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| IALA Guideline |

1234

R-Mode - Aims, technical approach and current status.

Edition 1.0

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Revisions to this IALA Document are to be noted in the table prior to the issue of a revised document.

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# INTRODUCTION

The need for resilient positioning, navigation and time (PNT) data has been well documented [1]. Systems such as AIS (Automatic Identification System), ECDIS (Electronic Chart Display and Information System), ARPA (Automatic Radar Plotting Aid) and other navigation sensors use GNSS derived PNT data, the reception of which can be denied through natural and man-made interference.

In the near future further GNSS will become operational (Galileo and BeiDou) which will further increase the number of available satellite signals. However, these all GNSS share similar signal structures, frequency bands and low signal power levels, and therefore have a common vulnerability to signal interference; and the development of an alternative backup system is recommended.

R-Mode (Ranging Mode) is a proposed terrestrial backup navigation system, independent to GNSS, which uses ranging signals typically transmitted from existing maritime infrastructure, for example, medium frequency (MF) radio beacons and/or AIS base stations.

This Guideline provides a review of the current view of R-Mode operation, specification, hardware and software and provides a review of its current development. It is envisaged that this Guideline will be updated at key intervals and used to track progress of R-Mode development. It is provided as a living document detailing the current situation to allow other interested parties to participate in the development of R-Mode without having to start from the beginning. Interested parties interested in assisting in the development of R-Mode are invited to liaise with the IALA ENAV WG5 vice Chair, Mr Michael Hoppe (contact details provided in Section 14).

# Scope

The aim of this guideline is to capture the current considerations for R-Mode to enable the widest possible support in its development. Publication of the plans, activities and technical considerations should allow for collaboration and a cohesive development, in an open and unrestricted manner.

# Background

Adding additional ranging mode (R-Mode) information to existing maritime infrastructure is appealing as much of the hardware is already in place, removing the need to procure and install expensive transmitters and antenna systems. The system is already standardised and frequencies assured for maritime navigation. In addition, marine radiobeacons are already installed along most major shipping routes as shown in Figure 1.

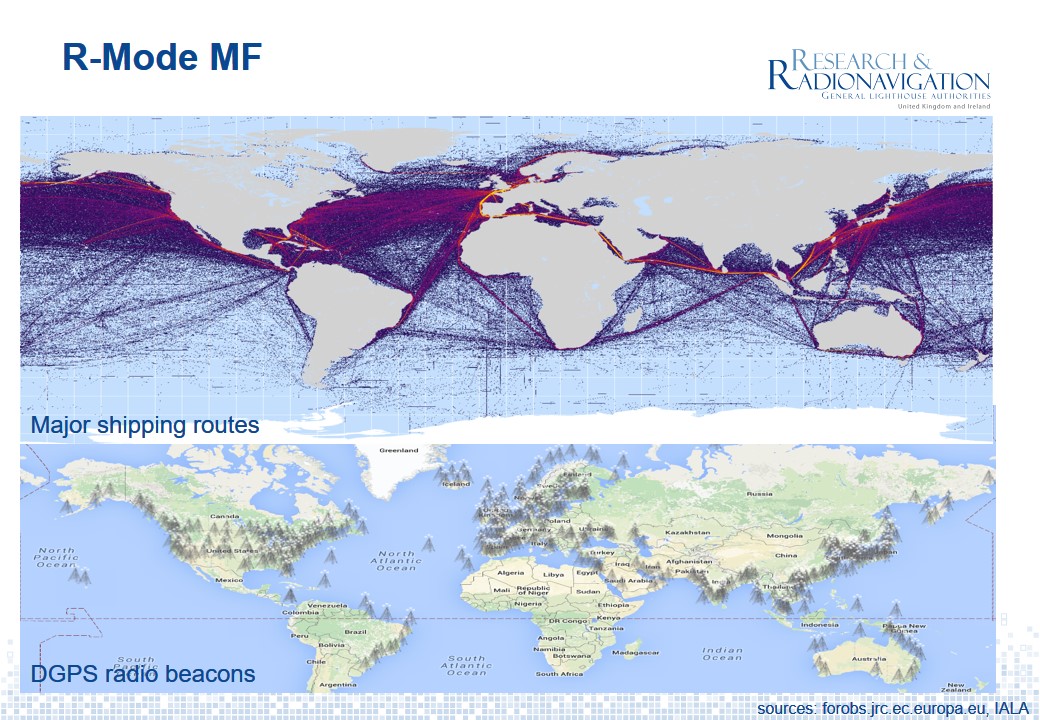


Figure 1: Image of the major shipping routes identified though AIS tracks (Top) and the location of marine radiobeacons (Bottom) showing good alignment of services [source forobs.jrc.ec.europa.eu & IALA]

AIS base stations have also been installed in significant numbers around many coastlines, have protected frequencies and already serve the mariner; and therefore are a good candidate for R-Mode transmissions.

## ACCSEAS

The European collaborative project ACCSEAS developed the idea of R-Mode by supporting a feasibility study which considered the suitability of adding ranging information to marine radiobeacon DGNSS and AIS base stations.

The ACCSEAS feasibility study was split into the following parts:

* Parts 1 and 2 examined the R-Mode potential of the MF DGNSS signal [2, 3]; the recommended approach was to add CW signals to the broadcast and to develop the pseudorange from the carrier phase.
* Part 3 and 4 examined the R-Mode potential of the AIS signal [4, 5]; the recommended approach was to estimate the pseudorange from timing bit transitions and requires no modification to the signal structure.
* Part 5 examined the combination of MF transmission together with AIS and the combination with eLoran which at that provided time operated from 5 stations around the North Sea area [6].

The performance assessments for each of the three signal types outlined above were considered in the feasibility study, and the lower bounds of the expected positioning accuracy were calculated, based on conservative assessments.

As the position is calculated through trilateration from terrestrial transmitters, the resulting performance is a function of the received signal power, the observation time of the receiver (nominally assumed to be 5 seconds), and the geometry of the known transmitter locations. For each signal considered, sources of error were considered where possible, however errors such as unknown offsets in the synchronization of transmitters (this is relevant to all three signals) and propagation delays that would increase the observed range estimates (this is known to impact both MF and eLoran signals since they propagate as ground waves) were omitted.

The ACCSESS project concluded in 2015, and the project information remains available on the project website [www.accseas.eu] with the project deliverable reports available on the IALA website, within the e-Navigation test bed area.

# R-Mode MF

Marine radiobeacon transmissions are configured to provide signals over large geographical areas and are well distributed around the northern hemisphere and parts of the southern hemisphere.

The ACCSEAS feasibility study considered a number of possible methods of adding a ranging signal to the existing marine beacon system. The different options considered are outlined in the ACCSEAS feasibility study [1, 2], from which the approach outlined in section 2.1.3 was selected as the optimum solution at this time.

