R-MODE TESTBED IN THE BALTIC SEA

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SUMMARY

The southern part of the Baltic Sea between Germany, Poland, Sweden and Denmark is a challenging area for maritime navigation. Here safe navigation requires reliable positioning and timing information even in times with reduced performance of global navigation satellite systems. This area is characterised by a dense network of IALA beacons and AIS base stations with strongly overlapping service areas. This is a perfect region for the first permanent R(anging)-Mode testbed which utilises both signals-of-opportunity proposed so far.

This paper describes the planned process to setup a transnational R-Mode testbed in the region between Kiel, Rostock (both Germany), Danzig (Poland), Kalmar and Halmstad (both Sweden). Based on the IALA R-Mode road map from 2016 key issues have been identified including the topics of signal design, multipath mitigation, time synchronisation, ranging and positioning. These will be addressed during the time of a three year testbed development process within the project R-Mode Baltic.

RESUME

Le sud de la mer Baltique, entre l'Allemagne, la Pologne, la Suède et le Danemark, est une zone de navigation difficile. Là, une navigation sure demande une information de position et de temps fiable même lorsque la performance des systèmes mondiaux de navigation par satellites est réduite. Cette zone se caractérise par un réseau dense de marques AISM et de stations de base AIS avec de larges zones de recouvrement. C'est l'endroit parfait pour le premier banc d'essai permanent du R-Mode qui utilise les deux opportunités.

Cet article décrit le processus prévu pour le déploiement d'un banc d'essai R-Mode transnational entre Kiel, Rostock (Allemagne), Danzig (Pologne), Kalmar et Halmstad (Suède). Sur la base de la feuille de route R-Mode de l'AISM de 2016 des points clés ont été identifiés, dont la conception du signal, l'atténuation multi-trajets, la synchronisation du temps, la portée et la localisation. Ces points seront traités lors du processus d'élaboration du projet R-Mode Baltique, qui va durer trois ans.

CONTENTS

1. INTRODUCTION

Global Navigation Satellite Systems (GNSS) are today the primary mean for positioning, navigation and timing (PNT) for many maritime operations. GNSS based PNT data are used as an input for different systems e.g. Automatic Identification System (AIS) and position display on Electronic Chart Display and Information System (ECDIS). The worldwide availability and high performance of GNSS makes it such a valuable tool for mariner. But GNSS is vulnerable as it was shown in different studies. Interferences caused by natural sources but also man-made can provoke degradation of service performance and furthermore loss of availability. Therefore, mariners worldwide looking for a system which can support them with sufficient accurate positioning and timing for save completion of begun operations. International bodies, as for example the International Maritime Organization (IMO) and the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) currently strengthen their efforts for more reliable PNT systems.

With Loran-C (and its extension to eLoran) and Chayka today two alternative terrestrial systems exist for positioning and timing which are based on long wave signals broadcasts by chains of well synchronised transmitting stations. But they cover only certain regions because most Loran-C / eLoran stations were shut down until 2015.

R-Mode which uses already available signals-of-opportunity is another approach to implement a terrestrial positioning system. In this case already existing maritime infrastructure will be extended with time synchronisation capabilities and the possibility to transmit R-Mode signals which are modified signals-of-opportunity that allow distance estimation to the transmitter on the user side [1]. Current research activities prove the possible implementations of R-Mode on IALA beacons which provide differential GNSS correction in Medium Frequency (MF) band and on AIS base stations which broadcast maritime safety information in the Very High Frequency (VHF) band. A good overview about the recent status of these activities is given by the paper of Hoppe et al. [2] which will be presented at this conference.

2. BALTIC SEA REGION

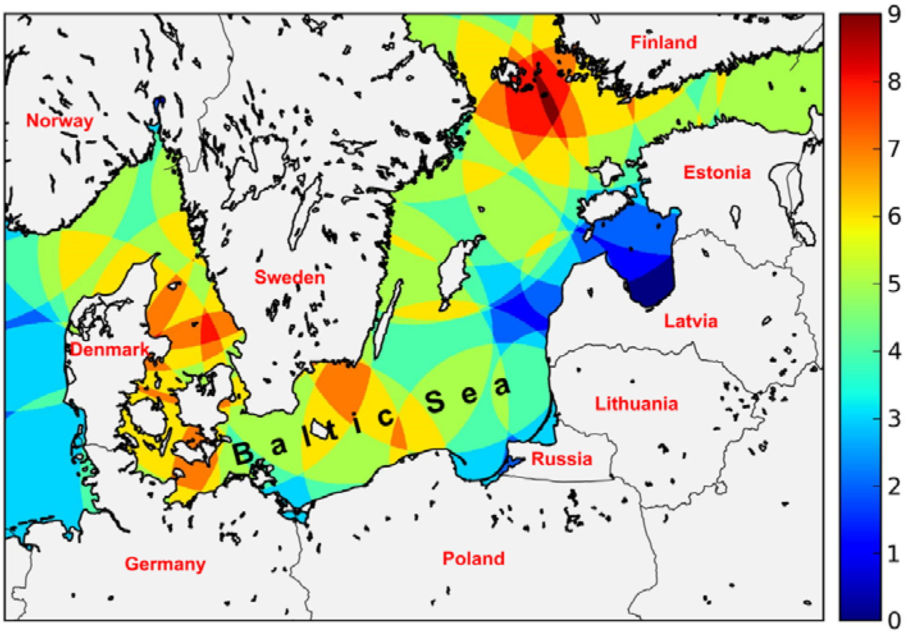
The southern part of the Baltic Sea between Germany, Poland, Sweden and Denmark is a challenging area for maritime navigation due to its high traffic density, crossing waterways, ice in the winter and numerous ports along the coastline. Safe navigation with reliable PNT information is one key challenge to prevent harm to the sensitive ecosystem of this region and disruption of sea traffic caused by grounding or collisions.

Due to the efforts of Baltic Sea countries for safe navigation the coastline of Germany, Poland, Sweden and Denmark is well equipped with IALA beacons and AIS base stations. This is a requirement when using them for a terrestrial backup system because the service area has usually a radius between 100 and 300 km for IALA beacons and less than 100 km for AIS base stations.

To prove the possibility to setup an R-Mode system as backup to GPS some geometric coverage predictions of station service areas were conducted. To solve the equation system for positioning and timing at least four distances to R-Mode transmitters have to be estimated.

Figure 1 shows the result of the coverage prediction of IALA beacon service for the Baltic Sea. The calculation is based on the lists of nominal ranges of the Differential GNSS (DGNSS) stations from the IALA website [3-5] and the current nominal range of 250 km of polish beacons. Here the beacons of all countries were used which signals reach the Baltic Sea. The colours in Figure 1 indicate the number of beacons which should be able to be received. This varies between null in some regions near Latvia and goes up to nine in a region between Sweden and Finland.

Figure 1 - Coverage prediction of IALA beacons in the Baltic Sea region. The colours from blue to red indicate the availability of beacon signals in one location.



In the southern part of the Baltic Sea between Denmark and Sweden in the north, and Germany and Poland in the south the number of available beacons varies between three and seven. Using the Time Of Arrival (TOA) method for R-Mode positioning and timing the reception of four beacon signals would be needed. Insofar except two regions positioning with R-Mode enabled IALA beacons might be possible in large areas of the southern part of Baltic Sea.

