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Feasibility Study of R-Mode using AIS Transmissions

Investigation of possible methods to implement a precise GNSS independent timing signal for AIS transmissions

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Executive Summary

High precision positioning in the maritime domain has been 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. Of interest to this study is the use of the Automatic Identification System (AIS) broadcasts as a SoOP.

AIS broadcasts are in the Very High Frequency (VHF) maritime mobile band (156.025 - 162.025 MHz) and currently transmit information both ship-to-shore and shore-to-ship (the base station broadcasts) using Gaussian minimum shift keying (GMSK) in a time division multiple access (TDMA) mode. This report considers several VHF-based solutions to provide a Ranging Mode (R-Mode) Position Navigation and Timing (PNT) alternative to GNSS. 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.

AIS R-Mode is a backup to GNSS that can meet the resilient PNT requirements of e-Navigation. Resilient PNT is one of the seven pillars of the IMO overarching e-Navigation architecture.

In the Milestone 3 report, a variety of potential ideas and methods to implement VHF R-Mode were identified. Each was evaluated using various metrics such as technical feasibility and implementation cost and difficulty; this evaluation is detailed in the Milestone 3 report. At the Milestone 3 meeting it was agreed to further examine three potential solutions:

1. Existing AIS: this solution involves ranging off of the existing base station AIS messages, using Message 8s to increase the signal energy and duty cycle.
2. CW Aiding: this solution consists of adding continuous wave (CW) signals in other VHF channels and ranging off of the carrier phase of beat signals generated from pairs of such CW signals.
3. Spread Spectrum: this solution considers using more of the VHF bandwidth by transmitting direct sequence spread spectrum signals, akin to GNSS pseudolites.

Each of these solutions is examined in some detail in this report. For the Existing AIS case, the analysis shows that the TOA performance is a function of the number of bits in the processed message(s) and the signal energy and that the performance ranges from 225m for a marginal signal level to 5m for a typical signal level. The raw TOA performance of CW Aiding using the CW carrier is a function of signal strength, averaging time, and frequency and can achieve sub-meter accuracy. However, since the cycle ambiguity must be resolved, the overall performance depends upon how many, and what frequency, CW signals are added. For example, 10m ranging accuracy is possible using 3 CW signals. Finally, while a complete analysis of the Spread Spectrum solution is beyond the level of this report, we argue that performance at a level of approximately 12 meters appears achievable over a limited coverage area.

The recommended solution is the first, Existing AIS including Message 8s. With this solution 10m performance appears achievable using the existing system with no modifications other than adding some additional transmissions. The CW solution is not preferred as it requires additional VHF channels plus adds the complexity of resolving cycle ambiguity. Spread

spectrum, while interesting, is also not preferred as its coverage area is likely to be more limited than the other solutions.

The ranging performance is impacted by a variety of factors that are explored in this report: time stability and synchronization, signal power loss with distance, noise levels, and geometry. In the position analysis it is assumed that the time stability (on the order of 1 ns) and synchronization (to within 50-100ns) to a common reference such as UTC is achievable. Algorithms to predict power as a function of distance for the line-of-sight transmission of VHF signals are known. Noise in the VHF band has been previously studied. The geometry of the position solution, as measured by the Horizontal Dilution of Precision (HDOP), is a major factor in overall positioning performance, but HDOP values in the North Sea Area are quite good (generally less than 2).

The predicted bound on R-Mode positioning using TOA accuracy bounds is good – better than 100m accuracy in most of the North Sea Area (see Figure 1). Accuracy at the 10m level could be achieved in critical waterways (Kiel Canal and Elbe River) by the addition of a few additional transmitter sites (see Figure 2).

This report also identifies the system modifications (both transmitter and receiver) that would be necessary in an all-in-view R-Mode receiver. Conceptual test beds are also described.

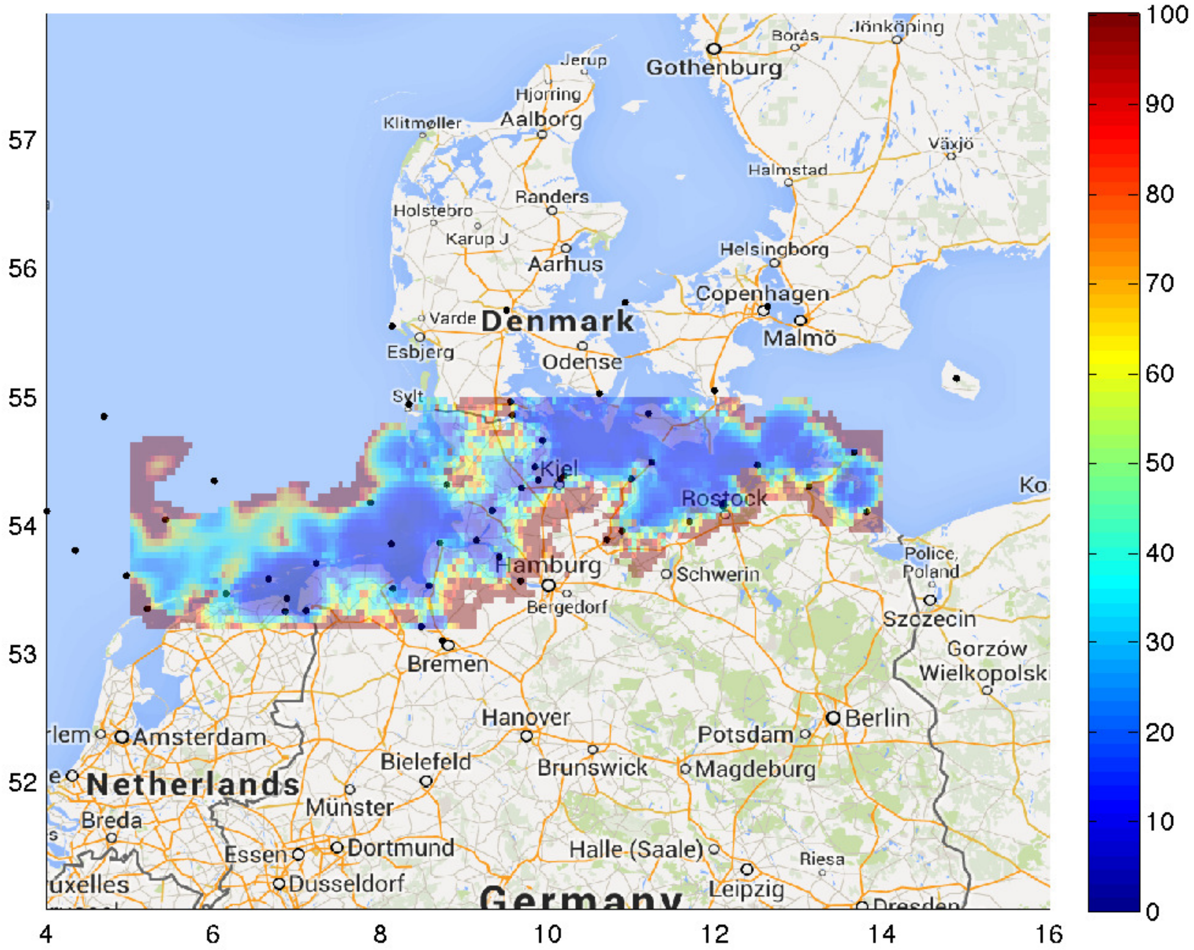

Figure 1: Predicted positioning accuracy (m) using a 0-100m scale.

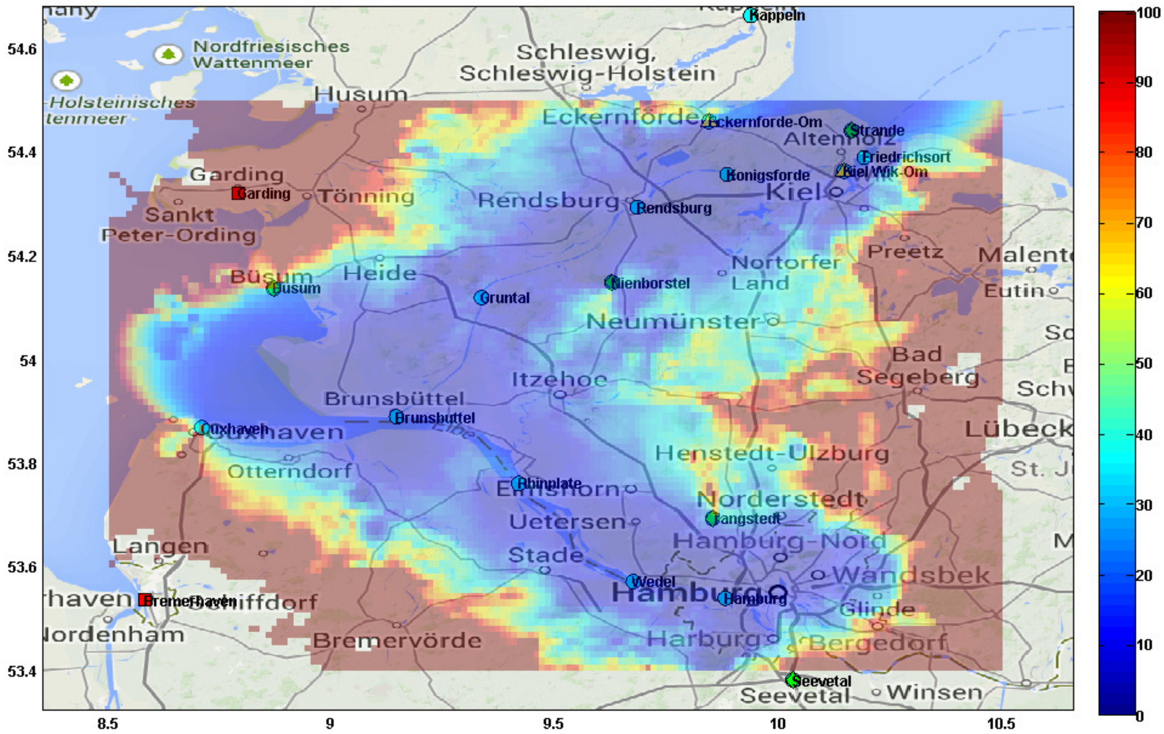

Figure 2: Position performance for the optimized set of transmitters.