The selected approach was the maintain the existing MSK signal for legacy users, but to add two continuous wave transmissions to the band, one above and one below the central frequency. The separation of the two CW signals allows for a carrier phase type solution to be performed in order to estimate the accuracy. In addition, the MSK signal may be used to provide other information to the receiver, and may be used in the future to help resolve any ambiguities.

The ACCSEAS report suggests the two CW signals are positioned ±250Hz with respect to the center frequency, however this has been amended to ±225Hz to prevent overlap of CW signals between neighboring (in terms of frequency) stations.

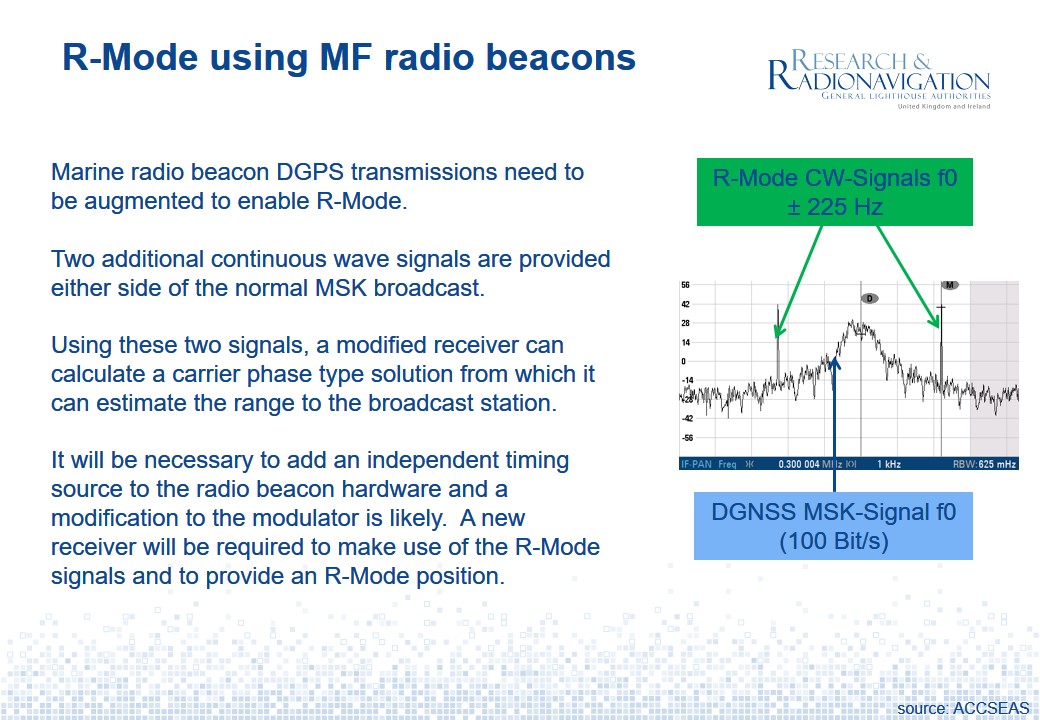


Figure 2: R-Mode spectral plot showing the two additional CW signals and the legacy MSK .

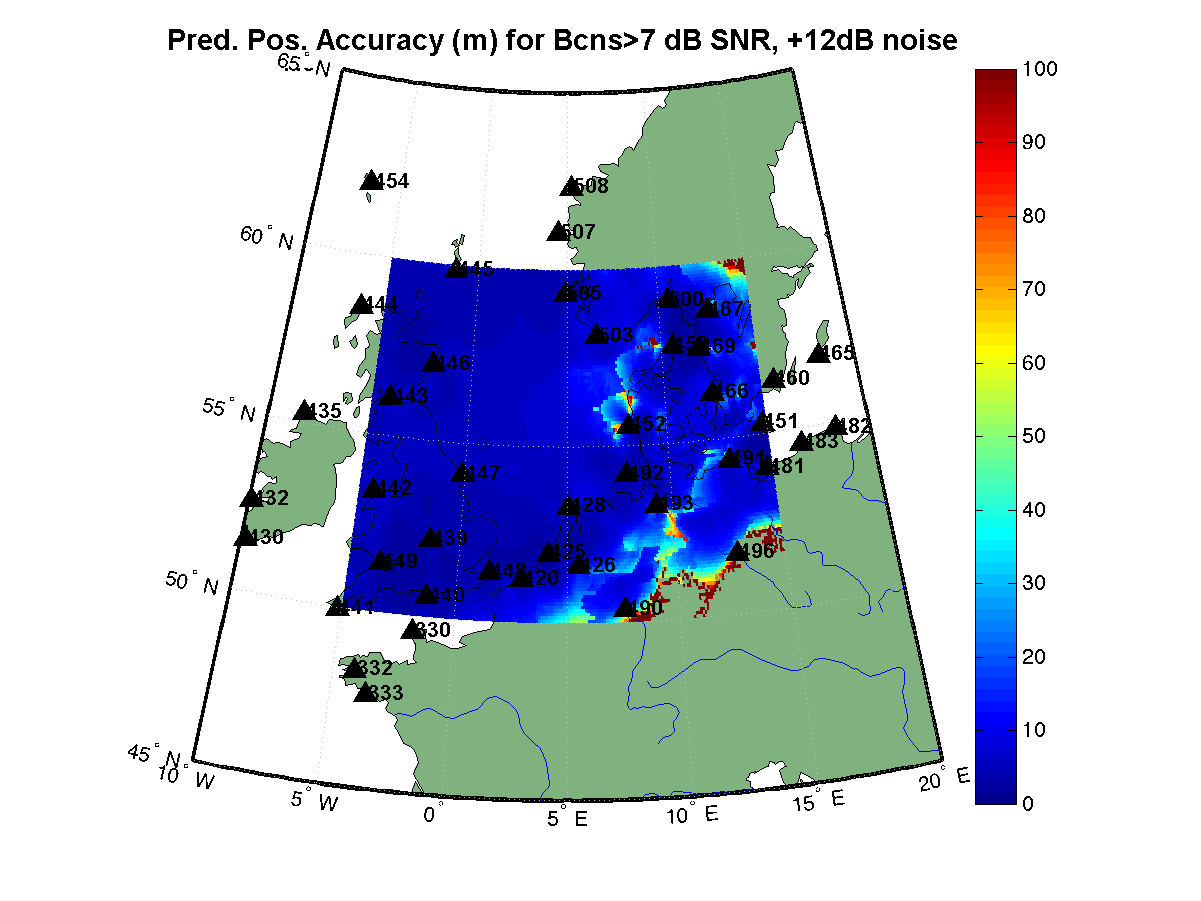
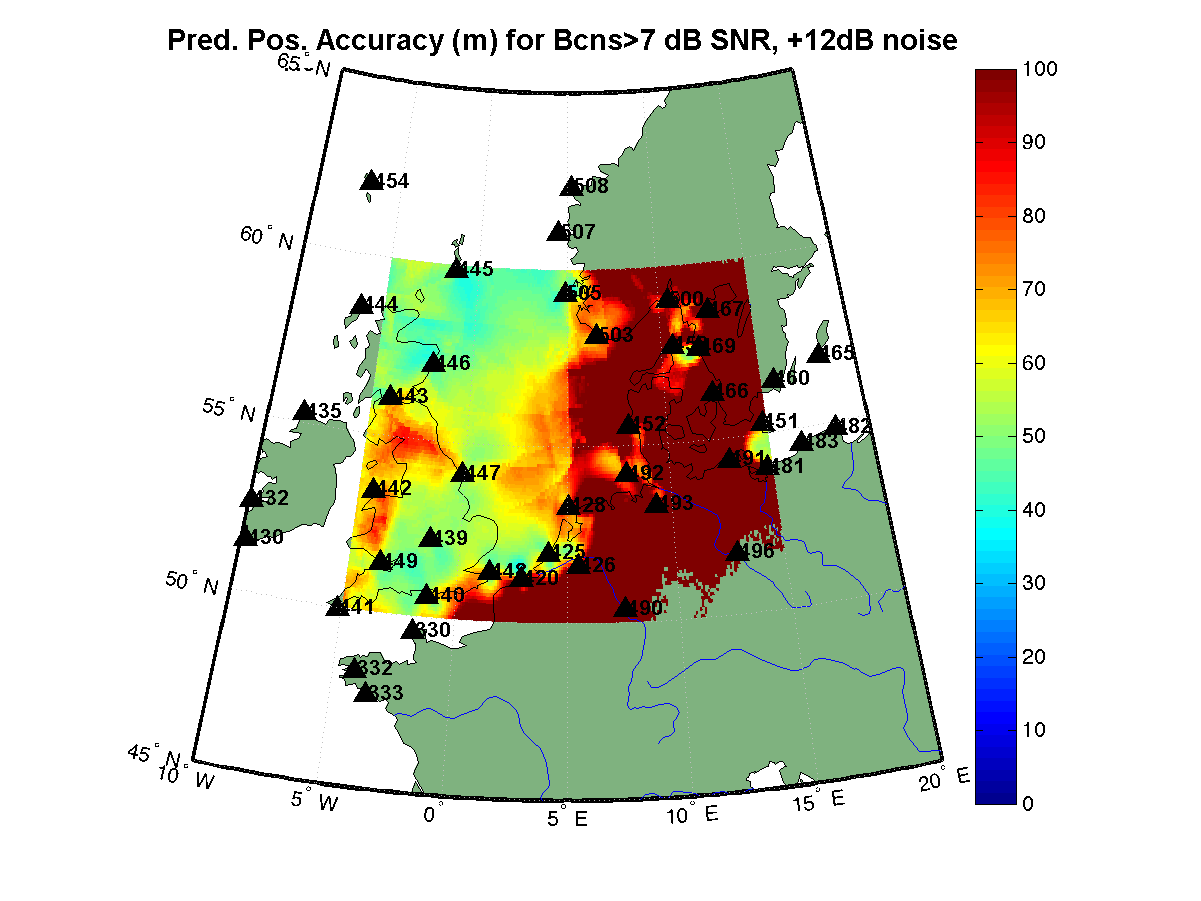
 

