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The Feasibility of R-Mode to Meet Resilient PNT Requirements for e-Navigation

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Biographies:

Gregory Johnson is a Senior Program Manager at Alion Science & Technology in the New London, CT office. His group provides research and engineering support primarily to the U.S. Coast Guard R&D Center. Recently he has been working on projects in R-Mode for the German Federal Waterways Administration, and AIS for the USCG and the U.S. Army Corps of Engineers. He has a BSEE from the Coast Guard Academy (1987), a MSEE from Northeastern University (1993), and a PhD in Electrical Engineering from the University of Rhode Island (2005). Dr. Johnson has over 20 years of experience in electrical engineering and R&D, focusing on communications, signal processing, and electronic navigation and has published over 75 technical papers. He is a member of the Institute of Navigation, the International Loran Association, the Institute of Electrical and Electronics Engineers, and the Armed Forces Communications Electronics Association. He is also a Captain in the U.S. Coast Guard Reserves.

Peter Swaszek is a Professor of Electrical Engineering at the University of Rhode Island. His research interests include statistical communication theory, digital signal and image processing, Monte Carlo simulation, and pretty much any problem with an interesting probabilistic/mathematical aspect. His early work focused on data compression and signal detection and estimation in non-Gaussian noise environments. Since a serendipitous sabbatical at the US Coast Guard Academy in 2001, he has been involved in various aspects of electronic navigation including eLoran, DGNSS, and GNSS spoofing.

Jürgen Alberding is the founder and CEO of Alberding GmbH (founded in 1994) specializing in developing and distributing solutions for GNSS service providers and control centres. Alberding also provides hardware and software solutions for mobile GNSS applications. Previously he was an employee of Trimble Navigation Europe Ltd. He has a Dipl.-Ing. Degree from the University of Hannover.

Michael Hoppe received his diploma as a radio engineer in 1990. Since 1991 he has been working for the Traffic Technologies Centre within the German Federal Waterways and Shipping Administration, responsible for the field of radio navigation systems for maritime and inland waterways applications. Michael Hoppe is actively involved in the development and planning of the German radio beacon network and the investigation of present and future radio navigation systems. He is member of various national and international working groups dealing with development and standardisation of integrated PNT systems.

- Since 1998 member of the IALA Radio navigation committee.
- Since 1998 member of IEC TC80 WG4a on GNSS/DGNSS standardisation
- 2000-2004 member of GAUSS standardisation group on Loran-C/Eurofix
- Since 2006 member of the IALA eNavigation Committee
- Since 2011 member of national eNavigation PNT WG
- Since 2013 Vice chair of IALA PNT WG

Jan-Hendrik Oltmann is Deputy Head of the Traffic Technology and Telematics Division of the German Federal Waterways and Shipping Administration. He received his master degree (Dipl.-Ing.) in Electrical Engineering from Darmstadt Technical University, Germany, in 1992. In 1993, he joined the Aids-to-Navigation Research and Development Center of the administration in Koblenz. There he started work on radio navigation in general and the application of transponder technology to Vessel Traffic Services (VTS). In 1999, Jan-Hendrik Oltmann joined the Waterways and Shipping Directorates at the German coast. Since 1994, he has been involved in the development of the Automatic Identification System (AIS) and terrestrial radio navigation services. He has been managing several domestic and international projects, chairing several international groups. Since 2007, Jan-Hendrik Oltmann is Chair of the Architecture Technical Working Group of the IALA e-Navigation Committee. In that capacity he contributed to the development of the overarching e-Navigation architecture at IMO and to the development of the concept of the Common Maritime Data Structure (CMDS). Already back in 2008, Jan-Hendrik Oltmann, together with Michael Hoppe, submitted a proposal on the R-Mode at both MW and AIS as carriers to IALA e-Navigation Committee to bring the potential of the R-Mode at those carriers to the attention of international service provider community of those services.

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 such as the North Sea. GNSS (primarily GPS and GLONASS) has become the primary PNT source for maritime operations. The GNSS position is used both for vessel navigation and as the position source for AIS.

Unfortunately, GNSS is vulnerable to jamming and interference – both intentional and unintentional. This can lead to the loss of positioning information or even worse, to incorrect positioning information. The user requirement is for dependable PNT information at all times, even under GNSS jamming conditions. One potential source of resilient PNT services is Ranging Mode (R-Mode) using signals independent of GNSS.

The German Federal Waterways and Shipping Administration has contracted for a feasibility study of R-mode using MF-DGNSS and VHF AIS signals as well as those signals in combination and in combination with eLoran. The first part of the study focused on the feasibility of using MF-DGNSS signals for ranging and timing. It examined the state of the art, identified potential solution methods, and, after examining Pros and Cons of the various options, selected a few options for further study. Part 2 examined the proposed solutions in depth and identified the modifications required for both the reference stations (transmitters) and user equipment (beacon receivers). Parts 3 and 4 of the study repeated Parts 1 and 2, but using AIS signals rather than MF. Part 5 of the study examined the possibility of combining MF and AIS R-Mode or combining MF R-Mode with eLoran.

This paper presents the results of this study including recommended R-Mode implementations and bounds on the positioning performance using the various R-Mode methods. Included are predictions of DGNSS and AIS R-Mode coverage and the resulting HDOP using existing and proposed DGNSS and AIS sites with specific detail in the area of the planned test bed in the North Sea.

1 Introduction

1.1 Background

High precision positioning in the maritime domain is now the norm since the introduction of Global Navigation Satellite Systems (GNSS). Unfortunately, it is well known that as low power, satellite-based systems, GNSS are vulnerable to interference (both naturally occurring and manmade); hence, the development of an alternative backup system is recommended.

A variety of technological solutions to this backup requirement are possible; in the radio frequency (RF) domain we have the so-called "Signals of OPportunity" (SoOP) approach. This term refers to the opportunistic use of RF signals, typically communications signals, which exist in the geographical area of the receiver. While these signals are not primarily intended for positioning, a SoOP navigation receiver attempts to exploit them as such. Specifically, if each SoOP can provide a (pseudo-) range to the receiver from a known location, a trilateration position solution is possible. Even if a complete position solution is impossible from the SoOP (perhaps due to too few signals being present), the resulting pseudorange information could be combined with measurements from existing positioning systems in a position solution (e.g. perhaps with GNSS measurements limited by urban canyons).

Of interest to this study is the integrated use of the Differential GNSS (DGNSS) broadcasts and Automatic Identification System (AIS) broadcasts, both together and as combined with eLoran. This report considers the potential performance of several integrated solutions to provide a Ranging Mode (R-Mode) Position Navigation and Timing (PNT) alternative to GNSS.

1.2 Regional Context

This work is being done in support of the EU INTERREG IVb North Sea Region Programme project ACCSEAS (Accessibility for Shipping, Efficiency Advantages and Sustainability), which is a 3-year project supporting improved maritime access to the North Sea Region through minimising navigational risk. The goals of the ACCSEAS project are to (see http://www.accseas.eu/about-accseas):

- Identify key areas of shipping congestion and limitation of access to ports;
- Define solutions by prototyping and demonstrating success in an e-Navigation test-bed at North Sea regional level.

The North Sea Region (NSR) as defined by ACCSEAS [1] includes the eastern part of the UK, Belgium, the Netherlands, the northern part of Germany, Denmark, the southern part of Norway, and the western part of Sweden as well as the Skagerrak and Kattegat, the Sounds and the south western part of the Baltic Sea. The three largest and busiest ports in the NSR are Rotterdam, Antwerp, and Hamburg. This area is shown in Figure 1 with ship traffic densities in red. Based on the traffic and risk analysis done using the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) IWRAP model, about 70% of the predicted collisions take place north of Germany and the Netherlands, making this a key area for testing and implementation of R-Mode.

The recently released "Baselines and Priorities Report" [1] contains an analysis of the traffic in the region, both current and projected. The planned enormous expansion of wind farms will reduce the navigable space and could impact key shipping lanes, raising safety and efficiency concerns. The report also traces user needs to system requirements using a system engineering approach. One of the low Level User Requirements identified was the need for resilient PNT.

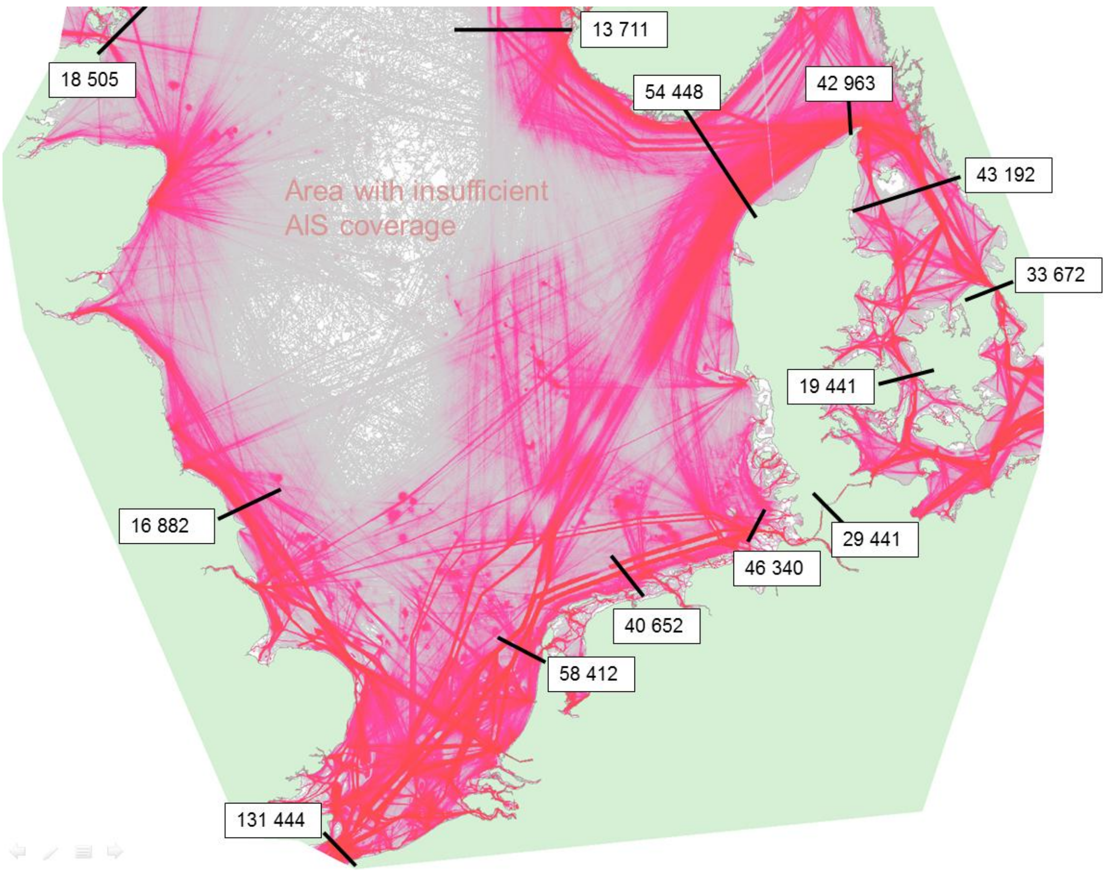


Figure 1: Ship traffic density in the NSR reprinted from [1]. The labels show the total number of ships passing each line from both directions during 2012.The red colour gradient shows the relative density of shipping in the NSR. The empty area in the middle of the North Sea is an area without AIS coverage (it does not mean that there is no traffic).

The ACCSEAS project activities are aligned with the IMO e-Navigation concept as shown in Figure 2. This can also be visualized as the so-called "7 Pillars of e-Navigation" as shown in Figure 3. The pillar of interest to this paper is the Resilient PNT pillar which is defined as "Highly reliable and robust determination of Position, Navigation data and Time (PNT) at the shipboard and shore-based electronic systems with the World Wide Radio Navigation System (WWRNS) of IMO at the core" [1]. The ACCSEAS potential solution that maps to this pillar is the Multi-Source Positioning Service (MSPS). "The resilient PNT technical services - e.g. Ranging Mode (R-Mode) – that are based on backup technologies independent of GNSS could be central to the e-Navigation and test-bed architectures to meet the user need for resilient PNT. These technical services could support a MSPS operational service that would provide, monitor and distribute resilient PNT information to a broad range of e-Navigation operational services" [1].

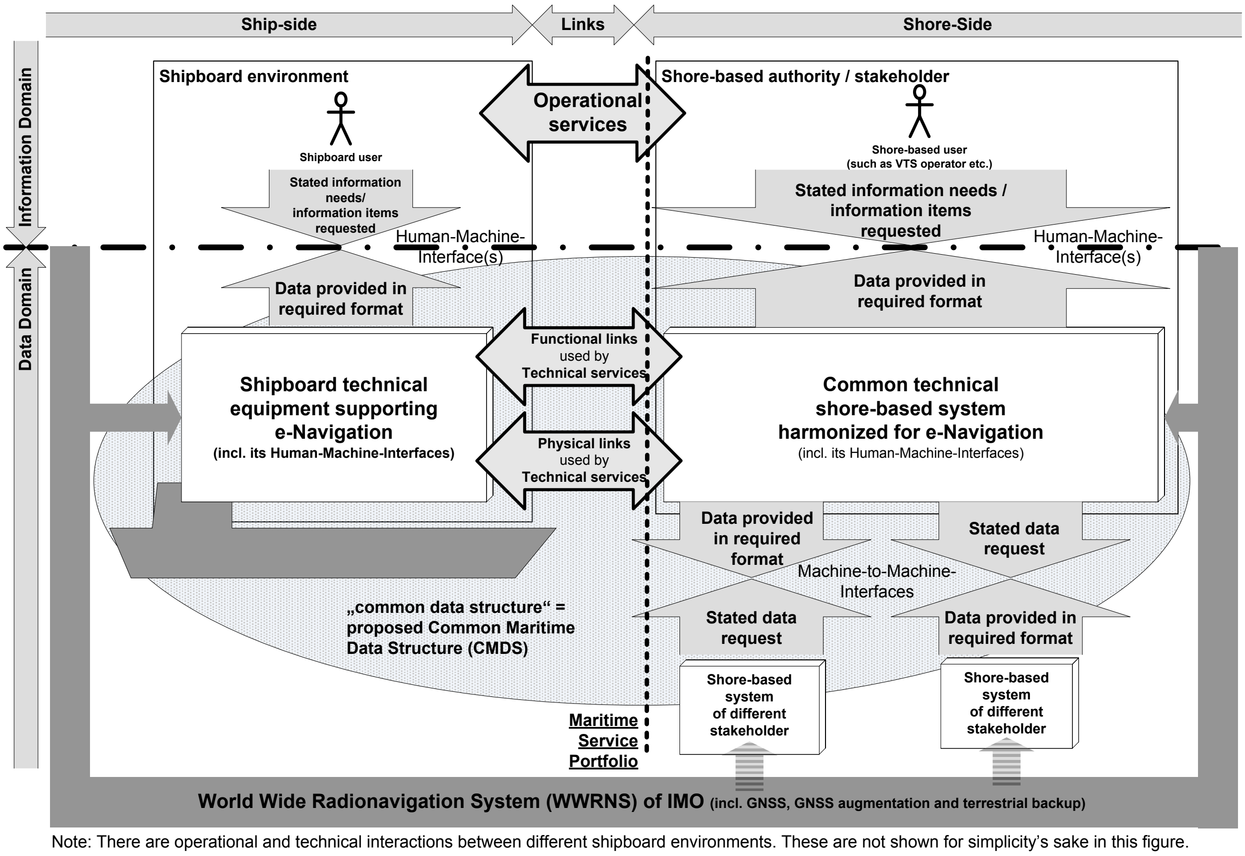
2 Review of the Potential Signals

2.1 The MF DGNSS Broadcast

The Milestone 2 report [3] presented methods to employ the MF DGNSS broadcasts in R-Mode. This section reviews the results presented in that report.