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1 Introduction

1.1 Background

High precision positioning in the maritime domain has been 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. combining with eLoran or perhaps with GNSS measurements limited by urban canyons).

Of interest to this study is the use of Automatic Identification System (AIS) broadcasts in the Very High Frequency (VHF) maritime band. This report presents several AIS-based 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[1]:

- 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 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 3 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.

[1] From http://www.accseas.eu/about-accseas.

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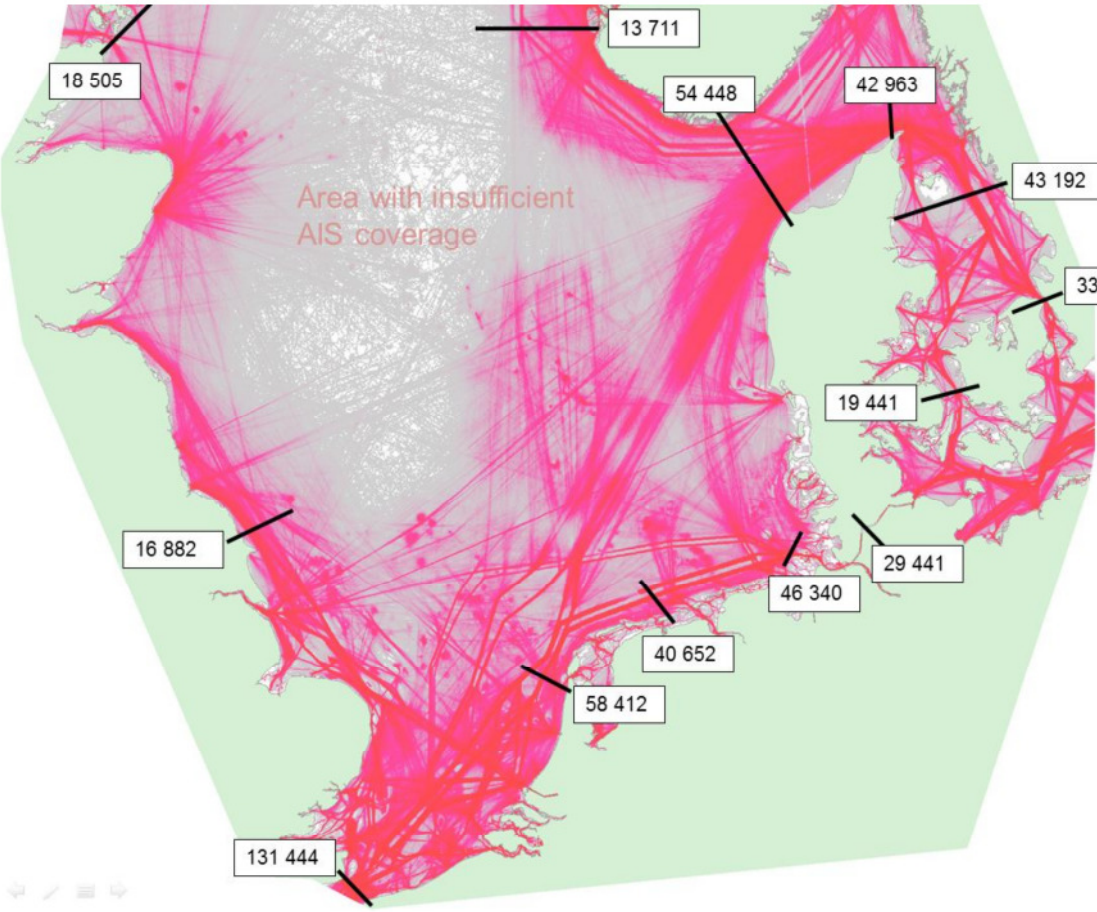

Figure 3: Ship traffic density in the NSR reprinted from [1]. The labels show the total number of ships passing each line from both directions during 2012.The red colour gradient shows the relative density of shipping in the NSR. The empty area in the middle of the North Sea is an area without AIS coverage (it does not mean that there is no traffic).

The 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.

The ACCSEAS project activities are aligned with the IMO e-Navigation concept as shown in Figure 4. This can also be visualized as the so-called "7 Pillars of e-Navigation" as shown in Figure 5. The pillar of interest to this report 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].

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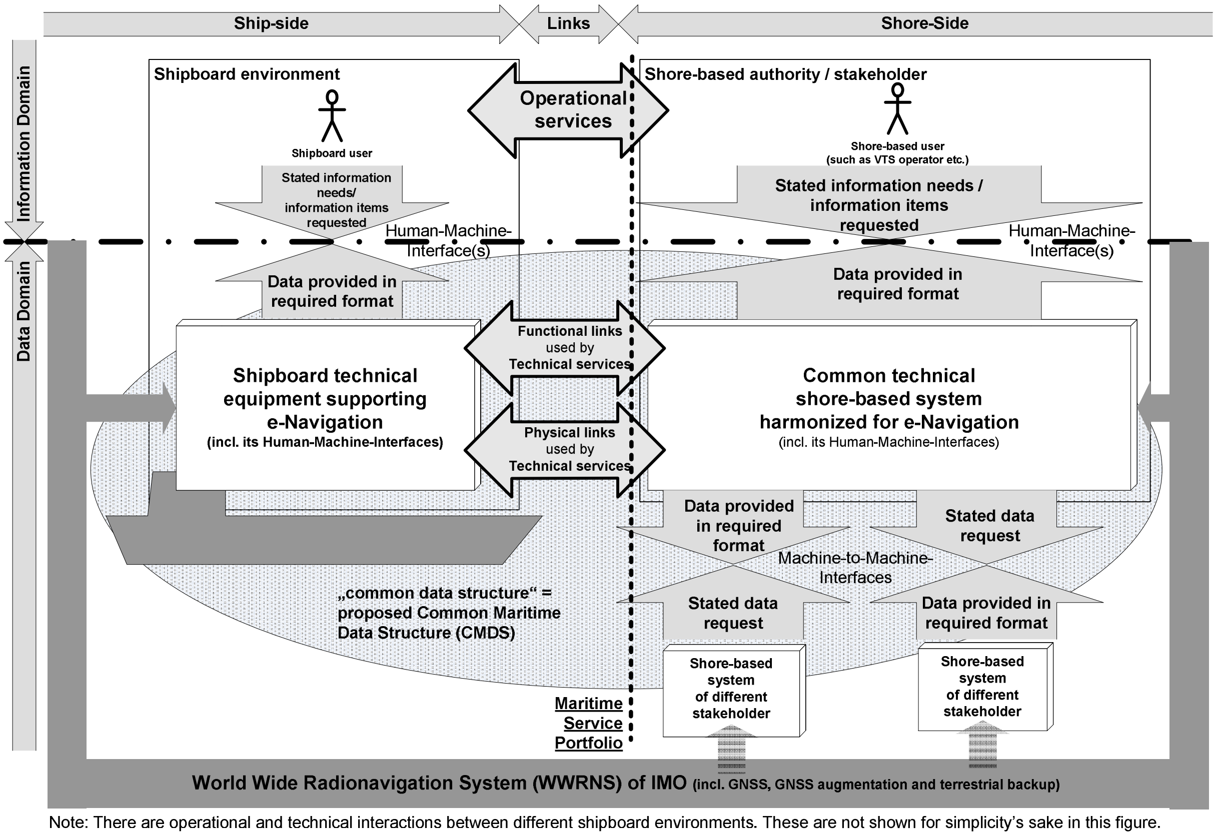

Figure 4: The overarching e-Navigation architecture from [2].

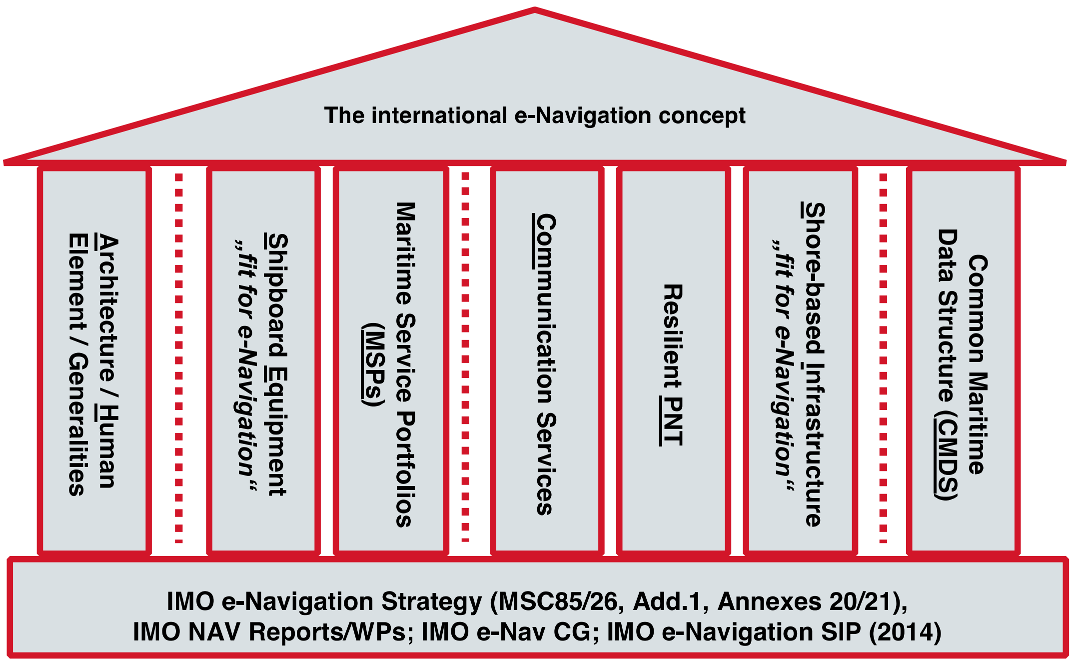

Figure 5: IMO overarching e-Navigation Architecture represented as "7 Pillars", reprinted from [1].