Figure 3: MF DGNSS R-Mode day (left) and night (right) predicted positioning accuracy (m) using a 0-100m scale [3].

The ACCSEAS feasibility study provides an estimation of the expected accuracies of marine radiobeacon R-Mode for day and night time conditions, taking into account the radiobeacon sites located in the North Sea region (Figure 3). The theoretical performance by day is promising with the expected accuracies in the order of 20-30m deemed possible. At night the expected accuracy drops to 90+m as the effect of skywave interference is observed.

Further consideration and work is required to understand the impact of skywave effects and whether they can be suitably mitigated for MF R-Mode solutions. This question, and others will need to be addressed in due course and will form part of the further work.

## Required hardware changes

R-Mode provision via marine radiobeacon stations will require the introduction of a new modulator including a CW signal generator, connected to a precise source of UTC (independent of GNSS). It is likely that most service providers will opt to modify one processing channel on site, leaving the second channel as is to preserve DGNSS correction availability, at least until the approach is proven.

Costs for the modified hardware are to be defined.

## Netherlands trials

The ACCSEAS project developed and installed an R-Mode transmitter along the Dutch coast at Ijmuiden, capable of transmitting a test signal for approximately 50km. For the transmission of the R-Mode signals a typical MF transmitter and MF transmitting antenna were used. Based on the different solutions evaluated in the feasibility study the R-Mode transmitter was able to provide a standard MSK signal (legacy signal) and two CW signals (R-Mode signal). For this purpose, a prototype R-Mode modulator was developed which enabled the transmission of standard RTCM messages used for the DGNSS service and two independent CW signals which can be adjusted in terms of frequency and output. A rubidium clock was used to provide a source of precise timing.

The ACCSEAS project also developed a test R-Mode receiver with the capability of measuring the pseudo-range from the R-Mode transmitter. Further the R-Mode receiver was able to demodulate the MSK signal and decode the RTCM messages. Data on pseudo-ranges were logged along with position and time for later analysis. For the R‑Mode test bed, a prototype R-Mode receiver was developed consisting of an H-field antenna, a band filter with pre-amplifier, and a PC with ADC board running MATLAB software. The receiver together with a rubidium clock were installed on a lighthouse tower in Noordwijk, about 25 km from Ijmuiden.

The first measurement campaign was performed over a two day period (07-08 February 2015). The recorded data were analyzed with respect to signal to noise ratio and the standard deviation of the measured range. The range was based on the phase determination of the two CW signals and the beat frequency of both signals to solve the ambiguity. The resulting ranging performance of the R-Mode signal using MF transmissions was very encouraging and validated the theoretical findings of the R-Mode feasibility study. The standard deviation (1-sigma) measured was in a range of 2-5 m (see Figure 4). Nevertheless, it must be noted that these results were taken on a short distance of about 25 km and do not consider skywave effects; they also do not constitute a position solution.

