IALA. Guideline G1081 Provision of Virtual Aids to Navigation

[2] IALA. Recommendation O-143 Provision of Virtual Aids to Navigation

AUTHOR BIOGRAPHY

Eivind Mong joined the Canadian Coast Guard in 2017 after having worked for nearly 20 years in the maritime industry. He is currently the Senior Adviser for e-Navigation and is actively working on implementing e-Navigation solutions in Canada. Mr. Mong is also the chair for the IHO Nautical Information Provision Working Group and leads the S-124 Project Team of the World Wide Navigational Warning Service Sub-Committee.

S116.4 Analysis of the Influence of Virtual AtoN setting on AIS Communication Network (052)

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ABSTRACT

In recent years, due to the increase of ships and water services, the number of AIS messages has increased significantly, and the original channel resources have made the pressure of AIS communication network increasing. Usually, the virtual AtoN information is broadcast periodically by AIS base station, which will occupy part of the channel resources and increase the probability of AIS slot collision. In view of the reasonable setting of AIS virtual AtoN, this paper simulates the channel capacity and system blockage rate of AIS system under different numbers of virtual AtoN, analyses the impact of virtual AtoN setting on AIS communication, and comes up with the threshold value of the number of AIS virtual AtoN that can be set under different water conditions.

Combined with the conclusions of the relevant simulation analysis, the suggestions for reasonable setting of AIS virtual AtoN are given, which can be used as a reference for setting virtual AtoN in different waters. Under the condition of ensuring less influence on ship communication, the reasonable setting of AIS virtual AtoN can better play its navigational warning function and guarantee the safety of ship navigation, and further promote the application and development of virtual AtoN technology.

(No paper submitted)

AUTHOR BIOGRAPHY

Weiyun LI has a master’s degree in Communication and information system. Since 2007 he has been in engineering, designing and researching of aids to navigation. He has been engaged in the design and aids to navigation engineering System in CCCC Shanghai Waterway Engineering Design and Consulting Co., Ltd for 16 years. The project he participated in has won the medal of China's national design.He also participated in the preparation of many Chinese national standards.

S116.5 VHF Data Exchange System - UK's first on air trials (136)

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ABSTRACT

Over the past decade, the General Lighthouse Authorities of the UK and Ireland's research and development team, GRAD, has been supporting international efforts to develop the VHF Data Exchange System (VDES). VDES includes the two existing AIS channels but expands the available bandwidth to provide an enhanced throughput, supporting future e-Navigation services, such as authenticated Aids to Navigation (AtoN). This paper presents the latest work of GRAD in the development of VDES, specifically focusing on the UK's first on-air VDES transmissions. Trials were conducted in early January 2021 off the east coast of the UK, with signals transmitted under license from the GRAD radio lab in Harwich, and received and responded to from equipment fitted to a GLA vessel while at sea. The paper outlines the trial, test methodology, equipment used, approach to calibration, expected results from modelling and then concludes with the results of the trial, including the signal strength, noise levels and packet error rates. All of this information is then used to refine and support GRAD's VDES coverage models that are also presented.

KEYWORDS: VDES, coverage prediction, performance testing, sea trials

1 INTRODUCTION

This work builds upon the VDES channel sounding campaign [1] and other VDES-related initiatives previously carried out by the GLA research and development team (GRAD). The objective of this project was to establish a semi-permanent VDES testbed off the coast of East England, which would enable GRAD researchers to conduct trials of prototype VDES equipment at sea, gather scientific data to support coverage and performance modelling and demonstrate the provision of GLA e-navigation services using VDES. Due to the COVID-19 pandemic, the testbed was designed to allow GRAD personnel to execute trials remotely while minimizing contact with ship and office-based staff.

2 METHOD

2.1 Testbed Area

Permission was obtained from the UK spectrum regulator to conduct over-the-air VDES testing within a 45 NM radius of Harwich, Essex, UK. Harwich is a historical maritime town with two major ports in the area: Harwich International Port and Port of Felixstowe. The former primarily serves ferry services, cruise ships, tankers, and general cargo vessels, while the latter is Britain's busiest container port, handling over 40% of the country's containerized trade. Additionally, Navyard Wharf on the northern tip of the Harwich Peninsula facilitates Roll on/Roll off cargo ships to continental Europe, and Trinity House (TH) lighthouse tenders berth at the Trinity Pier at the western end of the Harwich Quay. During the summer months, a foot ferry runs between Harwich, Felixstowe and Shotley, and the area is frequented by a variety of leisure craft.

For this work, an experimental VDES shore station was established at the GLA Radio Lab in Harwich. A second VDES station was installed on-board the Trinity House Vessel Alert. During the sea trial described later in this paper, THV Alert sailed from Harwich through the Felixstowe approach channel and further northeast, along the coast of Suffolk.

2.2 Time and Duration

The sea trial described in this paper was conducted on 27th January 2021. The test equipment remains in place and has been incorporated into a broader e-navigation service demonstrator that GRAD is currently developing based on the Maritime Connectivity Platform [2].

2.3 Testbed System Architecture

The testbed system consists of a *Shore Station*, a *Ship Station* and a *"Work-from-home" Station*. The Shore Station and Ship Station can function as both a transmitter and receiver and include the following components (also shown in Figure 1): a VDES Transceiver (CML Microcircuits VDES Evaluation Platform), a VHF Antenna (Amphenol-Jaybeam end-fed dipole with a stated gain of 0 dBd for the Ship Station and a Skymasts collinear antenna with a stated gain of 3 dBd for the Shore Station), a GNSS Antenna for VDES Transceiver synchronisation and positioning, a Laptop / Headless PC for controlling the VDES equipment and recording test data and an ADSL/4G Router for remote control over the internet.

The CML VDES Evaluation Platform includes the VDES1000 transceiver module, power supply and associated cabling, all fitted in a 1U 19" rack-mountable enclosure. The VDES1000 is a software-defined radio that allows for new features to be added via firmware updates as the VDES specification evolves. The system allows testing to be performed using all modulation and coding schemes (also referred to as 'Link IDs') currently being considered for use in terrestrial VDES.

The VDES1000 units can be controlled via an Engineering Control Application that can be accessed locally or remotely via the internet, making it possible for a single GRAD Engineer to execute trials from either the lab or home.

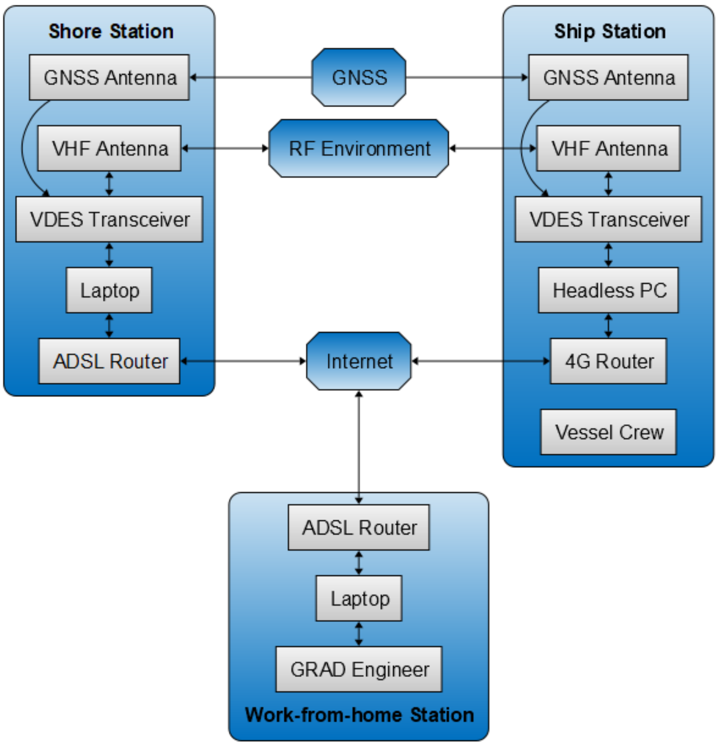

Figure 98: Simplified system architecture.

Figure 99: GNSS (left) and VHF Antenna installation on the TH Buoy Yard Building ‘rotunda’.

Figure 100: Shore Station equipment setup, with the Work-from-home Station laptop shown in top left.

2.4 Equipment Setup and Co-existence with Other Systems

2.4.1 Shore Station

The shore-based equipment was set up in the GLA Radio Lab in the TH Buoy Yard Building in Harwich. The GNSS Antenna and VHF Antenna were mounted on the 'rotunda' on the building's roof, as shown in Figure 2, at a height of 23 m above mean sea level. Several other VHF antennas are installed on the rotunda for testing purposes but none of them were being used during the trial. A mobile communications mast is located at the centre of the rotunda and is known to be actively in use.

Photos of the VDES and IT equipment used at the Shore Station are provided in Figure 3.

2.4.2 Ship Station

The shipborne equipment was installed on-board Trinity House's rapid intervention vessel Alert. THV Alert is 39 m long and has a maximum speed of 17 knots. The VHF Antenna was mounted on the vessel's mast, at the top of the port-side ladder, approximately 14 m above the water line. The GNSS Antenna was attached to a handrail to the left of the wheelhouse ladder. The mounting locations are shown in Figure 4.

The presence of numerous co-located radio systems on-board maritime vessels creates a challenging radio environment. On THV Alert, six VHF antennas are installed above the wheelhouse and on the mast, which are used for radiotelephony, DSC and AIS. To determine the strongest interferers and avoid damage to the VDES1000 unit, a spectrum survey was performed during equipment installation, as described in reference [3].

The VDES Transceiver was installed in a 19" rack cabinet on the bridge deck, while the Headless PC (with an integrated 4G Router) was fitted to the vessel's planning table, as shown in Figure 5.

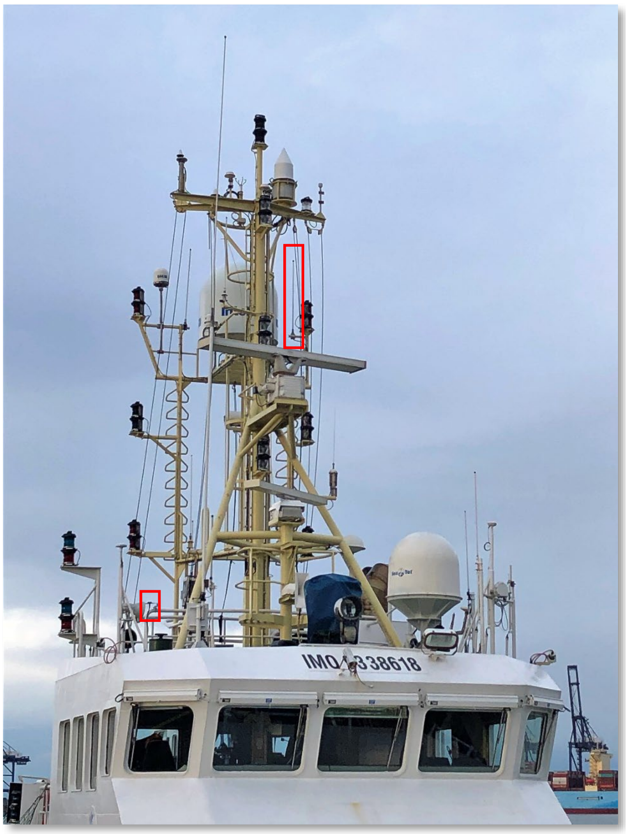

Figure 101: GNSS (left) and VHF Antenna installation on THV Alert.

Figure 102: Ship Station equipment setup including the VDES Transceiver (left) and Headless PC with an integrated 4G Router.

2.5 System Calibration

The system was calibrated to obtain accurate measurements of the transmitter power and to enable the conversion of the RSSI (Received Signal Strength Indicator) readings produced by the VDES Transceivers into a received power value (in dBm). The insertion loss of the VHF antenna feeders was also measured to determine the effective radiated power (ERP). The calibration results were documented in a custom data file format and applied during post-processing. Further details can be found in reference [3].

2.6 Test Methodology

2.6.1 Data Collection

The VDES1000 Engineering Control Application includes a 'Ping Test' application that enables the controlled assessment of VDES performance. The application can be used to send VDES messages from a Requesting Device (in this case, the VDES Transceiver at the Shore Station) to a Responding Device (the Ship Station's VDES Transceiver). The Responding Device operates autonomously and returns a response carrying various diagnostic data, as detailed further below.

The user can adjust several test parameters, such as the operating frequency, ping rate and the VDES Link ID to be used. The test progress can be monitored in real time and data can be logged to a text file for further processing and analysis. The logged data includes the position of the Requesting and Responding Device, Request and Response RSSI, Request and Response Signal-to-(Interference-and-)Noise Ratio (SNR), the number of Requests Sent/Received, and the number of Responses Received.

A custom meta-data file format was used to record the system configuration for each test performed and the prevailing environmental conditions (weather and sea state) during the test.

2.6.2 Data Processing and Visualisation

The recorded data was processed to extract additional characteristics of the VDES data link, including the following:

Station Separation (NM) – the distance between the Requesting (Shore) Station and Responding (Ship) Station, derived from the GNSS positions of the terminals.

UTC – the UTC time of each Request/Response message, derived from the Unix timestamps produced by the VDES units.

Transmitter Power (dBm) – accurate transmitter power values obtained using the bench calibration data.

Request / Response Power (dBm) – the power of the signal at the output of a loss-less receiving antenna, calculated using the Request / Response RSSI, calibration data and stated gain of the VHF antennas used. Comparison was also made with predicted values obtained using the radio wave propagation model described in Recommendation ITU-R P.2001 [4].

Noise-and-Interference Power at the Ship Station (dBm) – the power of noise and interference observed at the Ship Station, referenced to the output of the receiving antenna. This was calculated by subtracting the Request SNR from the Request Power.

Noise-and-Interference Power at the Shore Station (dBm) – the power of noise and interference observed at the Shore Station, referenced to the output of the receiving antenna. This was calculated by subtracting the Response SNR from the Response Power.

Shore-to-Ship Packet Error Rate (%) – the Packet Error Rate (PER) observed at the Ship Station. The Shore-to-Ship PER was calculated by dividing the Number of Requests Received at the Ship Station over the past 60 seconds by the Number of Requests Sent over the same time interval.

Ship-to-Shore Packet Error Rate (%) – the PER for the Ship-to-Shore link. The Ship-to-Shore PER was calculated by dividing the Number of Responses Received at the Shore Station over the past 60 seconds by the Number of Requests Received at the Ship Station (and therefore the number of responses sent) over the same time interval. It should be noted that this is likely a biased estimate of the actual PER in the Ship-to-Shore direction as a Response is sent from the ship only when a Request is successfully received (i.e. when the channel conditions are favourable); therefore, the actual PER in this direction may be expected to be somewhat higher than the estimates shown here.

Roundtrip Packet Error Rate (%) – the combined PER for the (bi-directional) Shore-Ship link. The Roundtrip PER was calculated by dividing the Number of Responses Received at the Shore Station over the past 60 seconds by the Number of Requests Sent.

Two types of visualisations were produced:

Link Characteristics vs. Time – observation of the VDES link characteristics described above (and in the preceding section) over time.

Link Characteristics vs. Position – Google Earth plots of selected link characteristics as a function of the Ship Station's location.

3 RESULTS AND DISCUSSION

This section presents the results of the first dynamic test conducted using the system described in this paper. The test was performed on 27th January 2021, while THV Alert was navigating from Harwich along the coast of Suffolk towards Lowestoft.

3.1 Test Setup

The Ping Test application was used to send test transmissions at a rate of approximately one per second. VDES Link ID 11 was used with a Forward Error Correction (FEC) rate of 1/2, channel bandwidth of 25 kHz and Pi/4-QPSK modulation.

The system was configured to operate at a frequency of 157.2 MHz, consistent with the VDES channel plan established at the World Radiocommunication Conference in 2019.

The transceivers were set to a *low-power mode* with a nominal power of 30 dBm, resulting in a corrected transmitter power value of 27.9 dBm (0.617 W) for the Requesting Device (Shore Station) and 27.8 dBm

(0.603 W) for the Responding Device (Ship Station). Accounting for the feeder losses and antenna gains, the ERP for the Shore and Ship Station was 25.3 dBm (0.339 W) and 26.8 dBm (0.479 W), respectively.

3.2 Environmental Conditions

The environmental conditions during the trial were characterized by partly cloudy weather with a temperature of 8^{o}C and westerly winds blowing at 7-9 knots. There was no precipitation during the trial period. Additional information on the weather and sea state can be found in reference [3].

3.3 Maximum Communication Range

Figure 6 shows the ship-shore separation plotted against time. The maximum communication range reached was approximately 16.5 NM (30.5 km), despite the relatively low antenna heights and *ERP of only around 0.4 W*. It is expected that the use of high-power transmissions in future trials will result in a significantly extended communication range.

3.4 Received Power

In this section we examine the power of the VDES test signals received at the Ship Station and Shore Station, referred to as the 'Request Power' and 'Response Power', respectively. Figure 6 shows the Request Power as a Google Earth overlay, while Figure 7 plots the Response Power over time. The power-vs-time profile measured at the Ship Station is very similar to that shown in Figure 7 and therefore has not been included.

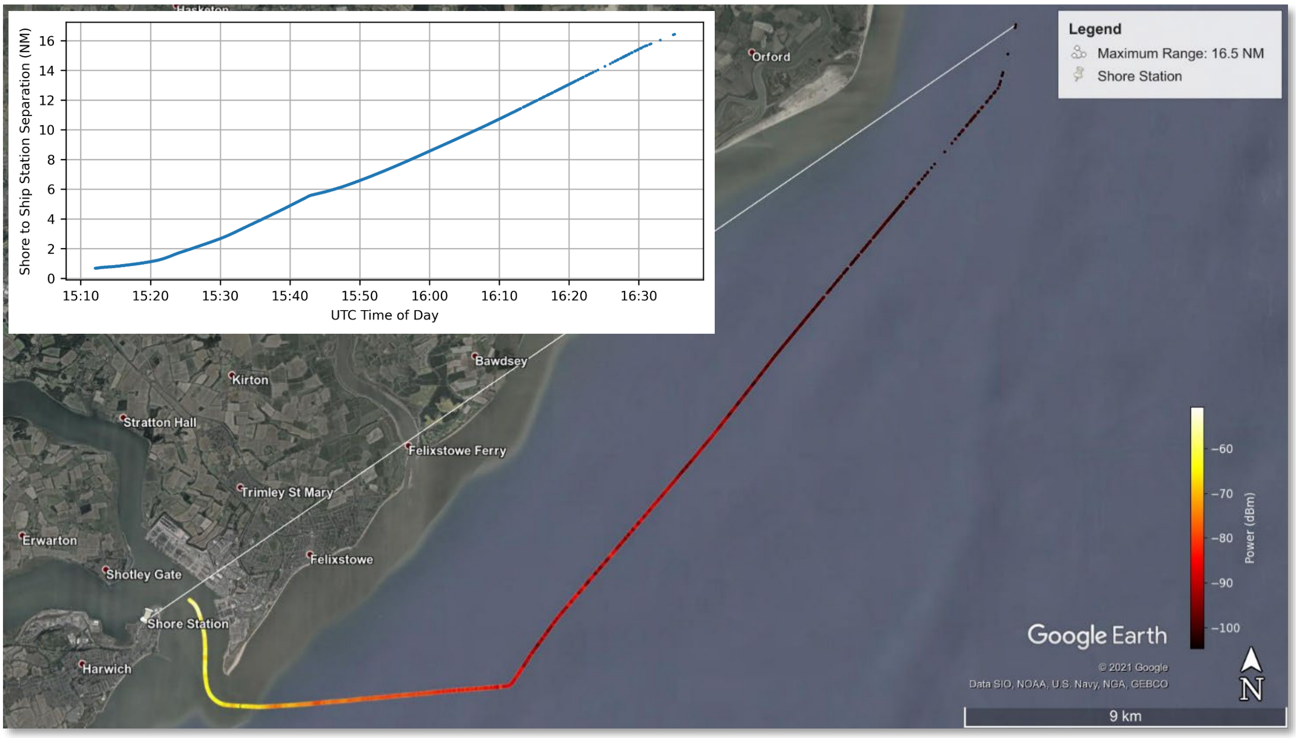

Figure 103: Shore-ship separation over time and Request Power along the route taken (as measured at the Ship Station).