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2 Detailed Description of Recommended Alternatives

2.1 Background on AIS

AIS is a packet-based digital communications system for maritime information transmitting in the VHF maritime band; its detailed characteristics are defined in the International Telecommunications Union Radiocommunications Sector (ITU-R) Standard 1371 [3]. The characteristics relevant to this discussion are:

- The signals are transmitted in the VHF maritime mobile band (156.025 - 162.025 MHz). Specifically, two channels (87 and 88 that are located at 161.975 and 162.025 MHz [4]) have been designated, although others are technically possible. All base stations use the same two channels.
- 25 kHz of bandwidth (BW) is allocated per channel – this is considered narrow band.
- The signalling rate is 9,600 bits per second (bps) per channel.
- The modulation is Gaussian-filtered or Gaussian Minimum Shift Keying (GMSK), with a BT product of 0.4; this is a slightly narrower spectrum than Minimum Shift Keying (MSK), with lower side lobes (see Figure 6) and with similar bit error performance.
- The typical transmit power level is 12.5 W at the transmitter.
- The channels are shared amongst the users using Time Division Multiple Access (TDMA); the system is organized into time slots (each channel has 2,250 slots per minute or 26.67 msec per slot).
- A single-slot AIS message is 256 bits long although multi-slot messages are possible (up to 5 slots).
- Individual messages all start with a 24 bit training sequence and then an 8 bit start sequence, giving 32 known bits at the beginning of each message; they also end with an 8 bit stop sequence.
- For the R-Mode analysis, we will focus on 2 message types that the base stations can transmit:
    - Message 4 transmissions (one slot long) are predictable both in time and content, which helps to remove any effects of randomness in the signal that might limit the performance of the estimation algorithms. Message 4’s are normally sent once every 10 seconds; if operating in semaphore mode, the interval decreases to 3.33 seconds.
    - Message 8 transmissions (binary broadcast, can be up to 5 slots) allow for longer, more frequent signals with a fixed form; note that more frequent transmission of longer, known signals increases signal energy which improves ranging performance and position update frequency.
- As part of its definition as a TDMA communications link, AIS transmissions are synchronized; the base stations derive time from GNSS signals, or by using a network protocol.

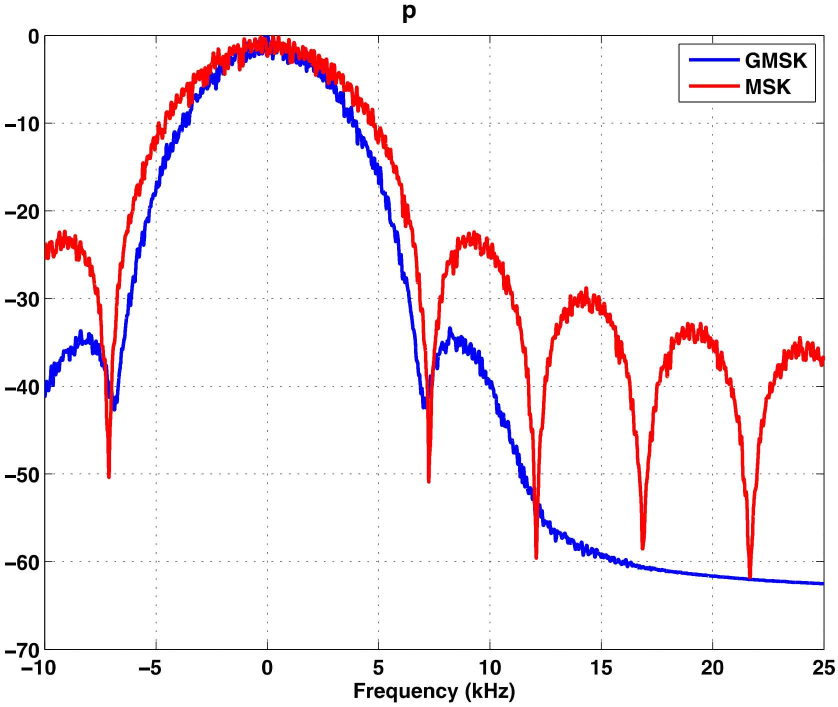

Figure 6: GMSK vs. MSK spectrums at 9,600 bps.

The AIS transmission uses GMSK, an example of a more general modulation technique called Continuous Phase Modulation (CPM) that is somewhat more narrow band than MSK [5-7] (MSK is also a CPM signal). The functional form of a binary CPM signal can be written as

$$s(t) = \sqrt{\frac{2E_s}{T_s}} sin\left(\omega_c t + \pi \sum_k b_k q(t - kT_s)\right)$$

in which E_s is the energy per symbol, ω_c is the carrier frequency, $b_k = \pm 1$ represents the binary data bits being transmitted, T_s is the bit interval, and $q(t)$ is the phase response of the modulator. Normally, CPM is described by the frequency response $g(t)$ that is related to the phase response by

$$q(t) = \int_{-\infty}^{t} g(s)\, ds$$

For GMSK the frequency response is

$$g(t) = \frac{Q\left(\frac{2\pi B}{\sqrt{ln\,2}}\left(t - \frac{L+1}{2}T_s\right)\right) - Q\left(\frac{2\pi B}{\sqrt{ln\,2}}\left(t - \frac{L-1}{2}T_s\right)\right)}{2T_s}$$

with B (bandwidth parameter) and L (correlation length) being system design parameters ($BT_s = 0.4$ for AIS; typically L = 4 or 5 for GMSK) and $Q(x)$ is the Gaussian tail probability

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-u^2/2} du$$

Assuming transmission through an additive white Gaussian noise channel (noise spectral height of $\frac{N_0}{2}$), a variety of GMSK demodulation approaches have been considered in the communications literature. A bit error probability below 10^{-3} is possible at symbol energy to noise ratio of $\frac{E_s}{N_0} = 8\ \mathrm{dB} = 6.3$ and about 10^{-6} at $\frac{E_s}{N_0} = 10\ \mathrm{dB} = 10$ assuming perfect receiver synchronization; these values give us a benchmark for typical receiver signal and noise levels. As a SoOP for a range based, trilateration positioning system, the time of bit transition and the carrier phase are the parameters of interest in the GMSK broadcast.

2.2 Availability of Base Stations

In order for the SoOP ranging system to work in the absence of GNSS, only transmitters that are at known, fixed locations can be used; for an AIS SoOP these would typically be the AIS base stations. For this AIS R-Mode Feasibility Study, we will focus only on the area covered by the German AIS stations, with the adjacent Danish and Dutch base stations used to fill in the edges of the coverage area. This provides a box spanning 5-14° Longitude and 53.2-55° Latitude. Figure 7 shows the AIS base stations currently operating in Germany; these form a pretty dense network in the North and Baltic Seas and on the Kiel Canal.

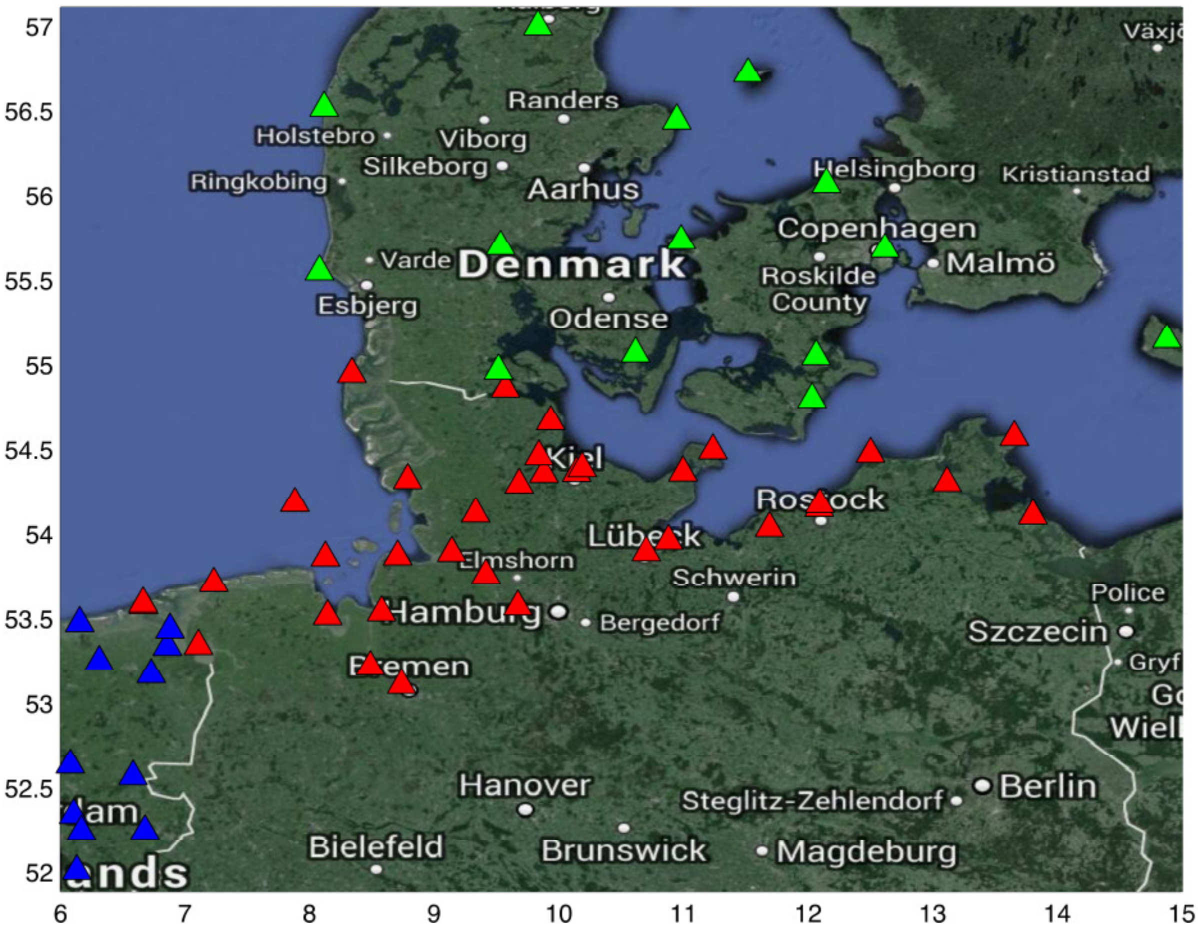

Figure 7: Study coverage area with German AIS stations (red triangles), Danish AIS station (green triangles) and Dutch AIS stations (blue triangles).