2.1.1 Estimating the TOA

The MF DGNSS system transmits its information via a binary modulation method known as Minimum Shift Keying (MSK). 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 report [3] examined the potential performance of estimators of



Note: There are operational and technical interactions between different shipboard environments. These are not shown for simplicity's sake in this figure.

Figure 2: The overarching e-Navigation architecture from [2].

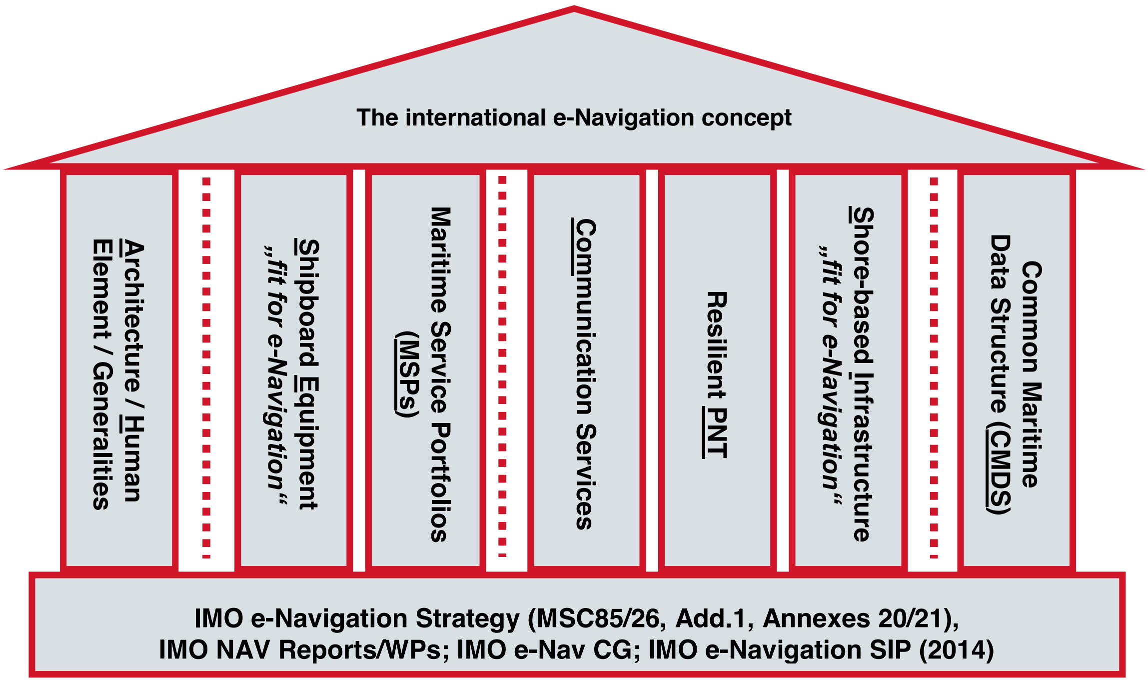


Figure 3: IMO overarching e-Navigation Architecture represented as "7 Pillars", reprinted from [1].

time of arrival (TOA) from these two parameters. It was argued that with the existing signal strengths and beacons locations, the time of bit transition is too imprecise for effective ranging. However, assuming that the lane 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 CW signals accompanied the MF and its phase was estimated. As an added benefit, producing beat frequencies from multiple CW signals could help resolve the ambiguity. For phase estimation the Cramer-Rao lower bound on accuracy is

$$\sigma^2_{\tau\ \widehat{carrier}} \geq \frac{1}{2\omega_c{}^2 T\ SNR} \text{ seconds}$$

in which T is the observation period, ω_c is the MF carrier frequency, and SNR is the received signal to noise ratio. Converting to meters and taking a square root for standard deviation

$$\sigma_{MF\ carrier} \geq \frac{1.2\times10^4}{\omega_c\sqrt{T\ SNR}} \text{ meters}$$

Figure 4 shows the potential performance (measured in meters of standard deviation) as a function of signal to noise ratio (SNR) (in dB based upon predicted signal levels and typical North Sea noise values in dBμV). The lines labelled "weak" and "typical" suggest the level of performance available in the North Sea region assuming a 5-second averaging window on the estimator.

There are several important points to remember for MF DGNSS ranging:

- Ranging using carrier phase requires the resolution of cycle ambiguity, the fact that the phase repeats every wavelength of the signal (this is approximately 1 km for MF DGNSS signals). CW allows for several ambiguity resolution approaches: (1) initializing the receiver at a fixed location and "counting" cycles as the platform moves or (2) using time synchronized, multiple frequency signals and solving for a position that simultaneously satisfies all of the ambiguity equations with integer solutions. This was accomplished in the Omega system by using different frequencies from spatially separated transmitters.
- A second point is that this performance expression is the best possible (as predicted by a Cramer-Rao bound for the additive Gaussian noise model); actual performance will be somewhat worse.
- A third point is that the propagation of an MF transmission is delayed according to the characteristics of the ground over which it is traveling. These additional secondary factors (ASFs) must be taken into account for positioning applications. While computer modelling tools can "predict" ASFs using databases of ground conductivity and topography, the quality of the prediction is typically insufficient for the desired positioning accuracy [4, 5]; the tools also do not describe the time varying nature of the ASFs. The current solution to ASFs involves surveying the area of interest to account for spatial effects based upon topography and ground conductivity and establishing monitor sites (with appropriate communications links) to provide temporal corrections to account for the time variation in the delay.
- Finally, MF transmissions can suffer from multipath interference due to signal reflections off of the ionosphere; this is referred to as sky wave interference. This effect is most pronounced at night. While pulsed signals (such as Loran) can mitigate this effect, continuous transmission (as in MF) will always suffer from it.

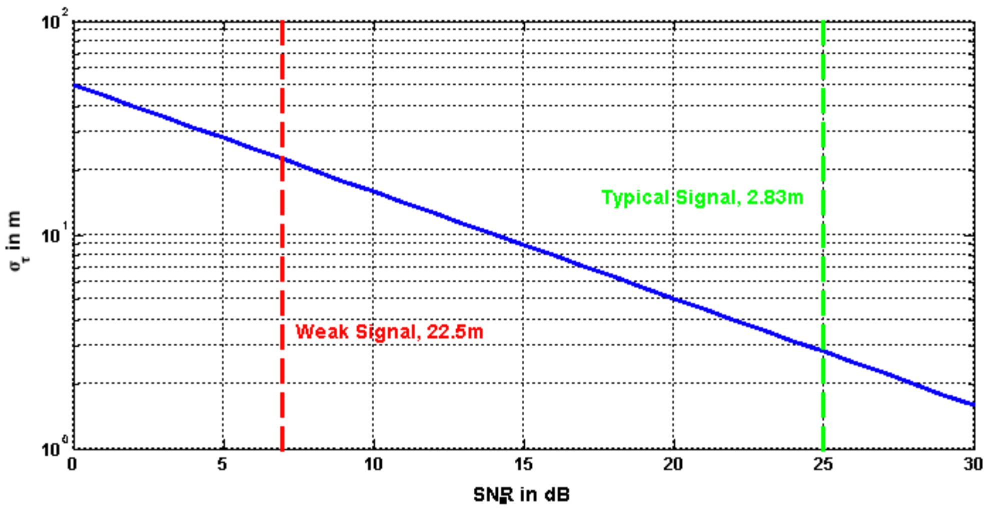


Figure 4: The Cramer-Rao lower bound on performance of estimating the time of arrival from the phase of the MF ranging signal as a function of signal to noise ratio.

2.1.2 Geometry and Signal Strength

For positioning, the quality of the solution is impacted by the signal strength and the distances and bearings to the beacon sites relative to the receiver. The signal strength can be well predicted by software tools and signal to noise ratio (SNR) is computed by subtracting the noise for each location (described in more detail in [3]). The effect of the bearings is captured in the Horizontal Dilution of Precision (HDOP). Figure 5 shows the HDOP of the existing MF DGNSS sites for the North Sea area of interest (using only those transmitters providing a SNR at that location of greater than 7 dB); this area is defined as region I and runs from 50°N to 60°N latitude and 5°W to 15°E longitude. Interpreted as a multiplier on the user range error, lower HDOP values are better. As can be seen from this figure, most of region I has a very good (small) HDOP.

2.1.3 Positioning Accuracy

At a particular location the pseudorange accuracy expression in 2.1.1 is evaluated using the predicted SNR at that location (computed using the method described in 2.1.2) to provide the accuracy of each individual MF DGNSS pseudorange. These accuracy values are combined with the geometry of the stations (only those with SNRs in excess of 7 dB and within 500 km) through a weighted HDOP calculation to provide a lower bound on the overall position accuracy (the general trilateration approach to computing the position and its accuracy for terrestrial RF TOA systems is described in 3.1). Figure 6 shows the result for MF R-Mode for the North Sea area. This plot, for daytime, does not take into account any additional errors due to timing offsets between the various transmitters (assumed perfect synchronization), nor does it take into account any secondary variations in propagation (additional secondary factors, ASFs) as these are judged to be very small over region I due to the limited land paths.

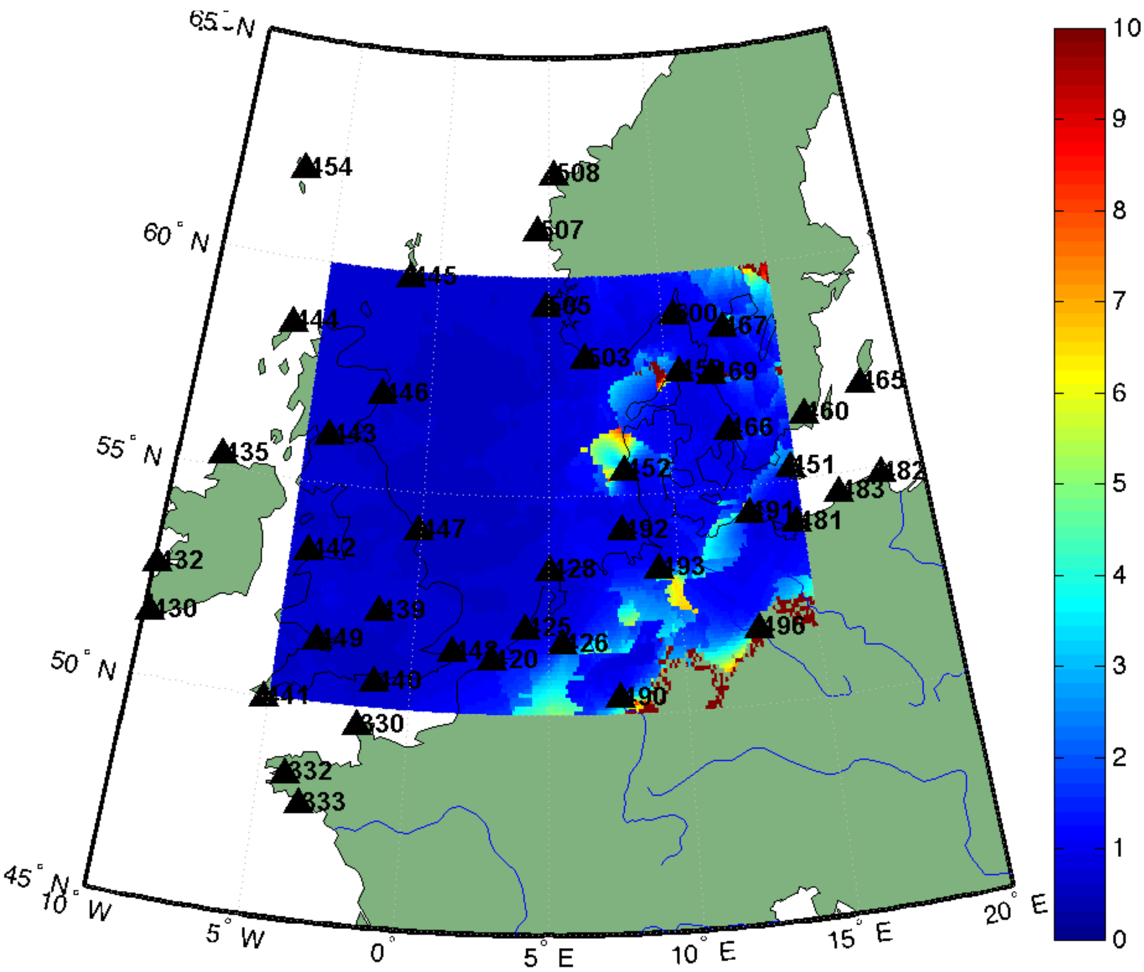


Figure 5: HDOP from the MF DGNSS sites (shown as triangles) for region I.

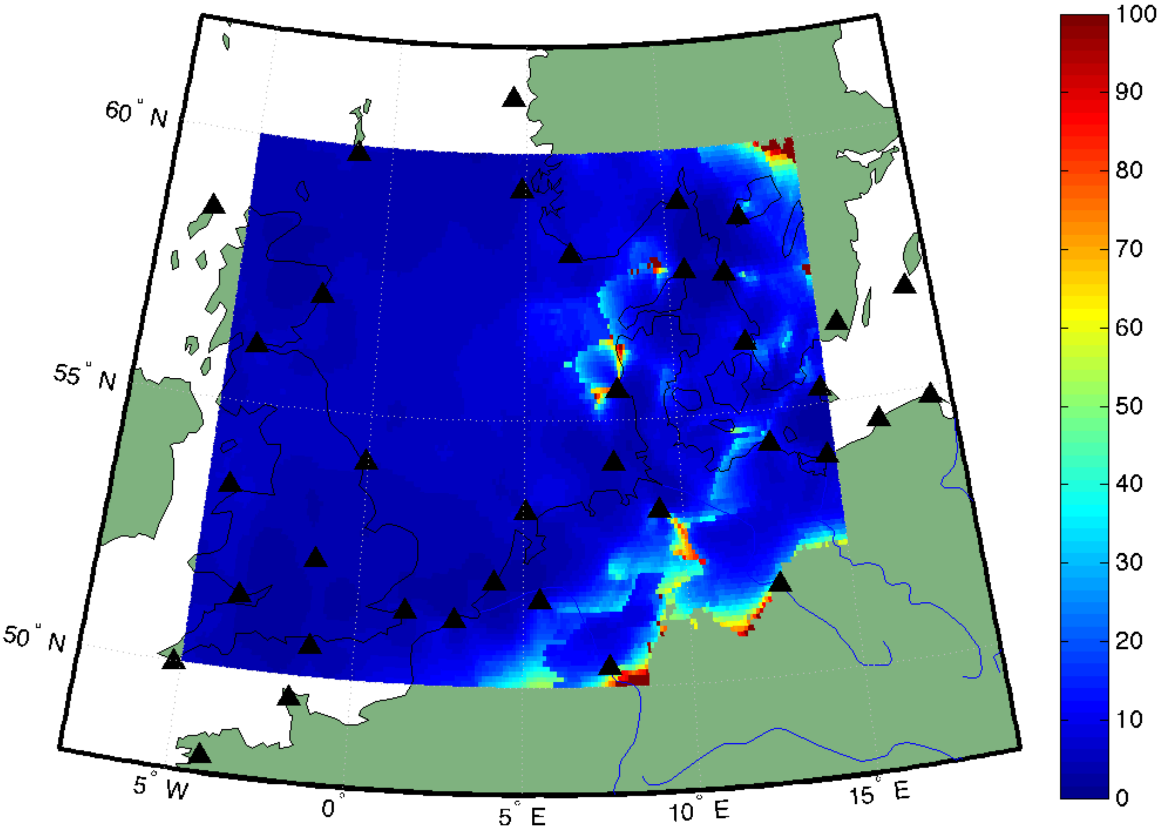


Figure 6: Lower bound to positioning accuracy of MF R-Mode (in meters) – day.