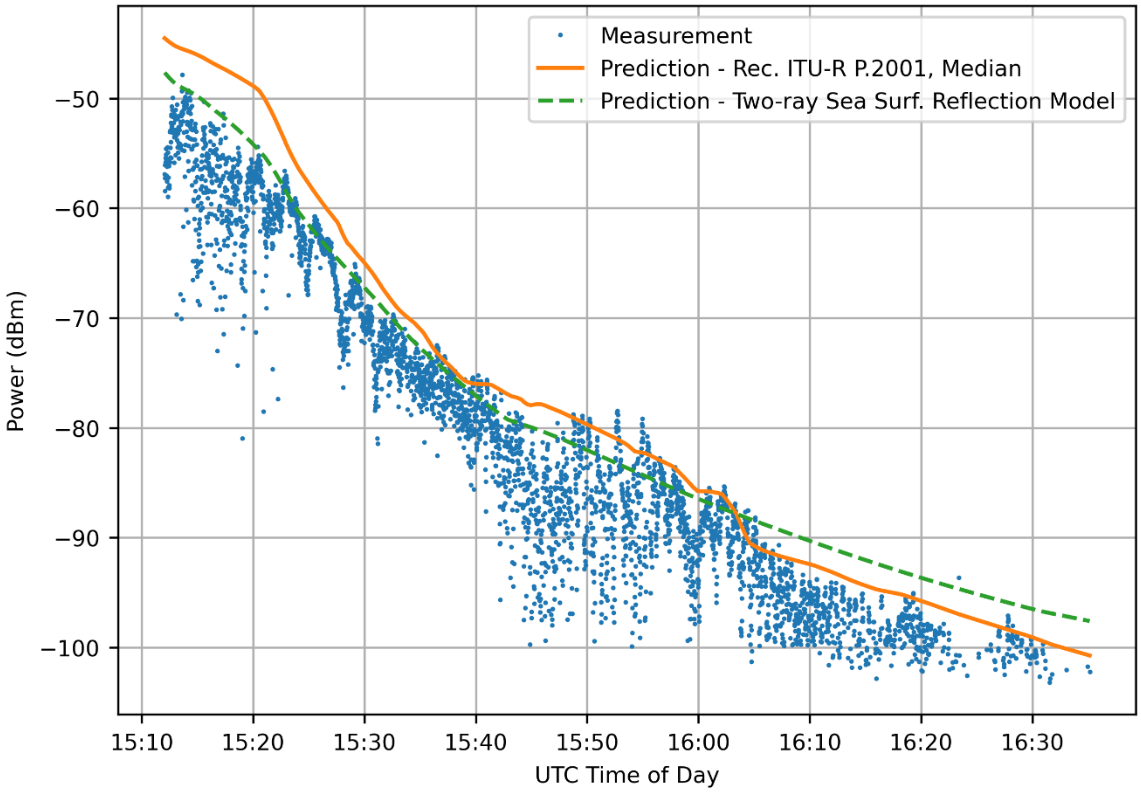

Figure 104: Response Power over time (as measured at the Shore Station).

Figure 7 also displays predicted signal power values obtained using two different radio wave propagation models: the terrain-specific model described in Recommendation ITU-R.P 2001 [4], and a simpler, two-ray sea surface reflection model, assuming an all-sea-water propagation path with no obstructions. The ITU-R model adequately matches the general trend in the data but tends to overestimate the measurements, particularly at short range, by an average of approximately 5 dB. This discrepancy may be attributed to various factors such as the VHF antennas having a lower gain than stated by the manufacturers, clutter surrounding the antennas (particularly at the Ship Station), and the resolution and accuracy of the terrain elevation database used. Additionally, since the plot in Figure 7 represents the median of the predicted signal level distribution, a larger dataset may be necessary to fully discern the trends anticipated by the ITU-R model.

Remarkably, the (simpler) two-ray model provides a better fit to the data collected at short-to-medium range than the ITU-R model. However, as expected, the two-ray model overestimates the power received in the area where the vessel sailed under the shadow of the Felixstowe peninsula (observed at approximately 16:05 UTC onwards). In contrast, the ITU-R model correctly predicts the signal level drop in that area.

The measurements reveal multiple nulls and peaks in the received power, indicating the presence of multipath propagation. Some of these fades are over 10 dB in depth. The primary reason for employing the two-ray model in this investigation was to determine whether the observed fading pattern could be reproduced analytically. However, the carrier phase difference between the line-of-sight ray and the ray reflected off the sea surface was found to be too small to generate any nulls within the maximum range achieved in this test. This finding suggests that the multipath fading observed was likely due, at least in part, to reflectors further afield, such as objects on land or the landmass itself or even irregularities in the troposphere. Indeed, by increasing the reflecting surface's distance in the two-ray model, the fading pattern could be reproduced at short-to-medium range. Further research is required to better understand the mechanisms that give rise to multipath fading in maritime environments.

3.5 SNR and Noise (plus Interference) Power

Figure 8 and Figure 9 show the SNR and Noise-and-Interference Power, respectively, measured at the Ship Station. The SNR plot also shows the theoretical FEC decoder threshold for Link ID 11, determined as described in reference [3]. The observed increase in the noise floor and the level of interference spikes at the onset of the voyage could have been due to the vessel's own VHF voice transmissions and/or voice and AIS transmissions of other stations in the harbour area. The persistent lower-level interference spikes were likely due to the vessel's own AIS transmissions. The rise in the noise floor between roughly 15:22 and 15:42 UTC is unexplained but could have resulted from an on-board electronic or electromechanical system being in operation at that time.

Figure 10 and Figure 11 show the SNR and Noise-and-Interference Power, respectively, as measured at the Shore Station. The interference spikes observed in both figures were probably caused by PAKNET[13] and AIS AtoN stations operating at TH premises during the trial.

The median Noise-and-Interference Power measured at the Ship Station was -105 dBm. Assuming a measurement bandwidth of 25 kHz (consistent with the channel bandwidth for Link ID 11) and that the power of the noise and interference was uniformly distributed across the receiver's passband, then this corresponds to a median noise-and-interference power spectral density of -149 dBm/Hz, which is 25 dB above the thermal noise floor (kT). The median Noise-and-Interference Power measured at the Shore Station was - 114 dBm, which is 9 dB lower than the noise power at the Ship Station. Under the same assumptions as above, this corresponds to a median noise-and-interference power spectral density of -158 dBm/Hz, or 16 dB above kT. The noise levels observed at both the Ship and Shore Station are consistent with the findings of earlier noise-floor surveys conducted using a high-sensitivity spectrum analyser setup.

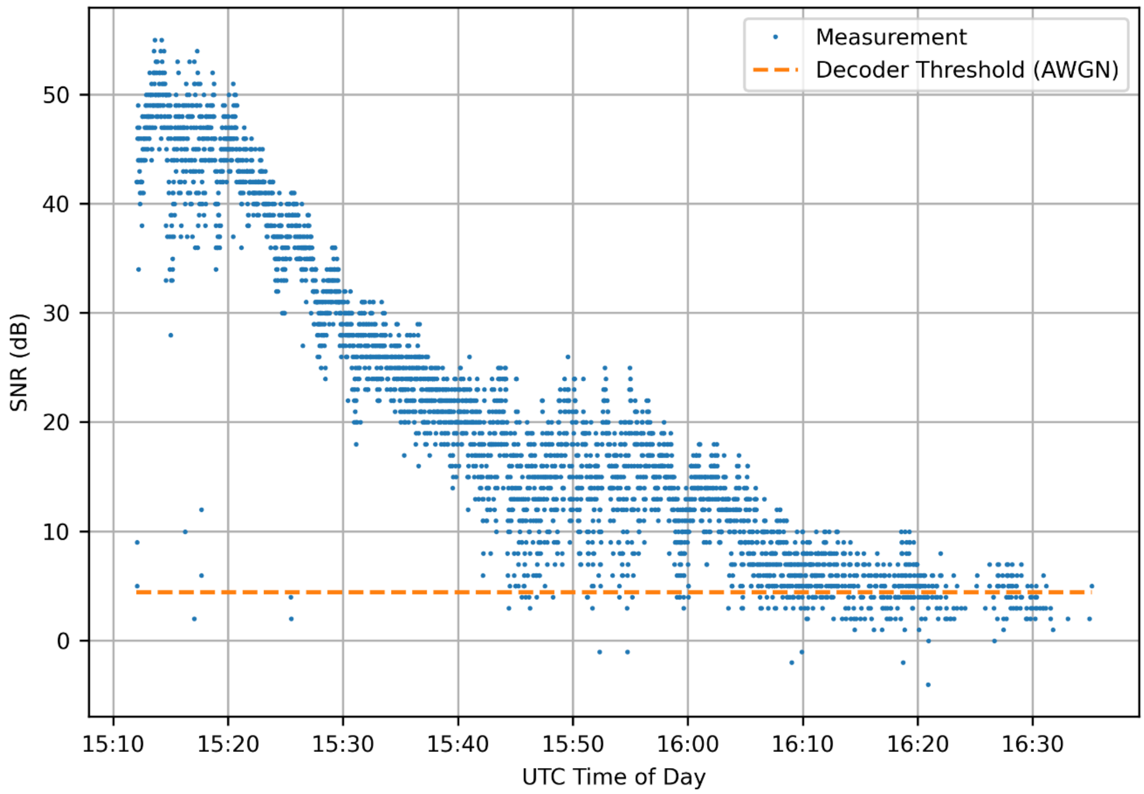

Figure 105: Request SNR over time (as measured at the Ship Station).

[13] PAKNET was a cellular packet data network operating in the VHF band, which was used by TH for AtoN monitoring.

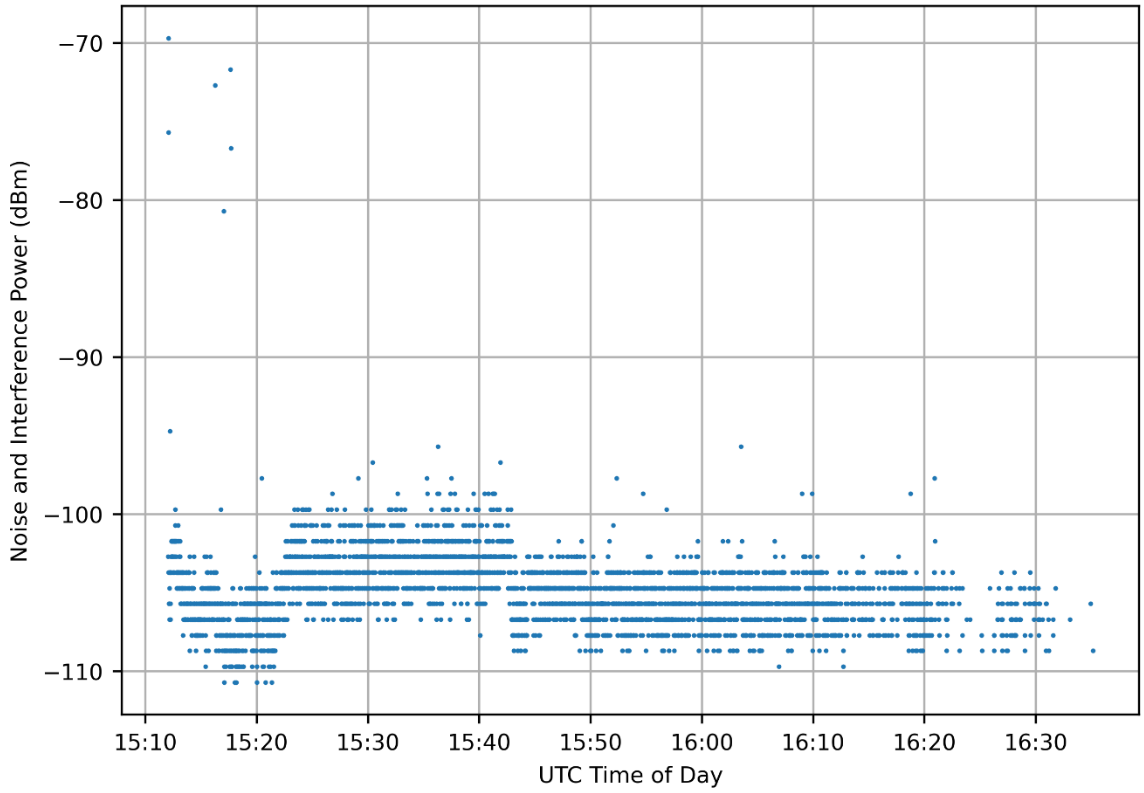

Figure 106: Noise-and-Interference Power over time as measured at the Ship Station.

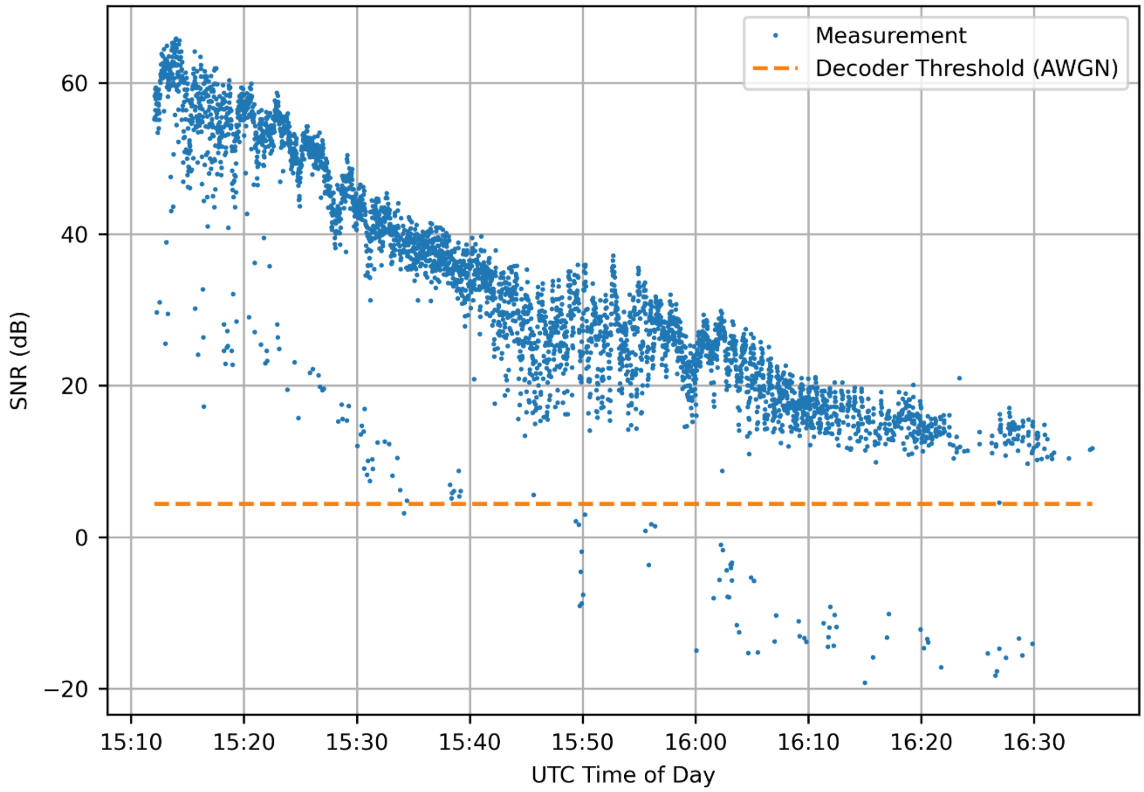

Figure 107: Response SNR over time (as measured at the Shore Station).

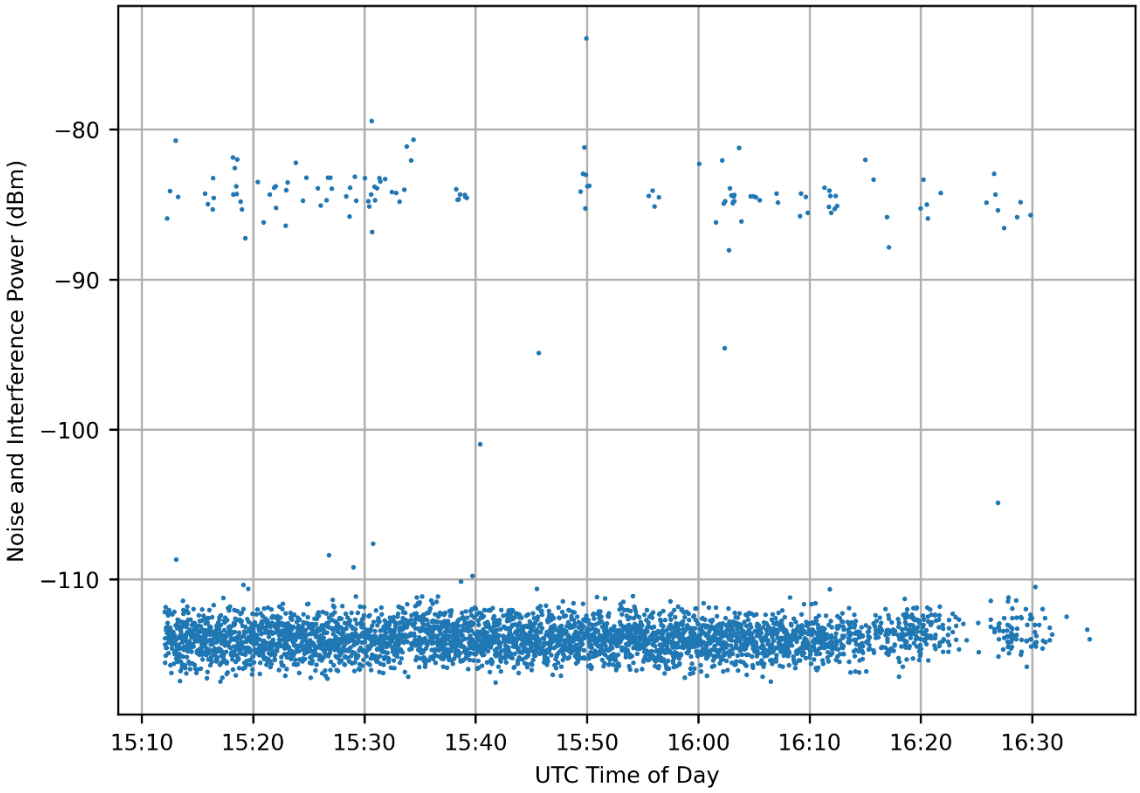

Figure 108: Noise-and-Interference Power over time as measured at the Shore Station.

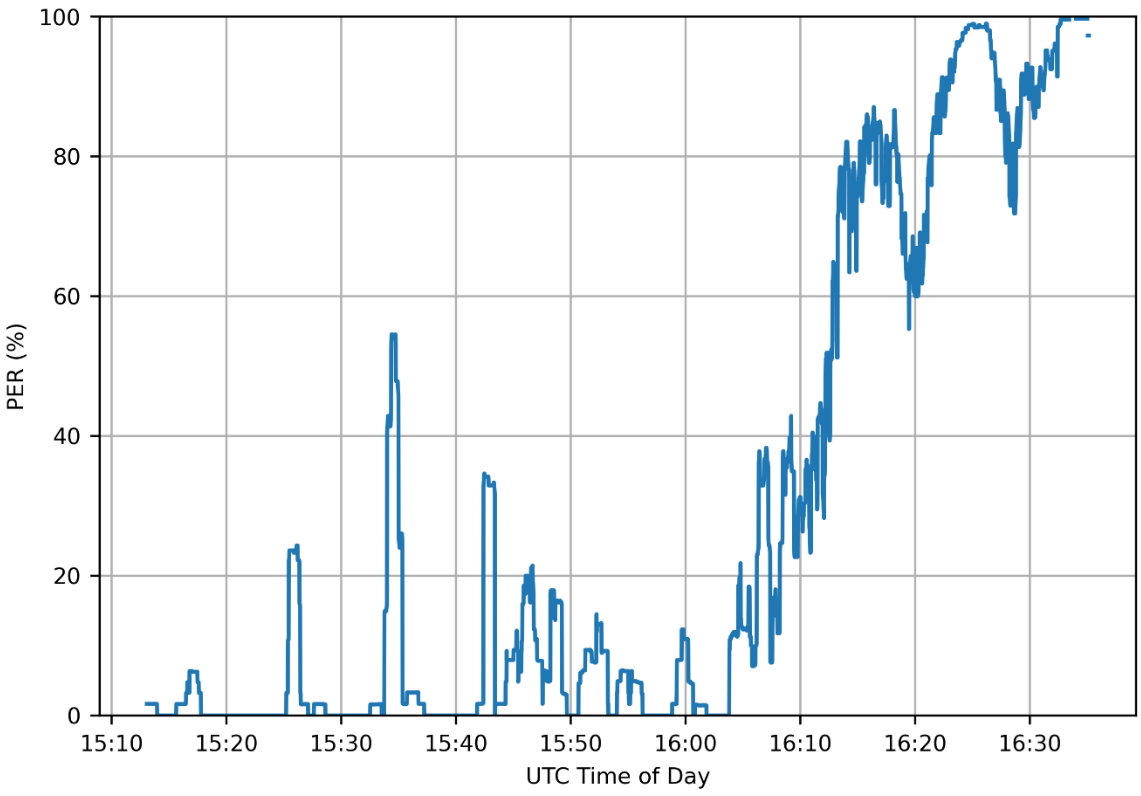

Figure 109: Shore-to-ship PER over time.