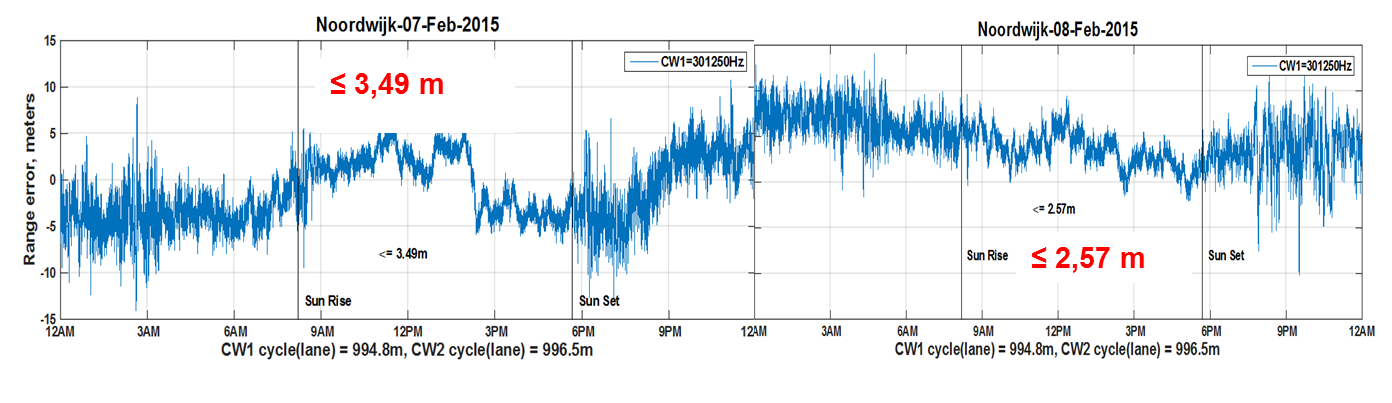
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Figure 4: First R-Mode range accuracy measurements from Ijmuiden Noordwijk, February 2015

This was the extent of the work on marine radiobeacon R-Mode conducted under the auspices of the ACCSEAS project.

# R-Mode AIS

As indicated previously, AIS base stations provide a significant opportunity for ranging, given the number installed and the timing nature of the signal. AIS transmissions are suitably configured to ensure the best range for a given location, generally providing data to users within line-of-sight reception.

The ACCSEAS feasibility study considered a number of potential options for using AIS for ranging [4,5]however the “Standard AIS transmission including Message 8” option [Section 2.3.1. in the above reference] was selected as the most suitable solution.

The feasibility report describes the solution in detail, however it can be summarised as making use of the existing signal specification through which a modified receiver would estimate both the times of bit transitions and the carrier phases of all available AIS base station signals. The approach would use the data bits from a Message 4 data string as they are predictable in both time and content, which enables better tracking. Message 8 data strings could also be used, for longer, more frequent signals with a fixed form which should improve the ranging performance and position update frequency.

The expected accuracy of R-Mode using AIS was considered in the feasibility report (Figure 5). As with all triangulation systems, AIS positioning will be a function of transmit power, station numbers and their geography to the user and the antenna height. The primary limiting factor of AIS ranging is the short propagation distance of the signal, which limits the coverage area provided by such a system since a user must receive signals from at least three different AIS base stations to solve for latitude and longitude. Therefore, this approach, when used on its own, may be more suited to waterways with land on two sides, such as port entrances, canals and straits.

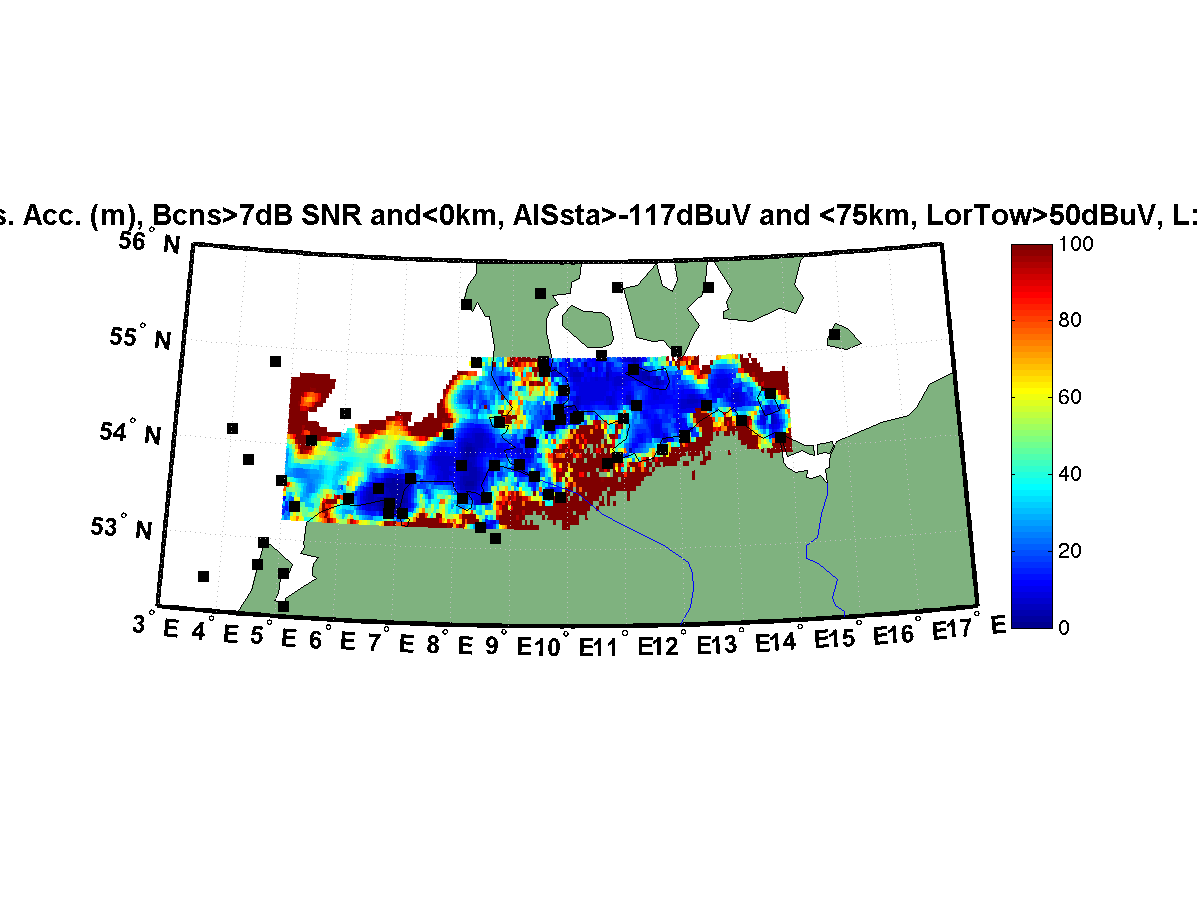


Figure 5: Predicted AIS R-Mode positioning accuracy (m) using a 0-100m scale [5].

The ACCSEAS project did not conduct any trials into AIS R-Mode. As such, there remain a number of questions to be addressed and investigated for AIS R-Mode, many of which are explained further in the guideline.

A different approach to positioning a vessel by using AIS transmissions have been presented at IALA ENAV18 by Dalian University [7].

It is also noted that a True Heading AB has a patent on the use of AIS data to confirm the reported position of vessels, which it considers may clash with AIS R-Mode. IALA is currently investigating this further.