As mentioned in 2.1.1 sky wave interference can have a large impact on MF DGNSS ranging performance, particularly during the night. The Milestone 2 report [3] described one method to include the effects of this interference on ranging performance by a modification of the relationship between received SNR and pseudorange accuracy. Specifically, the sky wave signal strength was estimated and subtracted from the SNR as if sky wave was perfectly destructive interference. Second, the fade margin (the difference between the ground wave signal strength and the sky wave signal strength) was calculated and used to increase the error variance of the phase estimate. These assumptions are, obviously, quite pessimistic. Using this result, a lower bound to positioning accuracy was developed. Figure 7 shows the result for region I; as for the daytime plot, this figure ignores any additional errors due to timing offsets between the various transmitters and ASFs.

2.2 The AIS Broadcast

The Milestone 4 report [6] presented methods to employ the AIS broadcasts in R-Mode. This section reviews the method recommended in that report.

2.2.1 Estimating the TOA

The AIS system transmits its information via a binary modulation method known as GMSK (Gaussian MSK), similar to MSK, but slightly more bandwidth efficient. Assuming that the GMSK transmission is controlled by a precise timing/frequency source, both the times of the bit transitions (256 bits per message at 9,600 baud) and the underlying phase of the transmitted signal (a sinusoid at approximately 162 MHz) could be exploited to estimate the TOA for ranging applications. The report [6] examined the potential performance of estimators of TOA from these two parameters. It was argued that at the existing signal strengths and transmitter locations, the time of bit transition is most useful for effective ranging. The Cramer-Rao lower bound on the accuracy of the bit edge was shown to be

$$\sigma_{\tau,GMSK\ bit\ edge} \geq \frac{0.12}{\sqrt{L_0}\ 10^{\frac{S}{20}}}\ nsec$$

Converting to meters

$$\sigma_{\tau,GMSK\ bit\ edge} \geq \frac{0.036}{\sqrt{L_0}\ 10^{\frac{S}{20}}}\ meters$$

Figure 8 shows the potential performance (measured in meters of standard deviation) as a function of signal strength (in dBm). The lines labelled “weak” and “typical” suggest the level of performance available in the North Sea region assuming a 5-second averaging window on the estimator (either five separate single-slot Message 8s or a single 5-slot Message 8).

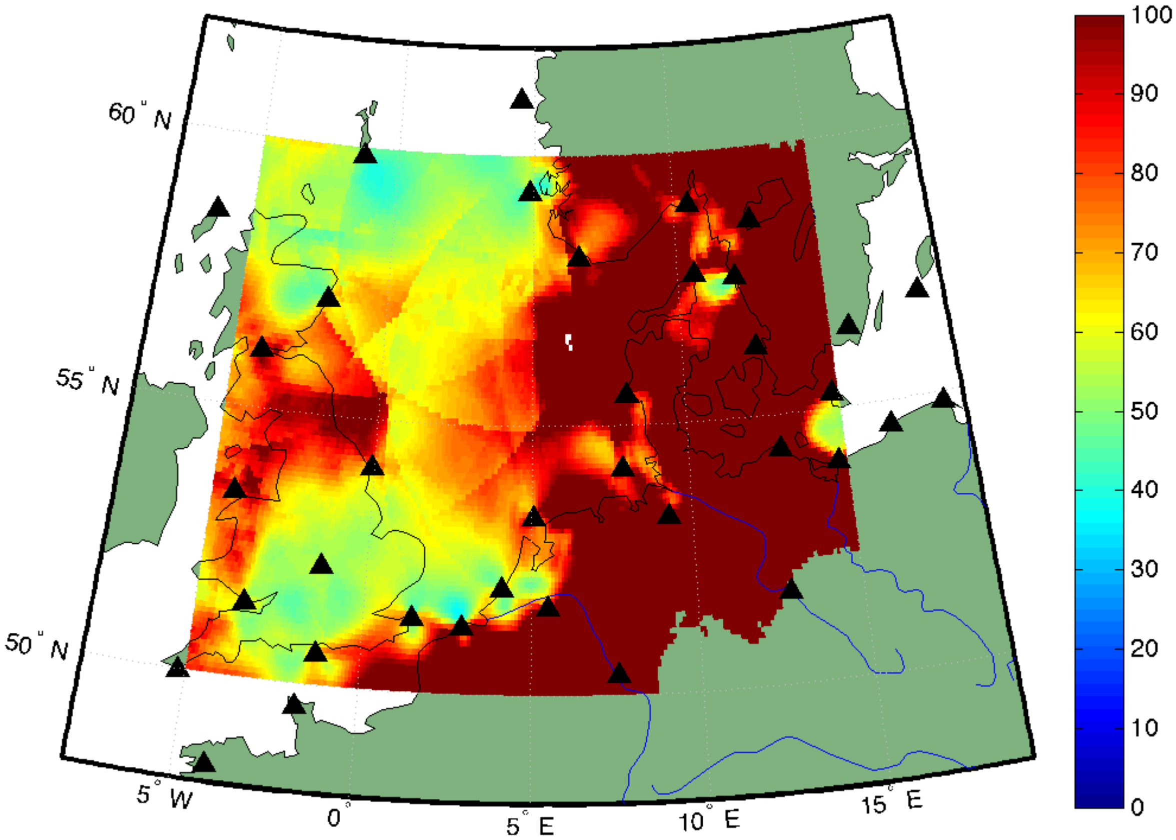


Figure 7: Lower bound to positioning accuracy of MF R-Mode (in meters) – night.

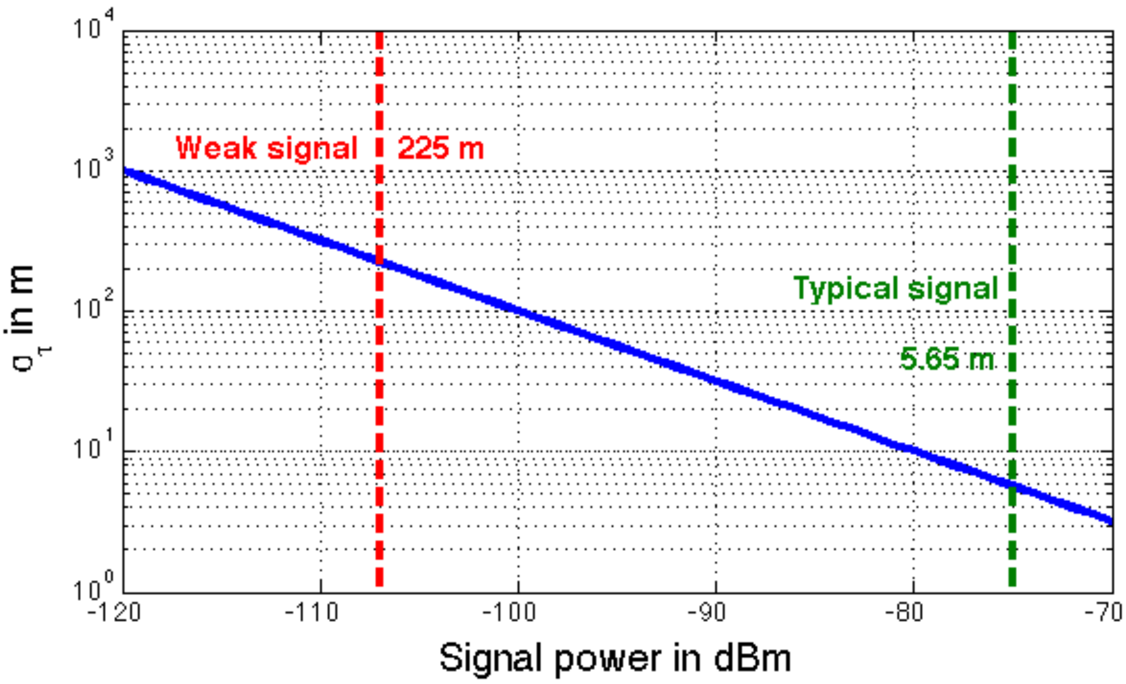


Figure 8: The Cramer-Rao lower bound on performance of estimating the time of arrival from the AIS bit transition as a function of the received signal level in dBm.

There are several important points to remember for AIS ranging:

- On its own, the time of a bit transition has an ambiguity of one symbol period, 26.67 msec or, in range, 31 km. Given that the propagation range for AIS for ranging is expected to be out to 75-100 km, the bit transition time has limited ambiguity to resolve. For example, if the start of each AIS message is clearly aligned with a fraction of a UTC second (or some other system-wide reference), then this ambiguity is eliminated by knowledge of which bit edge it is within the message.
- A second point is that this performance expression is the best possible (as predicted by a Cramer-Rao bound for the additive Gaussian noise model); actual performance will be somewhat worse.

2.2.2 Geometry and Signal Strength

As mentioned in 2.1.2 the quality of the position solution is impacted by the signal strength and distances and bearings to the beacon sites relative to the receiver; the effect of the bearings is captured in the HDOP. For R-Mode AIS these sites are the AIS base stations. In [6] the area of interest was further restricted from the North Sea area (20° of longitude by 10° of latitude, see Figure 5), to a smaller region to take into account the higher density and shorter range of the AIS system. Figure 9 shows this are (denoted region II), spanning 5° to 14°E longitude and 53.2° to 55° N latitude, and the relevant German, Danish, and Dutch AIS base stations (shown as black dots). These form a pretty dense network of transmitters in the North and Baltic Seas and on the Kiel Canal. Signal strengths for the AIS stations were predicted using software tools (described in more detail in [6]).

Figure 9 also shows the HDOP of these AIS sites for the restricted area of interest. In computing this figure we accounted for the following:

- At VHF frequencies, the signal primarily follows a Line Of Sight (LOS) propagation path. While under certain weather conditions ducting can occur, which allows the signal to be received at distances well beyond the LOS, we have restricted our analysis to signals that travel in a normal manner and use a distance threshold of 75 km.
- Many of the German AIS stations use multiple, directional antennas to concentrate the signal energy into sectors; we take this into account as well.
- As in 2.1.2 we restrict attention to usable signals, a signal level above -117 dBm for AIS R-Mode.

As can be seen from this figure, most of the study area has a very good (small) HDOP.

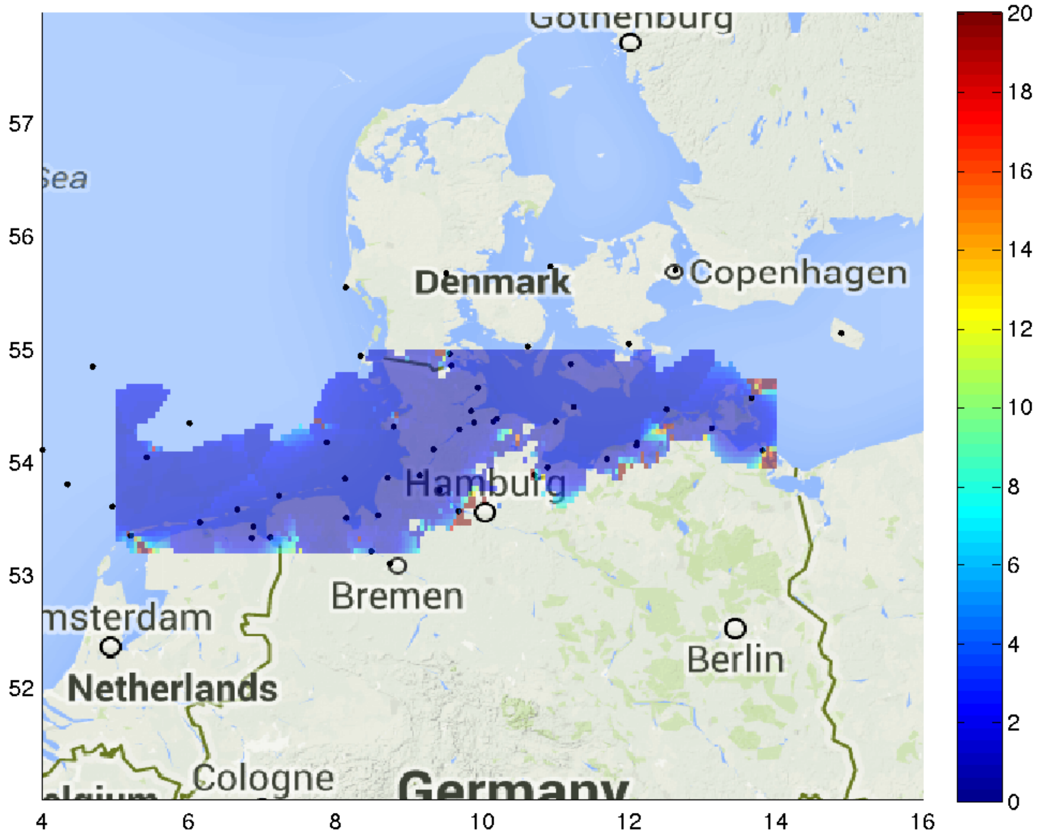


Figure 9: HDOP for the AIS base stations (shown as dots) in region II.

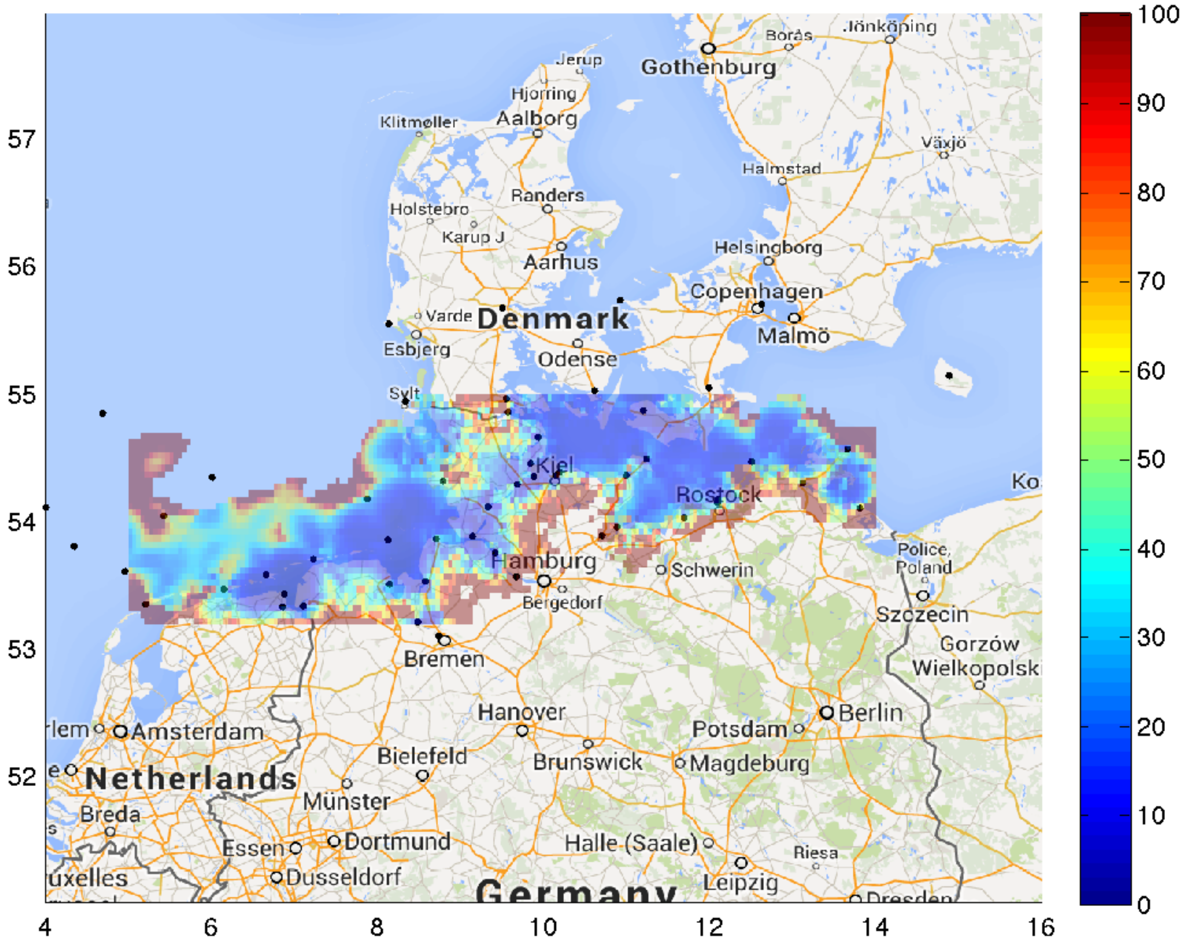


Figure 10: Lower bound to positioning accuracy of AIS R-Mode (in meters) in region II.