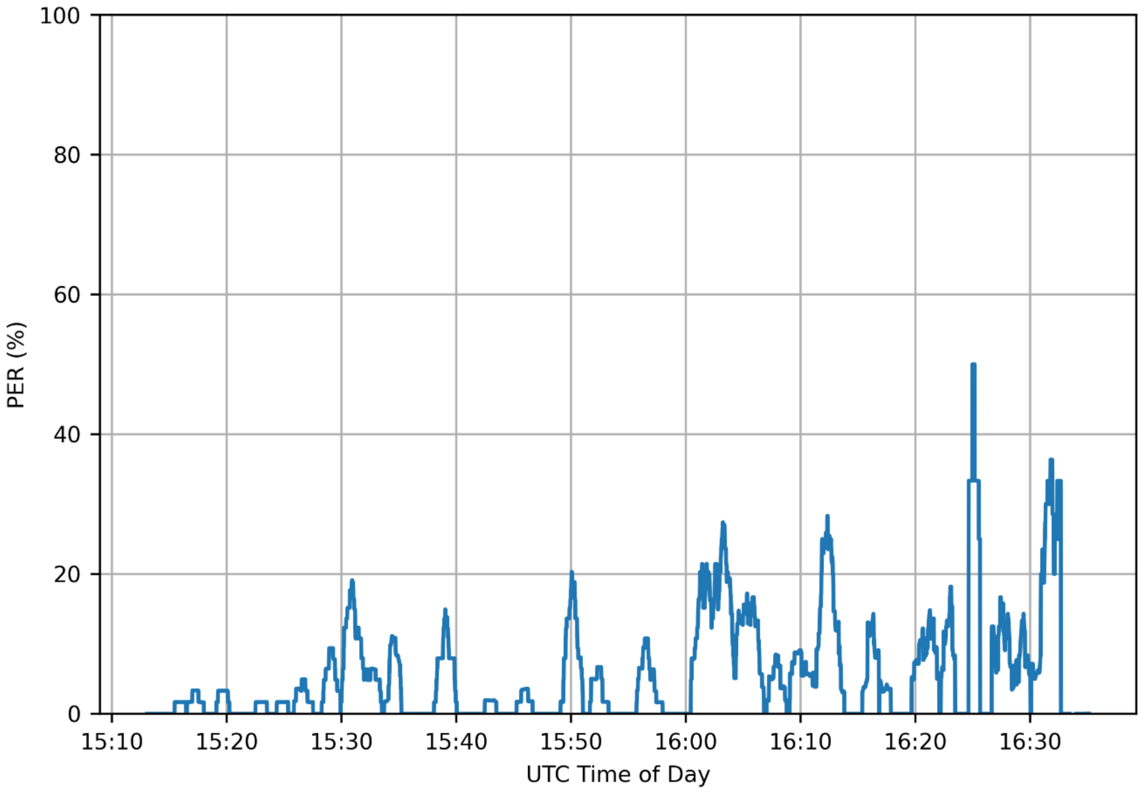

Figure 110: Ship-to-shore PER over time.

3.6 Packet Error Rate

Figure 12 and Figure 13 plot the Shore-to-ship and Ship-to-shore PER over time, respectively. Comparing Figure 12 with Figure 8 reveals a strong correlation between the times when the SNR drops below the decoder threshold and instances of increased PER. Isolated errors occurred during the first part of the voyage, likely due to interference and signal fading. From approximately 16:05 UTC, when the vessel entered the radio shadow of the Felixstowe peninsula, the decoder threshold was persistently breached, and the PER increased steadily until the end of the test. Reliable bi-directional communication was, therefore, possible up to a range of around 10 NM.

In Figure 13, the Ship-to-shore PER values plotted are generally lower than those measured in the opposite direction. This is likely due to a combination of the Shore Station's lower noise floor compared to the Ship Station (as discussed in Section 3.5) and the possible bias of the estimation method used (as explained in Section 2.6.2).

The Roundtrip PER is primarily determined by the Shore-to-ship PER and is not presented here.

3.7 Coverage Prediction

The collected data from this and future trials will serve to calibrate and validate a VDES coverage prediction tool developed by GRAD. Figure 14 illustrates the predicted coverage area of the Harwich Shore Station (operating in low-power mode) generated by the GRAD tool, superimposed with the Shore-to-ship PER data from this trial. The contour of the coverage area is defined by a set of points where the predicted SNR (or rather C/N_0) falls below the decoder threshold for the Link ID used. Theoretically, the PER at the contour should be 1%. However, due to the threshold being determined based on a non-fading propagation channel and the propagation model overestimating somewhat the received signal power, the PER measured at the predicted coverage contour is higher than expected. As additional data becomes available, the model will be refined to ensure accurate predictions of real-world coverage and performance.

While this initial trial was conducted using a low-power mode with an ERP of only around 0.4 W, future trials are planned to be conducted at full power. The coverage area in the high-power configuration is predicted to extend up to 22 NM from Harwich, as shown in Figure 15.

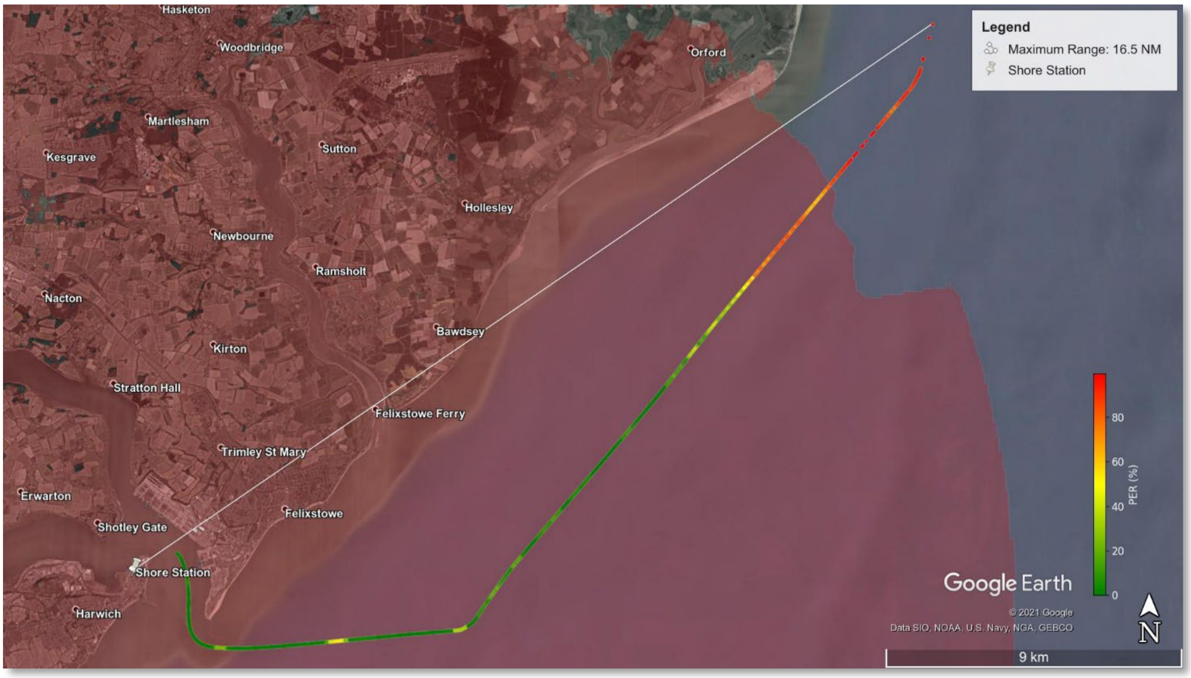

Figure 111: Predicted coverage area in low-power mode (shown in red) and measured Shore-to-ship PER.

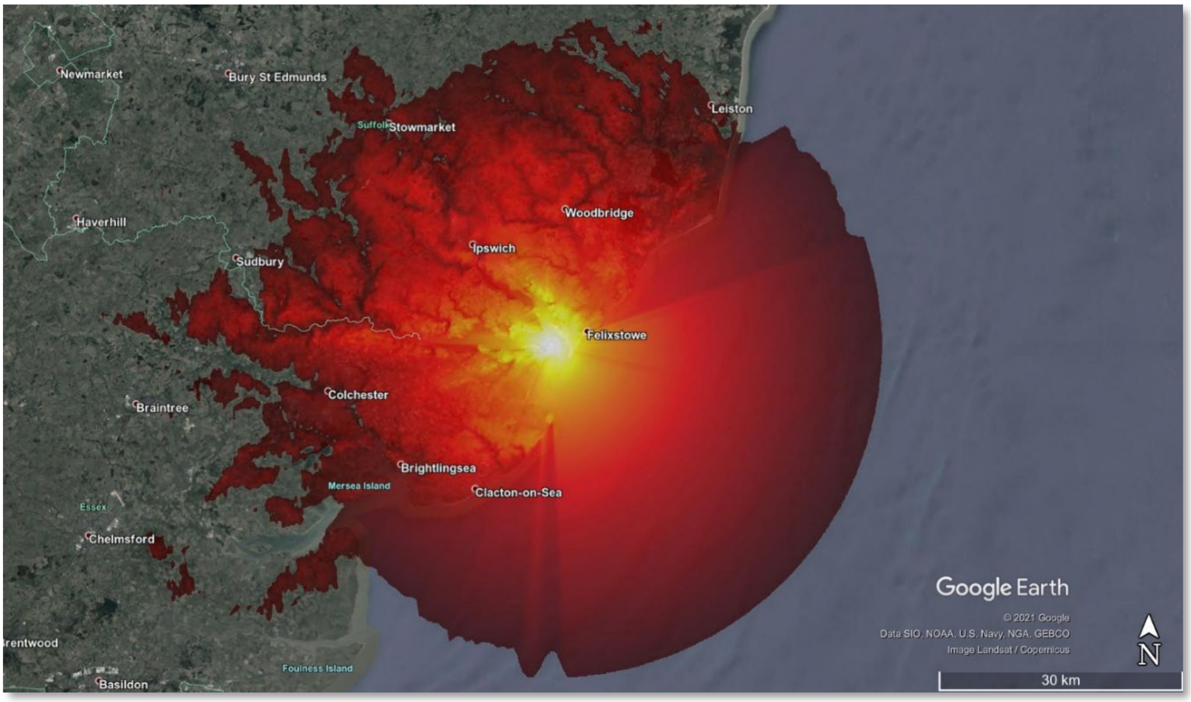

Figure 112: Predicted coverage area in high-power mode.

4 CONCLUSIONS

A VDES testbed has been developed to enable over-the-air testing of VDES equipment in the busy maritime area surrounding Harwich, United Kingdom. The testbed permits bi-directional communication between ships and the shore on any frequency channel and using any modulation and coding scheme (Link ID) proposed for use in terrestrial VDES.

The testbed allows for characterisation of various data link parameters, such as received signal power, SNR and PER. Results can be plotted over time or displayed on a map and provide valuable input for the development of VDES coverage prediction tools and VDES itself.

The first sea trial was carried out in January 2021 using a low-power transceiver mode with an ERP of approximately 0.4 W. The maximum communication range was 16.5 NM, and reliable bi-directional communication was possible up to approximately 10 NM. Modelling predicts that the testbed will provide VDES coverage up to approximately 22 NM from Harwich in high-power mode.

The received power data indicated the presence of multipath propagation, with multiple "nulls" observed, some with depths of over 10 dB. Analysis using a two-ray propagation model suggests that the multipath signal components responsible for the fading originated from land or irregularities in the troposphere rather than from reflections off the sea surface.

The SNR data indicated the presence of short-duration burst interference at both the Shore and Ship Station, likely originating from the AIS and PAKNET (now decommissioned). Although this does not necessarily result in packet loss, it may have the potential to desensitise the VDES receiver.

The noise floor on the vessel was found to be around 9 dB higher than at the Shore Station, consistent with the findings of previous noise-floor surveys conducted by GRAD. This makes shore-to-ship communication somewhat more challenging than ship-to-shore.

Collaboration with the VDES equipment manufacturer is ongoing to upgrade the control software for the VDES units used with the aim of enabling simultaneous performance testing of multiple VDES Link IDs, including the ones used in VDES ASM and AIS. In addition to performance testing, the testbed serves as a component in a prototype GLA e-navigation service infrastructure being developed by GRAD. It has been used in demonstrations of a proposed AIS authentication approach and prototype GLA e-navigation services, as described in references [5], [6].

5 ACKNOWLEDGEMENTS

The author wishes to express gratitude to the Second Officer and Chief Engineer of THV Alert, as well as the staff of the Trinity House Marine Operations department and Operations and Planning Centre, for their cooperation and assistance in conducting this trial. The author also wishes to acknowledge the technical support provided by CML Microcircuits Ltd and Stone Three Venture Technology.

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AUTHOR BIOGRAPHY

Dr Jan Šafář is a Research & Innovation Engineer with the General Lighthouse Authorities of the United Kingdom and Ireland. Jan has over 15 years' experience as a researcher in the radio navigation and communications field, working in the areas of Global Navigation Satellite Systems and augmentations, alternative positioning, navigation and timing systems and e-navigation communications. He is a member of the Royal Institute of Navigation, U.S. Institute of Navigation and several international working groups, including the Digital Communication Systems Working Group within the IALA e-Navigation Committee and the IEC AIS Working Group. He has been closely involved with the development and international standardisation of the VHF Data Exchange System (VDES), including its R-Mode component.

S116.6 Operational aspects for future VDES based services in maritime administrations (063)

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ABSTRACT

The VHF Data Exchange System (VDES) is an effective and efficient use of radio spectrum, built on the capabilities of AIS and addressing the increasing requirements for data through the system. New techniques providing higher data rates than those used for AIS are a core element of VDES. Furthermore, the VDES network protocol is optimized for data communication so that each VDES message is transmitted with a high confidence of reception.

Of utmost interest is the new terrestrial 100 kHz VDE-TER channel which enables new services to support navigation and communication from shore to ship. The German Waterways and Shipping Administration (WSV) are involved in research projects, which are aiming to make use of the new VDES capabilities, particularly by using VDE-TER. One is the use of VDES for ranging (VDES R-Mode) and another is to use VDES for the transmission of GNSS corrections to provide high accuracy positioning to support automation of shipping. Since years, the WSV has been operating AIS networks at the coast and along inland waterways to support traffic management. The use of VDE-TER is a challenging task, as these new functionalities need to be co-located to the existing AIS infrastructure.

The paper will provide information about potential VDES use cases, which are of particular importance for the WSV. Such services are implemented and tested in various research projects by using mainly VDES prototype equipment. The paper will summarize the experience gained in these projects. Another important part of the paper is coping with the colocation problem, based on first research activities in this field. Furthermore, the paper will provide practical guidelines for the installation and operation of colocated AIS/VDES services.

KEYWORDS: VDES, Colocation, High precision GNSS, PPP-RTK, AIS, ASM, R-Mode

RESUMEN DEL ARTÍCULO

1 INTRODUCTION

The evolution of communication technologies in the maritime industry has led to the development of various systems aimed at enhancing safety, security, and efficiency. The introduction of VHF Data Exchange System (VDES) has the potential to improve communication between ships and shore-based stations. This technology provides higher-bandwidth and reliable data communication, making it a potential solution for future maritime services. This report will discuss the operational aspects of future VDES-based services in maritime administrations using a range of possible services that have been investigated and tested in various research and implementation projects.

VDES is a radio communication system that operates between ships, shore stations and satellites on Automatic Identification System (AIS), Application Specific Messages (ASM) and VHF Data Exchange (VDE) frequencies in the Marine Mobile VHF band. VDES technology goes beyond AIS by enabling communication of various types of data, such as weather information, port and route data, and emergency notifications. As a result, VDES-based services are expected to provide more efficient and effective communication between ships and shore-based stations.

Future VDES-based services will also require the development of new applications to utilize the full potential of this technology. Maritime administrations will need to develop applications that can leverage the high-bandwidth and low-latency communication capabilities of VDES technology. Applications such as vessel traffic management systems, maritime surveillance, and environmental monitoring systems will be essential in enhancing the safety and efficiency of maritime operations.

The implementation of VDES-based services will require a significant investment in infrastructure. Maritime administrations will need to establish a network of VDES base stations to ensure coastal or inland waterway coverage. Additionally, ships will need to be equipped with VDES transceivers, which may require retrofitting of existing vessels. The implementation of VDES-based services will require collaboration between different stakeholders in the maritime industry to ensure that the necessary infrastructure is in place.

Of utmost interest for the German Waterways and Shipping Administration (WSV) is the new terrestrial 100 kHz VDE-TER channel, which enables new services to support navigation and communication from shore to ship. In this respect, WSV is involved in several research projects, which are aiming to make use of the new VDES capabilities, particularly by using the VDE-TER channel. One is the use of VDES for ranging (VDES R-Mode) and another is to use VDES for the transmission of GNSS corrections to provide high accuracy positioning to support automation of shipping.

Since years, the WSV has been operating AIS networks at the coast and along inland waterways to support traffic management. The use of VDE-TER is a challenging task, as these new functionalities need to be co-located to the existing AIS infrastructure.

The paper will provide a brief information about VDES and the intended services as identified by IALA. Further, it will deliver a short market overview about first VDES equipment identified by WSV. The main part will inform about recent research and implementation projects performed in Germany which aims to investigate and validate new VDES services, including the generation of high accuracy GNSS corrections, the provision of waterways information and the usage of VDES R-Mode. Another topic addresses the necessary considerations of an administration aiming to provide future VDES services on their existing shore site AIS infrastructure. This includes considerations for the trouble-free operation of the existing AIS services, ASM short messages and new services for VDE-TER on an existing transmitting site. Such an existing transmitter site usually has a building for the system equipment and an antenna mast with different antennas for voice communication and AIS. Thus, to solve the co-location between the operation of several services at the same time in a close frequency band is a real challenge which needs to be solved to enable an economic way to implement VDES in administration. The paper will describe some mitigation options which could be used to solve this problem.

1.1 VHF-Data Exchange System Overview

The International Telecommunications Union (ITU) revised the VHF maritime band frequency channels to establish duplex channels for VDES in 2015 and 2019. VDES is a digital communication system that allows communication between ships, coastal stations, and satellites. AIS (Automatic Identification System) is a well-recognized tool for safety of navigation and is a carriage requirement for SOLAS vessels [2]. As AIS has become heavily used for maritime safety, situational awareness, and port security, overloading of AIS 1 and AIS 2 created a need for additional AIS channels. In this respect the VHF marine band has been revised by ITU to designate channels for data transmission and recognized that both analogue voice and digital communications will share the band ITU-R M.2092 [1]. The VDES addresses the identified need to protect AIS along with essential digital communications contributions for e-Navigation and Global Maritime Distress Satellite System (GMDSS) Modernization. The developments in maritime radio technology, including the introduction of Software Defined Radios (SDR) coupled with enhanced capabilities for digital data exchange over existing VHF marine band spectrum resulted in the development of the VDES.

A detailed overview of the VDES system is provided in IALA Guideline G1117 [3].

VDES builds on the experience gained through the development of AIS, and provides the capability to communicate to:

- a specific vessel (addressed);
- all units in the vicinity (broadcast);

- a group of vessels (addressed); and
- a fleet of vessels (addressed).

The system concept, including VDES functions and frequency usage is illustrated pictorially in Figure 1 (full system).

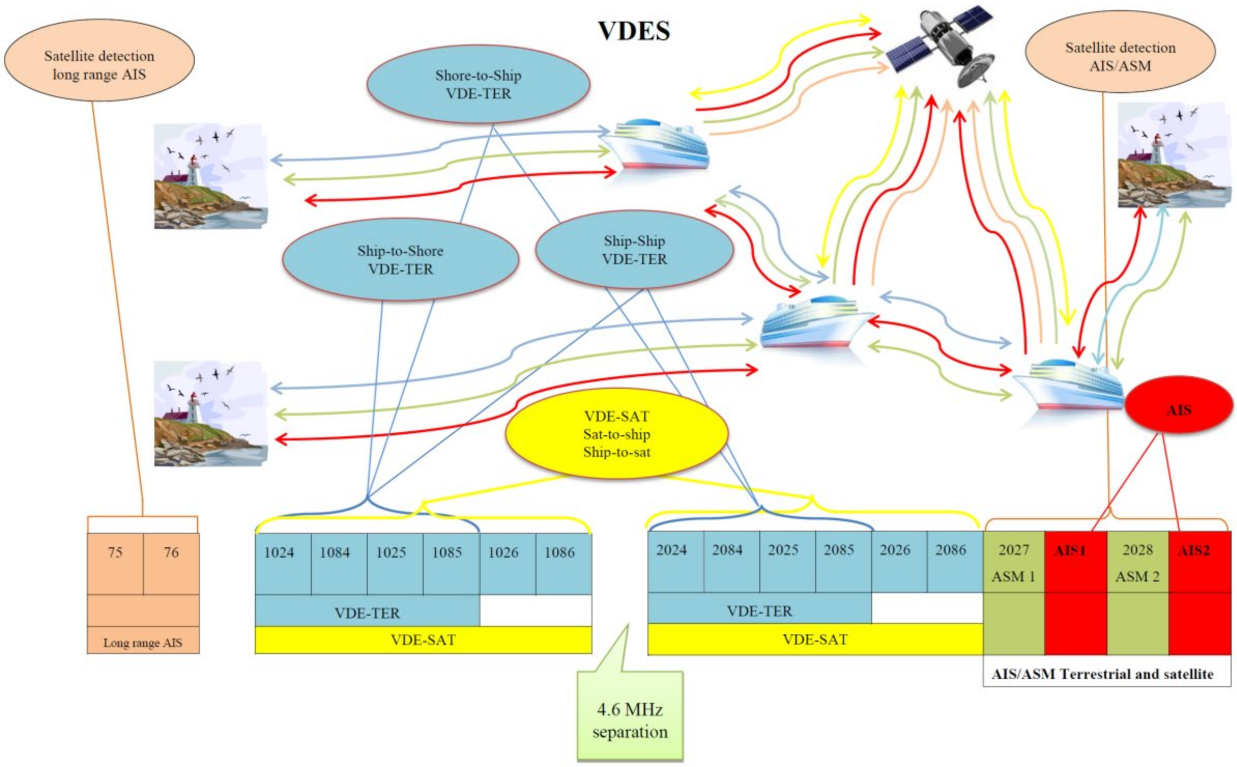


Figure 113 VDES functions and frequency use – full system

1.2 Potential use cases for VDES

A number of potential VDES use cases and scenarios are already identified and described in IALA Guideline G1117 [3]. Table 1 provides a brief summary of these identified use cases. Furthermore, the table shows the services that are of particular importance for the WSV and their assignment to the scenarios identified in the IALA Guideline.