2.3 Detailed Description of Agreed Upon Alternatives

2.3.1 Standard AIS transmissions including Message 8s

Based upon the existing signal specification, the receiver would estimate both the times of bit transitions and the carrier phases of all AIS base station signals available (in the

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literature, this is called an “all-in-view” receiver). The primary messages available from the base station to range off of are Message 4’s; these are predictable both in time and content, which helps to remove any effects of randomness in the signal that might limit the performance of the estimation algorithms. Also including Message 8 (binary broadcast) transmissions would allow for longer, more frequent signal with a fixed form; note that more frequent transmission of longer, known signals increases signal energy which improves ranging performance and position update frequency.

In its use as a communications link, GMSK receivers must be able to demodulate the transmission with high accuracy. While the modulation concept is simple, the continuous phase nature of the signal makes optimum decoding more complex than that of amplitude modulation; a number of decoding methods have been presented over the past 30 years [7-13]. As part of the decoding algorithm, and to account for variations at the transmitter, GMSK receivers normally estimate the carrier frequency ω_c, the carrier phase θ, and the time of bit transition τ. Methods to estimate these parameters are described in [14-28].

Assuming that the GMSK transmitter is controlled by a precise timing/frequency source, both the times of the bit transitions (once every T_s seconds) and the underlying phase of the signal carrier could be exploited to estimate the time of arrival (TOA) for trilateration-based ranging applications. Knowledge of how effectively an estimation algorithm performs can be combined with information on the geometry of the transmitter locations to predict overall positioning performance:

- On its own, the time of a bit transition has an ambiguity of one symbol period, 26.67 msec or, equivalently, 31 km. Given that the propagation range for AIS is expected to be up to 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.
- At 160 MHz the wavelength of the carrier (and, hence, its lane width) is less than 2 meters; hence, cycle ambiguity must be addressed in order to use the carrier phase for positioning. To avoid the difficulty of resolving this ambiguity, we concentrate on estimating the time of bit transition below.

In our research on GMSK we found two useful analyses of the performance of estimation algorithms for the time of bit transition. In both of these treatments the observed data (in complex baseband, I and Q, form) is

$$r(t) = e^{j(2\pi \upsilon t+\theta)} s(t-\tau) + w(t)$$

which consists of the transmitted GMSK signal $s(t)$ with an unknown time delay τ (the term of interest for ranging), an unknown frequency offset υ (due to a mismatch of the receiver oscillator in the demodulation process), an unknown phase θ (due to the phase offset between the local oscillator at the receiver and the signal carrier), and additive white Gaussian noise (AWGN) $w(t)$ with spectral density $\frac{N_0}{2}$. A modified Cramér-Rao Bound (MCRB) on the performance of any estimator of τ from the bit edges is developed in [9]; in this development, “modified” means that the transmitted data is assumed to be random and that the bound is simplified to take this into account, yielding a lower bound to the Cramér-Rao Bound (CRB). The MCRB for the time delay is

$$MCRB(\tau) = \frac{N_0}{E_{\upsilon,\theta}\left\{\int_0^{T_0} \left|\frac{\partial s(t,\tau,\upsilon,\theta)}{\partial \tau}\right|^2 dt\right\}}$$

in which T_0 is the entire observation interval (a total of L_0 symbol periods, $T_0 = L_0 T_s$) and $E_{\upsilon,\theta}\{\cdot\}$ is the statistical expectation operator over the random variables υ and θ. For any form of CPM this bound can be simplified to

$$MCRB(\tau) = \frac{T_s}{\pi^2 \xi L_0 \gamma_b}$$

in which the parameter ξ is determined by the type of modulation through the modulator's frequency response

$$\xi = \int_0^{T_0} g^2(t)dt$$

For GMSK with BT_s = 0.4 and L = 4, this results in

$$MCRB_{GMSK}(\tau) = \frac{{T_s}^2}{1.58\, L_0 \gamma_b}$$

A more recent analysis by Hosseini [29, 30] assumes that the data is known and evaluates the CRB of the time of bit transition as a function of the message. He is then able to find that message which minimizes the CRB. Letting L_0 correspond to the length of the message, the best synchronizing message has the following characteristics:

- If L is the correlation length of the modulator's frequency response (e.g. 5 for GMSK), let $L_1 = L_0 - \lfloor L/2 \rfloor$
- The first $L_1/4$ bits of the message take on value 0 (pulse amplitude –1)
- The next $L_1/2$ bits take on value 1 (pulse amplitude +1)
- The remaining bits take on value 0 (pulse amplitude –1)

(Of course, the complement message in which 0s are replaced by 1s and vice versa is equally optimal.) The corresponding minimum value for the CRB is

$$CRB_{min}(\tau) \approx \frac{T_s}{\gamma_b \pi^2 \left[L_0 R_g(0) + 2(L_0 - 5) R_g(T_s)\right]}$$

in which $R_g(\cdot)$ is the autocorrelation function of the frequency response of the modulator. For GMSK we have

$$R_g(t) = \begin{cases} \dfrac{0.158}{T_s} & ; \quad t = 0 \\ \dfrac{0.0453}{T_s} & ; \quad t = T_s \end{cases}$$

Substituting in for $R_g(\cdot)$ and assuming that $L_0 \gg 5$

$$CRB_{min}(\tau) \approx \frac{{T_s}^2}{2.49\, L_0 \gamma_b}$$

This result is quite similar to the MCRB above (the difference in the denominator constant, about 2 dB, shows the advantage of choosing the data in an optimal fashion). We note that the structure of the AIS format (specifically the bit stuffing procedure) will not allow use of an optimal message, but Hosseini's work does allow for the evaluation of the CRB for any specific bit sequence. For subsequent performance analysis in this report, we use the first form (the MCRB) with the constant 1.58 in the denominator.

To assess the capability of ranging using AIS, relevant values for the parameter γ_b must be identified. To do so, recall several facts from the AIS standard:

- The AIS packet length is 256 bits; no forward error correction coding is used.
- The AIS specification calls for 20% PER at a signal strength of -107 dBm.

PER in this context is "packet error rate," so the specification states that the probability of a packet error be at most 0.2 when the received signal level is -107 dBm. For a digital communications system without forward error correction the PER is related to the bit error rate, p_b, and the packet length, n, by

$$PER = 1 - (1 - p_b)^n$$

Solving this expression with $\mathrm{PER} = 0.2$ and $\mathrm{n} = 256$ yields

$$p_b = 1 - (1 - 0.2)^{\frac{1}{256}} = 8.7 \times 10^{-4}$$

Consider MSK signalling in AWGN of power $\frac{\mathrm{N_0}}{2}$, then the bit error rate is [31]

$$p_b = Q\left(\sqrt{\gamma_b}\right)$$

Assuming that GMSK and MSK give similar error performance (while no precise performance expressions exist for GMSK, the modulation methods are quite similar), this expression can be employed to find a reasonable value for γ_b. (Further, results in [10] suggest that GMSK performance is approximately of the same functional form as that of MSK, but with a scaling factor of 0.68 on γ_b for BT_s = 0.3, implying that GMSK requires slightly more power for equivalent error performance.) Solving for γ_b

$$\gamma_b = [Q^{-1}(p_b)]^2 = [Q^{-1}(8.7 \times 10^{-4})]^2 = [3.13]^2 = 9.8$$

so at a minimal (-107 dBm) signal level and AIS data rate of 9,600 bps (T_s=$\frac{1}{9600}$), the MCRB is

$$MCRB_{min}(\tau) \approx \frac{{T_s}^2}{1.58\, L_0\, 9.8} = \frac{7 \times 10^{-10}}{L_0}$$

Taking into account the signal level s in dBm, this is

$$MCRB_{GMSK}(\tau) = \frac{7 \times 10^{-10}}{L_0\; 10^{\frac{s+107}{10}}} = \frac{7 \times 10^{-20.7}}{L_0\; 10^{\frac{s}{10}}}$$

or in time

$$\sigma_{GMSK\ bit\ edge} \geq \sqrt{MCRB_{GMSK}(\tau)} = \frac{0.12}{\sqrt{L_0}\; 10^{\frac{s}{20}}}\ nsec$$

Consider the estimate based upon five AIS message slots; this could be five separate single-slot Message 8s or a single 5-slot Message 8. As long as the transmissions are controlled by a precise clock with little drift, multiple messages can be combined for a range estimate. More realistically, it would be better if they occurred as one block. The number of bits is $L_0 = 5 * 256 = 1{,}280$ bits. At a signal level of -107 dBm the CRB is

$$CRB_{min}(\tau) \approx 35.6 \times 10^{-13}$$

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or a standard deviation of 750 nsec or 225 m. However, at a more typical strong signal level of -75 dBm the standard deviation is just 18.8 ns or 5.65 m. Figure 8 shows the standard deviation of the estimation error of the time of a bit transition as a function of the received signal power in dBm for this example.