2.2.3 Positioning Accuracy

At a particular location, the pseudorange accuracy expression in 2.2.1 is evaluated using the predicted signal level for that location (computed using the method described above in 2.2.2) to provide the accuracy of each individual AIS pseudorange. These accuracy values are combined with the geometry of the stations (only those with signal strengths in excess of -117 dBm and within 75 km of the location) through a weighted HDOP calculation to provide a lower bound on the overall position accuracy (the general trilateration approach to computing the position and its accuracy for terrestrial RF TOA systems is described in 3.1). Figure 10 shows the result for AIS R-Mode in region II. As above, this plot does not take into account any additional errors due to timing offsets between the various transmitters (assumed perfect synchronization), nor does it take into account any multipath or other interference, only additive white Gaussian noise. For this analysis, 60 slots per minute (or one 256 bit slot per second) is assumed, and a receiver averaging time of 5 seconds for a total of 1,280 bits used.

2.3 eLoran

2.3.1 Estimating the TOA

Loran is a pulsed ranging system with a long history (see, for example, the years of proceedings of the Wild Goose Association and the International Loran Association). In [7] we examined the ranging performance of a typical Loran receiver as a function of the received signal strength (as measured at the third zero crossing). Figure 11, reprinted from [7], yielded an approximation to the accuracy of

$$\sigma_{Loran} \approx \sqrt{10^{\frac{123-SS}{10}} + \sigma_{jitter}^2} \ nsec$$

in which SS is the signal strength in units of dBμV and $\sigma_{\text{jitter}} = 60 \text{ or } 90$ nsec for a single or dual rated transmitter respectively (note that the referenced paper contained an error, replacing the constant 123 by 13). This expression is for a single received Loran pulse and must be scaled by the number of pulses averaged for the TOA estimate. As the scaling is reciprocal and follows the square root of the number of pulses, the equivalent expression would be

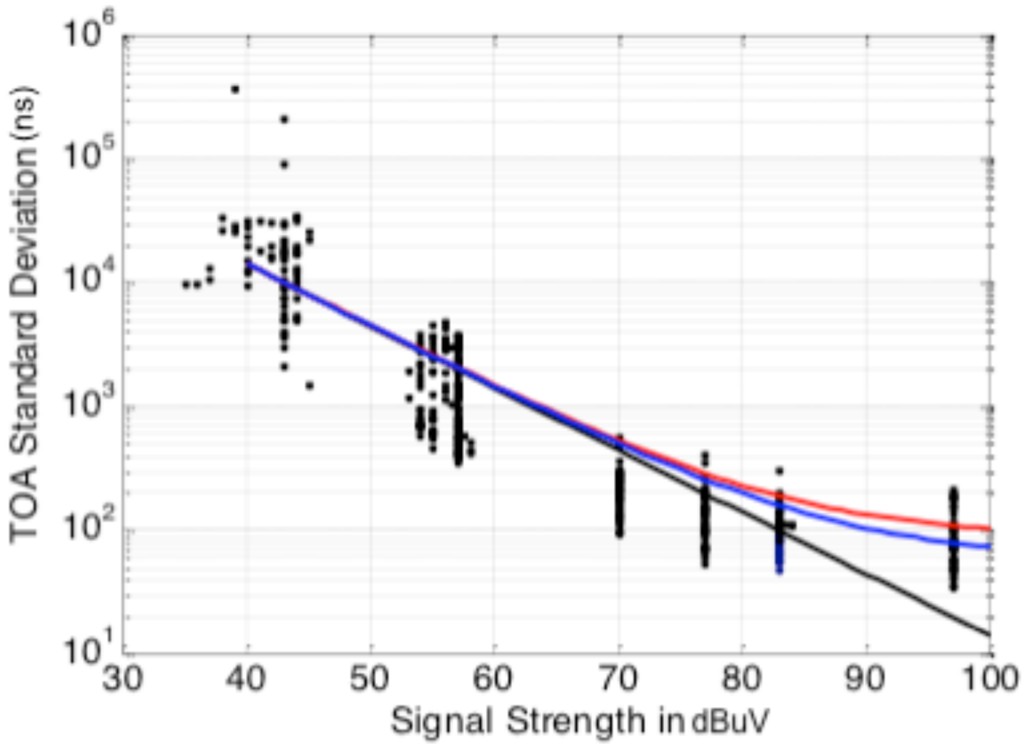


Figure 11: Typical performance of estimating the time of arrival from the eLoran signal as a function of the received signal strength in dBµV (reprinted from [7]).

$$\sigma_{TOA} \approx \sqrt{\frac{10^{\frac{123-SS}{10}}+\sigma_{jitter}^2}{number\ of\ pulses\ averaged}}\ nsec$$

Finally, converting to meters (0.3 meters per nsec)

$$\sigma_{TOA} \approx 0.3\sqrt{\frac{10^{\frac{123-SS}{10}}+\sigma_{jitter}^2}{number\ of\ pulses\ averaged}}\ m$$

For example, the dual rated Loran transmitter at Sylt transmits on two GRIs (Group Repetition Intervals), 6731 and 7499. In a 5-second period this is a total of approximately 1127 pulses (5 seconds × 10^6/67310 groups per second × 8 pulses per group = 594 pulses for the 6731 rate plus another 533 for the 7499 rate) of which a percentage is lost to blanking (for computational purposes, we assume that 10% of the second rate's pulses are blanked). So

$$\sigma_{TOA,Sylt} \approx 0.3\sqrt{\frac{10^{\frac{123-SS}{10}}+90^2}{1127\times 0.9}}\ m$$

There are several important points to remember for eLoran ranging:

- Similar to the MF DGNSS signal, the Loran signal is delayed by the characteristics of the ground over which it is traveling. These ASFs must be taken into account for positioning applications. Limited ASF maps have been generated for the Loran stations considered here, primarily for the Harwich harbour area; for example see [8].
- Loran receivers can suffer from multipath interference due to signal reflections off of the ionosphere (sky wave interference). This effect is most pronounced at night and at long distances. The Loran signal have been designed to mitigate this interference and at the shorter ranges considered here, these effects are negligible.

2.3.2 Geometry and Signal Strength

As already mentioned in 2.1.2 the quality of the position solution is impacted by the signal strengths and distances and bearings to the transmitter sites relative to the receiver; the effect of the bearings is captured in the HDOP. For eLoran in the North Sea area there are five relevant eLoran sites: Sylt, Lessay, Anthorn, Ejde, and Vaerlandet. Figure 12 shows the transmitter geometry with respect to the MF DGNSS evaluation area (the larger box covering the North Sea, region I), the AIS evaluation area (the smaller, inset box including Sylt, region II), and an even smaller area around the Kiel Canal and Elbe River, region III which covers from 53.4°N to 54.5°N latitude and 8.5°E to 10.5°E longitude.

Figure 13 shows the HDOP of these eLoran sites for the areas of interest. In computing this figure we restricted inclusion to strong signals, above 50 dBµV. As can be seen from this figure, the area within triads of eLoran towers has a very good (small) HDOP; to the east of Sylt the HDOP falls off dramatically.

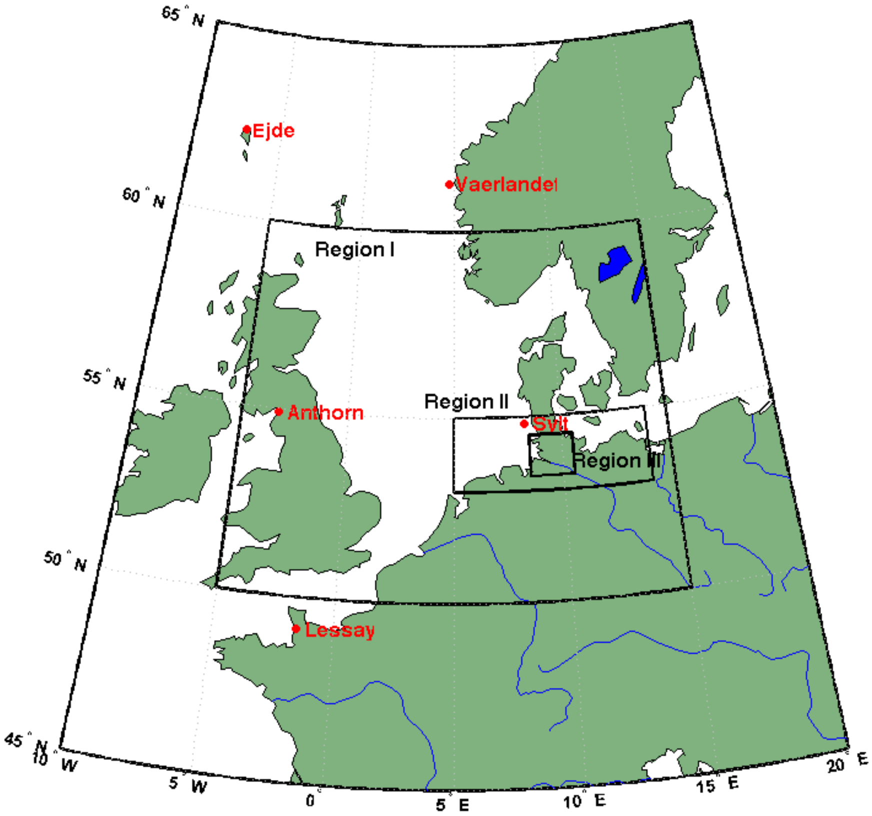


Figure 12: eLoran transmitter locations (shown as red dots) relevant to the three regions of interest (I, II, and III).

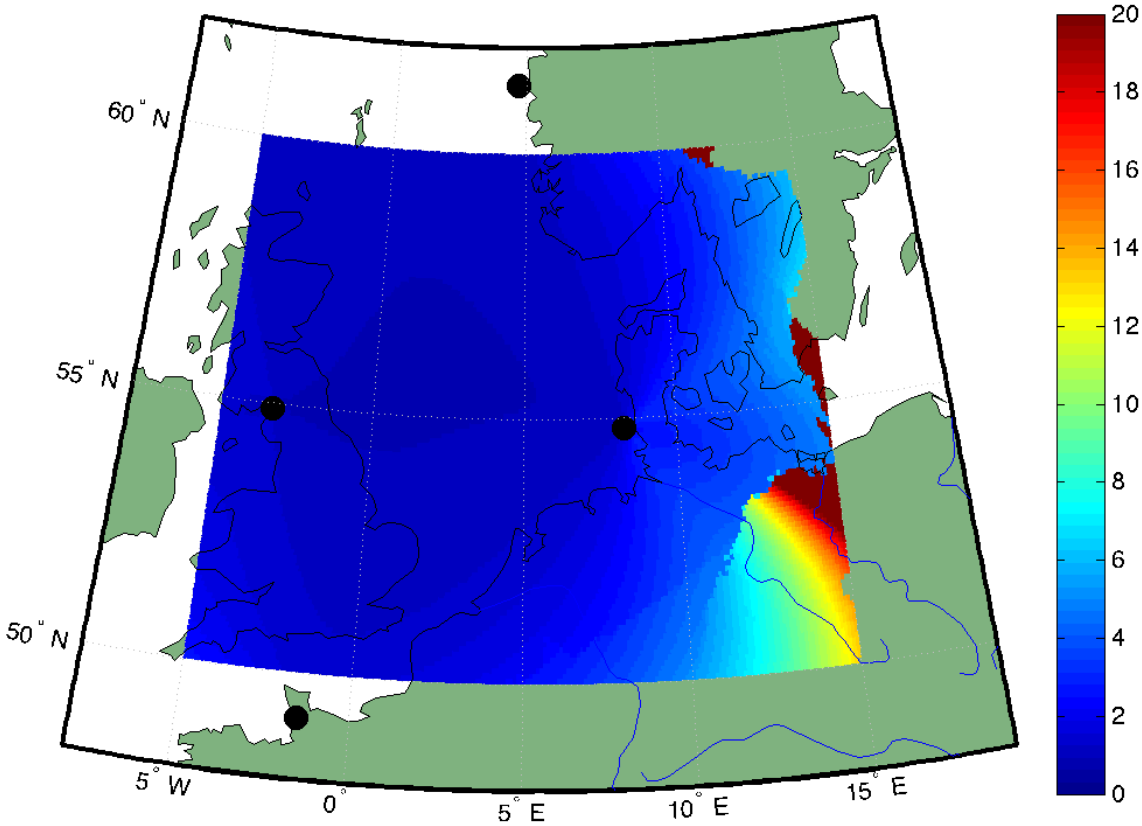


Figure 13: HDOP for the five eLoran stations in region I); Loran towers marked with black circles (Ejde is located to the northwest just off the plot).

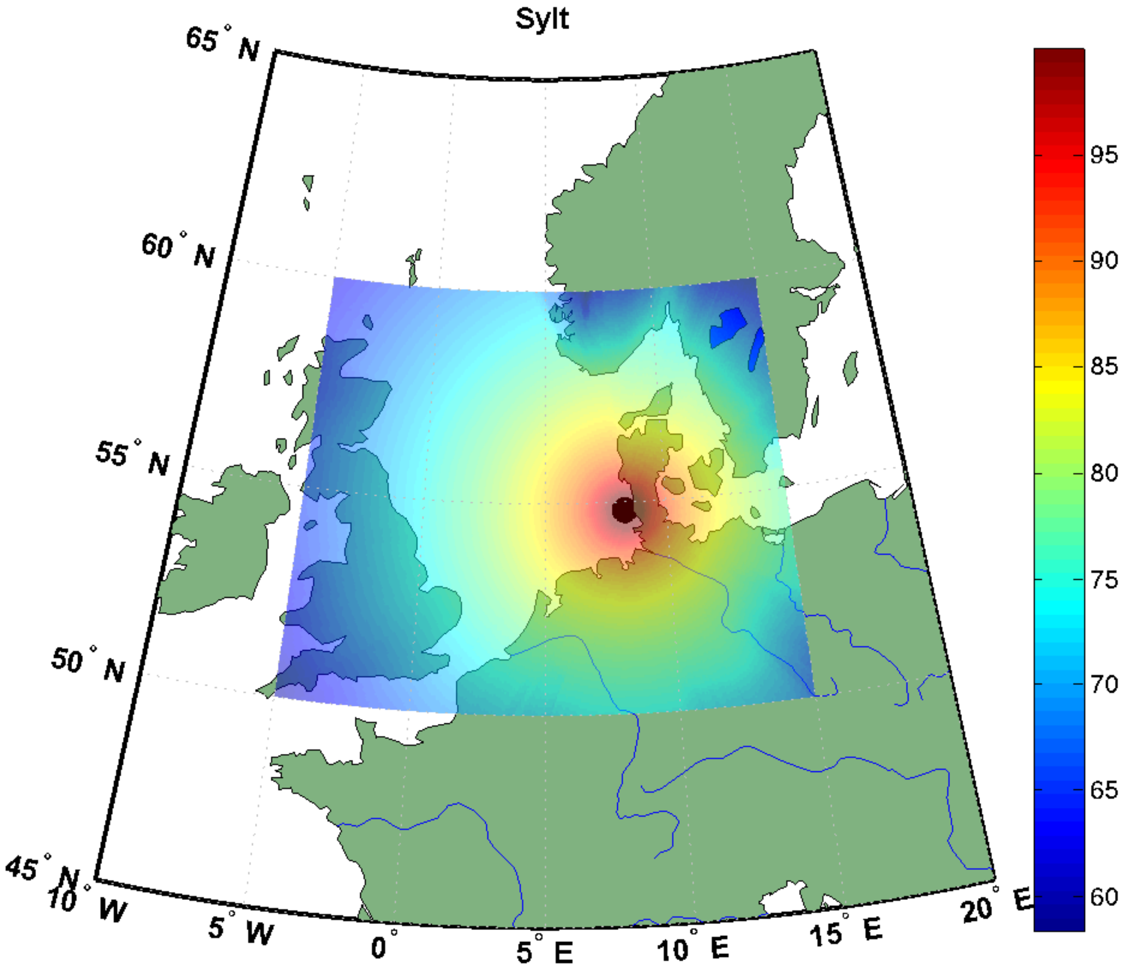


Figure 14: Predicted signal strength for a typical eLoran site, Sylt (in dBµV); Sylt's location is indicated by the black circle.