The second coverage prediction was conducted for the availability of AIS base station signals of Denmark, Sweden, Germany and Poland (Figure 2). In difference to the IALA beacons transmissions which typically reach the user as a ground wave the AIS signals need direct line of sight conditions for signal reception. Therefore, the size of service area depends on the antenna height of transmitter and receiver. In the coverage prediction it was assumed that the receiving antenna is installed at 10 m above sea level and that as a simplification all AIS base stations transmit their signals omni-directionally. The transmitting antenna heights were provided by the national maritime administrations.

Using the same colour coded number of available AIS base station signals as before Figure 2 shows that the availability of stations varies in the southern part of the Baltic Sea between null and nine. The coastline is usually covered by one to three stations in Poland and East Sweden. The number is higher along the German coastline and highest where Danish, Swedish and German station service areas overlap.

The AIS coverage prediction shows that the R-Mode implementation on current available AIS base stations is not sufficient for the entire southern part of the Baltic Sea not even for the coastline. Additional AIS stations or a combination with IALA beacons are needed to enable the user to receive at least four R-Mode transmitter signals.

A combination of both coverage predictions is shown in Figure 3 for the southern part of the Baltic Sea. The number of available transmitting stations is now at least four along the coastline of Denmark, Sweden, Germany and Poland and also in the Baltic Sea between these four countries. Especially at the westernmost part of the Baltic Sea it goes up to 15. These are sufficient conditions for a positioning system based on IALA beacon and AIS base station signals. In most regions the number is higher than four which means there may be additional transmitter signals available which help to reduce the error of the positioning solution.

Figure 2 - Coverage prediction of AIS base station for a vessel with 10 m antenna height. The colours from blue to red indicate the availability of AIS signals in one location.

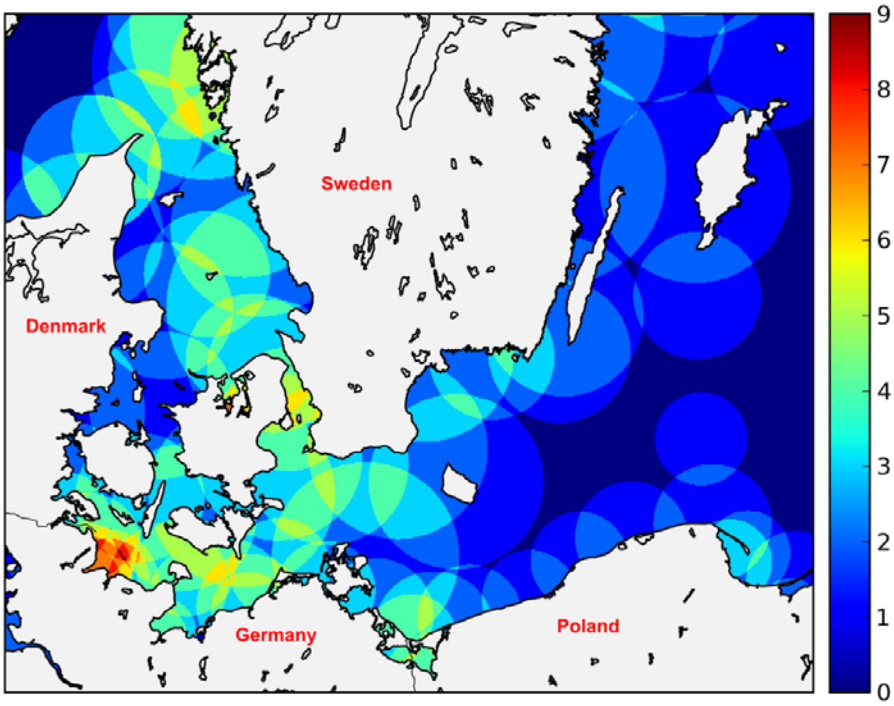
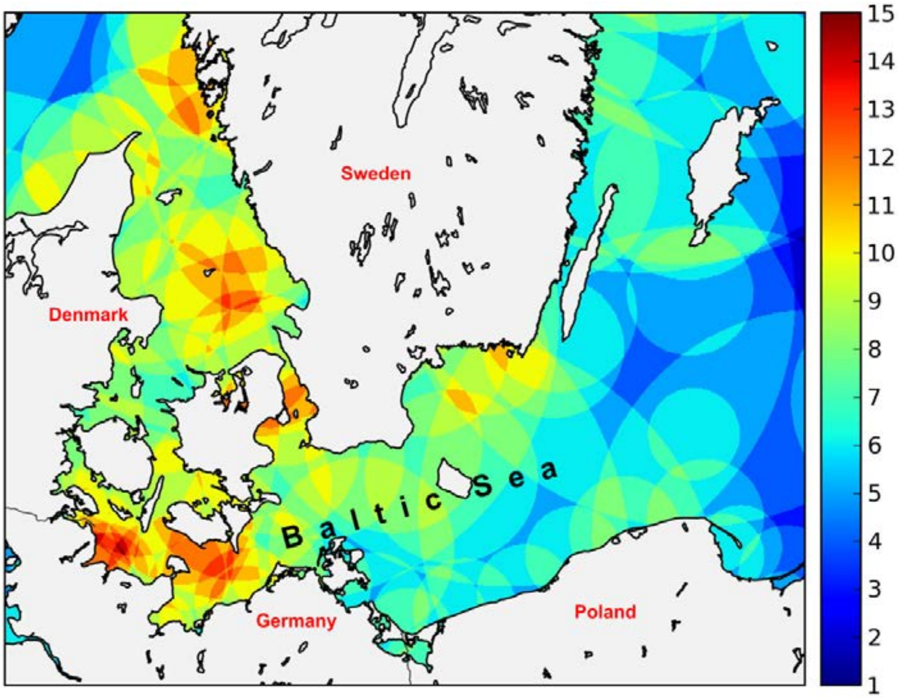


Figure 3 - Coverage prediction of AIS base station for a vessel with 10 m antenna height and IALA beacons. The colours from blue to red indicate the availability of signals for both in one location.



Considering the results of coverage prediction it can be concluded upgrading only IALA beacons or only AIS base stations with signals which enable distance estimation would not allow position estimation in all sensitive areas of the coastal line, port approaches and traffic separation schemes. A combination of both is needed. Furthermore, it can be concluded in some parts of the Baltic Sea only a fraction of stations need an R-Mode upgrade.

The coverage prediction, which is presented here, is only a first step in analysing the expected performance of R-Mode in the Baltic Sea. Further calculations which consider signal propagation, self-fading, atmospheric noise, geometry, receiver threshold limits and the expected accuracy degradation are planned as it was conducted in [2] for the North Sea. The project which will be described in the following will build up an R-Mode testbed in the southern part of the Baltic Sea. It will support mariners with a backup system for challenging maritime operations in this area.

3. PROJECT R-MODE BALTIC

The R-Mode Baltic Project (2017-220), funded from European Union Interreg Baltic Sea Region Programme, are conducted from a transnational team of 12 partners from

- Germany: German Aerospace Center (DLR), Federal Waterways and Shipping Administration, Federal Maritime and Hydrographic Agency, navXperience GmbH,
- Sweden: Swedish Maritime Administration, RISE Research Institutes of Sweden AB, Gutec AB, Saab AB (publ) TransponderTech,
- Poland: Maritime Office in Gdynia, National Institute of Telecommunications, NavSim Poland Ltd. and
- Norway: Kongsberg Seatex AS.

It has the goal to develop and demonstrate a new maritime backup system for PNT purposes. Within the project research will be done on optimal R-Mode signals for range estimation and positioning as well as time synchronisation methods for an R-Mode transmitter that meets the mariner requirements on resilient PNT. Furthermore, solutions for R-Mode transmitter and receiver prototypes and for a testbed concept will be developed.