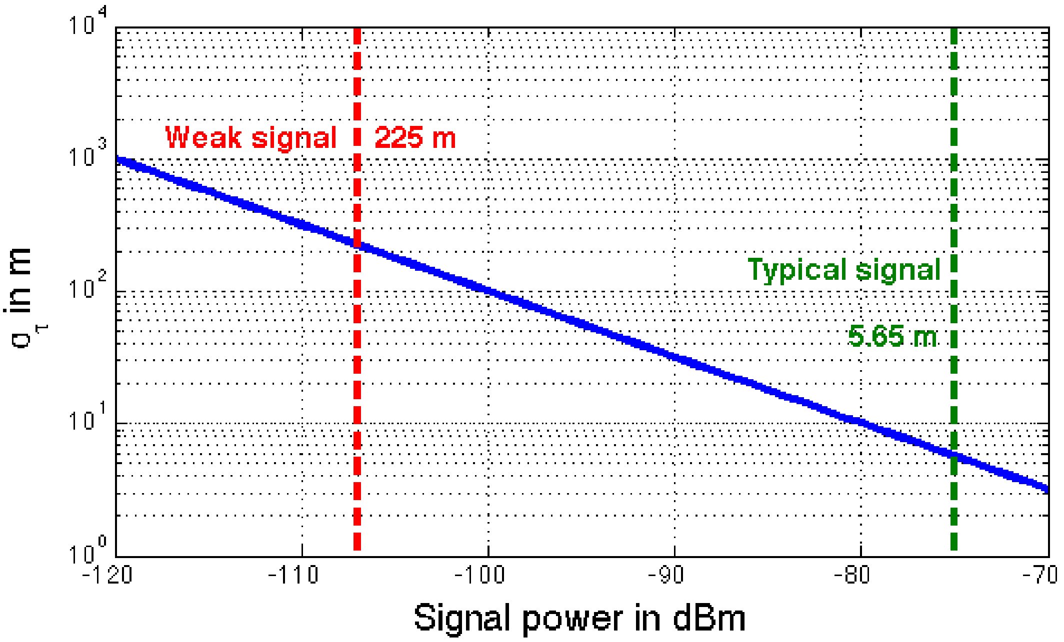

Figure 8: The performance of estimating the time of a bit transition, computed from the CRB, as a function of the received signal level in dBm.

Standard AIS Signals including Message 8s

Pseudorange performance using bit edges is bounded by:

$$\sigma_{\mathrm{GMSK}\ bit\ edge} \geq \frac{\mathbf{0.12}}{\sqrt{L_0}\ \mathbf{10}^{\frac{s}{20}}}\ \ \mathrm{nsec}$$

in which s is the signal level in dBm and L_0 is the number of bits in the message(s) used in the estimate

2.3.2 CW Signals in One or More Distinct VHF Channels

An alternative to processing the AIS transmissions is to broadcast multiple sinusoidal signals (so called continuous wave, or CW, modulation) from the base stations (using a parallel transmitter, potentially at a lower power level), within one or more VHF maritime channels and estimating the phase of the beat signal[2] for ranging.

Depending upon the number of and frequencies of these signals (and more than one from each base station is required to resolve phase ambiguities), this might be possible on a VHF channel(s) shared with other users or might require a channel(s) dedicated to ranging. In either case, a request would need to be made to the competent authority for the use of the separate VHF channel(s) for ranging.

If configured as a dedicated ranging channel, with all base stations sharing the same channel(s), this approach would require a time or frequency diversity protocol across adjacent transmitters to eliminate interference (we suggest one such frequency diversity method below); different VHF channels for different base stations would eliminate this need.

Potentially, depending upon the usage of the VHF channel under consideration, this approach might not require a dedicated ranging channel, but could co-exist with some other usage of the channel via time diversity (pulsed transmission), especially if the employed channel(s) has low duty cycle of alternative usage and/or the CW modulations were placed near the channel's band edges.

For a sinusoid with carrier frequency ω_m, the MLE of the phase angle is [32]:

$$\hat{\phi} = -\tan^{-1}\left(\frac{\int_0^T r(t)\cos\omega_m t\,dt}{\int_0^T r(t)\sin\omega_m t\,dt}\right)$$

The CRB for this phase estimate (measured in radians squared) is

$$CRB(\hat{\phi}) = \frac{1}{2T\,SNR}$$

where T is the total observation period and SNR is the signal to noise power (not energy) ratio. For example, at a signal level of $SNR = \frac{\gamma_b}{T_s} = 9.8 * 9{,}600$ (so that the CW signal is at the same amplitude as an AIS signal) and a 1 second observation (T=1), this is an estimation error standard deviation of 2 mille-radians or less than a degree. How this relates to time accuracy depends inversely upon the sinusoid's radian frequency

$$\hat{\tau} = \frac{1}{\omega_m}\hat{\phi}$$

The obvious advantage of ranging with a CW signal over the AIS bit edge is the simplicity and high accuracy of the estimator. At 160 MHz the wavelength is approximately 2 meters and positioning performance would better than 1 m (assuming good HDOP). However, the disadvantage is the ambiguity of the sinusoidal phase. Since it repeats every wavelength (2m), the specific cycle must be identified in some other way.

One approach to resolving this ambiguity is to generate multiple, synchronous sinusoids at each transmitter and to examine the beat signal of each pair at the receiver:

- For example, if two CW transmissions within an additional VHF channel are 4 kHz apart, then the lane width for the beat signal is 75 km. This large lane makes the

[2] If two sinusoidal signals are multiplied together, the result is a signal consisting of sinusoids of the sum and difference of the two original frequencies, which can be separated by filtering and used as two new individual frequency sinusoids.

initial ambiguity resolution simple as it is on the same scale as the VHF transmission range.

- A 1-degree accuracy estimate of the phase of this beat signal would place the pseudorange to approximately 200 m.
- If all of the AIS ranging transmitters employ this same channel, the individual transmitters could stagger their frequencies across the channel with adjacent transmitters aiming for frequency diversity. For example, they could use frequency pairs on 1 kHz centers scattered in a channel. Figure 9 shows the idea for 8 such pairs (two line spectra of a constant color, constant line type in this figure being each pair). If necessary for frequency reuse with adjacent transmitters, the lines could be closer spaced.
- To improve the first range estimate below 200 m, a third CW signal could also be transmitted in a second VHF channel. If this third signal was 100 kHz different than one of the first two, then the beat frequency would be on the order of 100 kHz, with a lane width of 3 km, and its lane could be easily identified by the first phase estimate. A 1-degree phase estimate on this second beat signal would yield 10 m accuracy.
- It is also possible that the AIS signals themselves could be used as this third CW signal, although additional processing would be required.
- This process could be continued, by adding additional beat frequencies to keep getting to smaller and smaller wavelengths and thus better and better accuracy.

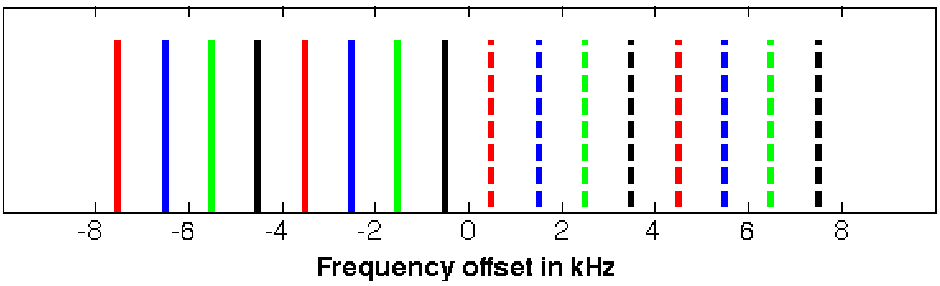

Figure 9: Frequency reuse for CW ranging.

CW in a non-AIS VHF Channel(s)

$CRB(\tau) = \frac{1}{2T\,\omega_m^2 SNR}$ ***where ω_m = the highest beat frequency***

10 meter ranging accuracy is possible using 3 CW signals; the cost is the use of two VHF channels.

The method uses phase estimates on CW signals; cycle (ambiguity) resolution is accomplished using beat signals (product) of multiple CW signals

2.3.3 Spread Spectrum Signal

2.3.3.1 Background on Spread Spectrum Ranging

GPS is a wideband digital communications system transmitting from a set of 24+ satellites using a technique called direct sequence spread spectrum modulation [33]. The term spreading refers to the fact that the signal is constructed by multiplying the data sequence of communications interest (50 bps for GPS) by a higher rate pseudorandom noise (PRN) code (or chipping sequence) of length 1023 chips (and 20 PRNs per data bit); the result is a wider bandwidth signal (in this case, wider by a factor of 20x1023). In essence the original narrowband signal is "spread" into a wideband signal of equal power.

Transmitted at low power from satellites in high Earth orbit (over 20,000 km away), the signal level received near the ground is below the noise floor of the receiver. However, the structure of the signals allows for advanced signal processing techniques to "despread" them back into higher amplitude, narrowband versions that can be effectively demodulated (to receive the needed data on clock parameters, satellite orbits, etc.) as well as to estimate the range to the satellites (to enable a trilateration position solution for the receiver). The spreading gain, on the decibel scale this is 10 times the base 10 logarithm of the chipping sequence length (approximately 30 dB for GPS), is enough to pull the assumed -130 dBm GPS signal above the noise floor and allow for good demodulation.

Spread spectrum signals useful for navigation do not need to come from satellites; ground-based transmitters, commonly called "pseudolites" in the GPS community, can also be employed [34, 35]. Such GPS pseudolites are commonly considered for installation in harbor or airport locations to provide higher levels of GPS positioning accuracy and/or integrity. It is also possible to build a stand-alone positioning system using ground-based transmitters (e.g. Locata [36], this system is discussed below).