The typical method to predict loss of signal power with distance is to use software tools. For the eLoran assessment in this report, signal strengths were provided by the General Lighthouse Authorities of the UK and Ireland for region I. A sample signal strength plot, for the Sylt transmitter, is shown in Figure 14. Although not shown, as it lies outside the region I boundary, the signal coverage from Sylt extends much farther to the East which could be used along with the MF sites around the Baltic.

2.3.3 Positioning Accuracy

At a particular location the pseudorange accuracy expression in 2.3.1 is evaluated using the predicted signal strength for that location to provide the accuracy of each individual eLoran pseudorange. These accuracy values are combined with the geometry of the stations (only those with signal strengths in excess of 50 dBµV) through a weighted HDOP calculation to provide a lower bound on the overall position accuracy (the general trilateration approach to computing the position and its accuracy for terrestrial RF TOA systems is described in 3.1).

Figure 15 shows the result for eLoran for region I. This plot does not take into account any additional errors due to timing offsets between the various transmitters (assumed perfect synchronization) nor does it take into account ASFs.

We note that much of region I is within the area of the triangles formed by the five Loran tower locations; hence, the positioning performance on that area is quite good (sub 20 meters on this scale). Moving to the east we lose signals; hence, the rapid degradation in performance. At the very eastern end of the region of interest, in the northern and southern corners, we have fewer than the required three signals to compute a position.

It is possible that both Norway and France will discontinue eLoran operations at their sites; if this were to happen then eLoran positioning would NOT be possible in the North Sea area (signals from at least three separate transmitters are needed to compute latitude and longitude). If only Norway were to discontinue operations but France kept Lessay, then eLoran positioning would still be possible in the southern part of the North Sea. Figure 16 shows the predicted performance using just these three Loran towers (Sylt, Anthorn, and Lessay).

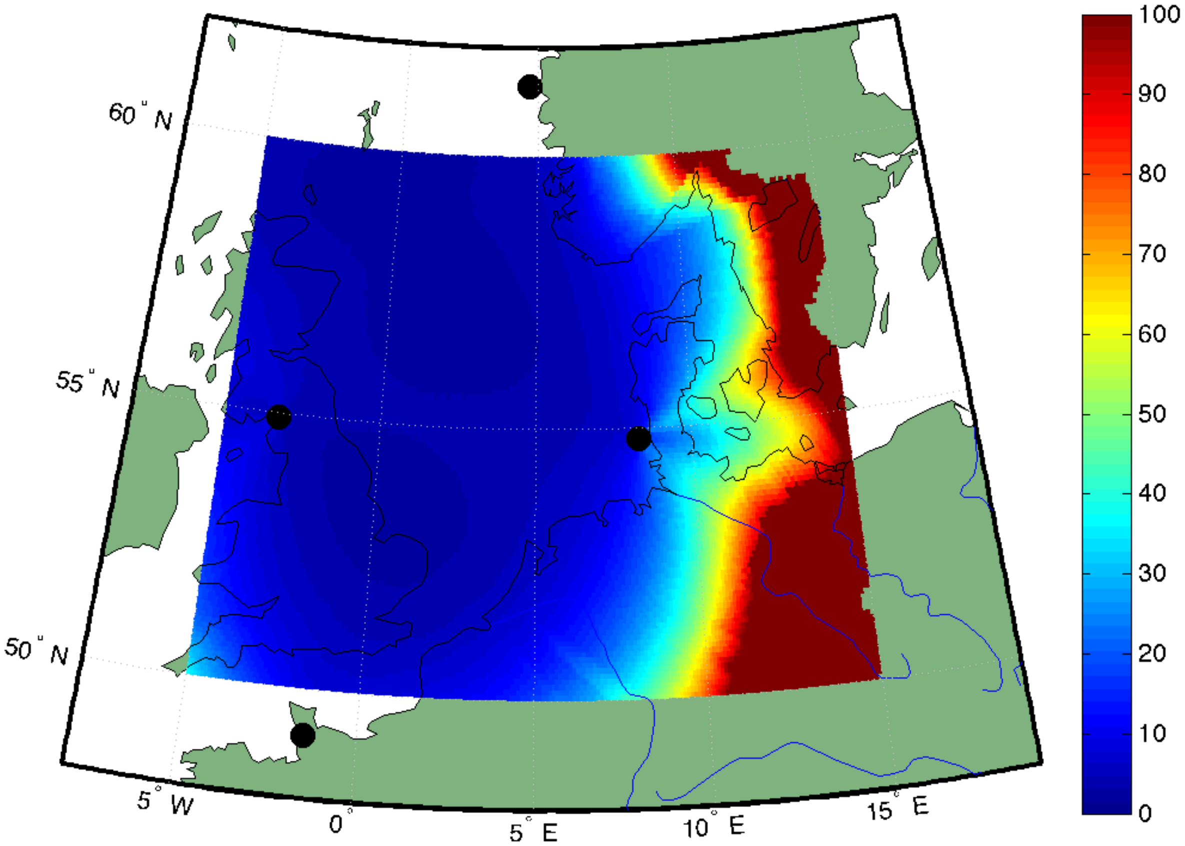


Figure 15: Lower bound to positioning accuracy of eLoran (in meters); Loran towers marked with black circles (Ejde is located to the NW just off the plot).

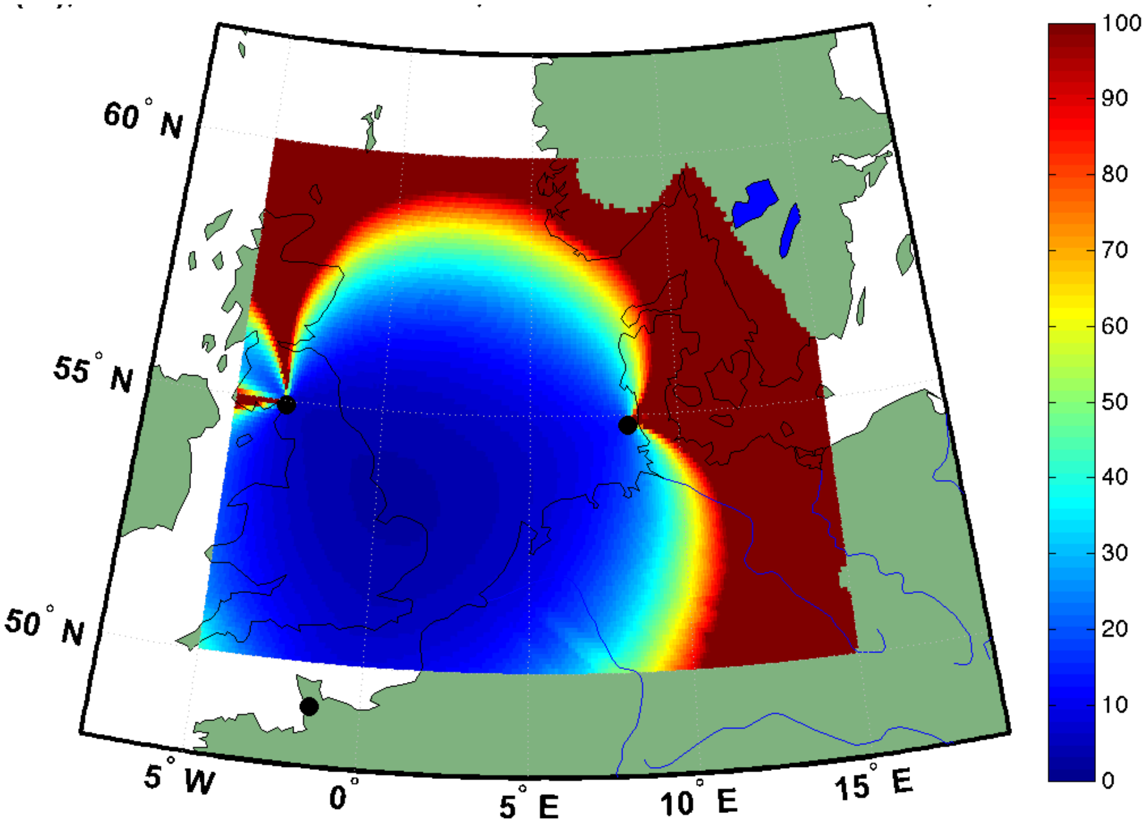


Figure 16: Lower bound to positioning accuracy of eLoran (in meters) with just three stations; Loran towers marked with black circles.

3 Combining Ranging Signals

3.1 The Truly "All-in-View" Receiver

The position solution (actually position and clock offset) from radionavigation TOA observables does not, in general, have a closed form solution. The usual approach is to assume some approximate position and iteratively solve a linearized version of the problem. For terrestrial systems (such as Loran) this is typically a weighted least squares solution with error weights dependent upon the accuracy of the individual TOA measurements [9]. Assuming n transmitters, at azimuth angles φ_k with respect to the assumed position, the linearized equations are [9]

$$\begin{bmatrix} sin\,\varphi_1 & cos\,\varphi_1 & 1 \\ sin\,\varphi_2 & cos\,\varphi_2 & 1 \\ \vdots & \vdots & \vdots \\ sin\,\varphi_n & cos\,\varphi_n & 1 \end{bmatrix} \begin{bmatrix} \delta x \\ \delta y \\ c\delta t \end{bmatrix} = c \begin{bmatrix} \delta TOA_1 \\ \delta TOA_2 \\ \vdots \\ \delta TOA_n \end{bmatrix}$$

in which δx, δy, and δt are the differentials in the x and y position and clock offset solutions, respectively (relative to the assumed solution), c is the speed of light, and each δTOA_k is the differential in the TOA measurement. It is common to write this in set of equations in matrix form as

$$A\delta = z$$

defining the directions cosines matrix (**A**), the vector of differential TOAs (**δ**) and the position/clock differential vector (**z**). The HDOP if defined by first computing

$$\boldsymbol{H} = (\boldsymbol{A}^T\boldsymbol{A})^{-1}$$

and then

$$HDOP = \sqrt{H_{1,1} + H_{2,2}}$$

Assuming independent TOA measurements, the covariance matrix of **z** is

$$\mathbf{R} = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_n^2 \end{bmatrix}$$

(i.e. white noise with variances σ_k^2 on the k^{th} TOA measurement), the weighted least squares solution using weight matrix $\mathbf{R}^{-1}$ is

$$\boldsymbol{\delta} = (\boldsymbol{A}^T\boldsymbol{R}^{-1}\boldsymbol{A})\boldsymbol{A}^T\boldsymbol{R}^{-1}\,\boldsymbol{z}$$

which has error covariance (a 3-by-3 result)

$$\boldsymbol{G} = (\boldsymbol{A}^T\boldsymbol{R}^{-1}\boldsymbol{A})^{-1}$$

The weighted HDOP is found as

$$\sigma_{position} = \sqrt{G_{1,1} + G_{2,2}}$$

(skipping the variance of the clock offset solution, $G_{3,3}$). Hence, to measure performance at a particular location, we need to know which signals are available, the geometry to the signals, and what their accuracies are.

Assuming that all observable signals are synchronized at transmission, there is no need to limit the measurements to being from one type of source. We can combine measurements from multiple sources as long as we have estimates of their individual accuracies (in the same units) and angles to the transmitters. Specifically, angles φ_k, differential measurements δTOA_k, and variances σ_k^2 could come from MF for $k = 1,2,\ldots n_1$, from AIS for $k = n_1+1,\ldots n_2$, and from eLoran for $k = n_2+1,\ldots n$.

Note that the addition of new measurements from additional transmitters cannot increase the HDOP or weighted HDOP. At worst, if the new transmitter's location is at the same azimuth as a current transmitter, the HDOP and weighted HDOP stay the same [10].

Figure 17 contains a block diagram of such a combined signal, "all-in-view" R-Mode receiver. It essentially combines the TOA processing of separate MF, AIS, and eLoran receivers with a common "position calculation" block implementing the algorithm just described. For simplicity the diagram shows three distinct antennae although eLoran and MF DGNSS could potentially share an antenna due to their closeness in frequency.

3.2 MF DGNSS and eLoran

For a first example of combined performance, consider MF DGNSS R-Mode plus eLoran on the full North Sea area, region I.

3.2.1 Performance Analysis

Accuracies for MF R-Mode and eLoran alone are shown in Figure 6 (MF-day), Figure 7 (MF-night), and Figure 15 (eLoran). Since the performance of both eLoran and MF alone during the day is good; we have presented the combination only for the night when MF performance alone is poor (see Figure 18). The addition of eLoran improves performance of the night time MF considerably. The addition of MF to eLoran, improves performance in the western Baltic Sea area and allows for position solutions in the northeast and southeast corners of region I. Although not shown, as it lies outside the region I boundary, the signal coverage from Sylt extends much farther to the east which could be used along with the MF sites around the Baltic Sea.

If France and Norway do shut down their Loran stations then it becomes impossible to do an eLoran solution in the North Sea. However, the addition of one or two Loran stations can improve MF performance considerably at night; see Figure 19 for the night performance using just Sylt and Figure 20 for the night performance using both Sylt and Anthorn. The coverage "hole" seen at night in the middle of the region can be partially filled by adding an MF transmitter at Ekofisk as discussed in the Milestone 2 report (see Figure 21).

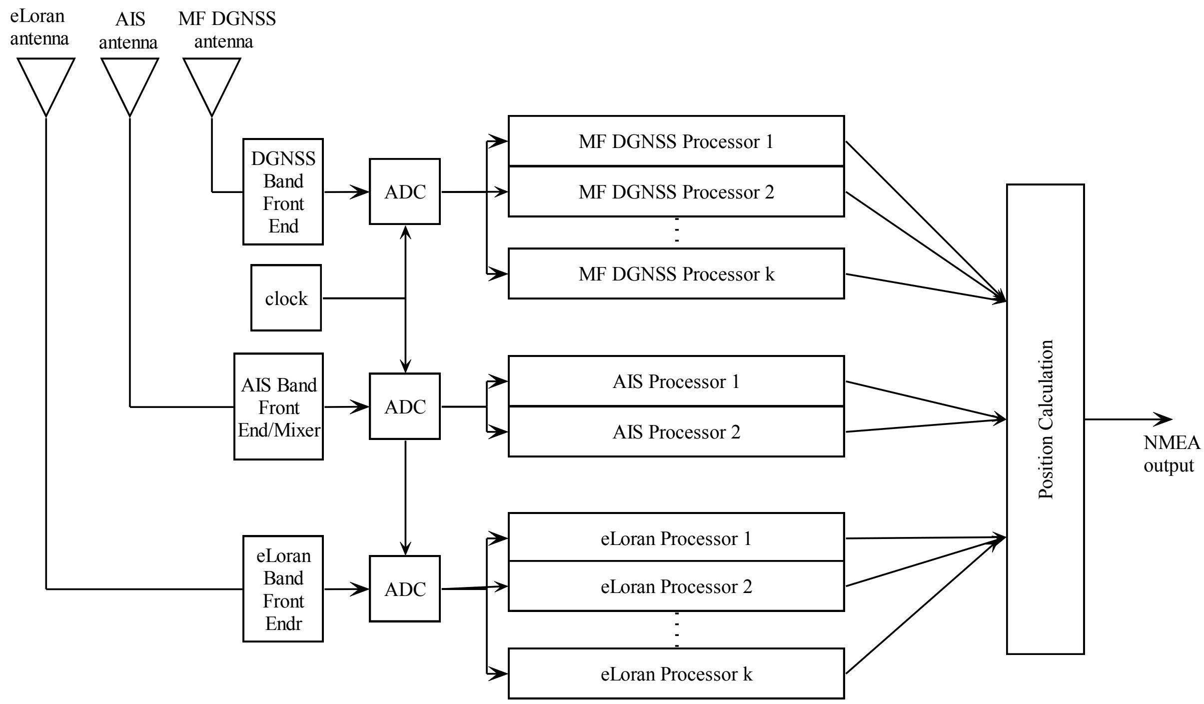


Figure 17: MF+AIS+eLoran "All-in-View" R-Mode receiver.