The R-Mode Baltic project will install and promote the first worldwide operational transnational R-Mode testbed which utilises already existing IALA beacons as well as AIS base stations. As it was shown before the Baltic Sea is an ideal place for this purpose. The high density of IALA beacons and AIS base stations enables testbed installations which cover regions of different navigational phases (open waters, coastal waters, port approach …). It will be shown in the project that the R-Mode receiver for IALA beacon and / or AIS can support mariners with backup functionalities during a voyage from port to port.

There already exist several guidelines, recommendations and standards for IALA beacon and AIS signals and transmitting stations. These are necessary for services and equipment which work together world-wide. They will be recognised in two ways. On the one hand R-Mode development will be done in accordance with these documents so that legacy equipment will not be disturbed by R-Mode signal modifications. On the other hand the modification of the signals (and transmitting stations) will be reported back to standardisation committees so that national maritime administrations all over the world can upgrade their infrastructure with the same R-Mode capabilities. This will help to reduce costs for own developments and ensure compatibility with R-Mode receivers which implement these standards.

In the following a detailed overview about project activities is given. This is structured in four theoretical, three implementation and one standardisation subchapter. All this activities are in accordance with the IALA roadmap for R-Mode developed in 2016 [6].

3.1. TIME SYNCHRONISATION

Sufficient time synchronisation of the transmitting station network is the most important pre-requisite for R-Mode as a method and one of its major performance limitations. Depending on the geometry, synchronisation errors in a set of base stations used for positioning directly convert to user ranging errors of the same order. Thus, the synchronisation requirements can directly be derived from the positioning requirements, e.g. ten meter positioning accuracy roughly translates into sub 30 ns mutual agreement for an average geometry if no other errors sources are considered. However, a budget for such errors, present in any realistic system, must be taken into account and most likely results in tighter synchronisation requirements.

For the above example we can assume that R-Mode network synchronisation must be in the order of 10 ns. With respect to metrological timekeeping this can be considered demanding and necessitates potent local clocks, comparison methods and a rigorous calibration exercise. Further, R-Mode aims to ultimately synchronise to the Coordinated Universal Time (UTC) by means of at least one national UTC(k). Traceability of the R-Mode timing may also be of use to other applications, ashore and on vessels.

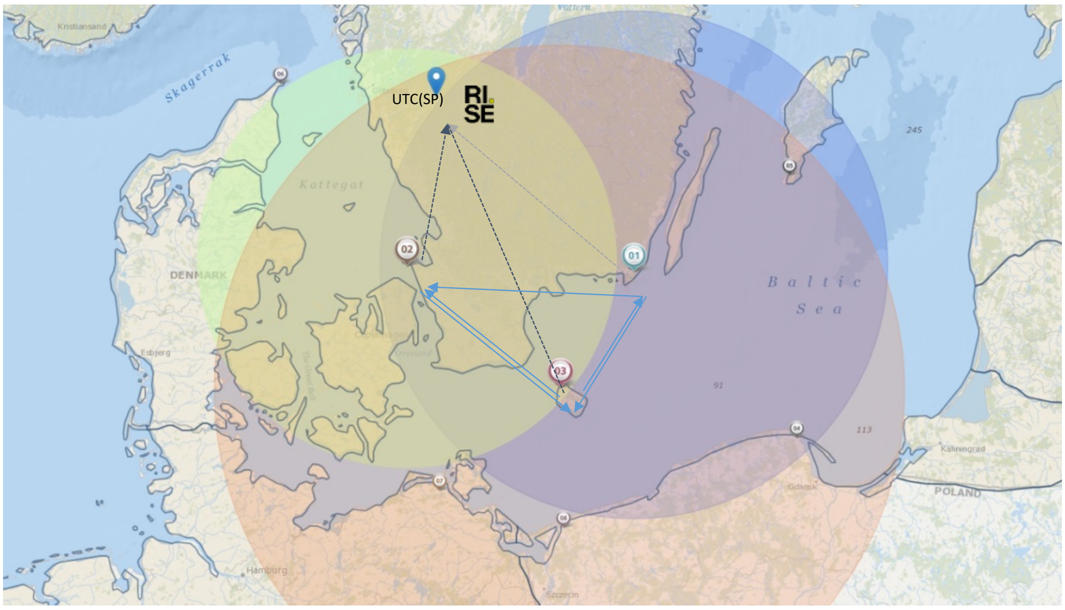
R-Mode Baltic will suggest a limited number of different performance levels that can be met by corresponding general setups. Common to all of them is the optimal utilisation of the time stability of the used local clocks (or redundant clock ensembles) as holdover clocks. A balanced time comparison method shall meet the clock stability for optimal performance. A compliant setup could use atomic Caesium standards (CS) with typical time stabilities of about 1 ns at averaging times of a few hours (TDEV) and can be well matched by a number of techniques, such as different differential GNSS methods or White Rabbit Precise Time Protocol (PTP) on dedicated optical fibres. CS in combination with the latter would be a preferred solution for a resilient R-Mode system with holdover times, in cases of loss of link, of a few days. A more moderate choice would consist of Rubidium based oscillators with TDEV of 10 ns for some hours of averaging. A suitable GNSS independent comparison method could use a passive variant of Two Way Satellite Time and Frequency Transfer (passive TWSTFT), or possibly IEEE1588 PTP distributed in well behaved switched networks.

Apart from classical time transfer methods, R-Mode Baltic will study self-synchronisation using the R-Mode signals themselves (Figure 4). As R-Mode stations often are able to see neighbouring nodes, two-way reciprocal path measurements are suitable to resolve base station clock offsets. This method may be used to establish a chain of synchronisation throughout a network. Possible segmentation, for example due to maintenance, needs to be handled by a secondary method. Total GNSS independence may not always be required or wanted, especially if GNSS is used as a secondary method. Common view with Galileo PRS is for example a feasible option that mitigates a number of the identified threads in the use of GNSS.

State space filtering, such as the use of Kalman filters, is suggested in order to optimally use the local clock stability and to process the link measurements in real-time. The mentioned in-band synchronisation can easily be included in such a clock-link filter, as well as the combination of secondary clock comparisons of possibly different quality and capabilities. The filter and a steering strategy will suggest phase and frequency corrections relative to the local clock that should, preferably, be fed to timescale equipment that generates and distributes corrected physical signals.

UTC traceability shall be obtained by connecting at least one R-Mode node to a National Metrology Institute (NMI) with a UTC(k) realisation using an appropriated method (RISE in Figure 4). In order to maintain proper synchronisation, repeated time calibration of all the nodes in a network is mandatory. In order to be meaningful for ranging and positioning, the geometrical calibration of the R-Mode antenna system (used for the transmission) has to be done and the traceability to a common reference frame (World Geodetic System 1984 (WGS84), International Terrestrial Reference Frame (ITRF)) has to be established. Continuous monitoring of the R-Mode timing is also advised, preferably using independent GNSS common view that presents a metrological standard.

Figure 4 - Overlapping of signal reception can be used to form a self-sustained R-Mode synchronisation network of R-Mode stations. Map created using https://mapmaker.nationalgeographic.org/



It is important that IALA beacon and AIS base station modulators have a standard interface for the timing input. In this case the timing source can easily be exchanged when a new time synchronisation system will be available. In the project the research and development activities will start with a combination of GNSS receiver and rubidium clock as timing source.