## Required Hardware Changes

A precise source of UTC will be required at the AIS base station, however most AIS base stations should be designed to accept an external clock and therefore should not require replacement.

# R-Mode combination

The feasibly study also considered the use of multiple ranging sources, including a mixture of R-Mode signals from marine beacon and AIS transmitters. One of the strengths of the approach to R-Mode is that any timing signal can be considered, as long as its time can be traced to UTC, without the use of GNSS.

The study considered the addition of an eLoran signal and modelled the performance of it combined with marine radiobeacon and AIS R-Mode signals serving the Kiel canal (Figure 6). As expected, the best performance was achieved when all signals were used. This approach reduced the degradation in the estimated position at night to being marginally poorer than the day time accuracy. The eLoran signal provides accurate timing over a very large area and therefore few are needed to provide a significant improvement, with the additional benefit of being able to provide time to the R-Mode transmitter. Precise timing of transmissions is one of the fundamental pre-requisites for any R-Mode services.

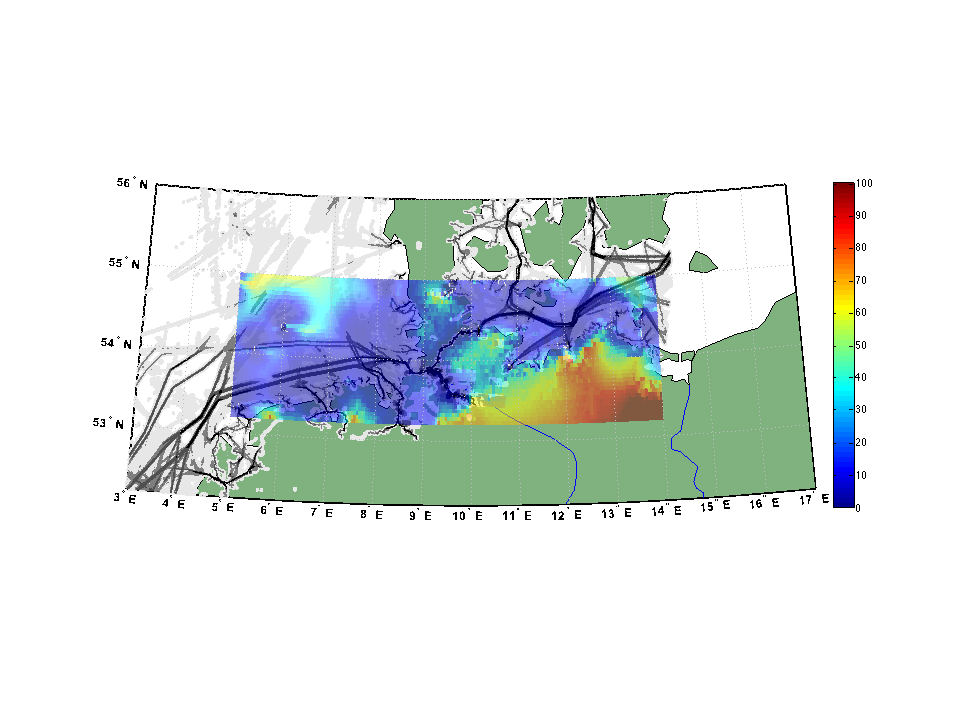


Figure 6: R-Mode performance overlaid on top of shipping density plot. Predicted R-Mode performance shaded using 0-100m accuracy scale. Shipping density shaded so that darker is higher density traffic.

The feasibility study concluded that as expected, more signals will result in increased performance and recommended that to achieve widespread resilient PNT, the best solution would be to use all signals available in a true all-in-view receiver.

It is also important to note that the need for a backup PNT is not uniform. The performance of a backup PNT system is most critical in the areas with the highest density of shipping traffic. Figure 6 shows the predicted R‑Mode performance overlaid on top of the AIS derived shipping density plot. It is likely that this alignment of R‑Mode performance with the high density shipping lanes will be true in other parts of the world as well, since those are the areas with the largest numbers of AIS and MF DGNSS stations.

The ACCSEAS project did not conduct any trials for combined performance.

# Prototype Transmitt and receive equipment

Tests performed during the ACCSEAS project, and since, have used one R-Mode transmitter and one R-Mode receiver. Both were connected to an atomic clock (Rb) to provide timing synchronization and therefore ranging measurements to be made at various distances. Figure 7 show the general system architecture and pictures of the prototype system equipment used for the tests to date.

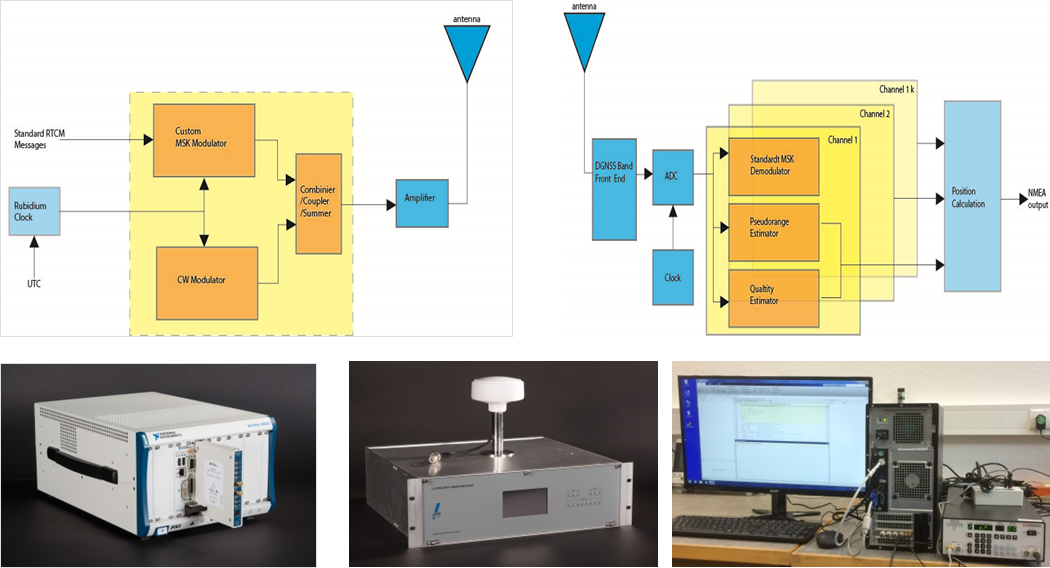


Figure 7: R-Mode test equipment and system architecture

# R-Mode Roadmap

Since the ACCSEAS project closed, a number of interested parties have been continuing the development of the R‑Mode concept within the IALA E-Navigation Committee (ENAV). The ENAV Committee has developed an R‑Mode development roadmap (Figure 8) which provides a high-level overview of the expected duration and tasks needed to develop R-Mode from the conceptual ideal to reality.