Table 13 Potential VDES use cases [3]

VDES use case (scenario)	Example	Investigated and tested in WSV
Vessel Traffic Services (VTS)	- VTS Timely and Relevant Information Service	DigitalSOW (channel closure)
Positioning Navigation and Timing	- GNSS Augmentation - R-Mode	SciPPPer Project (PPP/RTK) Digital SOW (PPP/RTK/R-Mode) R-Mode Baltic (R-Mode)
Safety Related Information	- Notices to Mariners	SciPPPer/DigitalSOW (Notices to Mariners *Lock status information)*
SAR	- Distress Communications	
Ship Reporting	- Secure ship reporting	
Route Exchange	- Ship to Ship - Ship to shore - Shore to Ship	

Figure 2 illustrates the potential VDES service as investigated within the research project DigitalSOW in the area close to Berlin. A detailed description of the project will be reported in chapter 2.3.

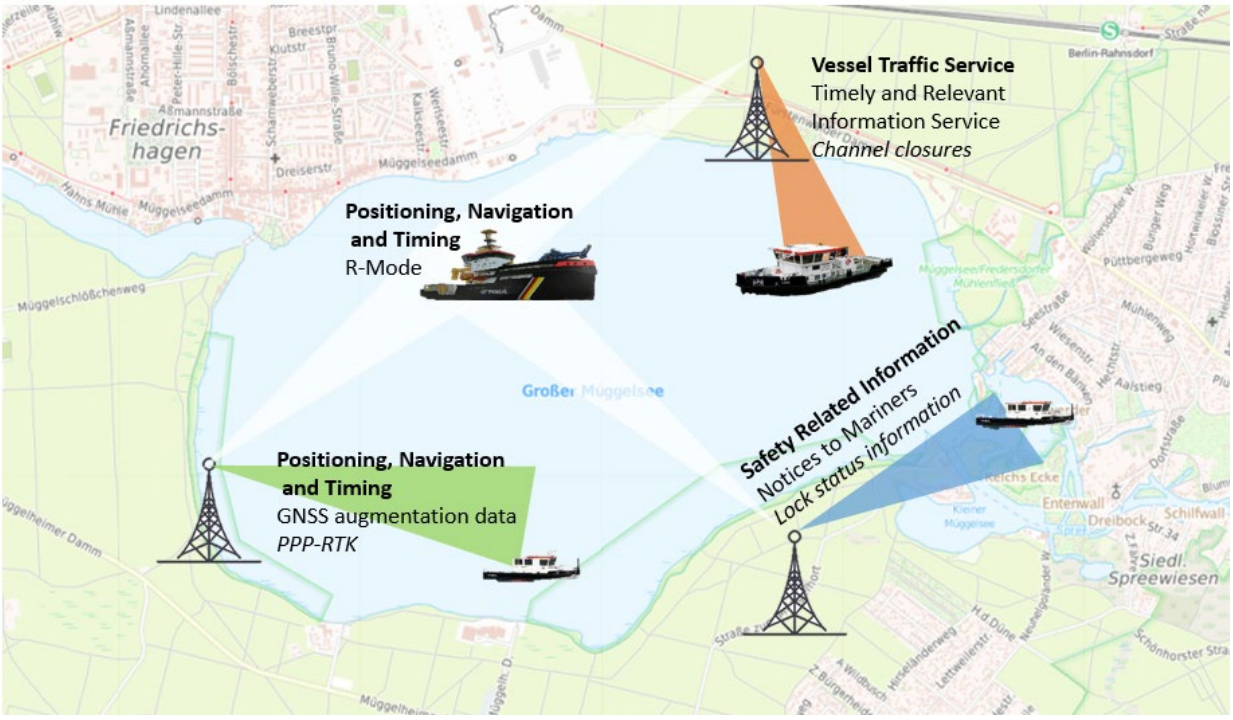


Figure 114 Potential VDES use cases investigated in DigitalSOW

1.3 VDES Hardware Market overview

The availability of VDES hardware on the market is currently limited, as the system is still relatively new and in the introductory phase. However, there are a number of companies that already offer VDES hardware or will be bringing it to market in the near future. The following is a list of the devices that have been procured and tested by the Waterways and Shipping Administration:

- Kongsberg is a leading provider of technology and services to the maritime industry. The company offers a range of VDES hardware components, including AIS/VDES base stations and

AIS/VDES mobile stations. In addition, the hardware is capable of providing and processing the R-Mode service.

- CML Microsystems is a UK-based semiconductor solutions provider that also offers VDES hardware components. A market analysis of CML Microsystems' VDES hardware shows that the company has a growing presence in the market and is focused on developing cost-effective and reliable solutions for the maritime industry. CML Microsystems offers a limited range of VDES hardware components, including the VDES-1000 evaluation Board.
- SAAB is a Swedish supplier for technology and also offers VDES hardware components. SAAB offers with the R60 VDES base station the latest generation base station designed for fixed shore and offshore installations, providing support for the new VDES standard including traditional AIS functionality. The WSV has purchased VDES equipment to replace existing AIS base stations with new VDES-ready equipment.

Working in the laboratory with the devices was an essential part of the testing plan. Before the devices were used for further testing on the waterway, communication tests were carried out. Figure 3 shows the Kongsberg and CML devices in various tests in the laboratory.

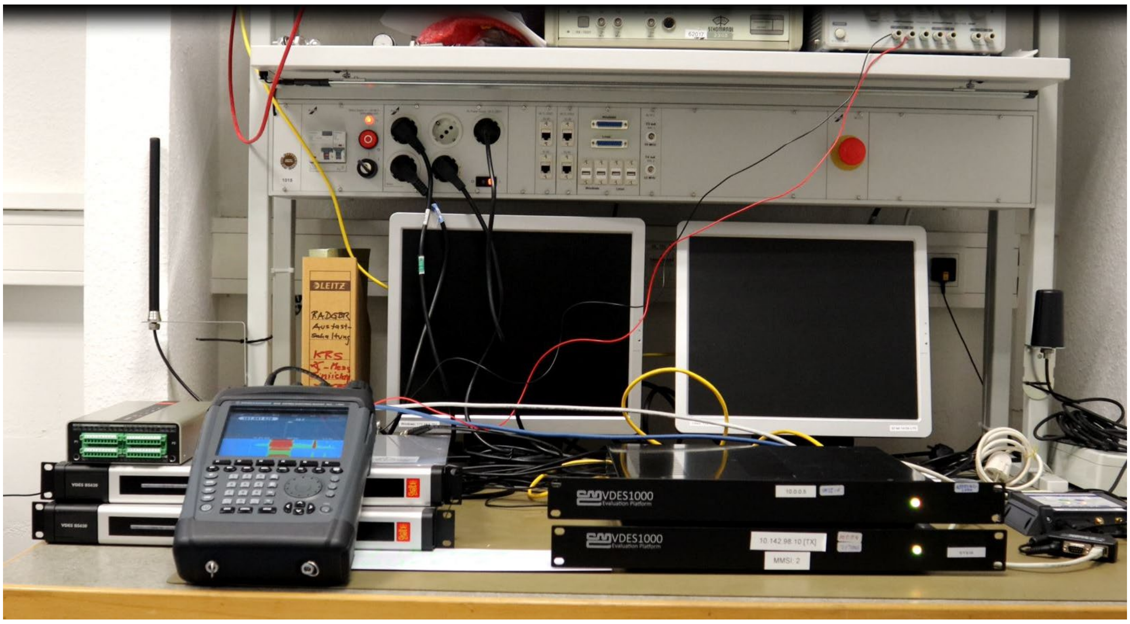


Figure 115 VDES Hardware from Kongsberg and CML

Overall, the availability of VDES hardware on the market is still limited, as the system is still relatively new and in the introductory phase. However, more companies are expected to bring VDES hardware to market in the near future to meet the needs of the marine industry. Prices for VDES hardware components can vary depending on the manufacturer and features, so it is recommended to conduct a thorough market analysis before purchasing to find the best option for individual needs.

2 VDES RELATED PROJECTS IN GERMANY

With increasing digitization and networking, efficient and reliable communication between different systems and devices is becoming more and more important. In this context, VDES based services are of utmost interest for safety related services. VDES is a new standard that enables reliable data transmission in the VHF range and provides improved communication between different ship and coastal stations, satellites and unmanned systems. By using VDES-based services, projects in the shipping and maritime industries, as well as other sectors such as offshore, environmental monitoring and rescue, can benefit from more efficient and secure data transmission. VDES-based services offer a variety of benefits, such as increased data transmission capacity, improved data quality, higher reliability and security, and easier integration with existing systems. In particular, two features of VDES are of great interest for the future use of reliable navigation and communication in the maritime sector as well as on inland waterways:

- The use of a higher bandwidth; Here VDES offers the possibility of data transmission for VDE-TER up to 250kBit/s.
- The possibility of addressed and authenticated message transmission.

Up to now, the WSV has operated an extensive network of approx. 200 AIS shore stations on the coast but also along inland waterways. The use of the future VDES for emerging applications, which should also enable and support automated navigation in particular, is therefore of great interest to the WSV. For this reason, the WSV is involved in various research projects that aim to develop automated navigation. The development and validation of new shore-based services to support navigation and communication are particularly important for the WSV.

In the following chapters recent research projects are described, which investigate the usage of various VDES services (shown in Figure 2).

2.1 SciPPPer

The project SciPPPer (Lock assistance system based on PPP and VDES for inland navigation), which was founded by the German Federal Ministry for Economic Affairs and Climate Action, started in November 2018 and ended in February 2022.

2.1.1 Introduction

Locking is one of the most frequent but also most critical manoeuvres in inland navigation. Typical for the waterways in Germany is the situation where an 11.40m wide vessel enters a 12m wide lock chamber (see Figure 4). The time the ship needs to enter and leave the lock can take up a considerable part of the travel time to the destination. Automation of this process aims on the one hand to increase the ease of shipping traffic and on the other hand to speed up the entire lockage process.

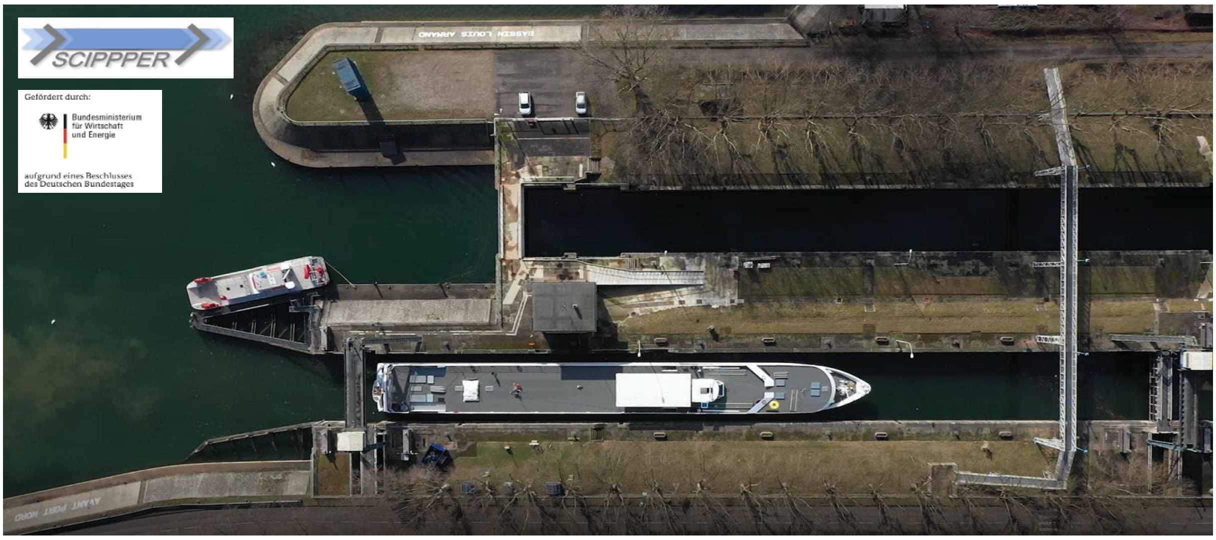
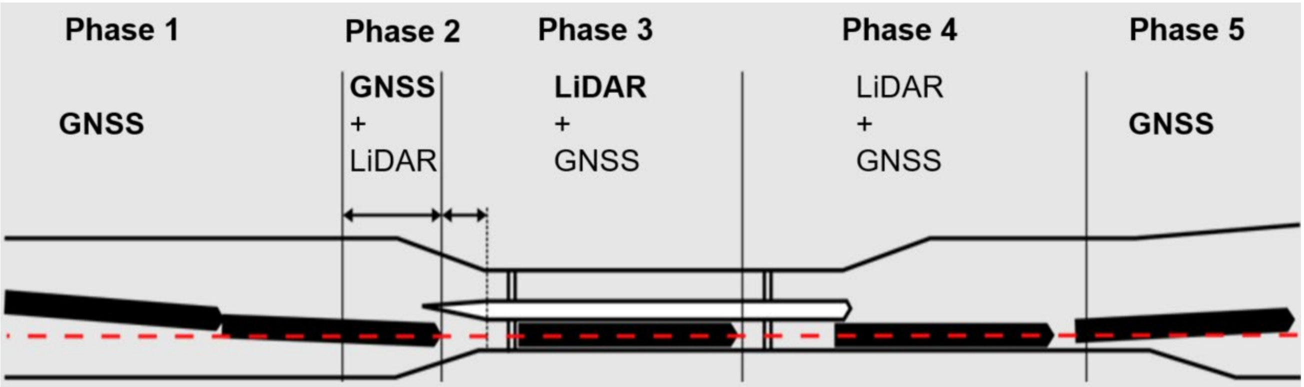


Figure 116 MS Victor Hugo at the autonomous lock entrance in Strasbourg during the final project presentation

One technological basis for the new driver assistance function is the provision of reliable and highly accurate information on the position, altitude and speed of the vessel, especially for the phase of the approaching and departing the lock (see Figure 5). This leads to the development of an new VDES service (GNSS Augmentation) as already identified as potential VDES service in G1117 (see Table 1). Furthermore it is important to include detailed information about the lock status as well as safety related messages to get informed about navigational warnings (e.g. closing of locks/channels or about navigational areas with reduced fairway width, water level etc.). All this kind of information needs to be provided to the new on-board driver assistance applications. Within the SciPPPer project VDES was selected as communications system using the VDE-TER channel.

VDES GNSS Augmentation Service based on PPP/RTK

As mentioned above, high accuracy for PNT data is required to enable automated lock manoeuvring. Figure 5 illustrates the different navigation phases together with the required PNT accuracy levels when approaching and departing a lock. GNSS and other sensors (e.g. LIDAR) are used to provide absolute and relative positioning. Furthermore, it is important that integrity information is also provided for the PNT data.



	Phase 1,5	Phase 2	Phase 3, 4
Positioning accuracy [cm]	10	1 (Bow), 10 (Stern)	1
Heading accuracy [°]	11°/L	11°/L	0.5°/L
L=100m	0.1°	0.1°	0.005°
ROT[°/min]	0.3	0.3	0.3
Velocity [cm/s]	1	1	1
Integrity risk	10e-5	10e-5	10e-5

Figure 117 Phases of navigation and resulting PNT data requirements

To achieve high positioning accuracies using GNSS, enhancement methods must be used. These include methods such as precision point positioning (PPP), real-time kinematics (RTK) or - more recently - the hybridisation of the latter two, PPP-RTK. With these technologies, accuracies in the dm to cm range can be achieved [11].

In order to combine the advantages of PPP with the advantages of RTK, the PPP-RTK procedure was developed [11]. In this method, the PPP approach is extended. Additional atmospheric corrections are determined from a regionally condensed network of reference stations. This enables an immediate solution of the ambiguities for users within the condensed reference station network. The atmospheric corrections are determined in a grid, whereby the accuracy of the corrections is greatest at the locations of the reference stations. The greater the distance of the rover to the nearest reference station, the greater the convergence time [11]. The required data volume is significantly lower than with RTK, since the individual error components only have to be transmitted according to their temporal characteristics. Rapidly changing errors or error components are transmitted more frequently than slowly changing ones.

In addition, it is important to assess the required bandwidth demand of each correction method needed to broadcast the GNNS correction data to the GNSS user equipment. Although VDE-TER offers a channel bandwidth of 100 kHz with data rates of about 250 Kbit/s, it is important to minimise the data load in order not to interfere too much with other planned VDES services. Table 2 compare various GNSS correction methods (using phase corrections) and provide information of the resulting convergence time as well as the different demands on the amount of data to be transmitted and the resulting data rate for the transmission [11].

Table 14 Comparison of different GNSS correction methods regarding required amount of data and data rates (green: acceptable, red: unacceptable) [11]

	RTK	Network RTK	PPP	PPP-RTK
Accuracy	1 – 2 cm	1 – 2 cm	5 cm	1 – 3 cm
Convergence time	< 5 s	< 5 s	20 min	< 5 s to 1 min
Coverage	local	regional	global	local to regional
Broadcast capability	yes	no	yes	yes
Required data rates	3 – 6 kbit/s	3 – 6 kbit/s	up to 2 kbit/s	up to 1 kbit/s

For the purpose of potential future VDES service the PPP-RTK is of utmost interest, because this method has the lowest required data rate and provide sufficient position accuracy and convergence time.

2.1.2 VDES Testbeds

In order to be able to test the developed services that are to be broadcast via VDES, various test areas with different conditions were selected. The initial tests with VDES on the waterway were carried out on the Spree-Oder-Waterway close to Berlin, see Figure 6. This area is well suited for VDES tests due to the low traffic density and the fact that no AIS base stations are operated there. An important aspect in performing the tests

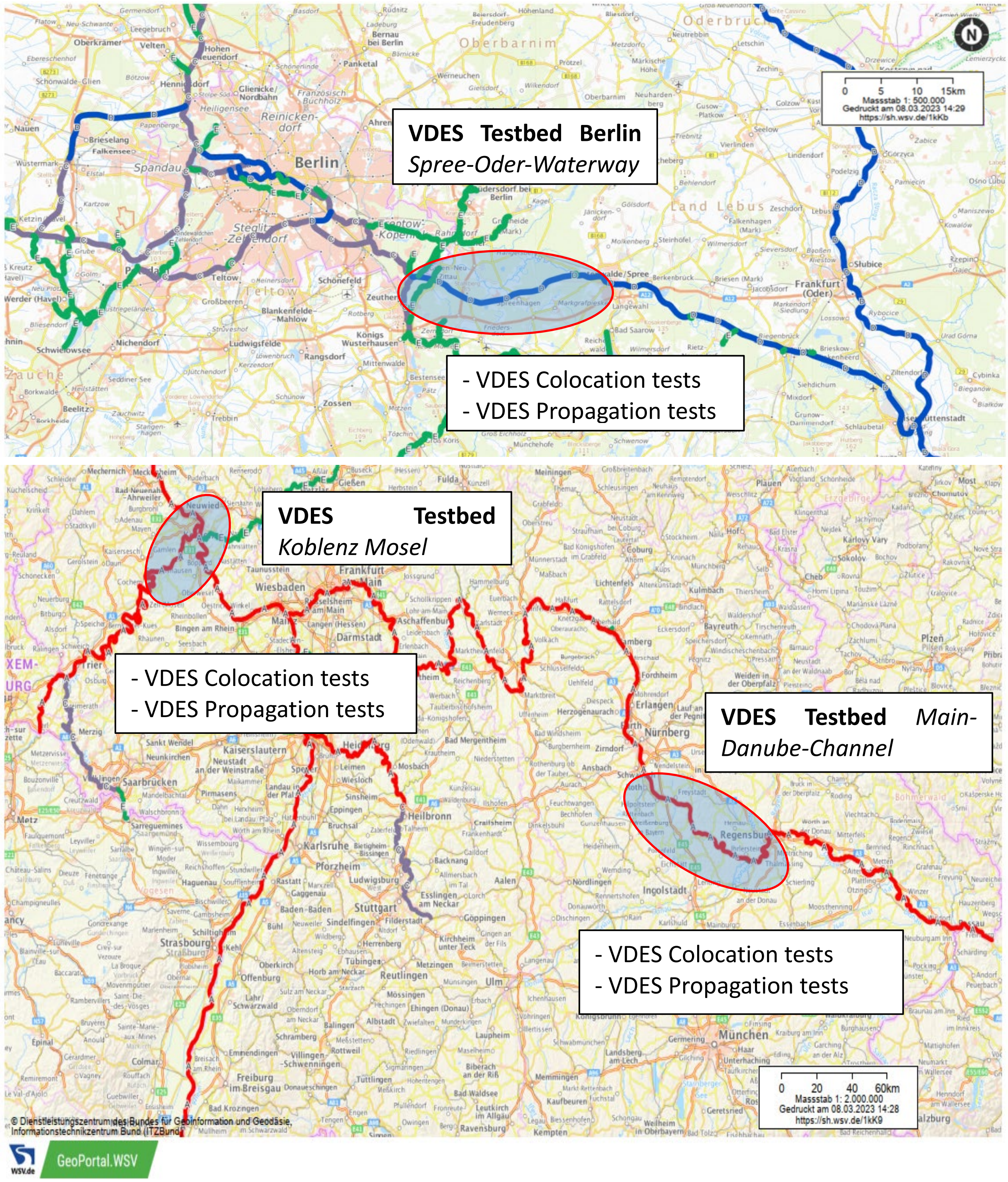


Figure 118 VDES Testbeds in Germany

was to use the existing infrastructure of the WSV. Accordingly, care was taken to ensure that a suitable antenna mast with sufficient VHF antennas was available. In most cases, a reserve antenna is already available on the antenna masts of the WSV. This was used to transmit VDES. In Berlin, studies have been conducted regarding propagation of VDES and collocation between VDES and the AIS channels. After completion of these tests, the test areas were expanded. A test area on the Mosel near Koblenz and a test area on the Main-Danube Canal near Nürnberg were added to perform further studies regarding the propagation of VDES and colocation. The results regarding colocation studies are discussed later in this paper in detail.