3.2. R-MODE IMPLEMENTATION ON IALA BEACONS

IALA beacons are designed to provide DGNSS corrections to the user within their service area of a few hundreds of kilometres. This supports mariners with the ability of positioning of better than 10 metres with a probability of 95% [7] which is needed for sailing in coastal and restricted waters, harbour entrances, harbour approaches and inland waterways [8, 9]. A modification of IALA beacons for R-Mode, which allows transmission of additional ranging information, has to be done without interruption of legacy service. Legacy DGNSS receivers which implement the RTCM (Radio Technical Commission for Maritime Services) standard version 2.3 [10] shall work without performance reduction.

Preceding research and development activities [2, 11] for an R-Mode implementation on IALA beacons, which operates in the maritime Medium Frequency (MF) band of 283.5 to 325 kHz (Region 1 to 3), showed the feasibility of this approach and also gave some first results about constrains. Theoretical analysis could be confirmed which predicts a degradation of distance estimation at night [2]. This is caused by a multipath effect when at night the skywave will be reflected at the E-layer of the ionosphere and interferes with the groundwave which is the main route of radio wave propagation in this frequency band. Within the project different approaches will be proven to identify and mitigate the skywave. This might be feasible because due to the longer propagation path with reflection at the ionosphere compared to the groundwave it has different amplitude and a delay of up to 200 wave lengths.

A second major error component beside the multipath is the different ground conductivity and permittivity of water (fresh, sea, ice) and land (dry, wet) which may depend on current weather conditions. This influences the groundwave propagation of R-Mode signals. For accurate distance estimation the so called Additional Secondary Factors (ASF) have to be measured or modelled and used by the mariner for correct assumption of wave propagation speed. Considering available documents of International Telecommunication Union (ITU) and for low frequency terrestrial positioning systems a concept for MF R-Mode will be developed which considers local effects on wave propagation.

Currently only one implementation of MF R-Mode was tested in reality in which two continuous wave (CW) signals were added to the standard MSK (minimum-shift keying) modulated signal. This approach has some disadvantages when solving the ambiguities while estimating the number of complete wave cycles between the mariner and R-Mode transmitter. Different and more elaborated methods of R-Mode implementation will be investigated to support solving the ambiguity problem. One approach is the usage of a special RTCM message with a known bit pattern.

Beside different options for R-Mode signal design there are different ways to estimate the signal phase or bit timing. Not all of them are real-time capable and also work in dynamic scenarios. To reach the goal of a demonstration R-Mode receiver at the end of the project different approaches for distance estimation will be analysed and tested under realistic conditions.

3.3. R-MODE IMPLEMENTATION ON AIS BASE STATIONS

AIS is a widely deployed and operational system for broadcasting dynamic data of ships. Like many communication systems, AIS defines signal parts, called pilot signals, which are known at the receiver side and originally dedicated for synchronisation and radio propagation channel estimation. Using these pilot signals, signal propagation delay based positioning methods can be applied. Such positioning methods rely on the estimation of the range, i.e. the distance between transmitter and receiver, by measuring the propagation delay of a radio signal between that transmitter and receiver. Our goal is to exploit signals, transmitted within AIS channels for ranging and finally for positioning, as a backup for GNSS.

The AIS has originally been developed for data broadcast. Its performance with respect to synchronisation accuracy is tailored to the requirements of data demodulation at the receiver. However, the signal time of arrival estimation accuracy, which is sufficient for synchronisation in a communication system, is far away from the requirements for ranging and positioning. Ranging accuracy is determined by the bandwidth of the pilot (ranging) signal and its signal-to-noise ratio (SNR) experienced at the receiver. For increasing ranging accuracy, the challenge is to increase bandwidth and energy of the pilot signal, such that constraints on those parameters are met. Constraints arise from different sides. For instance the maximum transmit power and the signal spectrum mask, defined within the AIS standard, must not be exceeded. Increasing the signal bandwidth goes in line with signal modifications. Signal modifications must be kept conform to the standard such that a legacy AIS receiver is still able to receive and demodulate the modified AIS signal. Signal processing and Radio Frequency (RF) hardware may induce further constraints, in particular with respect to signal modifications which for example increase the peak-to-average signal power ratio. In the following a few R-Mode implementation approaches are presented which will be analysed more in detail within the project.

The AIS standard specifies Gaussian Minimum Shift Keying (GMSK) for data modulation. Figure 5 shows the mean power spectrum density (PSD) of a standard AIS signal using GMSK with a transmit (TX) power of 30 dBm. GMSK concentrates signal power at the centre of the spectrum.

In order to increase the signal bandwidth, the transmission of a CW ranging signal within the AIS channel has already been proposed [12]. The corresponding PSD of a CW transmitted for the duration of an AIS slot (26,67 ms) with transmit power 30 dBm is shown in Figure 5. The frequency of the CW is chosen at the local minimum of the AIS signal spectrum.

Figure 6 shows the Cramér-Rao lower bounds (CRLBs) for the ranging error standard deviation of the considered signals. The AIS signal, which concentrates its signal power at the spectrum centre shows a ranging error standard deviation of 32 m at a typical strong input signal level of -75 dBm. Note, the symbol duration of the AIS signal is $\mathrm{T} = 104.17$ µs which corresponds to a symbol length of $\mathrm{T} \cdot \mathrm{c}_0 =$

31.2 km. The ranging error for the AIS signal is still within a small fraction of a symbol, which is sufficient for communication. Transmitting a CW ranging signal provides a significantly higher bandwidth compared to the AIS signal which results in a ranging error standard deviation of 8.8 m approximately. The performance gain when taking into account the AIS signal in addition to the same power level as the CW ranging signal (black dashed graph in Figure 5) is only marginal. The CW ranging signal as shown in Figure 5 provides an effective bandwidth of about 7 kHz.

Figure 5 - Average power spectrum density of AIS with CW ranging signal, both with TX power of 30 dBm.

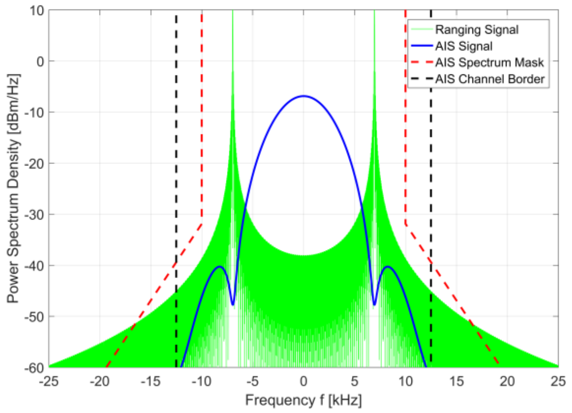
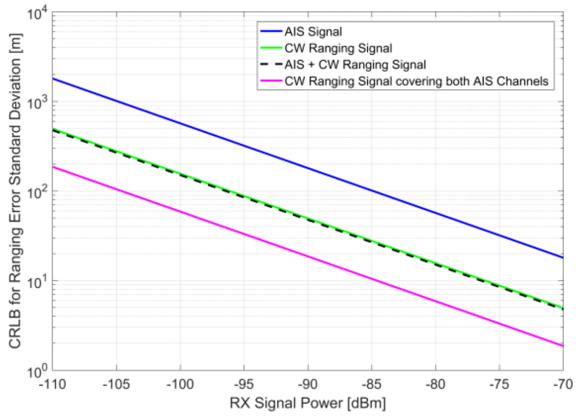


Figure 6 - Cramér-Rao lower bounds for ranging with AIS and CW signals.