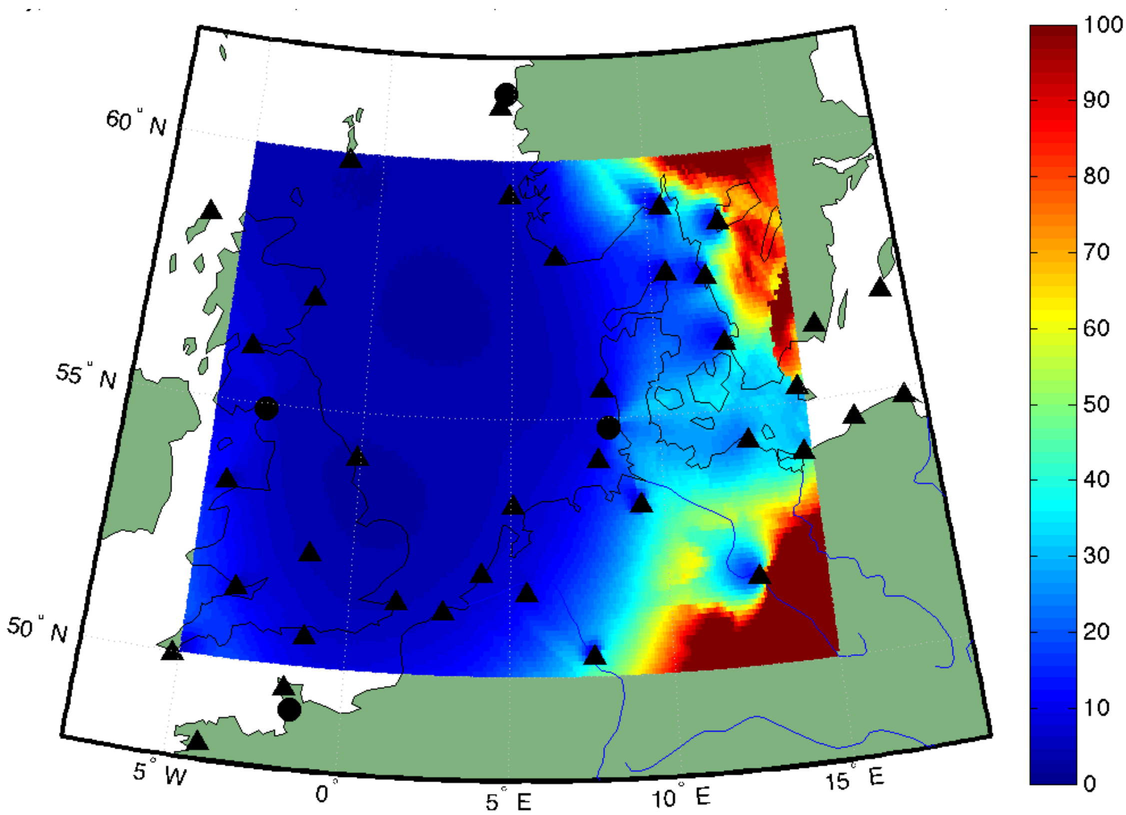


Figure 18: Lower bound to positioning accuracy of combined MF R-Mode and eLoran on region I – night.

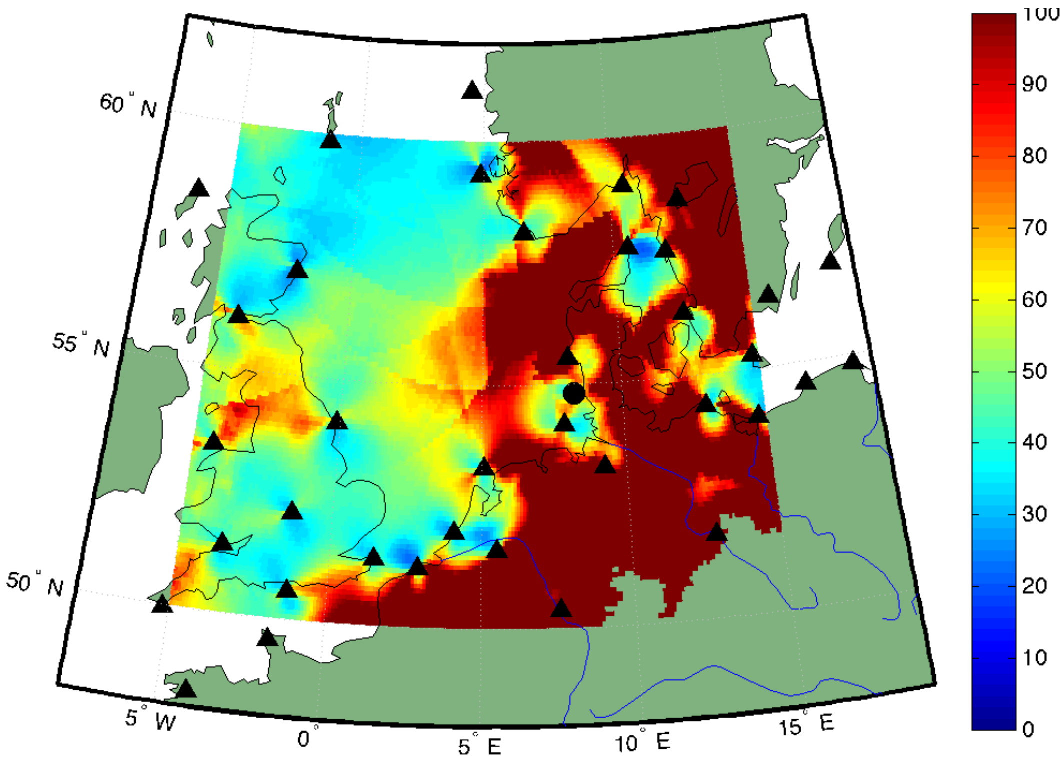


Figure 19: Combined MF and eLoran (Sylt only) on region I – night.

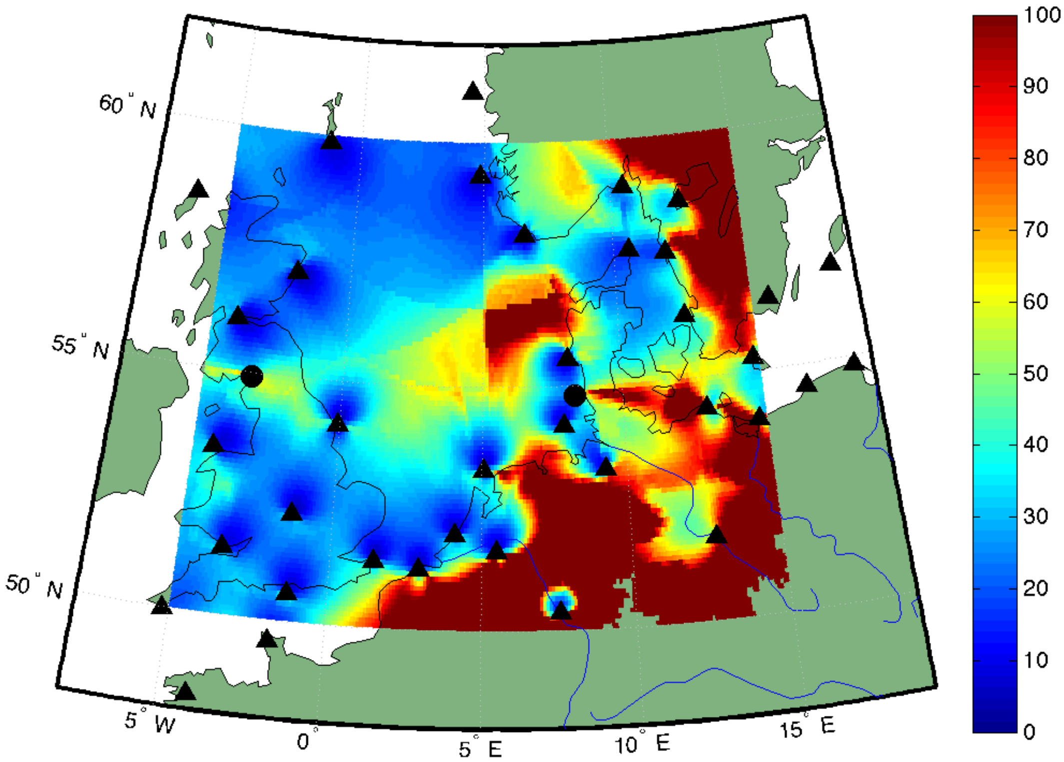


Figure 20: Combined MF and eLoran (Sylt and Anthorn) on region I - night.

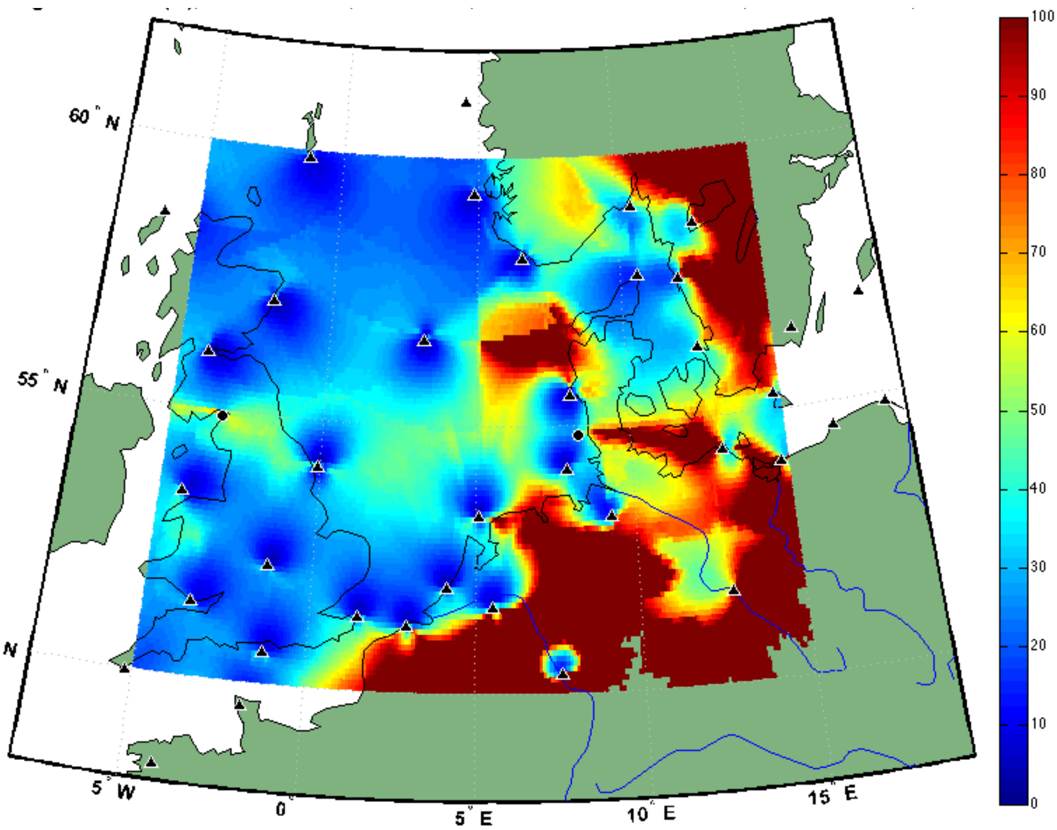


Figure 21: Combined MF and eLoran (Sylt and Anthorn) on region I – night with Ekofisk added.

We note the following for this example:

- During the day the potential performance of MF R-Mode is great; there is very little improvement seen by adding eLoran ranges. Except, as noted above, MF R-Mode requires a solution for cycle ambiguity; reception of even a single eLoran signal can assist with this ambiguity resolution.
- eLoran (the full system) is already quite effective in this region by itself so there is little improvement seen by adding MF (especially at night when MF performance is worse than the day). The primary aid is to the east where eLoran coverage is limited.
- If eLoran is reduced to only 1 or 2 towers then an eLoran solution is not possible. However, adding only 1 or 2 towers to MF can improve MF performance considerably at night.
- There has been some discussion in the industry for a low-power Loran system that might be lower cost; this is not needed in the North Sea area as Sylt and Anthorn are available and if additional sites are needed for HDOP reasons, then it is probably cheaper to install additional MF sites.

3.3 MF DGNSS and AIS

For a second assessment of combining R-Mode signals, consider a joint MF/AIS receiver. As the examination of AIS R-Mode alone (in [6]) restricted attention to areas near the German AIS network (region II), including the German bight, this example focuses on combined performance in that area.

3.3.1 Performance Analysis

To assess performance we consider both day and night conditions (due to the effects of sky wave interference on MF at night). Figure 10 showed the performance of AIS R-Mode alone. The lack of coverage in the northwest and southeast is apparent; the fringes of these areas, with only 3 nearby transmitters, exhibit poor positioning performance. The central region of this figure, with many AIS transmitters visible, sees better performance. Figure 6 and Figure 7 showed the performance of MF R-Mode alone for region I, day and night, respectively. Figure 22 and Figure 23 zoom in on these figures for region II. The accuracy of MF alone during the day is good over the majority of region II; at night, sky wave interference limits performance.

The combined bounds on performance are shown in Figure 24 (day) and Figure 25 (night). Adding AIS improves the performance during the day only slightly since the MF performance during the day is already quite good. The prime advantage would be as an additional aid to the ambiguity resolution. At night, the MF performance alone is very poor, and the AIS is good near the AIS stations; combining the two increases the area of good performance somewhat over AIS alone.

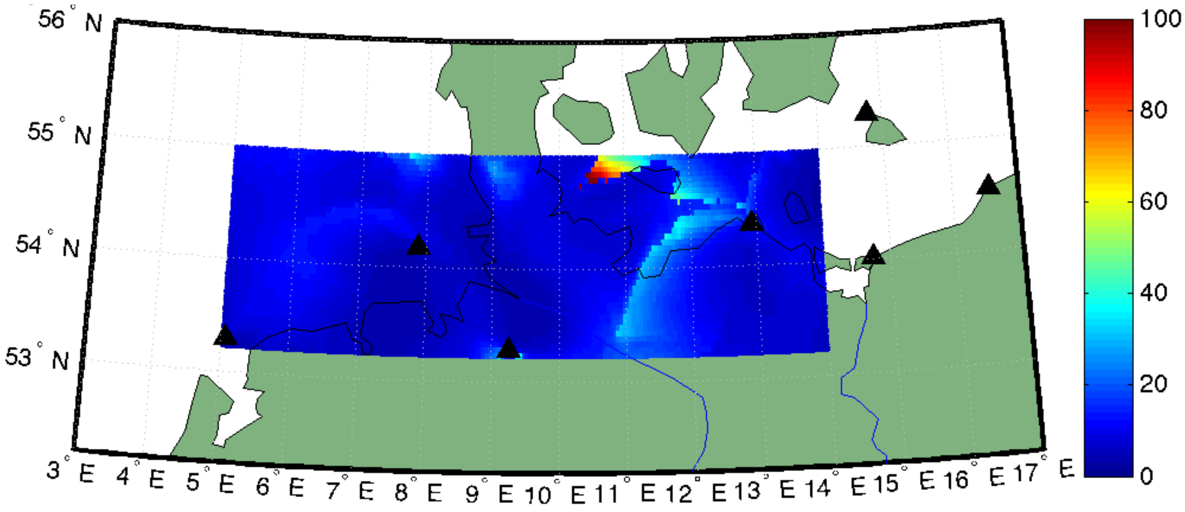


Figure 22: Lower bound to positioning accuracy of MF R-Mode on region II – day.