2.1.3 Standardisation of VDES-services

The transmission of GNSS PPP-RTK correction data as well as waterway and lock information via AIS/VDES is only partially specified and standardized. So far, only the AIS message 17 is approved for the transmission of DGNSS data. Regional or international Application Specific Messages (ASM) are used for the additional transmission of navigation relevant information.

The following will describe one way in which PPP-RTK data, waterway information and lock information should be encoded and transmitted via VDES. The resulting proposals for the encoding and transmission of the messages have to be agreed upon in a subsequent step internationally in the appropriate committees. With this solution, it is possible that PPP-RTK-based driver assistance functions can be realized. On the mobile side, all these data are then decoded and fed into the on-board system. The GNSS correction data and lock information are to be transmitted using the AIS Message Type #8 (Binary Message). The AIS MT #8 is variable in length, depending on the data to be transmitted, which will be embedded in the "Binary Data" block. The single messages should not occupy more than 5 slots [7].

Coding and transmission of PPP-RTK data

The PPP-RTK data, which is in RTCM-3.x format [4], is encoded as a complete data block. Due to the amount of data, it may be necessary to split the data into several related ASMs. Unfortunately, the available/defined ASMs are unsuitable in terms of type and scope and make a separate format definition necessary for the application area required here, see Table 3.

Table 15 Structure of the ASM for PPP-RTK data

Parameter	Bits	Description
Standard Message Header (40 bits)		
Message ID	6	Identifier for Message 8; **always 8**
Repeat indicator	2	Used by the repeater to indicate how many times a message has been repeated; 0-3; default = 0; 3 = do not repeat any more
Source ID	30	MMSI number of source station
Spare	2	Not used. Should be **set to zero**. Reserved for future use
Application identifier (16 bits) – RTCM 3x message identifier		
DAC	10	Regional DAC; **always 875**
FI	6	Function identifier; **always 16**
Application data (max 952 bits) – RTCM 3.x message content		
Maximum block	4	Maximum block number for split message; 0-9
Current block	4	Current block number for split message; 0-9
Data	0-946	RTCM 3.x binary data

Note: Since a RTCM3 message with up to 8232 bits can be much larger than the supported 5-slot AIS data, it must be split into several parts. Each part contains the current number and the maximum number (starting with 0, so the last block of 7 messages is 6). If "Current Block" is equal to zero, a new message starts. If "Current block" is equal to "Maximum block", the transmission is finished. Short messages may only use one block and are therefore sent with both values 0. Since RTCM3 has its own transmission controls, no additional check data is required.

Waterway Information

Based on the draft ASM "Lock Status" (DAC 366, FI 19) [10], this ASM was extended to be able to transmit the lock information required for the project. The advantages result from the use of an already defined ASM, which was defined for waterways in the USA, and the 88 bits still available within this 2-slot message. The ASM "Lock Status" occupies 272 bits of max. possible 360 bits in a 2-slot message (see ITU Rec. ITU-R M.1371-5, Table 21) [5].

For the transmission of information about the form and status of light signals at the lock, the already defined ASM "Signal Station" (DAC 200, FI 41) can be used [6]. This message is only sent from shore to inform all vessels in a certain area about the type and status of different light signals. This should be done at regular intervals. The information should eventually be displayed to the skipper on an external display, such as the Inland ECDIS, as dynamic symbols.

Further information regarding the SciPPPer project can be found at the following web address: http://www.scippper.de/.

2.2 R-Mode Baltic

2.2.1 Introduction

The R-Mode Baltic project developed and tested a ranging mode system using both AIS infrastructure and VDES signals. Measurement tests were carried out to analyse the impact of propagation conditions on ranging accuracy. The project concluded on 03/31/2021 but continued with the R-Mode Baltic 2 project, which aimed to evaluate the R-Mode Baltic test bed and test new R-Mode concepts and signals over a nine-month period. The project increased the monitoring capabilities of the R-Mode system in the Baltic Sea and observed its performance stability in varying weather conditions. The results of the R-Mode Baltic 2 project are crucial for further development and transformation of the proposed solution into a reliable and internationally accepted backup system for maritime navigation.

2.2.2 VHF installation Germany – preparation of testbed

During the R-Mode Baltic 2 project, preparations were made to build a VDES R-Mode testbed in the Baltic Sea at the German-Polish border. The testbed covers three German and one Polish VDES station. In addition, a monitor station is planned on the German side in Karlshagen. Figure 7 shows the four stations of the testbed. Thiessow, Greiswalder Oie and Zecherin on the German side and Swinoujscie on the Polish side. During the R-Mode Baltic 2 project, the infrastructure of the German stations has been prepared to the extent that they are ready to be used as VDES R-Mode transmitters. The stations were equipped with appropriate VDES compatible antennas as well as with the appropriate system cabinets for the R-Mode components. The testbed could not yet be put into operation, as the corresponding VDES transmitter hardware for the operation is not available.

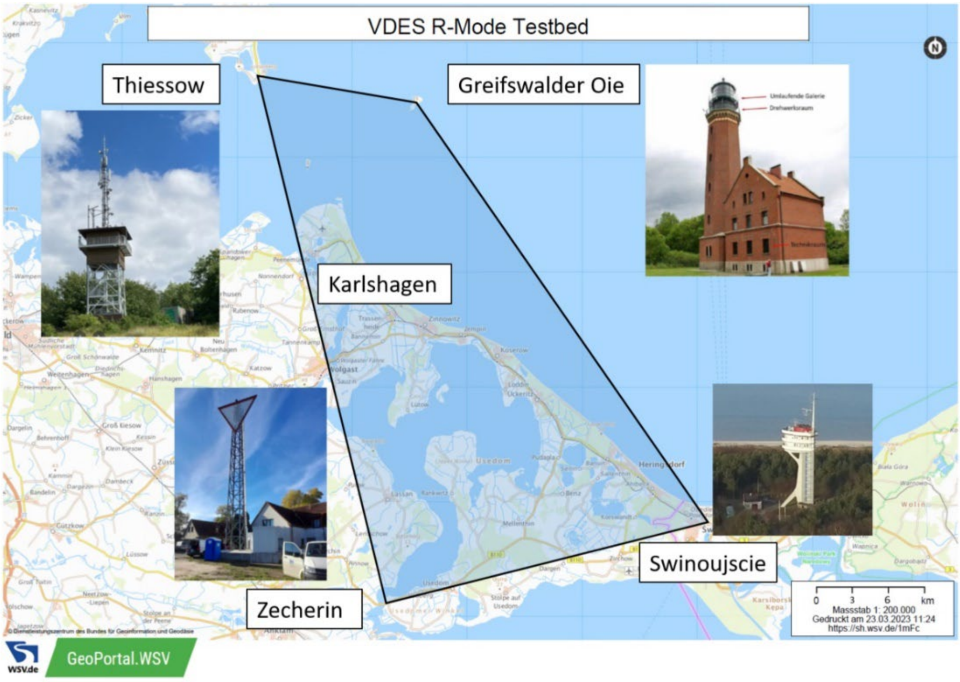


Figure 119 VHF installation Germany – preparation of testbed

2.2.3 VHF installation Poland

The R-Mode Baltic 2 project successfully developed a VHF system capable of real-time position monitoring using static and dynamic measurements. In summer and autumn 2021, a measurement campaign was conducted, validating the system's effectiveness. The transmitting station in Figure 8 was installed in Gdynia's port, transmitting at 25W EIRP with an antenna height of 28 meters above sea level. The receiver (Figure 8) was situated in Jastarnia Harbour, roughly 20 kilometres away from the transmitter. To calculate the receiver's

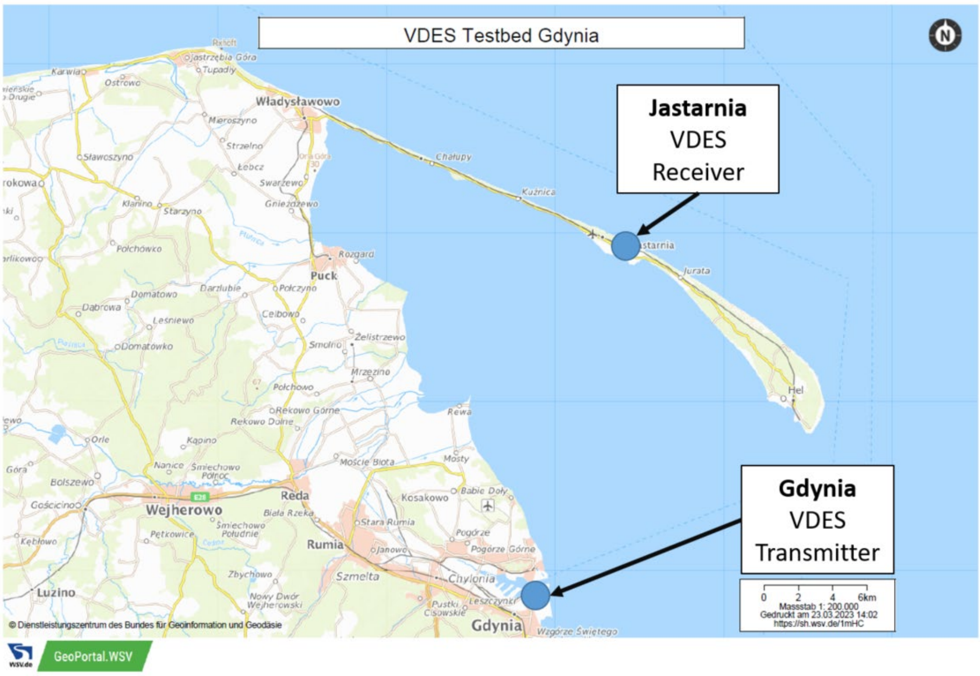


Figure 120 VHF Testbed Poland - Port of Gdynia

position accurately, a measurement scenario was employed where additional base stations were simulated to emulate the distances between Jastarnia and the actual transmitting station in Gdynia. The emulated stations coordinates were selected to match the exact ranges between Jastarnia and the transmitting station, see Table 4.

Table 16 Coordinates of the emulated stations as well as the transmitter and receiver

Station	Latitude [N]	Longitude [E]
Transmitter Station in Gdynia	54.529286	18.559539
Receiver Station in Jastarnia	54.6954586	18.673196
emulated Station 1	54.5292887	18.5595547
emulated Station 2	54.6057741	18.4064813
emulated Station 3	54.7261218	18.3690009
emulated Station 4	54.7925510	18.4137167

At a height of 17 meters above sea level, the receiving antenna was used for transmission between stations entirely over a sea path under line of sight (LOS) conditions. Both stations were synchronized using rubidium disciplined oscillators. Additionally, the receiver was outfitted with an LNA amplifier (NF=0.6 dB) and a VHF band-pass filter. The first few days' collected values are displayed in Figure 9.

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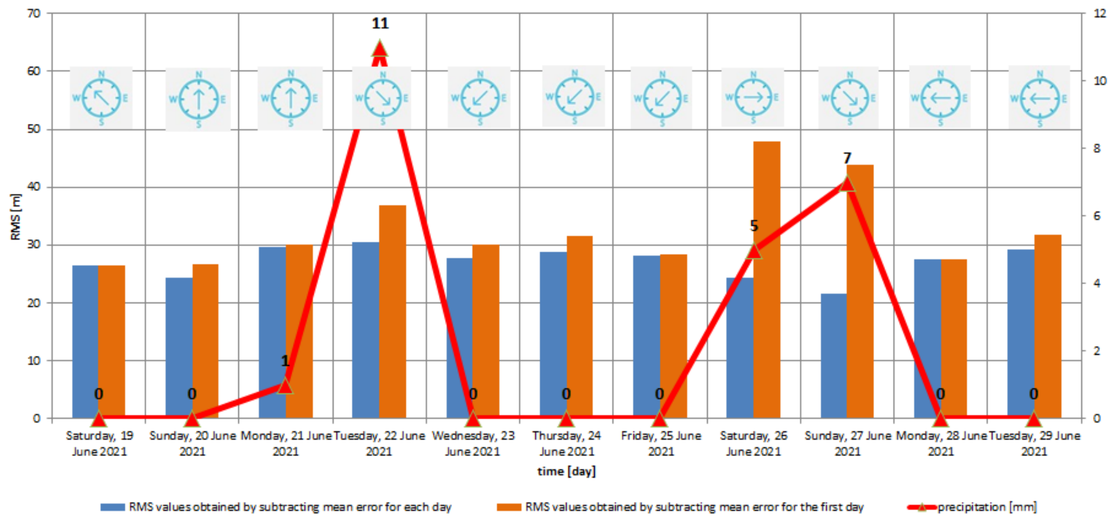

Figure 121 Analysis of the observed RMS depending on the meteorological conditions [8]

The obtained results display the RMS values for two cases: (a) daily with the mean error from measurements subtracted, and (b) once on the first day of measurements. This approach aims to reveal the potential accumulation of mean error, but monitoring depicted in figure 2 revealed no such effect. The measurements demonstrate the reliability, stability, and long-term invariability of propagation conditions. The graph also illustrates the impact of atmospheric factors, notably wind direction and precipitation, on the double delta correlator algorithm's ranging accuracy [8]. However, the presented values underscore the necessity for continuous VHF propagation conditions monitoring for the VDES R-mode system. Nonetheless, final and quantitative conclusions require additional research with more significant data sets and diversified geographical distribution of monitoring stations around the Baltic Sea.

In June 2020, another measurement campaign was conducted on the Gdynia-Karlskrona route, employing the VHF transmitting station in Gdynia's port and the receiver on board the Stena Line ferry [8]. The receiving station, originally designed for long-term position monitoring, was modified and repurposed for dynamic tests on board the vessel. Additionally, more optimized signals and modifications were introduced to the VHF station [8].

Figure 10 depicts charts of the ranging errors observed during the 2020 measurements. The orange line shows the distance between the receiver and the transmitting station, while the blue points represent the error resulting from the correlator's output and the reference measurement (i.e. output of the EGNOS + GNSS device). The main chart is divided into three environments in which the measurements took place: LOS, indicating the measurements carried out in the Gdansk Bay; Sea+Land Mixed Path, representing measurements taken when the ship was behind the Hel Peninsula, and NLOS, signifying measurements conducted when the ship had left the LOS zone and sailed further into the open sea, for a better illustration.

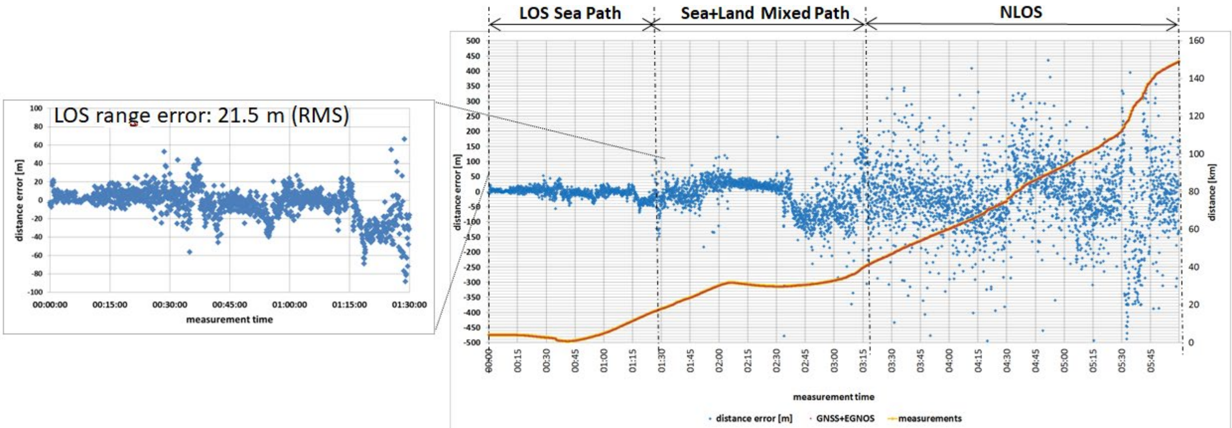

Figure 122 Ranging errors in the VDES 2020 measurement campaign for the double delta correlator [8]

The double-delta algorithm achieved an RMS of 20 meters in the LOS environment, which is a significant improvement compared to the previous measurement campaign where the values exceeded 30 meters [9]. The mixed path scenario is also noteworthy as it demonstrates good ranging precision with poor accuracy due to a constant error (offset) likely caused by the Hel Peninsula between the transmitter and receiver locations. To better illustrate this, Figure 10 displays a map of the measurement campaign route with ranging error values depicted.

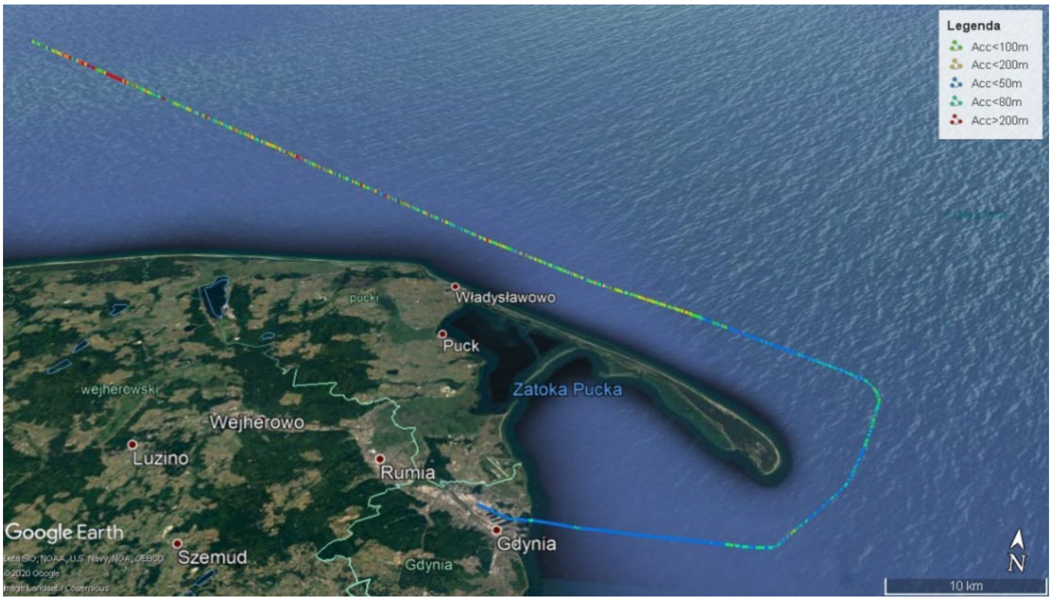

Figure 123 Overview map - Measurement campaign 2020 Gdynia – Karlskrona [8]

When the distance between the transmitting antenna and receiving station was short (and in LOS conditions), the ranges calculated by the signal correlation algorithm closely matched those obtained from the GNSS receiver. This allowed for the calculated ranges to be transferred to the positioning software module, which in turn estimated the position of the receiving station. This is particularly significant for navigation in port approach scenarios, where precision and accuracy are essential. For distances greater than 66 km, the observed error was 180 meters, representing an improvement compared to previous measurement campaigns [9]. It is worth noting that at distances of around 120 km, accuracies were on the order of 300 meters, which may be acceptable for certain applications. In such cases, the VHF-based ranging system could still be used in NLOS conditions.