For further increasing the effective ranging signal bandwidth, both AIS channels can be exploited for ranging signal transmission. Transmitting a 32 kHz CW signal at a carrier frequency of 162 MHz places the CW signal power at the lower edge of the AIS 1 channel (161.975 MHz) and the upper edge of the AIS 2 channel (162.025 MHz). The increased ranging signal bandwidth improves the ranging performance to a ranging error standard deviation of about 3.3 m at a RX power level of -75 dBm.

The approach described above increases the effective signal bandwidth by simultaneously transmitting a CW signal with the AIS signal itself, thus increasing the range estimation performance. The AIS signal power density, shown in Figure 5, relates to an average GMSK modulated AIS signal. Compared to the average signal, a binary sequence optimized for ranging, maximises the effective signal bandwidth of the corresponding GMSK signal. This approach is addressed in [12]. In [13] the authors design training sequences for burst mode CPM, in particular GMSK. The proposed design aims in optimising symbol timing estimation, which corresponds to range estimation. Accordingly, using an optimised sequence promises a reduction of the ranging error by a factor of ≈ 1.6 (2 dB) compared to the average case, i.e. using a random training sequence.

The use of the AIS carrier itself promises performance improvements of several orders of magnitude. However, the challenge here is to resolve ambiguities arising as multiples of the carrier wavelength of approximately 185 cm. The CRLBs in Figure 6 provide a first indication about the expectable ranging performances. Combatting impairments due to hardware imperfections or the optimisation of the CW ranging signal superimposed to the AIS signal subject to constraints mentioned above are parts of further work towards a maritime backup navigation system.

In the busiest ports of the world the AIS channel load is at the limit. Insofar a limitation exists when additional AIS messages for R-Mode should be transmitted. This may cause that it is not possible to meet the user needs for a backup system. Therefore other solutions need to be analysed as well. One of those is the utilisation of the VDES system which provides up to four times greater symbol rate than the AIS. For this reason, the applicability of the VDES will be discussed and the future VDES signals will be considered for R-Mode ranging.

Furthermore, advanced correlation techniques, bit edge detection and significant oversampling of the AIS signal in the receiver will be considered.

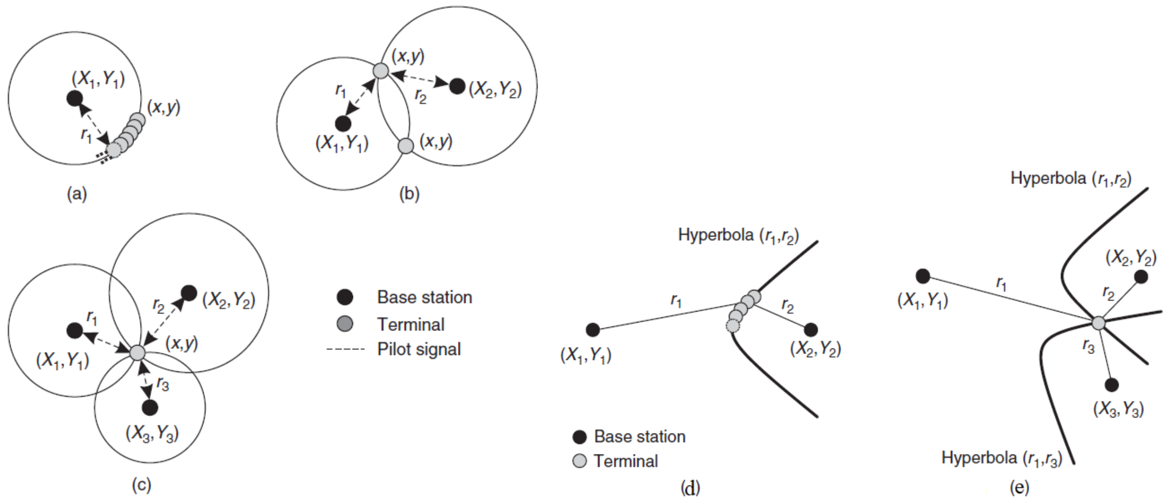
3.4. POSITIONING

One of the main topics of the R-Mode project is positioning. The application of one of the two methods of determining the position, TOA (Time Of Arrival) or TDOA (Time Difference Of Arrival), is considered in the project based on the assessment of the accuracy and precision of these algorithms. Both techniques use measured time (or time difference) of the radio signal propagation between the terminal and base stations (used to compile a system of nonlinear equations for calculating the target's position). In both cases, the range or the range difference between the target and at least three base stations is needed to obtain the 2D position. If positioning is based on range measurements, the position fix is calculated by circular lateration, while range differences form the basis for hyperbolic lateration. Regardless of which method is used, these measurements are always subject to errors, and hence the resulting values are often denoted as pseudoranges, which differ from the true range according to a certain error potential.

For circular lateration the range between a terminal and a single base station limits the target's position to a circle around the base station, with the range being the radius of the circle (Figure 7a). If the range to an additional base station is taken into account, then the target's position can be further reduced to the two points where both circles intersect (Figure 7b). The range to a third base station then finally leads to an unambiguous position of the target (Figure 7c).

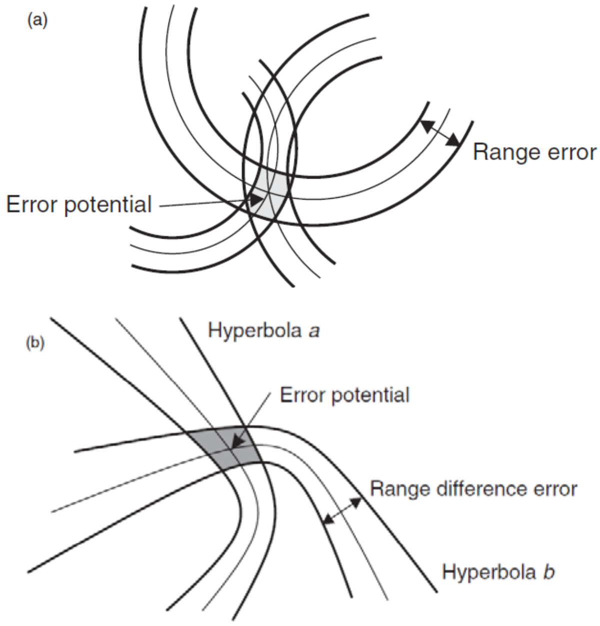
Instead of determining the absolute range, hyperbolic lateration is based on range differences. A hyperbola is defined to be the set of all points for which the difference in the range to two fixed points is constant. These fixed points are denoted as foci, and, in the special case of positioning, are given by two base stations. The range to the first base station is given by r1, and the range to the second one by r2. The difference r2 − r1 now limits the target's position to a hyperbola as shown in Figure 1d. If the range difference is determined for another pair of base stations, for example, to the second and third one, an additional hyperbola is created, and the intersection of both then delivers the target's 2D position (Figure 7e).

Figure 7 - Circular lateration (a, b, c) and hyperbolic lateration (d, e) 2D solution [14]



In practice, the circles or hyperbolas do not intersect at a certain point, but span an area of some size, which depends on the degree of accuracy of range measurements. Figure 8 shows the error potential that results from inaccurate range measurements and limits the accuracy of the position fix.

Figure 8 - Error potential of circular lateration (a) and hyperbolic lateration (b) [14]



At this point, it should be observed that the TDOA method has some advantages over the TOA method. As mentioned above in TDOA the difference of the propagation times is measured rather than the actual propagation time (as in TOA). This fact has two consequences:

- First of all, the differential measurement in TDOA allows minimising the impact of some of the phenomena which occur in the radio channel (including refraction or multipath effects) that potentially might negatively affect the positioning accuracy and reliability. It translates into a better performance of the method.
- Secondly, in TDOA it is not required to obtain a full time synchronisation of the base station's clocks with the mobile terminal's clock and to calculate the clock error in the mobile terminals. Only the time synchronisation of the base stations is needed. This reduces the requirements on the mobile terminal hardware.