There are several advantages to a wideband signal for ranging/positioning [37]:

- In spread spectrum the chipping signal is implemented as a pseudorandom sequence of rectangular (constant amplitude) pulses of amplitudes +A and -A (so called BPSK modulation). A modern communications receiver can track the times of the bit transitions in such a signal at or below 1% of the pulse interval; in other words, the faster the pulse rate, the higher the accuracy of the time of arrival of the signal (and, equivalently, accuracy of the pseudorange measurement). For example, the GPS C/A code has a chipping rate of 1.023 megachips per second, so the length of a chip is approximately 300 meters and a 1% estimate of the transition time yields a (one sigma) range accuracy of about 3 meters.
- If the chipping sequence has good autocorrelation properties then the ambiguity of which edge in the PRN sequence is being observed is easily resolved. The pseudorandom Gold codes used by GPS make the likelihood of an error in the bit edge ambiguity very rare (this margin is also approximately 30 dB).
- The term "multipath interference" refers to the deleterious effects of additional copies of the signal that follow different, and longer, propagation paths from transmitter to receiver. These additional copies, arriving later, and with different amplitudes, distort the signal seen by the receiver. For GPS this issue has been explored extensively and the advantages of spread spectrum to limiting multipath are well known. Conceptually, higher chipping rates means that those multipath channels with longer path delays cause the additional signals to arrive during later chips; PRN codes with good autocorrelation characteristics effectively suppress such late signals and, hence, control the impact of multipath (again, approximately 30 dB protection against multipath later by one or more chips). Antenna polarization for GPS also reduces multipath. For terrestrial transmission multipath is more of an issue as the line of sight path is close to the ground, increasing the opportunity for multipath. This issue

has received study in the communications context, but it has seen little attention for ranging [36, 38].

- Wideband spread spectrum signals can also provide protection against narrowband interference, both intentional and non-intentional. Conceptually, the despreading process at the receiver both collapses the wideband signal to the desired narrowband signal and spreads a narrowband interfering signal out into a lower amplitude, wideband signal. The amount of protection depends very much on the type of interference.
- Wideband signals have also been employed as an "overlay" communications signal to allow additional users in frequency bands with other types of communications signals [38-41]. Typically the intent has been to increase the number of simultaneous users of that part of the radio spectrum. Nothing appears to have been published on how a ranging overlay might work while sharing a band with other users.

2.3.3.2 ITU-R Recommendations

The ITU has considered the potential desirability of using spread spectrum signals in conjunction with other broadcasts:

- CCIR Recommendation 691-1 [42] envisions spread spectrum radiolocation in the MF band and recommends that the added signal spectrum should be Gaussian noise-like, free of periodic components – this suggests long chipping codes (the longer the code, the narrower the spacing of the spectral components) – and that the signal level never exceeds that of the existing channel noise.
- ITU-R SM.1055 [43] discusses spread spectrum communications overlays onto frequency bands with other users. It defines the relevant technical terms and measures, and proposes analysis tools to evaluate potential interference. The recommendation notes that a small number of SS signals would cause negligible performance degradation as long as the total SS power remained sufficiently below that of the conventional signals.
- ITU-R M.1087 [44] extends the discussion to spread spectrum communications transmitted from low earth orbit and its possible impact on land mobile services.

2.3.3.3 Terrestrial Spread Spectrum in the VHF Band

The marine VHF radio band is wide, ranging from 156 to 162 MHz, larger in size then the 2 MHz allocated for the GPS L1 C/A signal; thus it appears that spread spectrum signals might provide some advantages in the R-Mode investigation. Upon looking closer; however, the band is seen to be non-contiguous, split by restricted marine channels (e.g. channel 16) and other, non-maritime users. Conservatively, the largest continuous piece of spectrum appears to be approximately 500 kHz. The implication is that a VHF ranging system could employ a chipping rate of 250 kHz, so that each chip is approximately 1200 meters in length. While larger than that of GPS, the potential accuracy seems quite adequate; 1% accuracy is 12 meters. There has been some published work on so-called "multicarrier" CDMA, in which non-contiguous frequency bands are combined, but the methods appear to only provide advantages to communications capacity (i.e. data rate or number of simultaneous users) and not to ranging performance [45-47].

The marine VHF band is already populated by both voice and data users and one requirement for a spread spectrum ranging overlay would be to have no impact on the current users.

- Each current VHF channel is nominally of width 25 kHz (although data channels can grow to 100 kHz), so a 500 kHz ranging channel might observe interference from up to 20 other users.

- Several methods have been proposed in the literature to reduce/eliminate interference to these other users by the spread spectrum signal. One obvious idea is to keep the spread spectrum signal very low so as to be below the noise floor for the other users; this, of course, would require that the spread spectrum coding allow for enough despreading gain to provide sufficient signal strength for range estimation. An alternative is to blank (disable) the spread spectrum transmission whenever the other users come on air [40]. Depending upon the duty cycle of users on each channel, this approach could seriously diminish the availability of ranging. This concern has received no attention in the literature.
- Methods have also been proposed to account for the effects of interference on the spread spectrum signal from the other users. The despreading gain of the chipping code already does some of this, especially if the other user is extremely narrowband. Dedicated narrowband filters that adapt to the interference could be used at the receiver front end in the spread spectrum system. This idea, and its impact on performance, has been considered in the communications context [48], but not for ranging. While this seems feasible for very narrowband interference, the scale of the VHF channels (25 kHz each) makes this of concern.

Another issue that needs resolution is the “near-far” problem. For position determination a receiver needs to receive and track several (3 or more) of the spread spectrum signals. Since these signals are all in the same portion of the radio band, they do interfere with each other (so called multiple access interference or MAI). Over the coverage area of the system some of the transmitters are much closer to a receiver than others are so there can be a wide range of signal levels observed; “near-far” refers to the fact that the stronger (near) stations can “drown out” the weaker (far) ones [49, 50]. Recall that a simple model of how the signal power decreases with distance from the transmitter is inversely proportional to the square of the distance (some models use a larger exponent, perhaps 3 or 4). For example, a signal at 50 km from the transmitter is at least 10,000 times (40 dB) weaker than that same signal at 500 m. We note:

- GPS does not significantly suffer from this problem as all of the transmitters are already very far away due to the satellites’ orbits; the variation in distance for receiver locations on the Earth results in only a few dB change in the received signal powers. The cross correlation characteristics of the individual Gold codes (approximately 20 dB of protection) are sufficient to solve this slight near-far problem.
- Chipping codes in general are designed to provide protection against other PRN signals, this being the definition of Code Division Multiple Access (CDMA). Specifically, for a length m code, the maximum cross correlation is approximately the square root of m (they are not perfectly orthogonal); hence, implementing longer codes would provide more interference protection [51]. We note that the autocorrelation characteristics of the codes are much better than their cross correlation characteristics.
- It is also possible to implement optimum or near-optimum multi-user detectors (MUDs), which are known to provide protection from the near-far problem [52-54]. However, this does not appear to be have become all that popular in current spread spectrum receivers due to the complexity of their implementations (especially for many users). Further, it is unclear how much isolation the MUD approach really provides once the dynamic range of an actual receiver is taken into account.
- The near-far problem is quite significant when pseudolites are used to improve GPS positioning. The most common solution in this case is to pulse the pseudolite, having it transmit only a fraction of the time (10% duty cycle is commonly quoted) [35].
- Frequency translation (moving the transmission to a slightly different carrier frequency) can also reduce near-far interference [35] (the 802.11b Wi-Fi standard is a communications example; GLONASS is a ranging example). This could apply in a

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limited fashion to a VHF spread spectrum system if the different, non-contiguous portions of the spectrum were assigned to adjacent transmitters.

- Finally, a directional receiving antenna could greatly resolve this problem.

Also relevant to this discussion are some of the details of a current, commercial terrestrial spread spectrum ranging system, Locata [36]. While many of the details of the system are proprietary, the following can be gathered from its Interface Control Document [55] and other published reports:

- The Locata system is a terrestrial spread spectrum ranging system that transmits in the ISM (2.4 GHz) band with an 80 MHz bandwidth and a 10 MHz chipping rate (10 times faster than GPS). The system broadcasts two CDMA signals at different carrier frequencies to provide diversity, possibly against other users of this public radio channel.
- The transmitters broadcast at 100 mW with a design range of 10 km; smaller than that desired here.
- The PRN codes are proprietary with no information on length or correlation characteristics provided by the manufacturer. However, the system does allow for 10 LocataLites to be within the same service area. Separate analysis suggests that the code length is 1023 and that the codes are standard Gold codes [56].
- The transmitters are time locked. The near-far problem is solved by pulsing the transmitters at a 10% duty cycle; the time-hopping pattern appears to be variable [56].

Spread Spectrum Ranging

Concept is well understood

Appears to be precedence for this type of overlay in ITU-R

Exact accuracy TBD

Coverage likely to be limited by the “Near-Far” problem

2.4 Elaboration of Requirements for Time Synchronization

In order to do positioning from multiple ranges or to establish time from a single range, the times of transmission must be precisely timed. There are two timing concerns: time stability and time synchronization.

2.4.1 Time Stability

Time stability is important to ensure that the signal does not drift appreciably over the receiver averaging time (perhaps 5 seconds). For this purpose, time stability on the order of one nanosecond over the 5-seconds would be more than sufficient. If we can measure range to 100ns then time accuracy needs to be better than 1ns. This equates to clock stability at the transmitter of ~ $1x10^{-10}$. This would argue for a Rubidium (Rb) clock (typical performance of $1x10^{-11}$) at the transmitter, not a Caesium (Cs) clock (typical performance of $1x10^{-13}$). Currently the only clock specification in the relevant International Electrotechnical Commission (IEC) standard [57] is for a maximum frequency deviation of 500 Hz from the assigned carrier frequencies. This implies an accuracy on the order of $3x10^{-6}$ which can be met by low cost Quartz or Oven Controlled Oscillators (OCXOs). Therefore to meet the stability requirements, the AIS base stations would need to be upgraded to a Rb clock (the German AIS stations already have this).

2.4.2 Time Synchronization

Time synchronization is needed to determine Universal Coordinated Time (UTC) from the received signal and to eliminate relative clock biases between the various transmitters, which otherwise would be added to the position error (1 m for every 3.3ns). There are two methods to accomplish this: synchronize each transmitter to a known common time signal such as UTC or use common reference site(s) to sort out the time differences.