2.3 DigitalSOW

The joint project DigitalSOW - Digital Test Bed for Automated and Autonomous Inland Navigation on the Spree-Oder-Waterway (SOW) started in 2016 and is expected to run until the end of 2023. The project is funded by the German Federal Ministry of Digital Affairs and Transport.

2.3.1 Introduction

The overall objective of the project is to establish and operate a digital test field for the investigation, development and testing of concepts, algorithms and technologies for automated and connected driving on the Spree-Oder waterway.

In recent years, numerous logistics centres have been built in the immediate vicinity of the Berlin beltway (A10) to supply the Berlin metropolitan region. From these centres, goods are largely transported by road to the capital. Due to the forecast growth in online retailing, a further increase in the volume of delivery traffic can be expected in the future.

Since the metropolis of Berlin and the surrounding area are crisscrossed with main and secondary waterways, a basic infrastructure for the transport of goods by waterway is available in the region. To integrate waterway transport into multimodal logistics chains and the use of intelligent automation solutions, extensive investments in the digitalization of this mode of transport are therefore required.

Parallel to the development of a digital infrastructure along the waterway, the transport units and transport process logistics must be adapted to the new requirements of city logistics. Digital transport documents, precise ship position and environment detection, automated and autonomous driving, and a suitable communications infrastructure for networking the vehicles with a control centre are important challenges in this complex of topics.

2.3.2 VDES Testbeds

VDES testbeds are built up to evaluate and test the new communication network capabilities utilizing existing VHF infrastructure and potentially identifying gaps in the coverage that need to be closed. Further, new applications are being developed that in the past failed because of the low capacity of AIS networks.

In Germany around Berlin the project digital Spree-Oder waterways builds up a testbed for logistical applications to support autonomous vessels in the digital modal transport domain. The special focus on the logistics allows a faster commercialisation of the existing waterways and to reduce the load on the busy city roads for trucks and cars. Further, it is planned to employ an alternative navigation and timing system based on the VDES communication link. First measurements in the southern-east zone of Berlin along the Dahme and the Müggelsee were performed with the most robust terrestrial-VDE link-ID 11 (25 kHz). Three bases stations were built up by using existing AIS infrastructure. Figure 12 shows the route and Figure 13 shows the capacity performance vs the route time linked to the different base stations. The terrain around Berlin and the buildings limit the coverage range to less than 14 km. The received signal strength down to -105 dBm and the link never failed. However, link-ID with 25 kHz bandwidth is the most robust configuration and to utilize the full capabilities of terrestrial VDE asks for a 100 kHz bandwidth which offers not just four times more bandwidth but also at least 6 times more data bits because of less overhead.

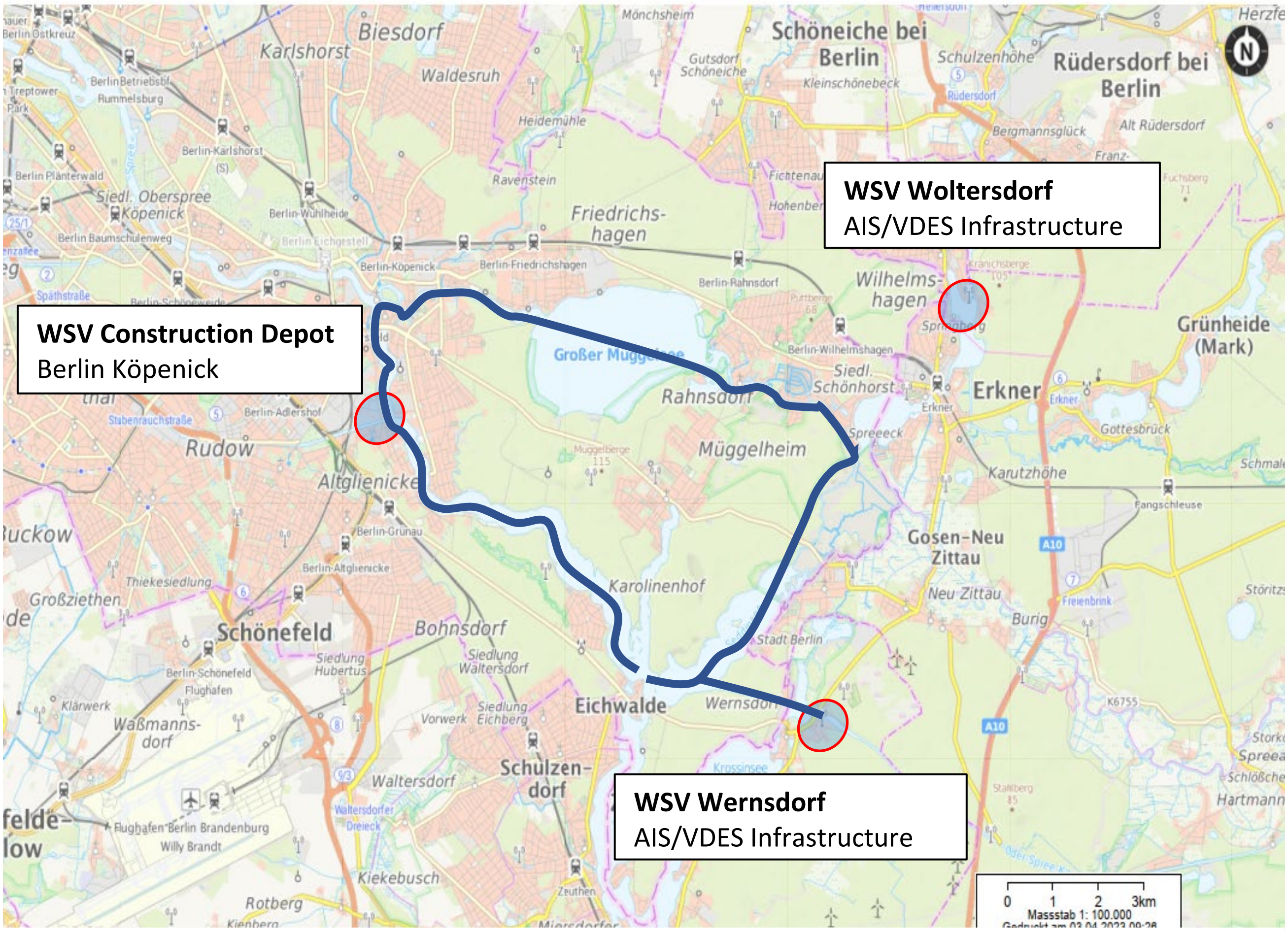

Figure 124 DSOW Testbed in the south-east part of Berlin. In white the route of the measurement trials to evaluate the coverage of the three VDES base stations

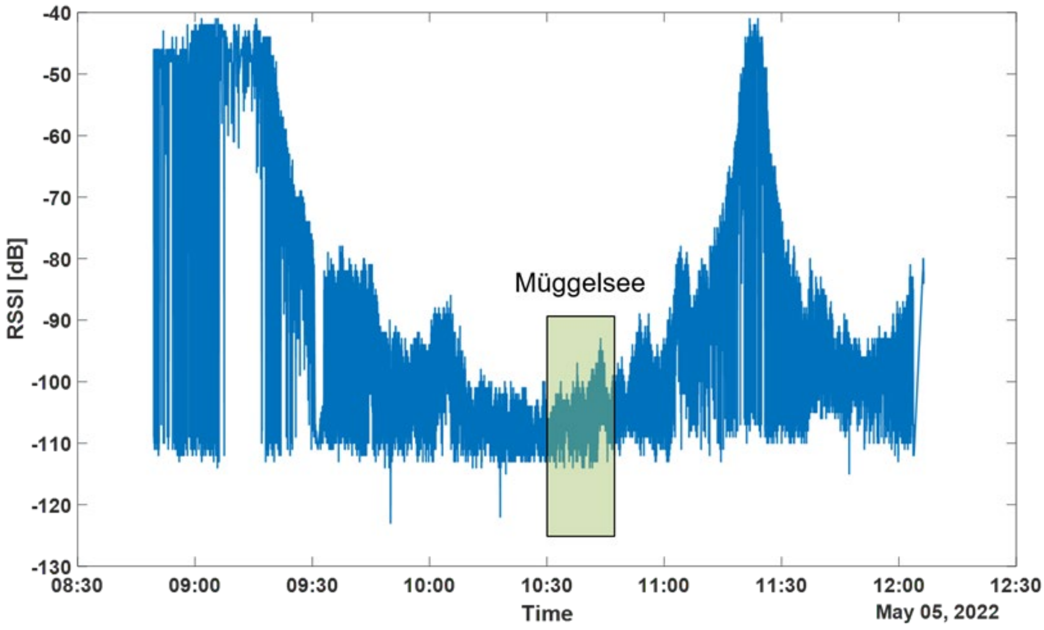

Figure 125 Overall performance of received signal strength [dB] of all three base stations during the trial route

The VDES test area in the DigitalSOW project is described below. In this particular urban environment, there are a number of challenges that can affect the use of VDES.

- Interference: In an urban environment, there are many sources of radio interference that can interfere with the transmission of VDES signals. These can come, for example, from other wireless communication systems such as WLAN, mobile phone networks, Bluetooth or other VHF transmitters.
- High signal absorption: The tall buildings in an urban environment can cause VDES signals to be absorbed by the buildings and structures, resulting in a weak signal and poor reception quality.
- Multipath propagation: Multipath propagation occurs when a signal from a transmitter to a receiver is reflected and scattered by different paths, which can cause signal distortion and interference. In an urban environment, buildings and other obstacles can lead to a high number of reflections, which can increase signal transmission problems.
- Shadowing: The tall buildings and structures in an urban environment can also cause shadowing, which means that the reception of VDES signals is blocked in certain areas.

In order to be able to cover the described test area in the best possible way, additional locations in the public space were equipped with VDES transmission technology in addition to the existing WSV locations. Particularly high buildings were chosen to ensure optimal signal propagation.

2.3.3 VDES-Services in the Test Area

One of the main objectives of the WSV in the DigitalSOW project is the implementation of the VDES services described in Figure 2. The focus of the project is to evaluate the services and assess the benefits for shipping and administrations. As the project is currently still in the implementation phase, there are currently no results regarding the VDES services. A comprehensive evaluation of the results will be published by the WSV at the end of the project within the framework of DigitalSOW.

3 COLOCATION OF AIS AND TERRESTRIAL VDE

The VDE-TER downlink is currently foreseen to transmit the regional correction data and concurrently receiving AIS messages from distant vessels. The upper edge of the VDE-TER downlink, however is located only 75 kHz away from the lower AIS channel at 161.975MHz. As AIS is an important and mandatory tool for safety of navigation, it is important that the new services do not interfere with AIS. This provides a challenge for implementer which want to place a full VDES base stations in the same locations as their existing AIS base stations, especially those that operate base stations in remote locations where setting up a new structure including additional infrastructure can be prohibitively expensive. Typical band pass filters for AIS radios do not filter out signals this close to the AIS frequency band. AIS receivers are expected to have a sensitivity of 20 % PER @ −107dBm, and VDE-TER has a transmit power of 12.5W or 41dBm poses a problem for the dynamic range of the AIS receiver.

3.1 Mitigation options

The separation of AIS and terrestrial VDE antennas would ease the blocking of the reception of the AIS signal. This comes at the expense of reducing the coverage of terrestrial VDE due to the slightly lower height. To address this issue, we investigate what strategies can be utilized to mitigate interference between the two systems. Possible approaches to this issue are:

- Accept interference from terrestrial VDE on AIS
- Limit the amount of time that terrestrial VDE is allowed to transmit
- Utilizing up- and downlink jointly in the lower lag of the terrestrial VDE spectrum (channel: 1024, 1084, 1025, 1085) with a tight time-scheduling protocol [12]
- Utilize steep filters that separate the two frequency bands
- Employ analogue and/or digital interference cancellation techniques

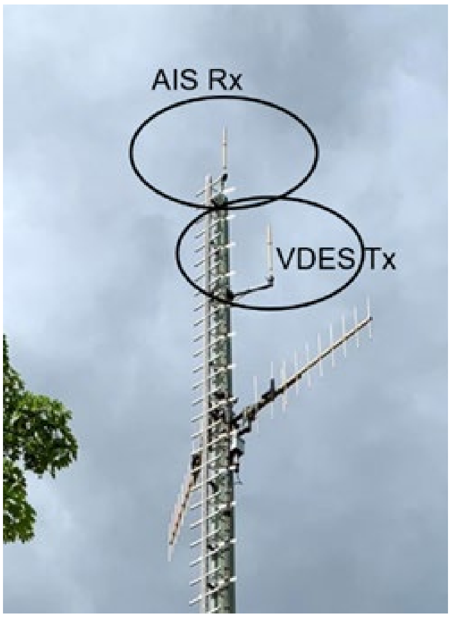

Figure 126 Vertical separation of the AIS Rx and the terrestrial VDE-Tx and Rx antenna

3.2 Assessment of solutions

To simply accept interference is a non-solution and can be assumed to usually not be viable, except for rare circumstances. However, it may be tolerable or necessary to accept remaining interference after other measures have been employed to reduce it. Limiting the transmit time of the VDE-TER system does not reduce the strength of the interference during transmission, but reduces the probability that an AIS message is affected by local interference. When a certain probability of package loss is acceptable at the AIS system, this can be a viable method. The obvious downside to this approach however, is that the downlink capacity of the VDE-TER system will be severely reduced. Utilizing analogue filters will be an element in any strategy to reduce interference. However, filters with such a steep transition between pass band and stop band as would be necessary for this use case would be expensive and have large physical dimensions.

Commercially available duplex filters for the VHF band designed for a frequency spacing of 600kHz, already exhibit physical dimensions of 26cm*48cm*60cm and a mass of about 14kg. Quartz filters for the VHF band are more promising as their frequency spacing is much less than 100 kHz with a strong attenuation of 60dB of the interfering signal, but it accepts only a low input power of 0dBm.

Interference cancellation techniques exploit the fact that the transmitted signal is known and thus can be subtracted from the received signal [13]. Theoretically resulting in complete removal of the interfering signal from the received signal. However, it relies on precise knowledge of the signal parameters at the receiver. Factors such as relative antenna placement and (dynamic) surrounding reflectors affect the channel between the transmitter and the receiver, even though they are located very close together. Further non-linearities in the RF hardware introduce signal distortions, leading to imperfect knowledge of the signal at the receiver. In the case of digital interference cancellation, the dynamic range of the Analog to Digital Converter (ADC), plays an important role to differentiate the AIS signal with low received power vs the VED-TER signal with strong power.

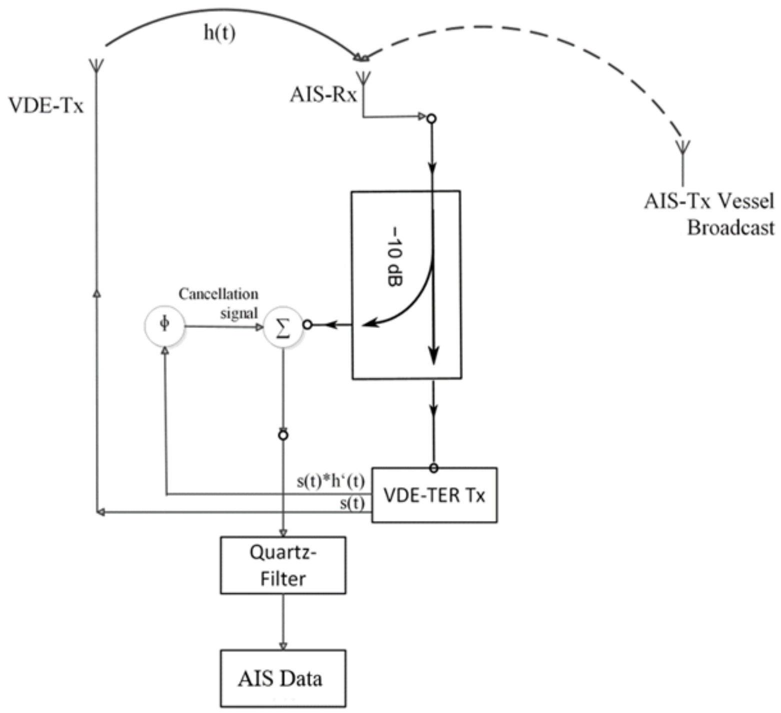

Figure 127 Colocation structure by cancelling the terrestrial VDE signal to improve the concurrent AIS reception of a distant vessel. The quartz filter finally filters out the remaining signal component of the terrestrial VDE signal.

The operating principal of an analogue interference cancellation approach is shown in Figure 15. Trials along the river Mosel proved that the reception quality of AIS improved significantly by applying the interference cancellation structure. Without the interference cancellation the AIS receiver was blocked and could not resolve any AIS signals.

The Canadian coast guard investigated to utilize only the lower lag of the terrestrial VDE spectrum [12]. The outcome showed that their expectations for their anticipated load of ASM and AIS messages were sufficiently fulfilled.

4 CONCLUSION

VDES offers high-bandwidth and reliable data communication between ships, shore stations, and satellites on AIS, ASM, and VDE frequencies. This enables administrations to develop new services to further improve safety of navigation by providing appropriate services. The use of the 100kHz VDE-TER channel enables such services without overloading the existing AIS.

The IALA Guideline G1117 has identified and described various potential use cases and scenarios for VDES technology, and Table 1 provides a brief summary of these identified use cases, as well as the services that are of particular importance for the German Waterways and Shipping Administration (WSV). The identified services are implemented and tested in various research projects by using mainly VDES prototype equipment. The availability of VDES hardware on the market is currently limited, as the system is still relatively new and in the standardisation and introductory phase. However, there are a number of companies that already offer VDES hardware or will bring it to market in the near future.

VDES-based services offer increased data transmission capacity as well as higher reliability and security. Two features of VDES, higher bandwidth and addressed authenticated message transmission, are particularly useful for reliable navigation and communication in the maritime field and on inland waterways [14]. The WSV operates an extensive network of approximately 200 AIS shore stations along the coast and inland waterways, and they are interested in using VDES-based services to support automated navigation. Thus, the WSV is involved in various research projects to develop automated navigation and validate new shore-based services.

The research project SciPPPer mainly implemented and validated a VDES based transmission of GNSS augmentation data (based on PPP-RTK). Here, the paper provides information about a potential new VDES service that delivers high accuracy GNSS for automated inland vessels. The method PPP-RTK was chosen to provide bandwidth optimised GNSS corrections fitting to the specifications of the VDE-TER channel of VDES. Another service, also addressing the use case PNT, is the use of VDES R-Mode. The paper briefly reports about first VDES R-Mode tests and results gained in the R-Mode Baltic project. Furthermore, the research project DigitalSOW was described. This challenging project aims to provide VDES services like GNSS-Augmentation, VDES R-Mode and VDES safety related information in an urban environment on a small channel in Berlin. These services shall support automated small vessels used for transport packages into the City centre.

The new VHF data exchange system (VDES) paths the way for new marine and applications. However, the operational challenges have increased versus the operational aspects of the AIS networks. The colocation of the different communication subsystems requires a prioritized use of all three systems as well as a good awareness of the communication needs within the network. Strategies to collocate the different systems are applicable but either increase the complexity or decrease the potential communicational throughput. Further, the communication coverage of the different subsystems varies depending on the need and the density of the network on the shore site as well as on water. Higher density of diverse vessels on water demands a denser infrastructure on the shore to fulfil the communication demands of the various applications.

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- the German Federal Ministry for Digital and Transport for founding the Project DigtalSOW.

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Stefan Bober is a senior engineer within the German Federal Waterways and Shipping Administration, Directorate General Shipping, Section Traffic Technologies - national and international Standards. He is working on radio aids and transponder techniques for Vessel Traffic Services (VTS) and River Information Services (RIS). He has been involved in the AIS and VDES projects for maritime and inland waterways applications. Stefan is a member of various international working groups dealing with development and standardisation of AIS, VDES and radio communication systems. He is member of the digital communication system WG within the IALA e-Navigation Committee, chair of IEC AIS WG and chair of the European expert group for Vessel Tracking and Tracing for Inland Navigation. He is also IALA representative at ITU-R WP5B.

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S116.7 Implementing Digital Aids to Navigation Information in European Inland Navigation (061)

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ABSTRACT

The European RIS COMEX project offers the opportunity to evaluate new possibilities for digital aids to navigation on inland waterways. AIS and ECDIS have proven that they can improve safety of navigation. Improved traffic awareness on board is a well-known benefit. However, the existing digital infrastructure of AIS and ECDIS has even more to offer: The digital data exchange between ships and shore allows for the provision of dynamic digital aids to navigation and other safety related information.

The project investigates how the constantly changing navigation-relevant information on inland waterways can be provided in the context of Aids to Navigation applications with ASM and ECDIS.