Notwithstanding the above, it should also be observed that in existing positioning systems, the TOA method is currently more prevalent. The final selection of one of these methods (TDOA vs. TOA) will depend on many factors and will require a thorough discussion and analysis (theoretical and practical – using simulations). This will include an assessment on how the potential sources of errors affect the R-Mode system's performance and reliability.

3.5. R-MODE TESTBED IMPLEMENTATION

The project R-Mode Baltic has started with an analysis of already available documents regarding the specification of user needs for a backup system. Based on this analysis requirements for the R-Mode system will be derived which will be used as an input for the four research activities of time synchronisation, signal design and positioning method but also for the implementation of a testbed. Latter should enable to prove the feasibility of R-Mode fulfilling the user requirements on a maritime backup system. Furthermore, the testbed shall be as realistic as possible and include shore-side transmitting stations and receivers on board ships travelling in the Baltic Sea. Both R-Mode enabling transmitting equipment and R-Mode receivers will be developed within the project.

The testbed will be based on the IALA e-Navigation Guideline 1107 "Planning and Reporting of e-Navigation Testbeds" and will be published on the IALA website for e-Navigation Test Beds/Projects.

In order to realise a good testbed, the most suitable places for tests with respect to practical tests with ships and best geometry of transmitting stations must be found. This includes a survey of available AIS and MF stations around the Baltic Sea which are situated in partner countries or countries that are members of the project advisory board. Data for each suitable station must be obtained to continue with a deeper analysis. Every station shall be analysed with respect to coverage and availability, but also analysed with respect to practical issues like maintenance etc. A coverage prediction of AIS and MF stations for the Baltic Sea will support selection of a testbed area and stations, which have to be upgraded, considering constrains of predicted and required accuracy.

All transmitting shore-side stations are existing and operating as AIS or DGNSS stations, and are included in respective nations monitoring organisation. Further, the transmitting stations shall be monitored with respect to R-Mode function which must be added to the ordinary monitoring. There will also be specific R-Mode far-field monitors in the same fashion as the far-field monitors in the DGNSS. They will continuously monitor the R-Mode signals during the different trails.

The tests will be planned by writing a test plan for the campaign. Each test campaign will then be further detailed in a test specification where each individual test will be explained with reference to requirements and how it will be fulfilled.

The different tests to be performed can be divided into two main parts: static and dynamic. The static tests will be performed with fixed receivers at a specific place (with precisely surveyed positions) during a long period to validate basic distance measurements.

The dynamic tests will be performed by receivers mounted on moving targets at sea and possibly also on land. The sea trials can further be divided into three possible parts. First, receivers can be placed on ordinary ferries travelling between countries in the Baltic Sea during their daily route. Secondly, receivers can be placed on ships operating in a specific area closer to the coast, e.g. pilot boats. Thirdly, dedicated routes will be performed solely to test the R-mode receivers.

Data will be collected during the campaign for analysis of the performance of the R-mode technique and ultimately prove the capability of R-mode as a terrestrial back-up system for navigation.

3.6. HARDWARE DEVELOPMENT

3.6.1. R-MODE RECEIVER

The development of the R-Mode receivers will be conducted based on existing GNSS receiver technology of project partners. They will use only the MF signal or in a second device MF and VHF signals for positioning.

The MF-VHF version will utilise an existing GNSS receiver as a controller for a set of MF and VHF receivers. A second GNSS receiver in the same setup may be used for getting reference GNSS measurements. These two receivers can share the same Temperature Compensated Crystal Oscillator (TCXO), as the receiver has provisions for oscillator signal sharing.

Furthermore, it is planned to perform Direct Sampling (DS) and Digital Signal Processing (DSP) of the MF signal. The front end to the antenna may encompass different gain stages, filters and possibly a power supply to a MF antenna Low Noise Amplifier (LNA) located on the antenna. For the VHF receiver it is planned to use one Intermediary Frequency (IF) in a super heterodyne configuration with at least one digital IF and a final down conversion by DSP.

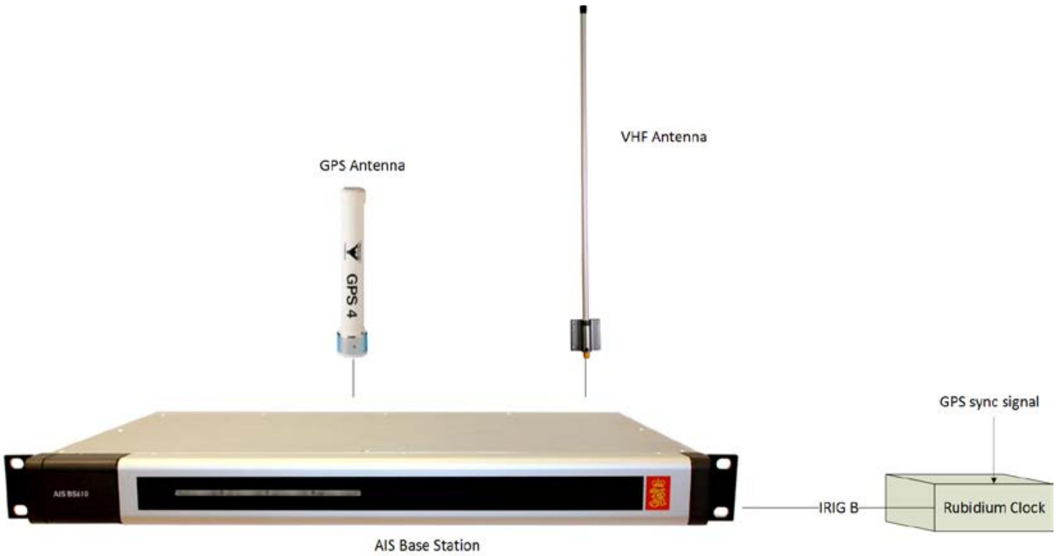
As described above the hardware of a GNSS receiver will be used for the control and as an interface for other instruments in the R-Mode measurement setup. If this assumption proves impractical dedicated hardware based on Field Programmable Gate Arrays (FPGA) and embedded computers will be used to perform that task.

3.6.2. AIS BASE STATION

The foundation for R-Mode implementation using AIS base stations is described in the ACCEAS project report [12]. To find a favourable solution it is important to keep the add-on cost for the R-Mode functionality within reasonable limits for the authorities. The maximum GNSS drop-out periods will be defined in the R-Mode requirement study of the project, where R-Mode shall take over is expected to be within the working area of a Rubidium clock. The AIS base station standard [15] has defined an optional timing interface; Inter-range instrumentation group, or IRIG B in short, which is a commonly known format for transferring timing information between devices. The AIS base station and the Rubidium clock will use the IRIG B format to communicate accurate timing information (Figure 9). The Rubidium clock will be synchronised with GPS time when the GNSS signal is available and hence will be able to deliver precise timing when the GNSS receiver in the AIS base station is experiencing drop outs. The Rubidium clock will deliver the timing information enabling the base station to transmit the R-Mode signal, which the R-Mode equipped vessels will use for their PNT calculation. It is suggested to use AIS message 26 to provide the AIS R-Mode signal.

Only providing a Rubidium clock in addition to the AIS base station is expected to be a cost-effective implementation of an R-Mode positioning station. The approach is expected to be found favourable by authorities on national level.