The roadmap was developed from an initial mindmap that was used to capture all of the remaining tasks required for the development of the system, for which estimated durations and priorities were added. These tasks were then ported to the Microsoft Project application through which the high level roadmap was generated. All three files are available in the following references [8, 9 and 10], should greater clarity be sought. The roadmap was calculated assuming consecutive tasks, however current developments are actioned as and when possible and therefore the dates indicated are unlikely to be met.

It is anticipated that the roadmap will be maintained annually during ENAV Committee meetings and updated within this document.



Figure 8: High level R-Mode roadmap

# Current activities

Interested parties continue to develop the R-Mode concept and the amount of interest in the approach is growing. The following sections outline the current investigations and studies taking place.

## R-mode (MF) field tests

After the tests in Ijmuiden, further tests were performed in the German Bight by re-locating the prototype R‑Mode equipment to an operational DGPS site in Helgoland. These tests are currently ongoing using various locations for the R-Mode receiver. This site enables a testing of the MF R-Mode ranging performance along the German and Dutch coastlines with distances of up to 230 km. The tests started in mid-August 2015 and will run over 2016. During the tests the R-Mode receiver was placed in different locations, starting from a distance to the transmitter of about 70 km with a stepwise increase towards a distance of 230 km. Table 1 provides information about measured distances and locations.

|  |  |  |  |
| --- | --- | --- | --- |
| Receiver location | Time/Date | Measured Distance [km] | Remarks |
| Tönning | 14.08.15 to 27.09.15 | 70 | Propagation over sea water, low influence of sky wave |
| List (Sylt) | 30.09.15 to 01.12.15 | 100 | Mainly propagation over sea water moderate influence of sky wave |
| Groß Königsförde  (Kiel canal) | 03.12.15 to 24.02.16 | 130 | Mixed sea and land propagation strong influence of sky wave |
| Terschelling (NL) | Ongoing since 05/2016 | 230 | Propagation over sea water, strong influence of sky wave |

Table 1: Performed measurements from R-Mode site Helgoland

Figure 9, Figure 10 and Figure 11 provide first results of the measured ranging error performed at locations in Tönning, List and Groß Königsförde. Measurements from Terschelling have not been analyzed, yet.