2.4.2.1 Synchronize to UTC

In the North Sea Area, the geometry of the stations is good, so for 20m performance we need better than 50ns of accuracy in the clock synchronization to UTC. This could potentially be done using a network time synchronization (using IEEE 1588 PTP) although this is beyond the accuracy of most Precise Time Protocol (PTP) implementations. Two-way Satellite Time Transfer (TWSTT) could be used, but would require point-to-point satellite links between each transmitter and the UTC reference clock. This could also be done using an eLoran time receiver; if the eLoran clock is synchronized to UTC then this would provide a UTC reference, but if not, it would still provide a common reference to all AIS transmitters. And finally, GPS could be used to provide the time synchronization up until the point in time that the GPS signal is lost. After this point the signal would remain in tolerance for ~28 hours for a high quality Caesium clock or ~0.28 hours for a Rubidium clock.

The time synchronization specification in IEC 62320-1 [57], is that the AIS base station has a time source synchronized to UTC, better than 50 μs and allows the use of an external clock sync signal. Any of the options above could be used. The German AIS stations already use an external clock synchronization; though the accuracy to UTC would need to be assessed.

2.4.2.2 Reference Site

The alternative to synchronizing each transmitter is to have one or more reference sites at known locations that can sort out the relative time differences between the various transmitters. Similar to the way that DGNSS can calculate corrections for GNSS, an R-Mode reference site could track the received R-Mode signals and establish the error in them at the receiver. This error would be primarily the clock offset of the transmitter. This clock offset could then be broadcasted on the AIS data stream, potentially in a Message 8. The disadvantage of this approach is that the mobile receiver would only be able to range off of the R-Mode signals that were also received by the reference site (and thus had corrections for) so this limits the coverage of the system to an area near the reference site.

Time synchronization (to within 50-100ns) to a common reference such as UTC is critical for positioning performance.

Time stability (on the order of 1 ns) is necessary to ensure the transmitter jitter does not impact positioning performance

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2.5 Performance Factors

Discussions of AIS as a SoOP are non-existent. Specifically, while references [58, 59] have promising titles, they have no content relevant to the problem at hand. Some potential performance-limiting factors of a ranging signal are described in the following subsections. For the remainder of this report the analysis has been restricted to the geographic area of the North Sea Area; we have used a bounding box of 53.2-55° N latitude and from 5°-14° E longitude.

2.5.1 Time Signal

As discussed above, a stable clock is needed to drive the RF modulator; the stability needed is on the order of 1 nanosecond over the averaging time constant of the receiver. This implies a stability rating on the order of 10^{-9}. This is easily achievable by a Rubidium or Caesium clock, but not by a quartz oscillator. Based upon the cost, it would make sense to use Rubidium clocks.

2.5.2 Time Synchronization

The time synchronization is more problematic. Equipment can be found that will synchronize to within 50-100ns of the UTC reference. Getting less error than this is very difficult (and expensive) and may only be realistically achievable by tracking the transmitter clock offsets and transmitting these offsets as R-Mode clock corrections for each transmitter site.

2.5.3 Propagation Conditions

At VHF frequencies, the signal is primarily a Line Of Sight (LOS) propagation path. It is fairly common, under certain weather conditions, for there to be ducting effects, which allow the signals to be received at distances well beyond the LOS. We have restricted our analysis to signals that travel in a normal manner, using a distance threshold of 75km. This serves to eliminate any seasonal or weather effects. There are no day-night differences at VHF frequencies.

The typical method to predict loss of signal power with distance is to use software tools; we have used Systems ToolKit (STK) software by Analytical Graphics Inc. that incorporates the Terrain Integrated Rough Earth Model (TIREM) developed by Alion. This tool estimates the signal strength at each location in a specified grid area taking into account the topography, the transmitter power, and the height and characteristics of the transmit and receive antennas. Many of the German AIS stations use multiple, directional, antennas to concentrate the signal energy into sectors; this is taken into account by the software. Some sample signal strength predictions are shown in Figure 10 thru Figure 12; the selection includes one German, one Dutch, and one Danish site. The sectorization can be seen in the German site plot. In each plot, the black line is the -117dBm contour and the red line is the 75km range line (maximum range that a site is used in the analysis).

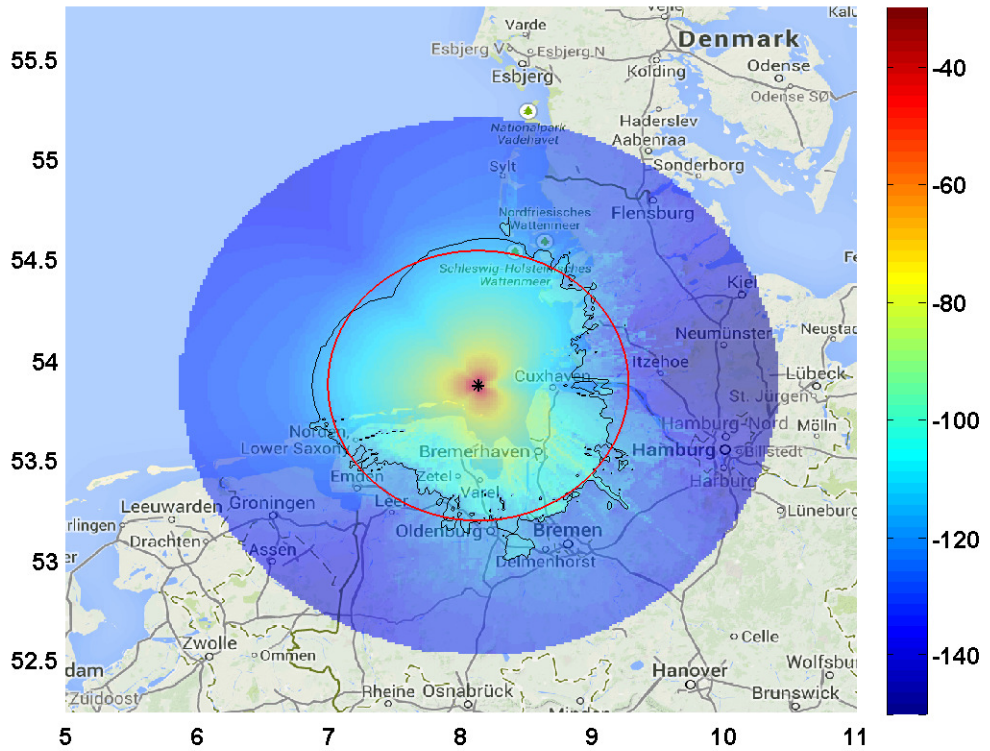

Figure 10: Predicted signal strength (in dBm) for the German site at Alte Weser, with 3 sectorized antennas.

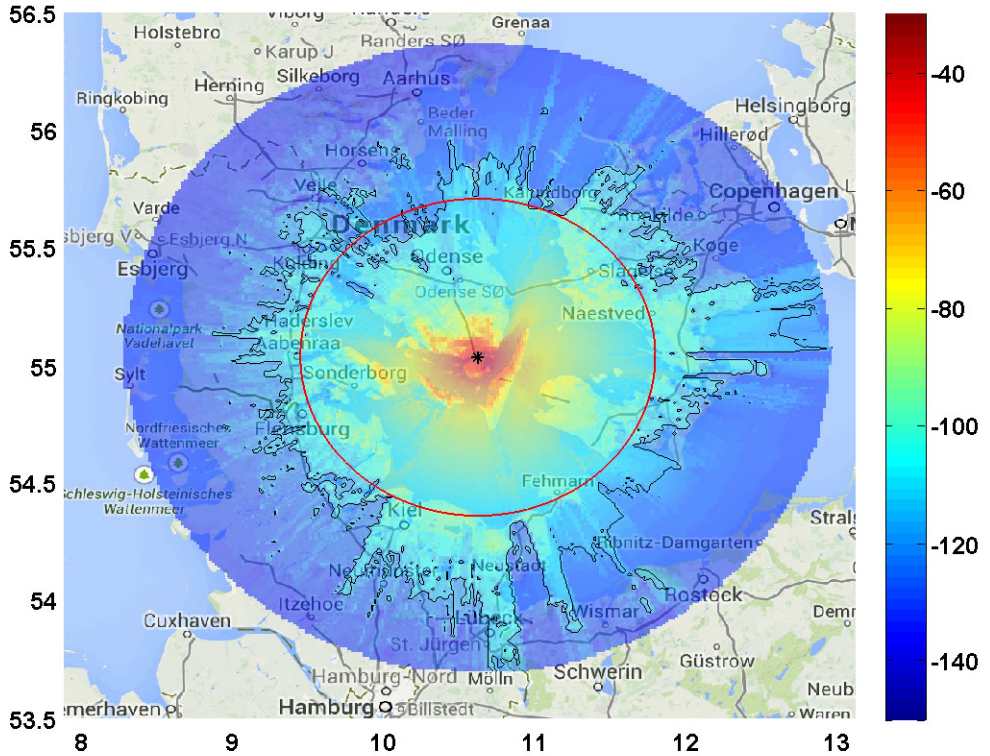

Figure 11: Predicted signal strength (in dBm) for Danish site Svendborg.