Figure 9 - Setup R-Mode enabled AIS base station



3.7. R-MODE APPLICATIONS

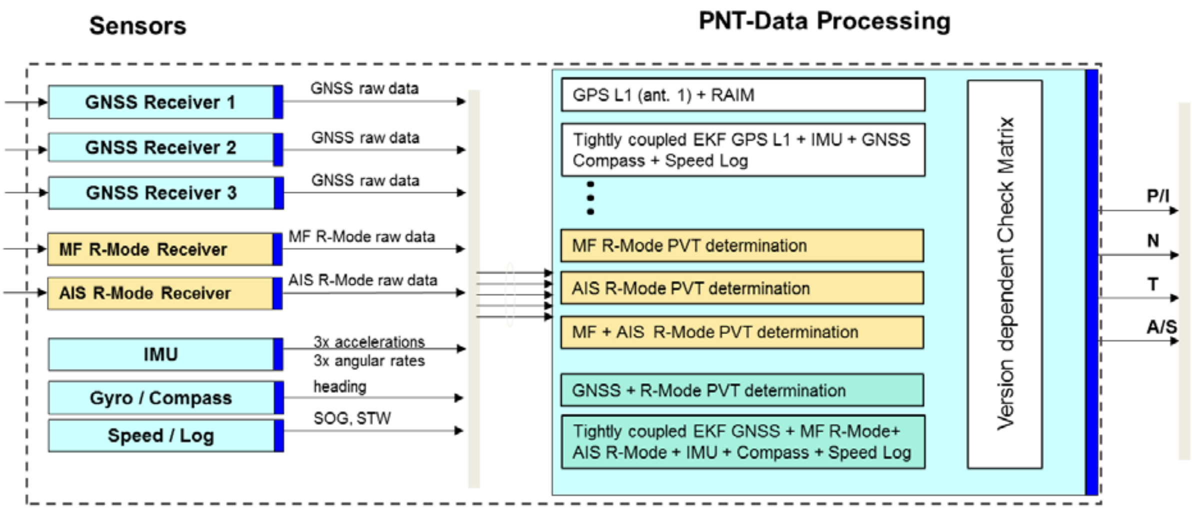
3.7.1. R-MODE INTEGRATION IN PNT DATA PROCESSING PROTOTYPE

In order to enable future on-board R-Mode applications, in a first step R-Mode based positioning will be implemented in a prototype of a PNT Data Processing unit. This prototype has been developed by the DLR in order to provide a technological basis for the standardisation activities at the IMO (see section 3.8.1). The existing prototype will be expanded by new raw data interfaces to a MF and AIS R-Mode receiver and by the implementation of three new processing channels (Figure 10). These include MF / AIS R-Mode positioning and combined MF+AIS positioning. In a first simple approach, the difference of the antenna positions between the MF and the AIS antenna will be ignored. In a second step, the ships' own Consistent Common Reference system (CCRS) based at least on the ships heading (delivered e.g. by the Gyro Compass) will be used in order to properly compensate for the different antenna positions on the vessel. While the position information is the most important information determined with R-Mode, furthermore also the ship velocity (speed over ground (SOG) and course over ground (COG)) might be determined independently by the R-Mode on-board system. Therefore this could by checked in a second step.

The approach of implementing R-Mode in the PNT Data Processing prototype enables in the future also the combined usage of GNSS and R-Mode for positioning applications. In this approach R-Mode measurements can also be used if measurements of less than four stations are available and an independent R-Mode positioning is not possible. The main advantage of using R-Mode together with GNSS will be the improvement of the position integrity.

In a next step R-Mode could also be used in a multi-sensor scheme together with GNSS, IMU, speed log and Gyro Compass. This scheme would allow positioning during GNSS outages even with less than four R-Mode measurements.

Figure 10 - Realisation of PNT Data Processing prototype (white: existing processing channels, orange: new processing channels, to be developed in R-Mode Baltic project, green: possible further processing channels)



3.7.2. R-Mode PPU

With the advent of new e-Navigation products and solutions, marine pilots around the world now routinely equip themselves with specialised decision support tools that integrate and display critical information from these recent technology innovations. One of the most commonly used tools is the portable pilot unit (PPU), which usually consists of two elements: hardware and software. On the hardware end, pilots use purpose-built GNSS receivers with enhanced functionalities (e.g. support for Real-Time Kinematic differential correction), built-in rate of turn generator (ROTG), independent heading and AIS receiver. The Electronic Charting System (ECS) software parses and integrates these data to provide pilots with accurate, real time and predictive navigation information, including distance to docking lines, approach angles and speeds, and movement parameters of other vessels.

Similar to other PNT devices, PPU's hardware relies entirely on GNSS infrastructure for determining position fix. One of the deliverables of the R-Mode project is a PPU with R-Mode support. Toward this end it is planned to construct a PPU with integrated R-Mode module ("R-Mode PPU", Figure 11).

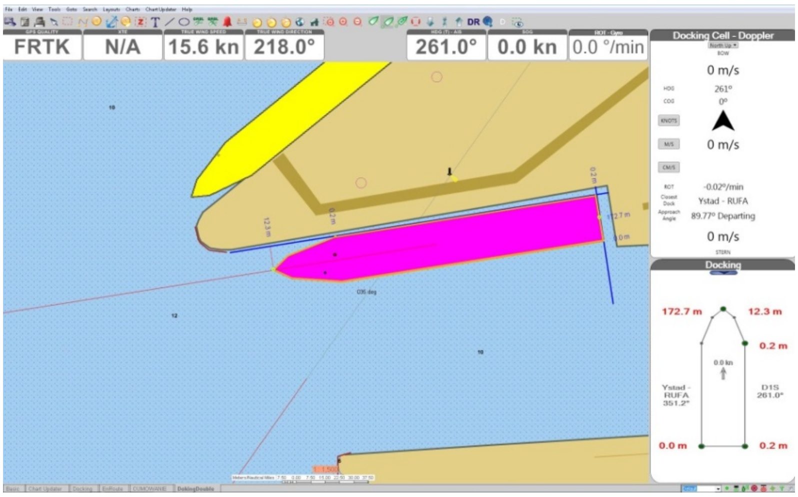
The R-Mode PPU will operate as an "all-in-one" unit, with all hardware components enclosed in one portable pilot box. The R-Mode PPU hardware will provide the pilots with crucial positioning, navigation and timing information, including independent heading (HDT) at 0.1° resolution, rate of turn (ROT) at 0.07°/minute resolution and AIS feeds. As a result of the built-in support for Real-Time Kinematic, the R-Mode PPU will offer a sub-centimetre positioning accuracy.

Figure 11 - Visualisation of the R-Mode PPU demonstrator. R-Mode PPU will be equipped with an integrated R-Mode receiver. The R-Mode receiver will be mounted in a dedicated socket on the PPU motherboard controller.

However, whenever GNSS signal is lost or degraded, the R-Mode PPU will switch to R-Mode operational mode. The integrated R-Mode module will be responsible for determining position fix and other navigation data (e.g. COG, SOG). The R-Mode PPU will also provide the pilot with information (displaying a relevant notification on the PPU screen) regarding the positioning mode currently in use (Figure 12).

The final objective of this deliverable is to develop a fully-functional PPU demonstration prototype which will seamlessly switch between GNSS and R-Mode operational mode (and vice versa) as required. The basic functionality of the PPU -- i.e. providing pilots with dynamic real-time voyage data and enhanced situational awareness – will be preserved for both operational modes.