For example, information such as recommended lane in shallow navigational channels, the crossing of a ferry, the vertical clearance of a bridge and the signal status of a traffic lights, can be provided via ASMs and displayed on an inland vessel's on-board ECDIS. Smart buoys can measure precisely and transmit information about the current water level in front of a bridge in addition to its position, type and operating status.

KEYWORDS: AIS, physical AtoN, virtual AtoN, ASM, ECDIS, inland waterways, RIS COMEX,

1 EU RIS COMEX PROJECT - ENHANCEMENT OF SAFETY IN INLAND NAVIGATION

Within the framework of the EU project RIS COMEX, inland waterway information services (RIS) are provided in a sustainable and uniform manner. In principle, these RIS services are harmonized across countries, in relation to the corridor in which they apply.

The "Sub Activity 5.1" is a subtask in the RIS COMEX project, which focuses on "Safety on inland waterways". New digital messages of the European Standard for River Information Services (ES-RIS) are to be tested in various conditions in inland navigation.

The Automatic Identification System (AIS) is a digital radio data exchange system, used worldwide to identify ships in both, maritime and inland navigation.

Navigation on inland waters differs considerably from navigation on the open sea. It is usually made more difficult by the narrowness of the navigation channel, bridges, crossing pipelines, cross currents, changing water levels and frequently changes in the waterway bed. In addition, there are temporary construction sites to remove traffic restrictions or to improve operating conditions. Navigation conditions on inland waterways change frequently and inland navigation needs up-to-date information about them in order to navigate safely.

Despite the differences between maritime and inland navigation, efforts are made to apply the standards established in maritime navigation to inland navigation as well. Parts of the maritime standards do not fit in inland navigation and are therefore not used. Other rules have to be supplemented to meet the conditions on rivers and canals. Thus, the standards "Inland AIS" and "Inland ECDIS" were developed, which take into account the specific requirements of inland navigation. These two standards interact as well and this area of overlap must therefore be further developed in close coordination during standardisation.

The information provided by the Inland AIS standard is mostly received by the Inland ECDIS on board the inland vessels, interpreted and displayed on the inland navigation chart, with symbols and concise texts that are as easy to recognise as possible. The inland navigation chart is the so-called Inland Electronic Navigational Chart (IENC), a part of the Inland ECDIS standard. It contains all information relevant for navigation on inland waterways, e.g. the fairway, navigation signs, bridges, locks, ports, and shows your target state. This is the state that the German Waterways and Shipping Administration (WSV) constantly maintains to ensure operation.

Inland navigation in Germany is obliged to be equipped with a certified AIS device according to the Inland AIS Standard as well as an Inland Electronic Navigational Chart (IENC) according to the Inland ECDIS Standard and to use it during the voyage. In this way, the skipper can already detect all vessels in his vicinity on the ECDIS, even if they are still out of sight.

The Inland AIS Standard has now been extended with a number of functions that provide inland vessels with information about the nautical environment they are in. These are for example recommended routes in shallow water, hazard warnings of ferries just crossing, warnings of restricted bridge clearance heights at high water levels, and the actual signal status of a traffic light system. These functions were implemented and tested in the Elbe-Weser corridor as part of the European project "RIS COMEX". As both standards are concerned, it was important to further develop the Inland ECDIS standard in parallel with the Inland AIS standard. These standardisation processes is not yet completed. The results of the RIS COMEX project still have to be incorporated in those standards.

In order to be able to carry out the tests in RIS COMEX, it was necessary to upgrade the Inland ECDIS systems on board in such a way that the new Inland AIS messages are also displayed on the navigation chart. This was realised through a research and development contract awarded to the Inland ECDIS manufacturers within the RIS COMEX project.

The temporary restrictions, that are passed on to the inland vessels via AIS AtoN messages or ASMs are now also visible on board on the Inland ECDIS with the new software versions of the Inland ECDIS manufacturers. This is done on a local basis, i.e. the restrictions appear where they exist.

This means that in addition to the static information of the navigation environment, temporary information on traffic restrictions are now also displayed on the navigational chart where it applies.

If the display of this additional temporary additional information obscures important important static information on the navigation chart, for example in the case of a difficult bridge passage, the skipper can also temporarily hide the additional information in the IENC.

2 RESULTS OF THE TEST APPLICATIONS IN THE ELBE-WESER CORRIDOR

In general, the objective of the European project RIS COMEX was to provide River Information Services (RIS) in a sustainable and uniform way within the inland waterway corridors. New Inland AIS messages, so-called Inland AIS AtoN messages and Inland Application Specific Messages (Inland ASM), were tested in the Elbe-Weser corridor with view to improving safety and ease of navigation.

Inland AIS AtoN messages and Inland ASMs have been specifically developed to take into account the special requirements of inland navigation. These messages are based on the maritime equivalent but adapted for inland navigational use. These developments are based on IALA Recommendation R0126 “The use of AIS in marine aids to navigation services” and IALA Guideline G1095 “Harmonised implementation of Application Specific Messages (ASM)”.

Inland AIS AtoN messages are special AIS messages for:

- fixed and floating navigation marks on inland waterways, equipped with an AIS AtoN station, so-called "Physical Inland AIS AtoN".
- virtual inland navigation marks, which are not physically present and for which the information is transmitted by an AIS land infrastructure. The so-called "Virtual AIS AtoNs".

Inland ASMs are application specific developments on inland waterways and are also transmitted via the AIS land infrastructure.

All these Inland AIS messages are received by the on-board Inland AIS device and displayed on an Inland ECDIS device, extended for these purposes.

3 PHYSICAL AIS ATON: BOUYS

"Physical Inland AIS AtoN" are physical navigation marks which are additionally equipped with an Inland AIS AtoN station. This Inland AIS AtoN station regularly sends an Inland AIS AtoN Report message with information about the type of AtoN and its position. The Inland AIS AtoN message also contains a so-called "off-position indicator". This indicates on the Inland ECDIS chart whether the buoy is at its nominal position or whether it is “off position”. The skippers and the waterway administration are thus made aware of buoys that have drifted.

The Inland AIS AtoN station is based on the maritime AIS AtoN station according IEC 62320-1, but by using AtoN status bits in the AIS Message 21, the information provided is extended by the Inland AIS AtoN type. The AtoN status page ID 1 is used and a set of up to 32 Inland AtoN types are defined. Details can be found in CESNI ES-RIS 2023/1.

Within the project, physical Inland AIS AtoNs are used to highlight the junction of navigable canals or lock canals at the river Elbe (Figure 1).

For the test operation in the Elbe-Weser corridor, physical Inland AIS AtoNs were laid out at the following points:

- Branch Elbe-Seitenkanal
- Lock entrance UW Geesthacht
- Branch Rothenseer Verbindungskanal

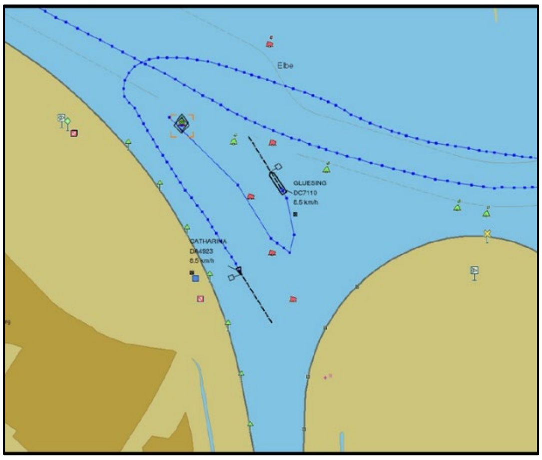


Figure 1: Visualization of a physical AIS AtoN at junction of the Elbe-Seitenkanal in Inland ECDIS

4 VIRTUAL INLAND AIS ATON: BUOYS AND BEACONS

Virtual Inland AIS AtoNs are navigation marks, e.g. buoys, which do not exist in nature. The information of a virtual AtoN is only send via the Inland AIS AtoN Report message and displayed on board of inland vessels in the Inland ECDIS system.

They can be used to highlight an isolated danger point, e.g. by displaying a buoy, or to mark an area where restrictions apply or special attention is required, e.g. during construction works.

During the project it was discussed whether a sequence of buoys, or a line connecting waypoints, or an area would be better suited to visualize certain aspects. For that purpose an ASM providing a line shape or an area shape on an Inland ECDIS could also be seen as a virtual AtoN.

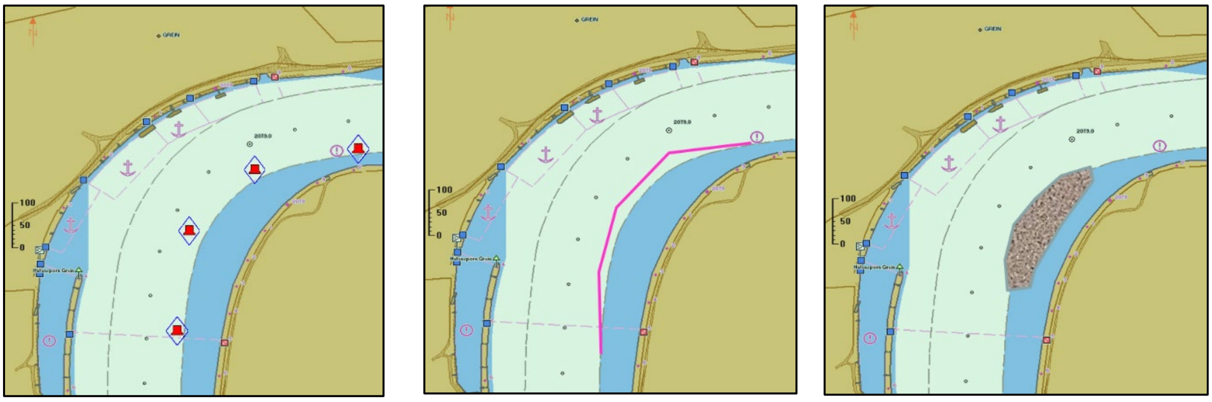

Figure 2: AIS AtoN and ASM depicting a restricted area at the right hand side of the river

5 VIRTUAL AIS ATON: RECOMMENDED ROUTE

In the area of the Lower Elbe near Lauenburg, the so-called residual water stretch, there are constant changes in the river bed. The riverbed is so unstable that even a small flood leads to considerable material shifts in the riverbed. The meandering fairway in the river is marked by buoys and additional beacons on the bank. And this marking often has to be adjusted on site.

With the help of a virtual polygon sent via an ASM, the "recommended route" can now also be displayed in Inland ECDIS (Figure 2).

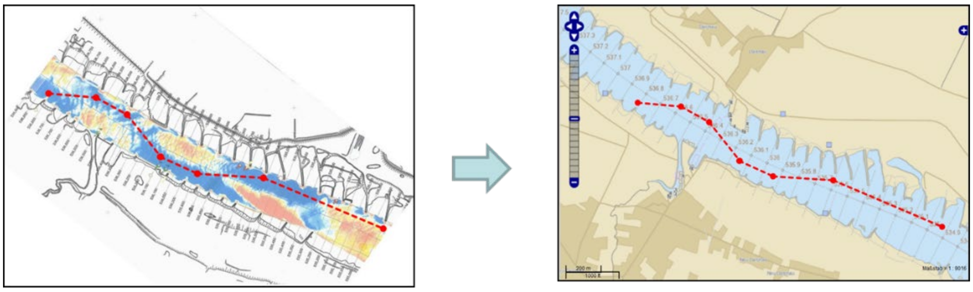

Figure 3: Construction of a “recommended route” from sounding results and visualization on an Inland ECDIS

6 VIRTUAL AIS ATON: WARNING OF CROSSING YAW ROPE FERRIES

On the Elbe, there are a number of yaw rope ferries whose yaw rope is anchored in the river. The yaw ropes are marked by buoys and runs close under the water surface. When the ferry moves from bank to bank, the yaw rope is a source of danger for continuous navigation.

For the test application, four yaw rope ferries were equipped with Inland AIS stations and the functionality to transmit the ASM "Yaw rope ferry crosses fairway":

- - Ferry Rathen, Elbe-km 22.67, DE
- - Ferry Sandau, Elbe-km 416.10, DE
- - Dolní Žleb, Elbe-km 731.9, CZ, in the area of responsibility of the Czech waterway authority
- - Velké Březno, Elbe-km 757.05, CZ, in the area of responsibility of the Czech waterway authority.

When crossing the waterway, the ferries send an ASM "geographical message" with an area shape representing a warning area at regular intervals (Figure 3). The ASM is manually triggered and stopped by the captain of the ferry.

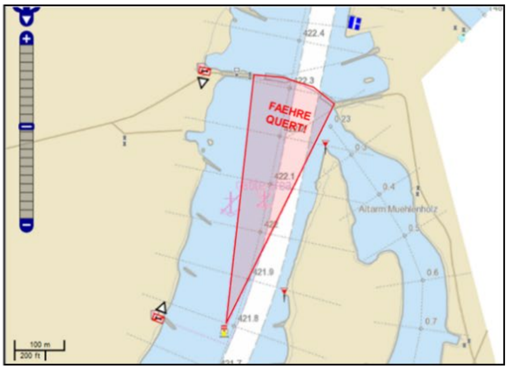

Figure 4: Yaw rope ferry at the river Elbe Virtual caution area while the ferry is crossing

7 VIRTUAL AIS ATON: WATER LEVEL MESSAGE

The German Waterways and Shipping Administration (WSV) publishes water level at specific stream gauges and related information on its website “Pegelonline.wsv.de”. Those information can be retrieved via the internet at the appropriate webpages or via web services for machine to machine communication.

In the project, the current water levels from https://www.pegelonline.wsv.de/ were transferred via AIS ASM “Water level” to the vessels in the vicinity of the gauge and displayed as a text field at the corresponding position of the gauge in the Inland ECDIS. In addition the current vertical bridge clearance for nearby bridges were calculated according the current water level, transferred via AIS ASM “Bridge Clearance” and displayed as a text field at the corresponding position of the bridge in the Inland ECDIS.

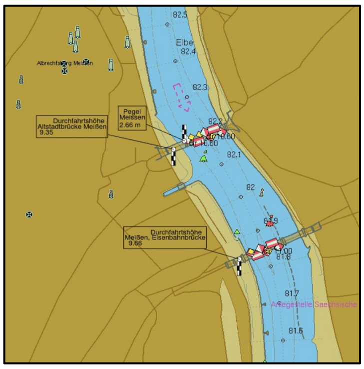

Figure 5: Website Pegelonline and display of the water level and vertical bridge clearance in Inland ECDIS

8 VIRTUAL AIS ATON: WATER LEVEL DEPENDENT WARNINGS

For the particularly low bridges on the Elbe, a warning area is automatically displayed in the Inland ECDIS, depending on the water level when the clearance falls below 7.00 m. The warning area is part of an "ASM area notice message". In addition to the warning area, the value of the currently available bridge clearance is displayed. The warning message disappears automatically again when a clearance height of 7.00 m and more is given (Figure 6).

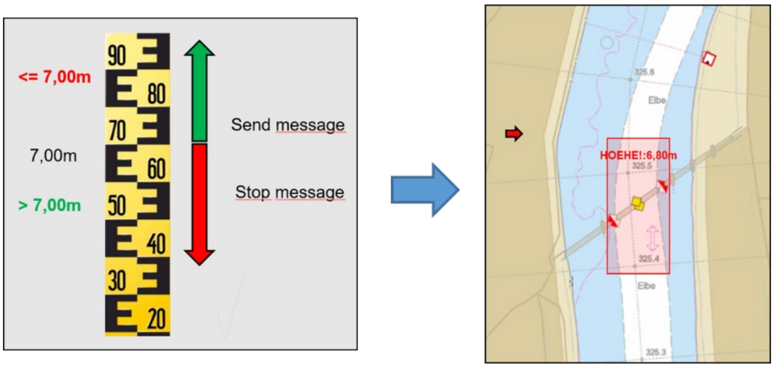

Figure 6: Warning area in Inland ECDIS at low bridge clearance height

9 ASM TEXT MESSAGE: POSITION RELATED WARNING MESSAGE

In order to alert navigation to temporary traffic restrictions and hazards at the waterway, there are Notices to Skippers (NtS). Via NtS service information such as the status of the inland waterway infrastructure (i.e. bridges and locks), failures of aids to navigation, temporary blockages of waterway sections, works, water level and water depth information, ice information and weather messages is provided.

For example, Notices to Skippers in Germany are provided via the web service ELWIS.de. Those information have to be retrieved from the corresponding server via internet access. Incidents and accidents at the waterway are usually reported via VHF voice communication from the appropriate Inland VTS center responsible for the area.

Within the project a functionality was implemented to automatically provide these messages via AIS ASM. The Inland ASM "Text message with position reference" offers the possibility to display particularly important traffic information directly in a text field at the referenced position on the electronic inland navigation chart on board the inland vessels (Figure 7).

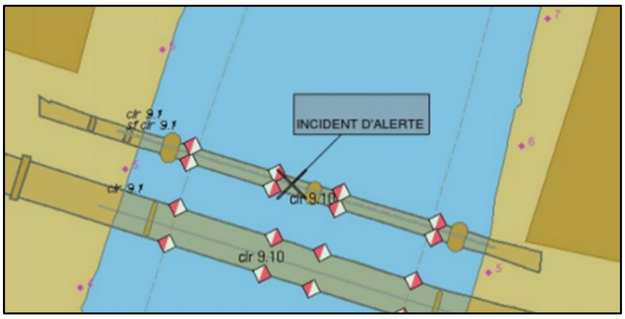

Figure 7: Position related text message

10 -ASM: TRAFFIC LIGHTS

In the area of the "Magdeburger Domfelsen (Wahrschaustrecke)", Elbe-km 325.10 to km 327.10, inland vessels cannot run accross at certain water levels. It's due to the lack of depth, caused by a rock formation partly in the river, the "Domfelsen". A so-called "Wahrschaustrecke" has been set up there. This is a section for which special dynamic regulations apply. Traffic lights at the end points of this section regulate temporary one-way traffic, depending on the traffic situation upstream and downstream. The traffic lights are manually switched on demand via VHF radio from the nearby VTS centre.

The project created an AIS based traffic image of the area, which is displayed on an inland ECDIS. The current status of the traffic lights is transmitted to the vessels via the Inland ASM "Signal Status" and displayed on the Inland ECDIS on board (Figure 8).

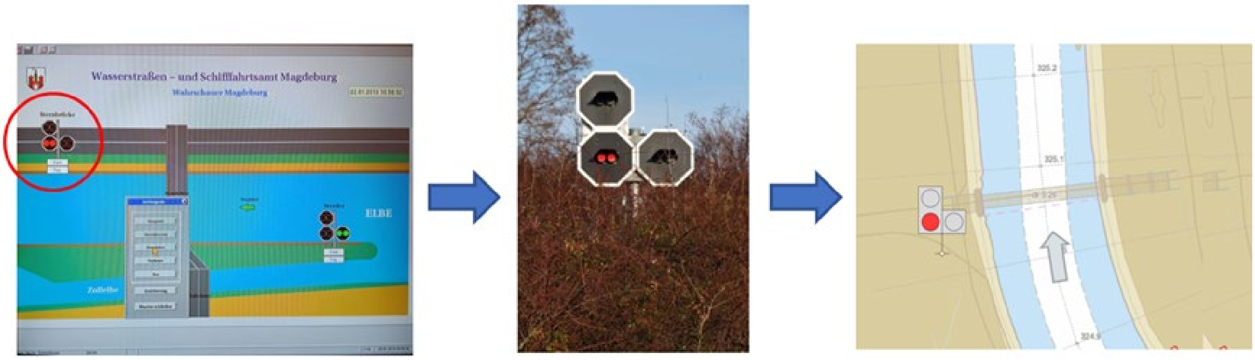

Figure 8: Status of the traffic light system in Magdeburg, shown on the right in Inland ECDIS.

11 SMART BUOY

The WSV operates bridge clearance indicators at some bridges crossing the federal waterways. They are usually connected to a stream gauge in the immediate vicinity of the bridge.

As part of the project an intelligent buoy was developed to measure the current water level which can be used as a basis for determining the current bridge clearance height.

An inland buoy was equipped with a solar power generator, an AIS AtoN station and a high-precision GNSS receiver using RTK information. The buoy thus became a "smart buoy" that records the water level at its location with high accuracy. This is the first buoy of its kind in the inland navigation. It turned out that the measurement results of the smart buoy fulfilled the accuracy requirements. A height accuracy of + -5cm could be achieved. In the future, such a smart buoy could be used as a flexible precise measuring tool for determining water level heights at any point on the river, independent of any infrastructure or relative costly stream gauges.

The high measuring accuracy is achieved by a high measuring frequency. During a measurement period of 10 minutes, measurements are taken every second. This usually results in 400 to a maximum of 600 validated measurements. The average of these results compensates for the sway and roll of the buoy during the measurement period (Figure 9). This was validated by independent terrestrial laser scanning of the water surface during different measurement periods of the buoy.