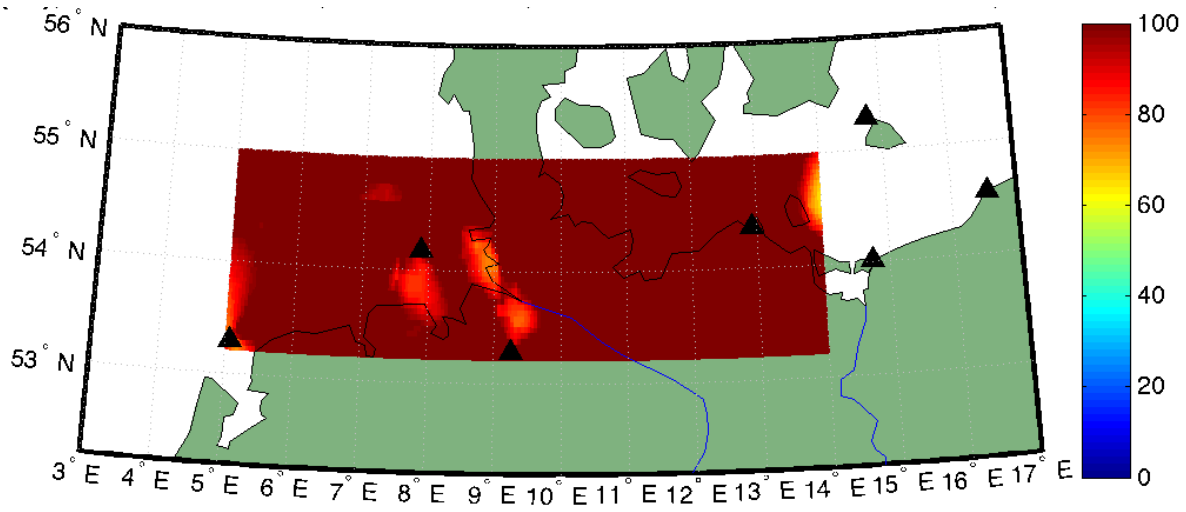


Figure 23: Lower bound to positioning accuracy of MF R-Mode on region II – night.

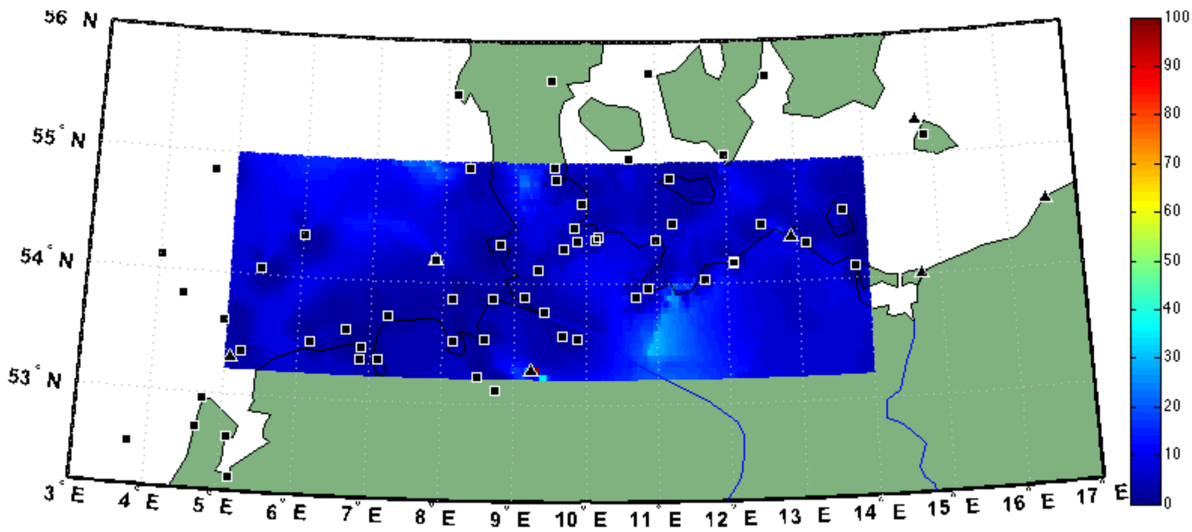


Figure 24: Lower bound to positioning accuracy of combined MF and AIS R- Mode on region II– day. MF beacon locations are triangles, AIS stations are squares.

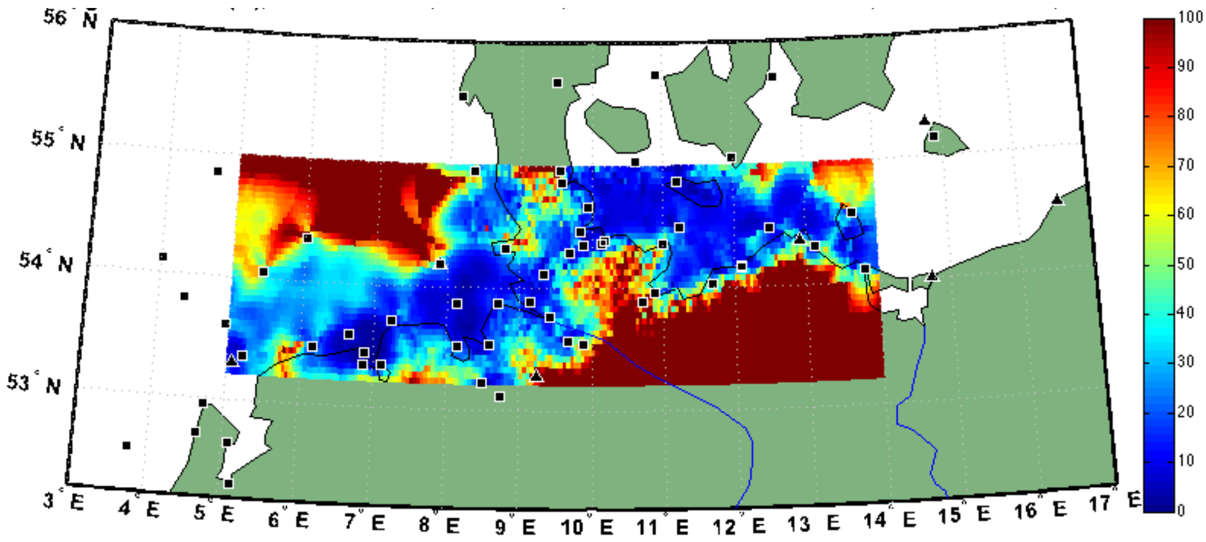


Figure 25: Lower bound to positioning accuracy of combined MF and AIS R-Mode on region II – night. MF beacon locations are triangles, AIS stations are squares.

We note the following:

- During the day, the only real benefit to the combination is AIS can be used to aid in the ambiguity resolution on the MF.
- At night, combining MF and AIS provides no significant improvement over AIS alone.
- Although there is a high density of both MF and AIS stations in the North Sea area, this is not globally true; combining AIS and MF could make positioning possible in areas where there is insufficient of either type of station alone.

3.4 MF DGNSS, AIS, and eLoran

3.4.1 Performance Analysis

The Milestone 4 report [6] also recognized that some portions of this study area are more important than others; for example, the waterways of the Kiel Canal and the Elbe River as far as Hamburg. The next analysis focused on these waterways inside a boundary box of 53.4° to 54.5° N latitude and 8.5° to 10.5° E longitude (region III). Figure 26 shows the potential performance in this region for AIS R-Mode alone. While some portions of this area appear to have moderate to good performance, the performance on the canal and river, themselves, is limited by the fact that the existing AIS transmitters follow the waterways, effectively in a straight line (which is poor from a DOP perspective). In [6] we demonstrated that it would be possible to improve AIS R-Mode performance along the canal and river by including the AIS base station at Hamburg (operated by the Port of Hamburg) and adding several new AIS transmitter sites. Another option to improve performance along these critical waterways would be to combine existing MF, AIS, and/or eLoran signals in this area. Several combinations are possible.

- As a first option consider combined AIS and MF R-Mode. Figure 27 shows the resulting performance bound for day; not unexpectedly (based upon Figure 6), the performance is excellent. Figure 28 shows the performance bound for night; even though MF R-Mode is susceptible to sky wave, we do see small improvement near Hamburg.
- A second option would be to combine AIS and eLoran. Since the AIS performance along the canal and river are primarily limited by geometry, consider the addition of only the Loran signal from Sylt. Figure 29 shows the resulting performance bound. In comparison to Figure 26 performance along the canal and river are much improved.
- Finally, consider combining AIS, MF, and eLoran. Figure 30 shows the resulting night performance bound (Sylt only). As expected there is slight improvement, but not especially along either critical waterway. Including Anthorn as well (Figure 30), improves performance some as expected. In the figures, AIS sites are squares, MF sites are triangles, and eLoran sites are circles.

We note the following for the various options in region III:

- Focused on night as limiting case (for MF).
- During the night, no individual system provides 100% high-accuracy coverage along the critical waterways.
- During the night, the combination of eLoran and AIS provides good high-accuracy coverage (slightly better than AIS-MF).
- Adding MF to AIS and eLoran improves performance slightly over AIS and eLoran alone.

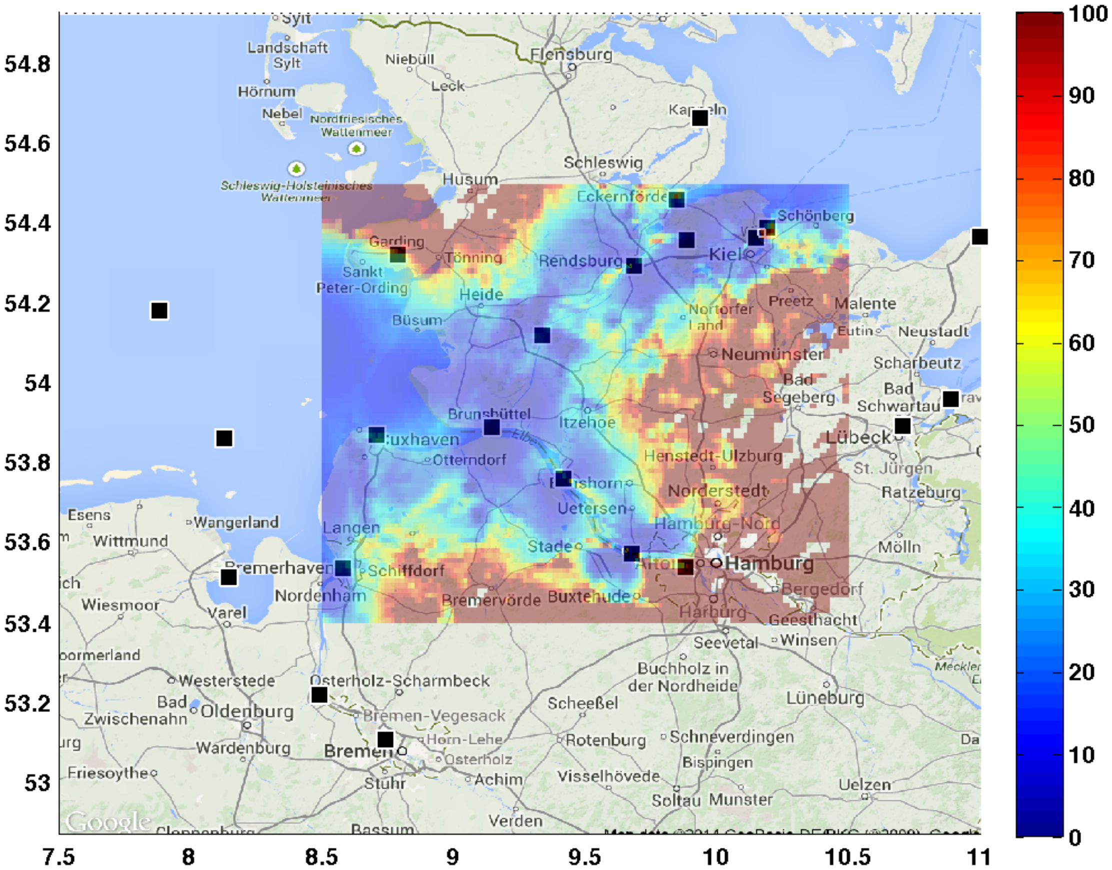


Figure 26: Lower bound to positioning accuracy of AIS R-Mode on region III (in meters)

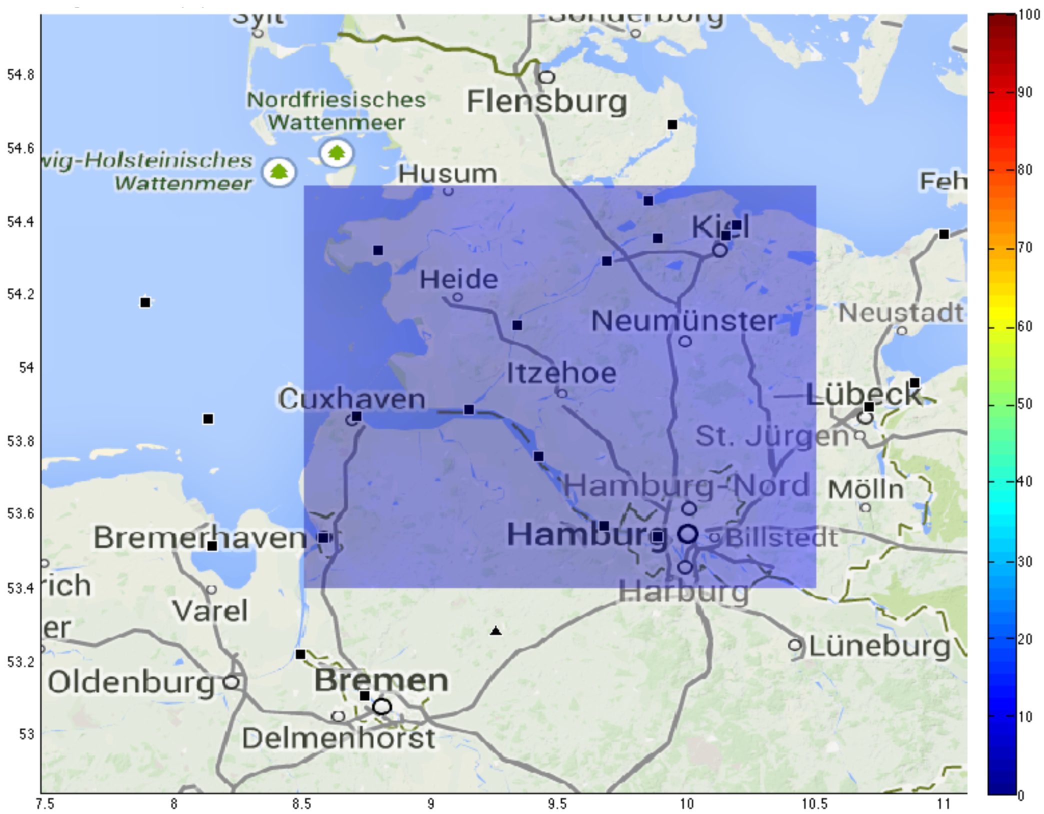


Figure 27: Combined AIS and MF R-Mode performance on region III – day; AIS sites are squares, MF sites are triangles.