Figure 12 - Argus 3.0 PPU software by NavSim – docking view. R-Mode will provide position fix, SOG, COG and other PNT data for pilots in the Baltic Sea testbed. This will include Port of Ystad (Sweden) depicted in the ENC.



3.8. STANDARDISATION

MF radio beacons and AIS base stations following several international standards as provided from IMO, ITU as well as recommendations and guidelines developed from IALA. Therefore the implementation of R-Mode signals on MF beacon sites and AIS shore installations require the change and extension of the existing standards as shown in Figure 13.

One important aim of the R-Mode Baltic is to forward and communicate findings which have impact on standardisation to the various standardisation committees. The involved partners are well connected to the various standardisation groups. Thus the project is able to cover all required standardisation domains.

Figure 13 - Overview of R-Mode related standardisation activities

Analyzation of existing standards, proposed changes or draft new standards should be provided at least in the following domains:

On-board [IMO, IEC, RTCM, etc.]	Radio link [ITU]	Shore Site [IALA]
• Performance Standards • Performance Requirem. • Test and Type approval • Output data protocols (61162) • Input data protocols for ASF, dR-Mode, Timing, etc.	• Standard for DGNSS transmissions in radio beacon band ITU-R M.823-3 • Standard for AIS in the VHF Band ITU-R M.1371-5	• Recommendations (e.g. R-121, R135, R-129, etc. • Guidelines (1112) • New R-Mode Guideline

3.8.1. On-board standardisation

Since 1974 the UN/ IMO SoLaS (Safety of Life at Sea) convention and its amendments enforce the carriage requirements on minimum equipment needed for safe voyage at sea. Currently any vessel operated under SoLaS is required to carry at least one electronic position fixing system (EPFS). The minimum performance of this system is described in IMO minimum Performance Standards. These standards are available for single GNSS like GPS, Galileo, GLONASS and BeiDou as well as for combined GPS/GLONASS.

IMO Resolution A.1046 [9] details the requirements for worldwide radio navigation systems considering vessels operating in ocean and harbour entrances, harbour approaches and coastal waters.

A stand-alone fully operational R-Mode receiver would need to comply with the above stated values at any time within R-Mode reception area. The R-Mode system will be a regional offered service unlike the GNSS. Depending on the different levels of R-Mode realisation, the R-Mode capability varies from simple augmentation service to fully operational, GNSS independent EPFS. If the R-Mode Baltic project demonstrates the usability of the R-Mode technology according to the requirements in general, two ways of R-Mode inauguration are to be considered. The first approach would be the development of an R-Mode performance standard within IMO, just as those already in force for GNSS. This implies an R-Mode development as stand-alone EPFS.

The second approach would be an open approach making use of the latest developments on the Multi-System Radionavigation Receiver (MSR). An integration of R-Mode capability into the MSR as a terrestrial component does not rely on fully stand-alone R-Mode capability and enables the exploitation of any kind of R-Mode signals at least for integrity calculations.

Furthermore IMO opened up a new path towards major improvements in accuracy, availability, continuity and integrity by the inauguration of the new performance standard for Multi-System

Radionavigation Receivers (MSR) [16] and the associated GUIDELINES FOR SHIPBORNE POSITION, NAVIGATION AND TIMING (PNT) DATA PROCESSING [17]. As a direct follow-up on the identified gap of missing resilient PNT data, as pointed out by IMO's e-Navigation strategy reports, the new possibilities described in the above mentioned IMO publications can be used to introduce new integrity concepts as well as improvements on redundancy in systems by making use of yet to come terrestrial services like the R-Mode.

One of the main goals of the R-Mode Baltic project is to provide input to the appropriate standardisation organisations for future on-board R-Mode receiver equipment (see Table 1).

Standardisation organisation	Standardisation topic
IMO	- R-Mode specific performance standard
IEC	- Operational and performance requirements, methods of testing and required test results - Output data protocols (61162 series)
RTCM	- Radio link messages (e.g. corrections for propagation, timing, etc.)

Table 1 - Planned input to standardisation organisations for on-board equipment

3.8.2. Radio link standardisation

R-Mode aims to add time synchronisation based on existing maritime radio systems. The options investigated within the R-mode Baltic project are the MF radio beacon system and the AIS shore infrastructure using VHF transmissions.

The various methods to implement a timing signal on these radio services are investigated in the ACCSEAS feasibility study [11, 12]. One of the main requirements for the selection of the used methods was to reduce the impact on the existing radio communication standards. Nevertheless the adding of timing information may have an impact on the existing international radio standards provided by ITU.

The R-Mode Baltic project aims to provide appropriate input regarding amendments or changes of adding an R-Mode timing signal on MF- and VHF-transmissions. Thus input to ITU-R standardisation could be foreseen in the following domains (see Table 2)

ITU standard	Standardisation topic
ITU-R M.823	- Standard for DGNSS transmissions in radio beacon band ITU-R M.823-3
ITU-R M.1371	- Standard for AIS in the VHF Band ITU-R M.1371-5
ITU-R M.2092-0	- Technical characteristics for a VHF data exchange system in the VHF maritime mobile band

Table 2 - Planned input for ITU standards

3.8.3. Shore site standardisation

The above mentioned candidate R-Mode systems (MF radio beacon and AIS/VDES) are typically operated by national maritime administrations. Recommendations and Guidelines to implement and operate such shore site systems are developed by the IALA in its appropriate committees.

For the development and operation of the R-Mode concepts IALA is well positioned to provide the required international coordination and standardisation. The IALA ENAV Committee considered this in 2016 and prepared a list of actions [6] which would need to be addressed for R-Mode (MF and AIS) to become fully developed and approved.

IALA is also well placed to document the specification and technical characteristics for R-Mode, including how any system should be developed, maintained and operated going forward. Work on this has already started and a guideline on R-Mode MF is due to be developed during the next work programme, capturing all relevant developments and key questions, as they emerge.

The R-Mode Baltic Project will closely cooperate with IALA and will provide appropriate input to support the coordination of the world wide R-Mode activities in various test beds as well as input to future R-Mode related recommendations and guidelines.

4. CONCLUSION

The maritime world is looking for a backup system for GNSS which can provide positioning and timing information in times with reduced GNSS performance. R-Mode which utilises already existing maritime infrastructure of IALA beacons and AIS base stations could form a transnational network of synchronised transmitting stations for ranging signals. Especially in the southern part of the Baltic Sea the high density of both station types and the strong overlap of station service areas promises good positioning capabilities if a sufficient number of stations will be enabled for R-Mode.

The project R-Mode Baltic with its team of research institutions, national maritime administrations and private companies will setup an R-Mode testbed in the Baltic Sea. It will cover an area where typical navigational phases from sailing through open waters to passing harbour entrances are conducted and a sufficient number of IALA beacons and AIS base stations is available which could be R-Mode enabled. Methods and concepts for time synchronisation, signal design and positioning will be analysed and selected for implementation so that they meet the maritime user requirements. Necessary transmitting and receiving hardware components and two R-Mode applications will be developed and demonstrated at the end of the project.

The R-Mode development affects several guidelines, recommendations and standards of different standardisation organisations. These have to be adapted before R-Mode can be a backup system along the major shipping routes which connect countries of different continents. Due to limitation in the size of the transmitting station service area R-Mode will never reach the coverage of GNSS.

5. ACKNOWLEDGEMENT

The project team thanks the members of the project advisory board for their support. Furthermore, we thank the European Union for funding the project through the European Regional Development Fund within the Interreg Baltic Sea Region Programme.

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