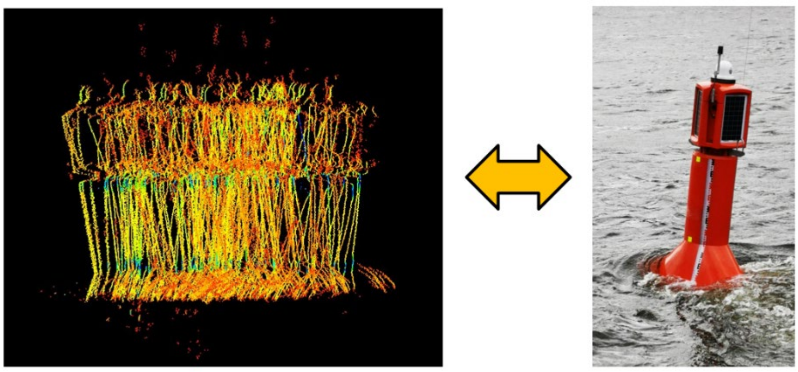

Figure 9: Waving and swaying of the measuring buoy in Dresden.

12 IMPLEMENTATION OF THE RESULTS IN EUROPEAN REGULATION FOR INLAND NAVIGATION

The results of the RIS COMEX project where input to the European standardisation group for river information services (RIS), the European committee for drawing up standards in the field of inland navigation (CESNI). This standardisation group publishes and maintains the European Standard for River Information Services (ES-RIS). This standard is updated every two years and contains standards for an inland vessel reporting system, notices for skippers, Inland ECDIS and Inland AIS. With the latest update of this standard, ES-RIS 2023 now also includes a standard for Inland AIS AtoN and Inland ASMs used on European inland waterways. It is expected that ES-RIS 2025, the next edition of ES-RIS, will include requirements for the visualisation of Inland AIS AtoN and Inland ASM in Inland ECDIS as well as test standards for these features.

13 SUMMARY

The potential of the new Inland AIS messages (AIS AtoN and ASM) lies in the versatility of the application possibilities and is far from being exhausted. The basic functionality could be created within RIS COMEX and the applications can thus also take place in other waterways.

The various test applications in the Elbe Weser Corridor have shown that the safety and ease of navigation is improved by these applications. Within the framework of RIS COMEX, a sustainable starting point for future applications could be created. However, the existing solution approaches should be refined and made more practicable. On the basis achieved, further useful technical applications can be found to take us forward in the direction of "digitalization of shipping". The components on board that are necessary to use these messages for navigation must be uniform across national borders. Therefore, a coordinated further development of the standards affected by the Inland AIS and Inland ECDIS applications, seems particularly promising to us in this respect.

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Stefan Bober is a senior engineer within the German Federal Waterways and Shipping Administration, Directorate General Shipping, Section Traffic Technologies - national and international Standards. He is working on radio aids and transponder techniques for Vessel Traffic Services (VTS) and River Information Services (RIS). He has been involved in the AIS and VDES projects for maritime and inland waterways applications. Stefan is a member of various international working groups dealing with development and standardisation of AIS, VDES and radio communication systems. He is member of the digital communication system WG within the IALA e-Navigation Committee, chair of IEC AIS WG and chair of the European expert group for Vessel Tracking and Tracing for Inland Navigation. He is also IALA representative at ITU-R WP5B.

S116.8 Applications of VDES system for the safe and sustainable use of ocean (215)

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ABSTRACT

VDES (VHF Data Exchange System) has been recognized as a new platform to meet rapidly increased demand for data communication among maritime AIS users. In addition, VDES function can be applied for the maritime domain awareness to collect and send information globally. A study group organized by OPRI has worked for two years and summarized potential VDES applications. Ship operation data via VDES will greatly help maritime safety inquiry for prevention of marine accidents, i.e., mutually coordinated navigations through VDES will be possible.

Electronically identified movements and ID of surrounding ships will reduce the collision risk in advance. To do this, all objects including small vessels and buoys are anticipated to deploy VDES terminals, which should be small enough and low cost or even free. Compensation of expenditure may include reduction of insurance fee and feedback fee for the data supplier from the data users. VDES can be a global marine information platform like IoT (Internet of Things) of the terrestrial network. Forming an ocean big data by accumulating small packets including sea surface temperature, salinity, depth, water color, and sea state from all of the vessels and objects, maritime domain awareness for the sustainable use of ocean will be extensively promoted. Establishment of an international coordination/cooperation body for VDES is crucial for easy but well-controlled accessibility for authorized and anonymous uses in multiple security levels. In the meantime, feedback value chain for the data suppliers such as vessel owners should be established. Our discussion is in progress. Updates will be presented.

KEYWORDS: VDES, coordination, cooperation, safety of ships, security at ocean

1 INTRODUCTION

Development of VHF data exchange (VDE) started early in the 21st century, and World Radiocommunication Conferences (WRC) allocated VHF frequency to VDE in 2012, 2015 and 2019.

ITU-R (International Telecommunication Union – Radiocommunication Sector) developed a recommendation on technical characteristics of VDES as M.2092 that revision (M-2092-1) has been published since 2022 [1]. IALA developed “VHF Data Exchange System (VDES) Overview” as G1117 and its third edition has been published since February 2023 [2].

In the revision work of IALA G1117, OPRI proposed several possible use cases, such as use in Maritime Domain Awareness (MDA), mutually coordinated navigation among vessels, fish catch certification (also for supress of IUU fishing) and disaster response to ensure communications. These proposals have been introduced in IALA G1117 third edition.

OPRI also proposed a new work item of the development of a guidelines/guidance for VDES resource sharing and cooperation/coordination to IALA ENAV Committee at tis 28th session in 2021 [3] and 29th and 30th session in 2022 [4] [5]. ENAV Committee at its 30th session agreed to add this work item in the work plan of IALA in 2023-2027 [6]. The council of IALA in December 2022 endorsed this proposal.

2 STUDY ON VDES USE CASES

OPRI started, in 2018, holistic investigation and study on VDES aiming at development of its proposals for promotion of use of VDES in Japan and the world. In the study, some of possible use cases of VDES for maritime safety were identified as described in the following sections. OPRI made proposals to IALA ENAV Committee to include them into the 3rd edition of IALA G1117 "VHF Data Exchange System (VDES) Overview".

2.1 VDES for mutually coordinated navigation

When ship meets another ship in close distance, it is necessary to communicate promptly to know and clarify each other the intention of the operation of the ships to avoid a collision. Especially large vessels need to react well in advance due to its latency of manoeuvrability. VDES can provide direct ship-to-ship communication when a ship comes close to another ship on the sea. In addition, automatic translation/interpretation can be introduced in this system, the communication can be done among different languages. (Existing system takes longer time to establish such communication: firstly, obtain ship's call sign by AIS; secondly, call the ship by VHF. Such voice communication shall be done the common languages; this is many times difficult for local fisherman.)

In case satellite VDES communication is available, the navigational coordination can be applied to ships and objects around such as small boats as shown in Figure 1. This "mutually coordinated navigation using satellite VDES will enhance the safe navigation of ships particularly in a congested sea area, or in cases that large ships navigate in area of fishing.

One of the important things of the mutually coordinated navigation through VDES is that the VDES communication among ships shall not be intervened, because any delay of the VDES communication may lead dangerous situations.

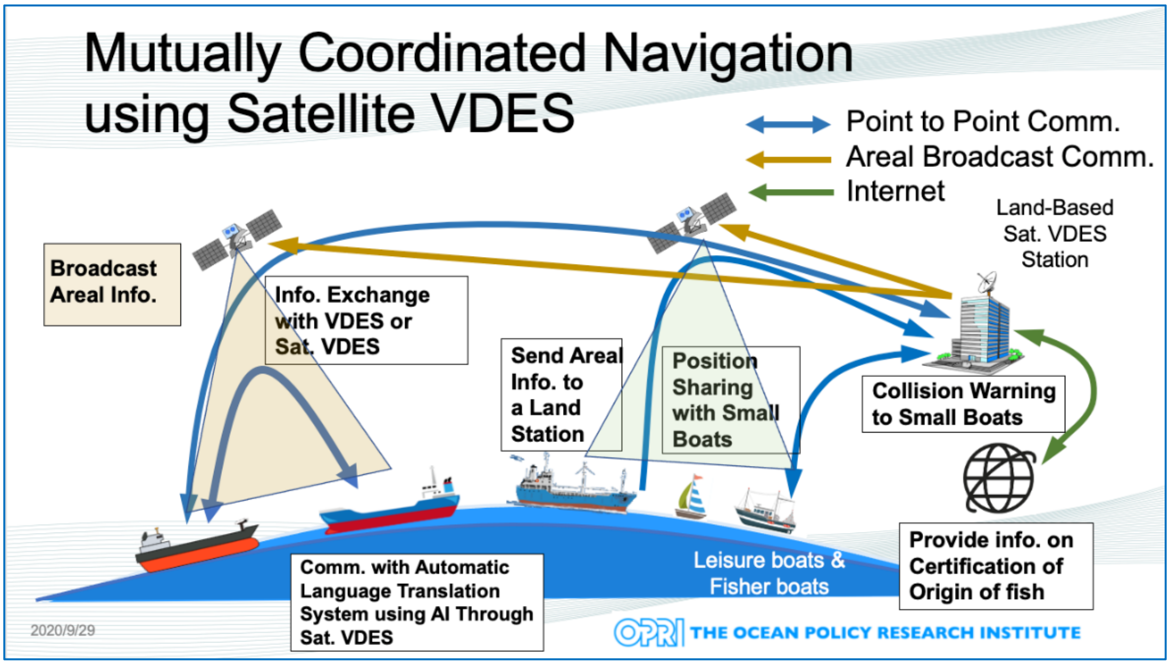

Figure 1: VDES for Navigational Coordination

2.2 VDES for MDA (Maritime Domain Awareness)

The maritime domain awareness (MDA) is defined [7] as "the effective understanding of any activity associated with the maritime environment that could impact upon the security, safety, economy or environment". MDA is the key for sustainable ocean management. Effective and immediate understanding of anything associated with the maritime domain could impact security, safety, economy or marine environment. VDES provides capability of communication on ship-to-shore, ship-to-ship and ship-to-satellite information gathering on MDA as a global IoT network.

2.3 Fish catch certification (Supress of IUU fishing)

Fishing vessels can provide, through VDES, the information of fish catch (fish name/type, amount) together with the AIS information (ship ID, location, date). This information is sent to fishing port, fishing operation control authority/center as well as supply chain that endorse the appropriate fishery product. The authority may send a certificate of fish catch to the vessel. The customers at fish market recognize that the fish was caught legally.

Independent authentication of the location of a fishing vessel with time will be used for the fishery certification to prevent IUU (Illegal, Unreported and Unregulated) fisheries. Consistency between R-mode and GPS location will give an endorsement to the authorization. Fishing vessels that do not send information of fish catch or do not have fish catch certificate, may be suspected for IUU fishing, and eliminated from the market.

2.4 Disaster response and communications

Once a distress alert is initiated and the information has been forwarded to a Rescue Coordination Centre (RCC) through the established GMDSS process, the RCC forwards information of the incident to vessels in the area. The forwarding of information, using existing formats, could be provided by various communications means, including VDES. The forwarding of data over a digital communications system such as VDES could facilitate the integration and display of information on external systems on-board (for example, Radar, ECDIS). Information could then be passed to the RCC and other vessels in the area including course to intercept, ETA on-scene, on-scene conditions, sharing of a common operating picture, etc.

Marine disasters include both man-made disasters, such as large-scale marine pollution caused by oil spills, and natural disasters, such as “Tsunami” and severe typhoon attacks occasionally happen. When terrestrial communications infrastructure is damaged by a natural disaster, VDES satellites can provide a communications link to meet emergency information transmission needs. Satellite VDES can ensure communication with vessels navigating along the coast in the event of the loss of VDES shore station infrastructure due to a natural disaster.

3 USE OF VDES UNDER SOLAS

International Convention of safety of Life at Sea (SOLAS) [8] stipulates, in its Chapter IV, the Global Maritime Distress and Safety System (GMDSS). One of the key functions of GMDSS is that ships shall have capability of receiving Maritime Safety Information (MSI), e.g., meteorological and navigation information, from land-based dedicated stations. IMO (International Maritime organization) adopted the revision of SOLAS Chapter IV GMDSS at 105th session of Maritime Safety Committee (MSC105) held in April 2022. The revision will enter into force on 1st of January, 2024. The methods of dissemination of MSI have been limited to NAVTEX, Inmarsat EGS and HF direct printing telegraphy until today. However, IMO decided to release the limitation and to leave the method to the decision by the authority that send out MSI. This change has been included in the revision of GMDSS, and it will become possible to disseminate MSI through VDES, if such infrastructure is established.

Another action taken by IMO is that Japan, Norway and Singapore proposed to Maritime Safety Committee, at its 103rd session (MSC103) held in May 2021, to introduce VDES as an alternative to AIS. MSC103 agreed the proposal in principle and expanded the proposal to consider the use of VDES under International Convention of Safety of Life at Sea (SOLAS) both in its chapter IV GMDSS and chapter V Safety of Navigation. MSC103 also agreed to develop IMO technical standard and operational guidelines for VDES.

MSC103 further agreed to allocate the consideration of this work item to the Sub-Committee on Navigation, Communication, Search and Rescue (NCSR) of IMO from 2023 for two years [9]. This will allow the use of VDES as an alternative to AIS and furthermore as a communication way for maritime safety, e-navigation and security at ocean.

4 VDES RESOURCE SHARING AND COOPERATION

It has been a long time since the announcement of the e-NAV concept to create a digital environment necessary for maintaining a sustainable marine environment. Since then, IALA-WWA (World Wide Academy) has been involved in the development, management and maintenance of navigational aids and is proceeding with the examination of issues related to the development of advanced technology. Considering that IALA is strongly required to contribute to the development of the sustainable marine environment by transforming into an IGO (Intergovernmental Organization), IALA welcomes the decision to start the development of satellite VDES, which will be the foundation of the marine digital society. Following this, OPRI has proposed measures for practical use of satellite VDES upon a coordination/cooperation of VDES communication providers and resources, since immediate and reliable commercialization of satellite VDES is essential for the sustainable use of the ocean.

IALA ENAV Committee discussed to identify near future use cases of VDES in various maritime communications among merchant vessels and small crafts including pleasure crafts and fishing vessels, and has work on this issue as the revision of IALA G1117. The third edition of G1117 has been published since February 2023.

It is also recognized that some bodies/groups have started establishment of VDES satellite communication systems, including space segments and land-based segments.

Therefore, it is necessary to consider the establishment of an international collaboration on the following points for the establishment of international cooperation and resource management of VDES communications, in line with IRU-R M2092-1 Annex 6 Resource sharing method for VDES terrestrial and satellite services. Such international cooperation and resource management of VDES communications can be specified as an IALA Guidelines. The major contents of the Guidelines should be as follows:

1. Coverage of land-based stations (control station of communication);
2. Sharing resources among land-based stations (control station of communication);
3. Co-operation between VDE-TER and VDE-SAT; and
4. Cooperation and resource sharing among VDES satellites.

In order to implement the coordination and cooperation of VDES communications, it would be necessary to establish an international body for coordination, resource sharing and management for VDES communications (See Figure 2). Such an international body may consider, establish, and manage protocols for harmonization of scenarios of use and application for VDES terrestrial and satellite communications. The principles of the Guidelines for VDES resource sharing and coordination/cooperation will as follows.

(1) Organizational framework

The international cooperation on VDES resource sharing can be implemented by a body (governmental organizations, NGOs, private sectors) which operates VDES communications. Such a body that wishes to coordinate and cooperate VDES communication should specify the system (e.g., terrestrial stations, satellites) and coordinating methodologies (e.g., roaming or other methods). The guidelines should specify the method and procedures of joining the coordination/cooperation, as well as the obligations of the body to the international cooperation of VDES communication. The Guidelines should also specify the code of operation of the international organization for international cooperation, resource sharing and management for VDES communications.

(2) Technical Methods and procedures of VDES communications for resource sharing among joining organs.

The Guidelines should specify technical methods and procedures of VDES resource sharing that realize the VDES communication exchanges (various usage of VDES based on IALA G1117) among the member of the body. This may include upper layers of protocols of VDES communications based on the ITU-R M2092-1. Such technical consideration and development may require participation of scientists/engineers and take a longer period. However, it also may require a development of onboard satellite system beforehand the implementation of the international cooperation on VDES resource sharing, therefore, the technological methods and procedures of VDES communication for resource sharing should be conducted as soon as possible.

OPRI put forward the proposal above to IALA ENAV Committee at its 28th, 29th and 30th sessions.

ENAV Committee at tis 30th session in September 2022 agreed to add this work item in the work plan of IALA in 2023-2027. The council of IALA in December 2022 endorsed the IALA work plan in 2023-2027. OPRI is now conducting the work item in ENAV Committee.

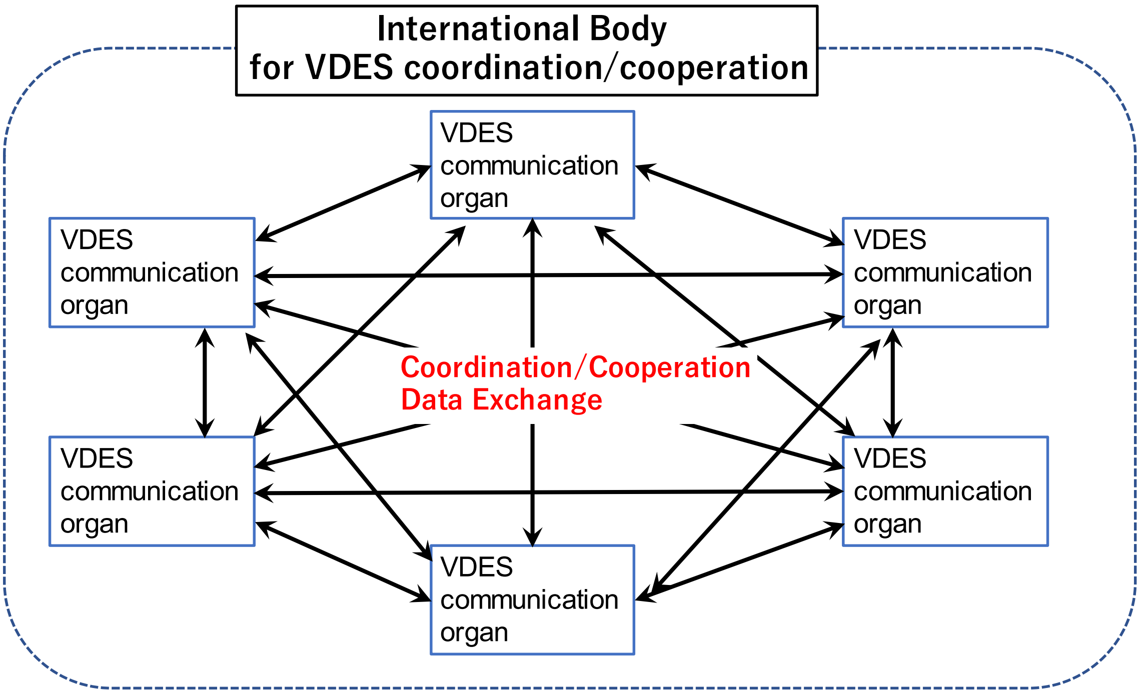

Figure 2: The image of VDES resource sharing and cooperation/coordination

5 CONCLUSIONS

VDES has been recognized as an important radiocommunication system for safety of ships and security of ocean, as well as effective operation of ships and future data-processing industries in the ocean, and it becomes important to secure, reliable and effective VDES communication. In order to liable and effective VDES communication, following issues are indispensable;

- Establishment of international standards on VDES communication in various use cases.
- Establishment of international guidelines on coordination and cooperation on VDES communication.
- Implement secure, reliable and effective VDES communication.

OPRI will further keep its activities for realize the items above.

6 ACKNOWLEDGEMENT

OPRI acknowledges Nippon Foundation for its financial support to the VDES project of OPRI. OPRI also acknowledges IALA for its acceptance to the proposal from OPRI as indicated in paragraph 2 and 4 above.

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S116.9 The present and future development of Skywalker Constellation (216)

Jinhui ZHAO, Vice President of China Head Aerospace Technology Co, China

ABSTRACT

(No paper submitted)

AUTHOR BIOGRAPHY

Jinhui ZHAO, Vice President and shareholder of China Head Aerospace Technology Co., is primarily responsible for the top-level planning, satellite design, and deployment of the Skywalker constellation, as well as product development and satellite application market expansion. He is dedicated to promoting the application of satellite data in various fields, including maritime, offshore meteorological services, water conservation, electricity, agriculture, and other industries.

As the co-founder of China Head, Jinhui has participated in major space projects such as lunar exploration, manned spaceflight, and high-throughput communication satellites. As the general leader, Jinhui led the team to complete the overall design of the Skywalker low-orbit communication satellite constellation and successfully developed and launched a total of five satellites: HEAD-1, HEAD-2A/B/C/D. Currently, Jinhui's main responsibilities include managing the marine applications of the Skywalker constellation and VDES product development.

Index by Conference paper number (paper no. in parentheses)