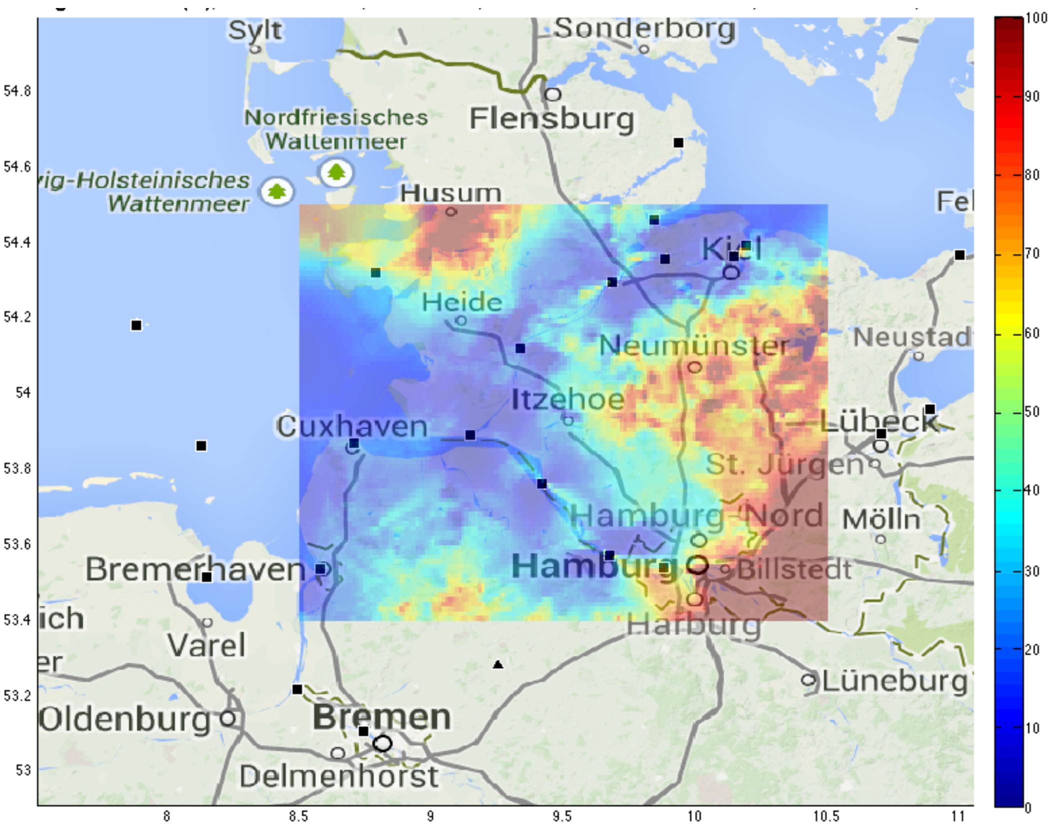


Figure 28: Combined AIS and MF R-Mode performance on region III – night.

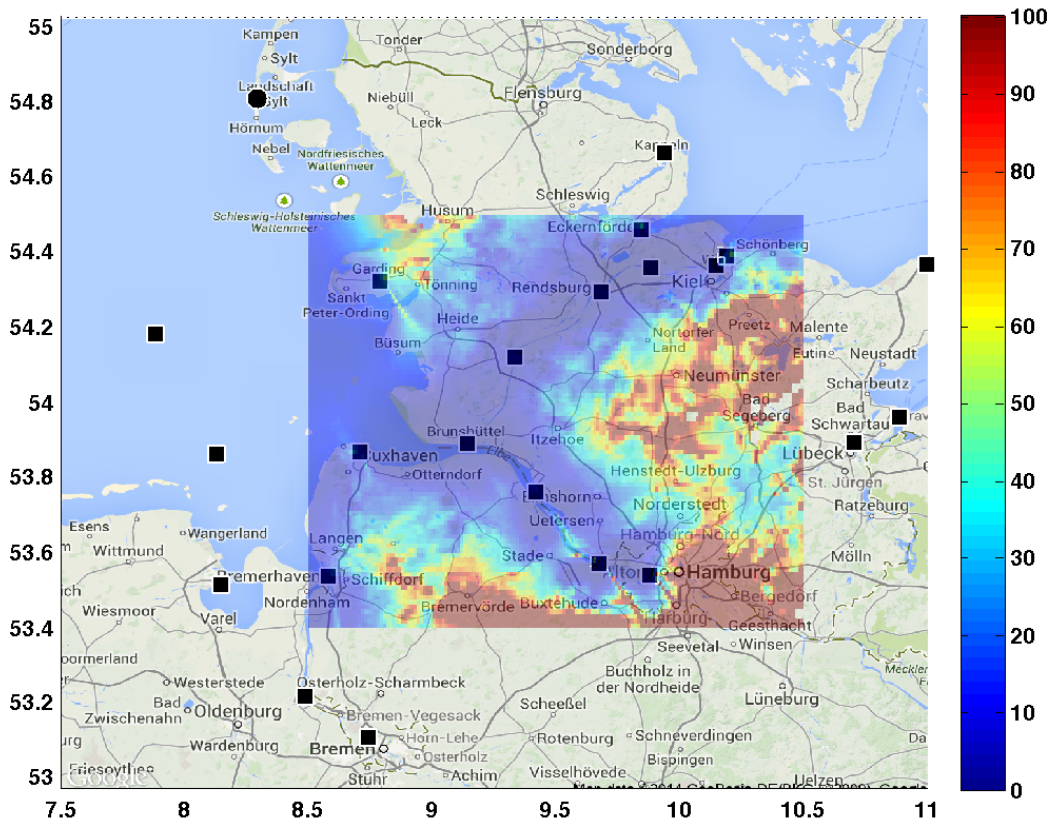


Figure 29: Lower bound to positioning accuracy of combined AIS and eLoran (Sylt only) on region III.

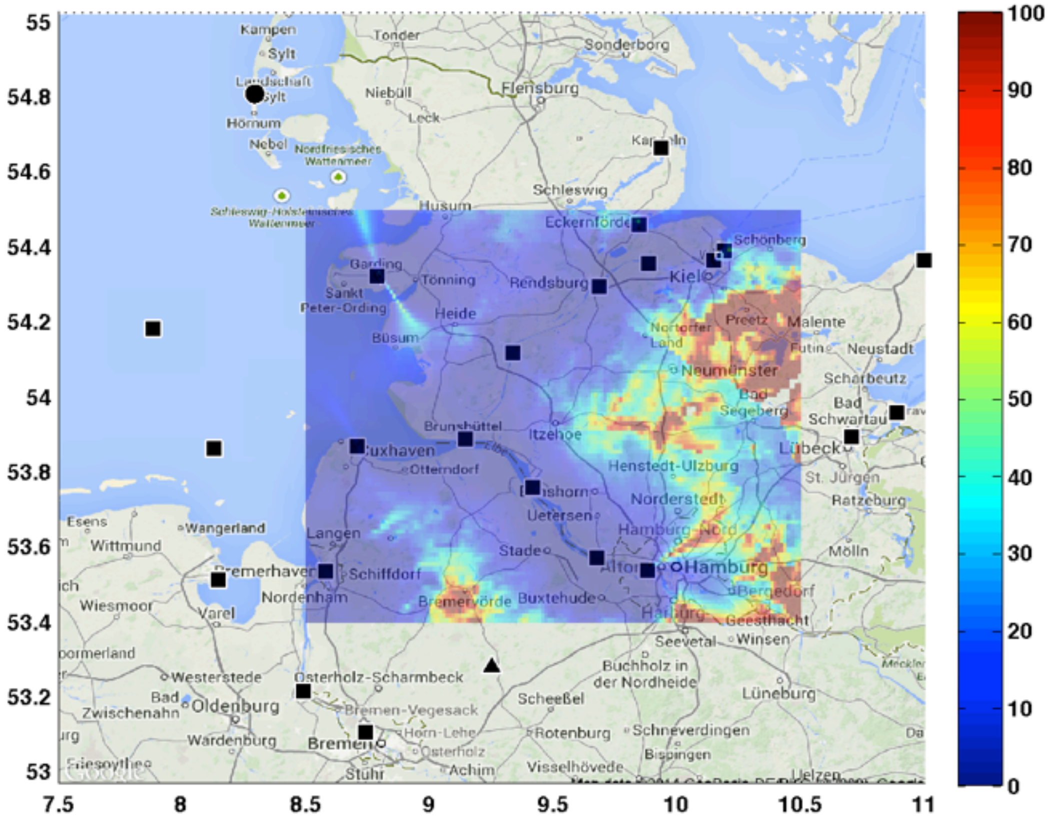


Figure 30: Combined MF, AIS, and eLoran (Sylt only) on region III – night.

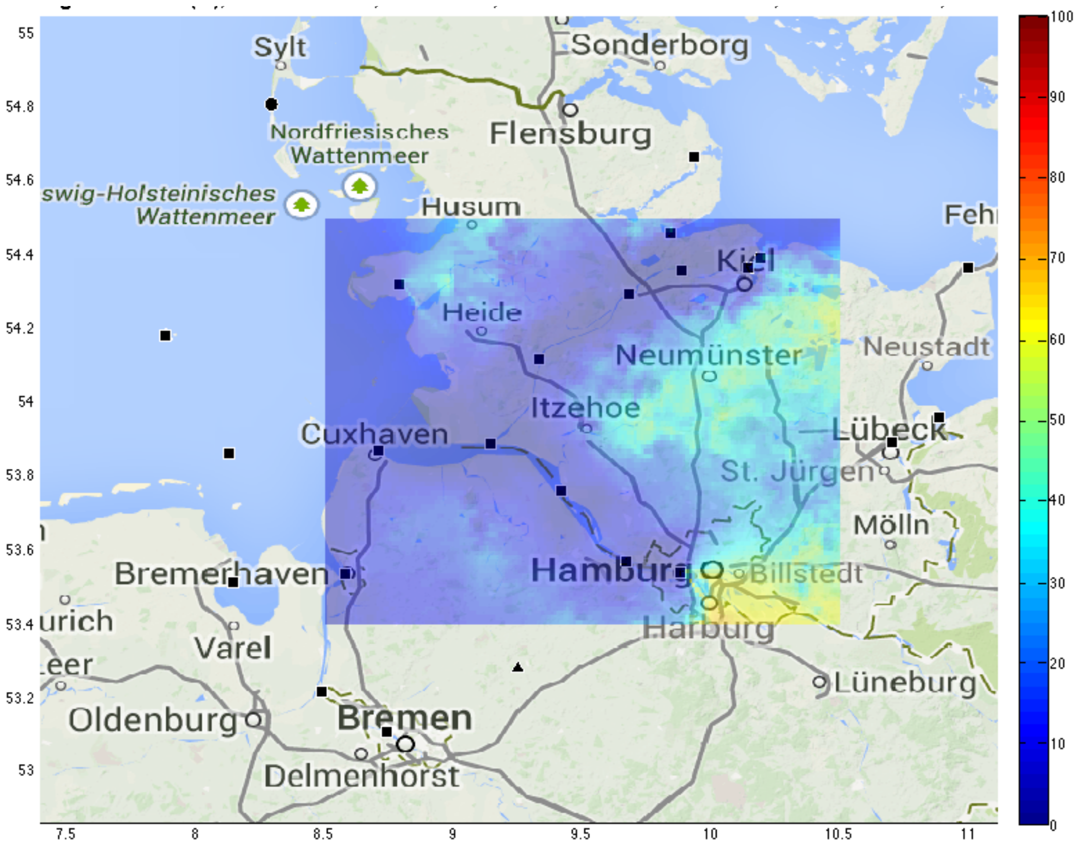


Figure 31: Combined MF, AIS, and eLoran (Sylt and Anthorn) on region III – night.

4 Conclusions

DGNSS R-Mode is a backup to GNSS that can meet the resilient PNT requirements of e-Navigation. The daytime bound on R-Mode positioning using TOA accuracy bounds is very good – better than 10m accuracy in most of the North Sea Area. The R-Mode performance at night is about a factor of 10 worse than daytime performance, but still better than 100m accuracy for most of the North Sea Area.

AIS R-Mode is a backup to GNSS that can meet the resilient PNT requirements of e-Navigation. Predicted accuracy of 10m appears achievable using the existing system with **no** modifications other than adding some additional transmissions. There is also no day / night difference in system performance.

While both signals display the potential for SoOP positioning, the MF DGNSS and AIS signals have some limitations in an R-Mode application:

- MF DGNSS ranging (based upon the CW carrier phase) appears to offer good performance during the day, but its performance is limited by sky wave interference at night. Further, the carrier cycle ambiguity must be resolved so as to yield a unique position solution.
- AIS ranging (based on the bit edge) is not impacted by sky wave (being a line of sight signal), but has limited coverage due to the finite range of this LOS propagation.

Conceptually, combining the signals together in an "all-in-view" R-Mode receiver, and potentially including eLoran into the mix (which is currently available in the North Sea area), should yield improved positioning performance. Several combinations were considered on different areas in and around the North Sea.

The combination of MF and eLoran was explored in an area (region I) covering a large part of the North Sea. Similar to the MF and AIS combination, performance pretty much matched that of the better individual system. In other words, the existing eLoran network provides good performance in region I as does the MF solution during the day. In the event that there was not a full eLoran network, adding even just a single eLoran station (such as Sylt) can improve the performance of the MF solution at night. In addition, any such signal can help with the required MF cycle ambiguity resolution.

The combination of MF and AIS was explored in an area (region II) containing the German bight and parts of the western Baltic Sea. During the day, MF DGNSS ranging alone appeared to offer good performance due to the high density of MF beacons in the region; the only real benefit of the combination with AIS is that the AIS bit edge can be used to aid in ambiguity resolution on the MF CW signal. At night, the combination of MF and AIS showed only slight improvement over AIS R-Mode alone. We note, however, there is a high density of both MF DGNSS and AIS (base station) transmitters in the region examined. This is not globally true (e.g. the density of MF beacons in the US is low), so combining AIS and MF signals could make positioning possible in areas where there is insufficient of either type of signal alone.

Table 1 summarizes the potential synergy gained by combining pairs of signals; the table separates MF into both day and night entries due to significant difference in potential performance. Similarly, eLoran is separated depending upon the number of transmitters operating (all 5 visible in the North Sea or a subset). Note that:

- Individual rows in the table correspond to the primary signal source; the first column lists the most significant issue(s) regarding performance for each.
- The columns correspond to the secondary signal; each entry is a quantized measure of how much synergy is created by adding that secondary signal. The scale is:
  - "none" (white) – this entry is only employed for the secondary signal of MF at night since MF is so impacted by sky wave as to be of little value in this case.
  - "little" (blue) – while the secondary does help to improve the issue, the amount is insignificant.
  - "some" (light green) – the second signal helps with the issue, but does not completely remove the problem
  - ✔ (dark green) – the second signal provides more significant progress toward resolving the issue

The combination of MF, AIS, and eLoran was explored in a small area around the Kiel Canal (region III). In this area all three signals themselves are severely limited: MF is limited by fewer signals and sky wave at night; the local AIS base stations, while plentiful, had poor geometry and limited range; and the region is outside of the eLoran triads so exhibits poor eLoran DOP. Combining signals, it was seen that good positioning performance can be achieved, even during the night. As expected, the more signals, the better the performance.

In summary, depending upon availability, 1 or 2 eLoran signals can be combined with AIS and MF DGNSS to offer improved performance. In general performance results are strongly position dependent – in many areas one system (signal type) dominates performance. Also, as expected, more signals results in increased performance (or at least no worse). To achieve widespread (global?) resilient PNT, the best solution is to use all signals available in a true all-in-view receiver.

Table 1: Pairwise synergy of the signal choices.

PRIMARY SIGNAL	Issue(s) concerning primary signal	SECONDARY SIGNAL					
		AIS	MF day	MF night	eLoran 5	eLoran 2	eLoran 1
AIS	coverage limited by tower locations		✔	none	✔	some	little
MF day	needs ambiguity resolution	little			some	some	some
MF night	needs ambiguity resolution; skywave limits accuracy	✔			✔	some	little
eLoran 5	coverage limited by tower locations	little	little	none			
eLoran 2	no stand alone position is possible	some	✔	little			
eLoran 1	no stand alone position is possible	some	✔	little			

It should be noted that the coverage analysis has been based on using existing transmitter sites only. Additional sites could certainly be added (eLoran, MF, or AIS) in areas where needed. A cost-benefit analysis to address the benefits of this has not been part of this feasibility study and would need to be done on an area-by-area basis. This is left as work for the future. In addition, the position and time requirements for a back-up system have **not** been established yet; this would need to be done prior to undertaking a cost-benefit analysis.

5 References

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