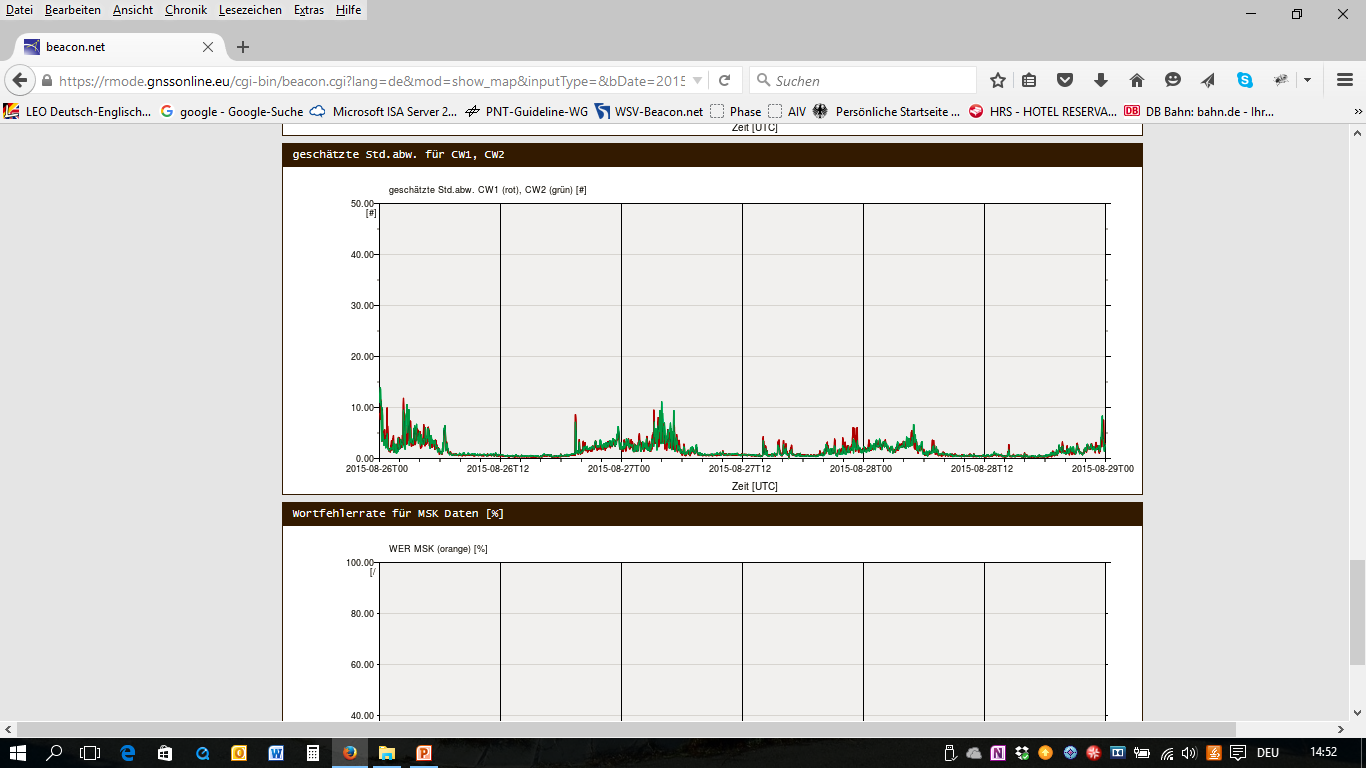


Figure 9: Ranging error measured in Tönning at 27-29.09.2015

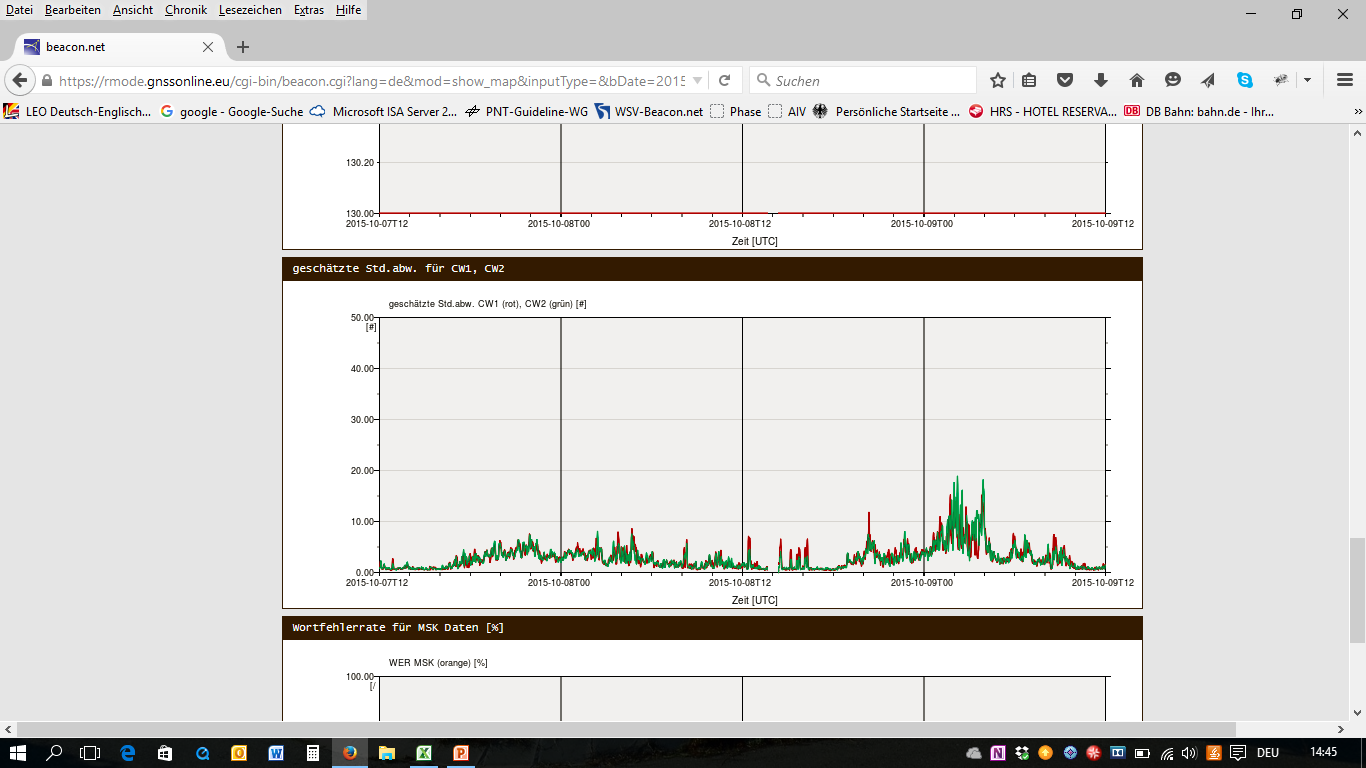


Figure 10: Ranging error measured in List at 27-29.09.2015

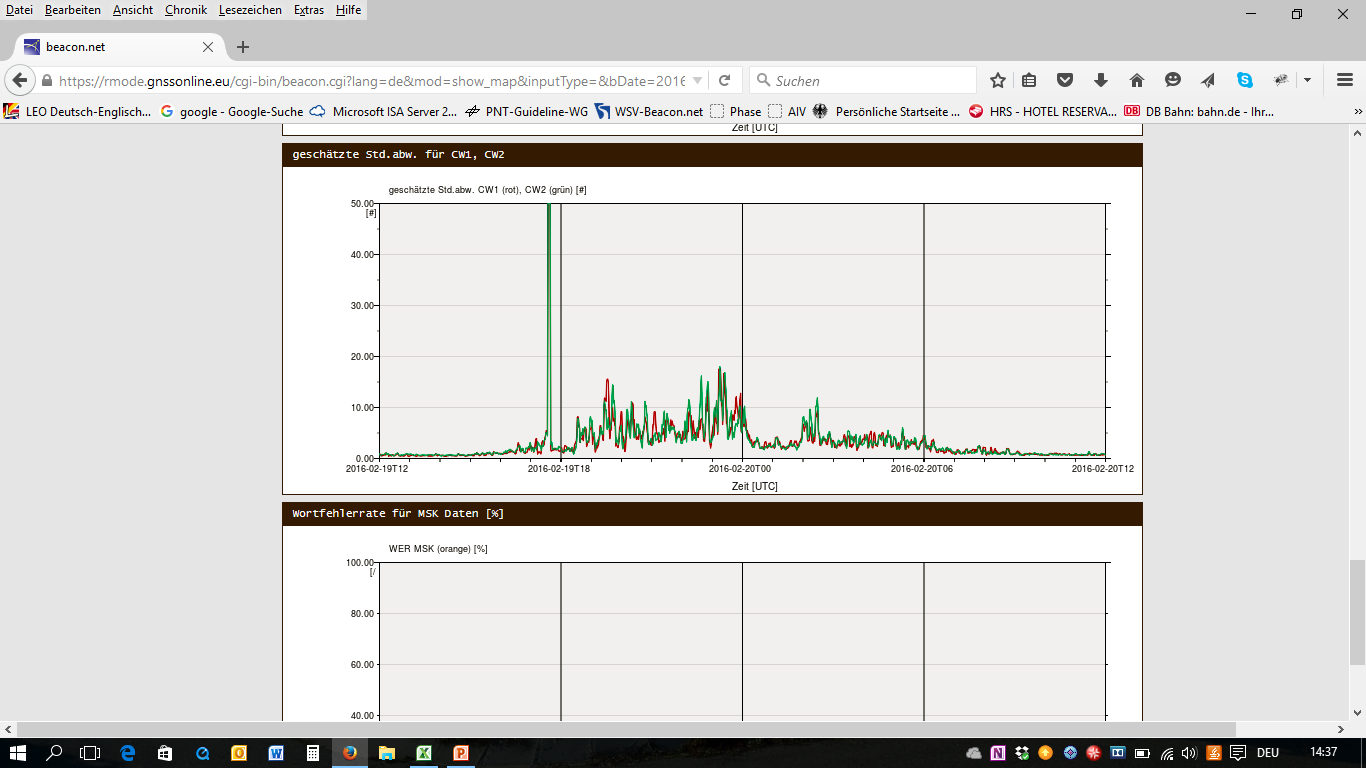


Figure 11: Ranging error measured in Groß Königsförde at 19-20.02.2016

An analysis of the figures during day time shows a range error of approximately 1 m (1-sigma). This is much better than the results measured in Ijmuiden/Noordwijk (February, 2015). The reason for this could be due to a more robust transmitting antenna located on Helgoland. The day time error is more or less the same for distances between 70 and 130 km. Maximum errors are in a range of about 5 m (see Table 2). The effect of skywave could be clearly seen during night in most cases, with range errors up to 10 m at night at a distance of 70 km, and a range error of up to 20m at a distance of 130 km.

As shown in the above figures the resulting ranging performance of the R-Mode signal using MF transmissions were very encouraging. Especially the daytime ranging accuracy of about a 1-2 m (1-sigma) shows the potential of MF R‑Mode as a possible backup to GNSS. Nevertheless, as already shown in the feasibility study, the performance will degrade during night by a factor of about 10. It should be kept in mind that these measurements are for a single baseline from the transmitter to the receiver and the results represent a 1-sigma accuracy. These results do not yet relate to a 2D position, which remains to be calculated.

The main results can be summarised as follows:

* For R-Mode via marine beacons, the standard amplifier and antenna equipment already located at a DGNSS transmitter site may be used without specific modifications
* The additional R-Mode signals could be modulated to the MSK signal (DGNSS) without any measured degradation of the legacy signal (measured through the use of a local DGPS receiver which maintained operation)
* The on air field tests could validate the findings and estimations of the feasibility study performed in the ACCSEAS project.

As a summary of the performed measurements and the findings of the feasibility study table 2 provides a comparison of estimated and measured accuracies.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Results | Ranging (Day)  [m] | | Ranging  (Night)  [m] | | Position Accuracy (Day)  [m] | Position-Accuracy (Night)  [m] |
| Estimated in feasibility study | 2,7 | | - | | < 10 | < 100 |
| Measurements from Ijmuiden/Noordwijk | 2,5 | | - | | < 10[[1]](#footnote-1) | < 101 |
| Measurements from Helgoland   * + - Tönning     - List     - Groß Königsförde | δ  0,5  1  1 | Max  4  5,5  7 | δ  1,5  3  8,5 | Max  10  20 46 | < 51  < 51  < 51 | < 201  < 201  < 501 |

Table 2: Comparison of estimated and measured range accuracies

Test measurements will continue to be conducted at different baseline lengths to investigate the effect and impact of skywave.

## Interference investigations

A contract has recently been let to investigate the potential impact of marine radiobeacon R-Mode signals to legacy marine DGPS receivers. The receivers have been developed to work to a set minimum interference level as defined by the ITU [11], however this approach does not consider the presence of the additional CW signals in the band.

While it is considered that the impact of the additional energy from the CW will be small, there are a large number of radiobeacons located across Europe in particular which could result in a receiver being exposed to multiple R-Mode transmissions.

As such, the study will investigate whether R-Mode is likely to cause interference and if so, how may simultaneous R-Mode signals are likely to be sufficient to affect legacy receivers. The results of this study are expected early 2017.

# Planned future work

The R-Mode concept is in its infancy and more work is required. The results of the ACCSEAS feasibility study and trials, along with the further trials since the close of the project show that there is significant potential for R-Mode using both AIS and marine radiobeacons.

However, a large number of issues remain to be addressed, which are contained in the R‑Mode roadmap documentation. At a high level, these include, but are not limited to:

* + Agree technical specification for R-Mode signals
  + Test to ensure there is no interference to legacy users
  + Investigate positioning accuracies and limitations (trials, test-beds etc)
  + Investigate the best approach for integration of different positioning systems
  + Perform cost benefit analysis
  + Develop international standards (IMO, ITU, IALA etc)
  + Encourage equipment development

## R-Mode Baltic Sea project

A number of interested stakeholders are currently investigating in an R-Mode specific project in the Baltic Sea region. The project is currently part of a competitive tender and if successful, will further develop the concept and introduce an R-Mode test bed to the Baltic Sea region.

This project is being led by the German Aerospace Centre (DLR) with other consortium members including service providers, users and equipment manufacturers. The main topics of this intended project [12] are:

* Setup advanced test beds for R-Mode using MF transmissions from IALA radio beacons installed in the Baltic Sea area
* Development of a test bed concept for the Baltic Sea
* R&D actions concerning the influence of sky wave and other environmental variations as well as transmitter and receiver setup
* Assessment of various R-Mode solutions and agree specification
* Equipment for reception of multiple MF-radio beacons with R-Mode functionality to perform real position tests
* Development of a solution for time synchronization independently from GPS or find another way to solve the time problem
* Development of an R-Mode receiver to perform position calculations
* Enlarge the test bed to include transmissions from AIS shore infrastructure and preparation of the R-Mode receiver for AIS functionality
* Test the combined solutions
* Support the standardization process by participation in dedicated committees and organizations as well as organization of workshops etc.

## North Sea test area

Assuming a good outcome of the current interference study, the General Lighthouse Authorities of the UK and Ireland expect to add R-Mode signals to two of its DGPS sites on the east coast of the UK, subject to gaining the necessary regulatory approval. Signals from these sites, in combination with the test site installed at Helgoland, would provide a large test area across the North Sea within which the user should be able to receive three R‑Mode signals.

The Netherlands is also considering the development of a marine radiobeacon R-Mode signal which would help enlarge the test area further.

Such a test area should then allow a modified receiver to calculate a full R-Mode position and facilitate a positioning accuracy measurement campaign designed to understand the effect of geometry, skywave and seasonal effects.

This work would be aligned with the ongoing activities of the R-Mode Baltic Sea project (if successful).

# Conclusions

As reported in the ACCSEAS R-Mode feasibility study the R-Mode concept has a potential to be used as terrestrial backup radio navigation system to GNSS. First on air measurements, using MF R-Mode validated the theoretical finding of the study. Furthermore, the practical field tests confirmed a proof of concept and the coexistence of the R-Mode signals and the legacy MSK signal in one transmission. Nevertheless, as identified in the roadmap, a lot of future work is still required until R-Mode could be used as an operational service in coastal areas.

Work on R-Mode continues, and the planned R-Mode Baltic project in particular should hasten the speed of development if successful. However, more contributing parties are sought and those interested are advised to contact the IALA ENAV WG5 Vice Chair, Mr Michael Hoppe (contact details in Section 14).

# ACRONYMS & Definitions

## Acronyms

ACCSEAS Accessibility for Shipping, Efficiency Advantages and Sustainability

ADC Analog-to-digital converter

AIS Automatic Identification System

ARPA Automatic Radar Plotting Aid

BeiDou Chinese GNSS

CW Continuous wave

DGNSS Differential GNSS

DGPS Differential GPS

DLR German Aerospace Centre

ECDIS Electronic Chart Display and Information System

eLoran Enhanced LORAN

ENAV IALA E-Navigation

Galileo European GNSS

GNSS Global Navigation Satellite System

GPS Global Positioning System

IALA International Association of Marine Aids to Navigation and Lighthouse Authorities

IMO International Maritime Organization

ITU International Telecommunication Union

LORAN LOng Range NAVigation

MF Medium frequency

MSK Minimum-shift keying

NMEA National Marine Electronics Association

PNT Positioning, navigation and time

Rb Rubidium atomic clock

R-Mode Proposed Terrestrial backup navigation system based on ranging signals

RTCM Radio Technical Commission for Maritime Services

UTC Coordinated Universal Time

WG5 IALA ENAV working group 5

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# Contact

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1. Estimated value considering a HDOP < 2 in the dedicated region of the North Sea Area as illustrated in in   
   [3, Figure 17]. [↑](#footnote-ref-1)
2. The references can be downloaded from the IALA website, <http://www.iala-aism.org/products-projects/e-navigation/test-bedsprojects/accseas/> [↑](#footnote-ref-2)