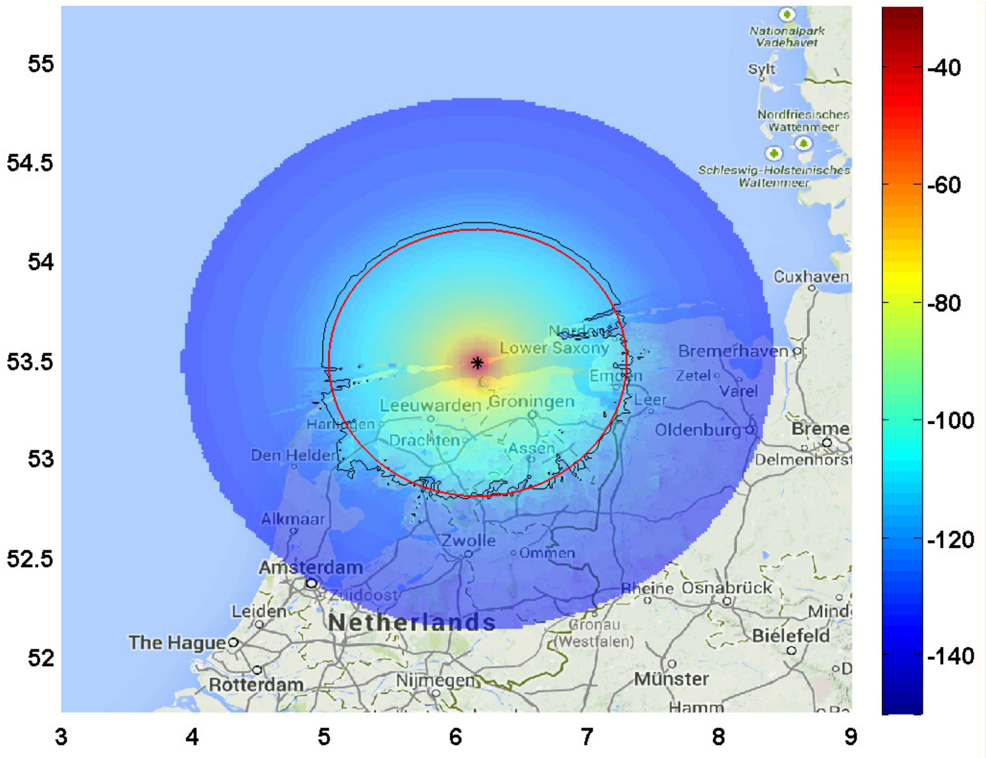

Figure 12: Predicted signal strength (in dBm) for Dutch site Schiermonnickoog.

2.5.4 Interference in the VHF Band

The primary source of interference is man-made noise [60]:

- Ambient atmospheric noise is modelled as Gaussian with a flat power spectral density. The average noise power level due to black body radiation is

$$kT_0b$$

  where $k = 1.38 \times 10^{-23}$ W/Hz/°K is Boltzmann's constant, $T_0 = 288$°K is the absolute temperature, and b is the receiver's noise equivalent bandwidth measured in Hz.

- Man-made sources account for additional noise above this level. A common model for the average noise power from these sources, above the noise floor and measured in dB, is

$$F_{am} = c - 27.7\, log_{10} f \;\; dB$$

  in which f is the frequency in MHz and c is a constant depending upon the locality (76.8, 72.5, and 67.2 dB for business, residential, and rural environments, respectively). For the VHF band of interest (near 160 MHz), the average man-made noise is 15.75, 11.4, or 6.1 dB above the noise floor, respectively.

- For example, a 25 kHz AIS channel observed in a residential environment would see an average noise level of

$$-160 \; + 11.4 = -148.6 \; dBW = -118.6 \; dBm$$

This corresponds with our use of -117 dBm as a minimum received signal level as this would correspond to approximately 0 dB SNR.

2.5.5 Geometry

For a position solution, a large impact on the quality of the solution is the location and relative bearings of the transmitter sites to the receiver. This error is captured in the Horizontal Dilution of Precision (HDOP), which is calculated based on the bearings to each of the transmitters. For the North Sea Area, the HDOP has been calculated on a 0.05° by 0.05° grid using only those transmitters within 75 km and providing a signal strength at that location of greater than -117 dBm; see Figure 13. Since the HDOP can be interpreted as a multiplier on the user range error, lower numbers are better. As can be seen, most of the coverage area has a very good HDOP (<2). The blank area off the coast of Denmark could be improved with the addition of an AIS transmitter in the middle of the North Sea (located in one of the windmill farms perhaps).

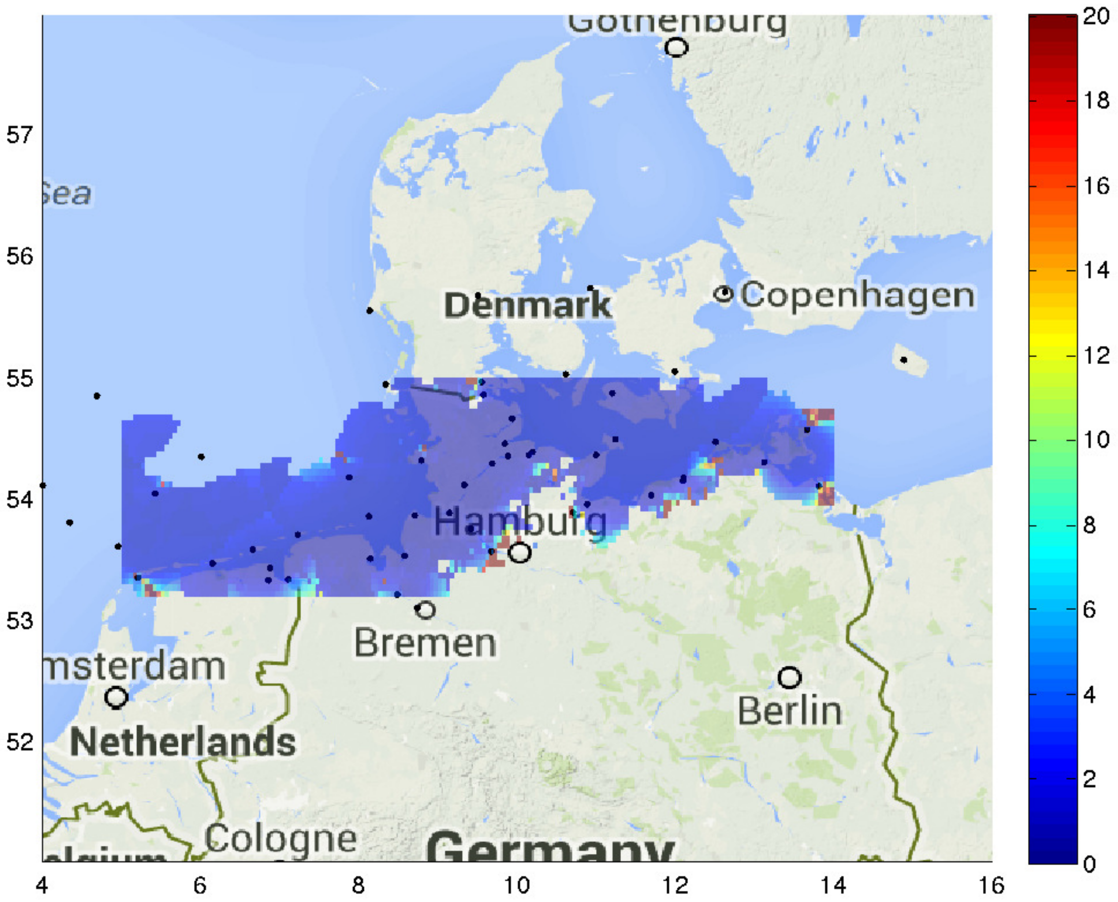

Figure 13: HDOP for the analysis area (53.2-55° N and 5°-14° E).

HDOP values across the analysis area are quite good (<2).

3 Accuracy Analysis

3.1 Timing/Range Accuracy

3.1.1 Standard AIS Transmissions Including Message 8s

The analysis in Section 2.3.1 developed a bound on the timing accuracy of tracking the bit edges in an AIS Message 8 transmission (5 slot). Converting to range accuracy, this is

$$\sigma_{GMSK bit\ edge} \geq 0.003 \times 10^{-\frac{s}{20}}\ meters$$

This equation takes into account distance from the transmitter through the value of s (signal strength in dBm, e.g. -107 dBm).

3.1.2 CW Signals in One or More Distinct VHF Channels

The discussion in Section 2.3.2 considered the range accuracy possible from beating multiple CW signals transmitted in other VHF channels. Using two channels with 3 CW signals, with the highest beat frequency 100 kHz, the accuracy is:

$$CRB(\boldsymbol{\tau}) = \frac{1}{2T\ (2\pi 100{,}000)^2 SNR}$$

3.1.3 Spread Spectrum Signal

As described above in Section 2.3.3, there are a number of technical issues that preclude a precise analysis of a spread spectrum ranging system at VHF frequencies. However, to attempt to assess performance, we make the following assumptions:

- That the power level of the spread spectrum ranging signal is set so that it is useful for ranging receivers at distances between 500 m and 50 km of the transmitter. Note that over this range, channel attenuation is expected to be at least 40 dB.
- That the power level is sufficiently low so that the spread spectrum signal does not impact VHF radio channels; in other words, it is below the noise floor of those receivers (-107 dBm) at all impacted ranges from the transmitter.
- That the chipping codes (both the sequences themselves and the code length) are selected to provide in excess of 60 dB processing gain (this is higher than that provided by the Gold codes currently used by GPS; hence, will require longer chipping sequences), sufficient to correct for both channel attenuation and to raise the signal to 8-10 dB above the ranging receiver's noise floor.
- That 10 or more distinct codes can be found so that a simple code reuse pattern allows the codes to reduce interference from the other spread spectrum transmissions within range of the receiver.
- That MUD receivers are implemented to further reduce MAI.

To demonstrate the potential of such a spread spectrum approach, we assume that the technical issues described above can be satisfactorily resolved so that the resulting ranging accuracy is a uniform 12 meters (1 standard deviation) out to 50 km from each AIS transmitter location (of course accuracy would be better closer to the transmitters, but we cannot at this point put a more specific functional form on this performance).

3.2 Positioning Accuracy

The results in Section 3.1 bounding the range accuracy for the three methods are used to provide the accuracy of each individual pseudorange. This error term is combined with the

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geometry of the stations through a weighted HDOP calculation to provide a bound on position accuracy estimates across the analysis area.

In the sections below, the plots do not take into account any errors due to timing offsets between the various transmitters (assumed perfect synchronization), nor do they take into account any multipath or other interference, only AWGN.

3.2.1 Standard AIS Transmissions Including Message 8s

Figure 14 shows the results for tracking the AIS bit edges; only AIS base stations with a signal level > -117 dBm and within 75 km of the receiver location are used. For this analysis, 60 slots per minute (or one 256 bit slot per sec) is assumed, and a receiver averaging time of 5 seconds for a total of 1,280 bits used.

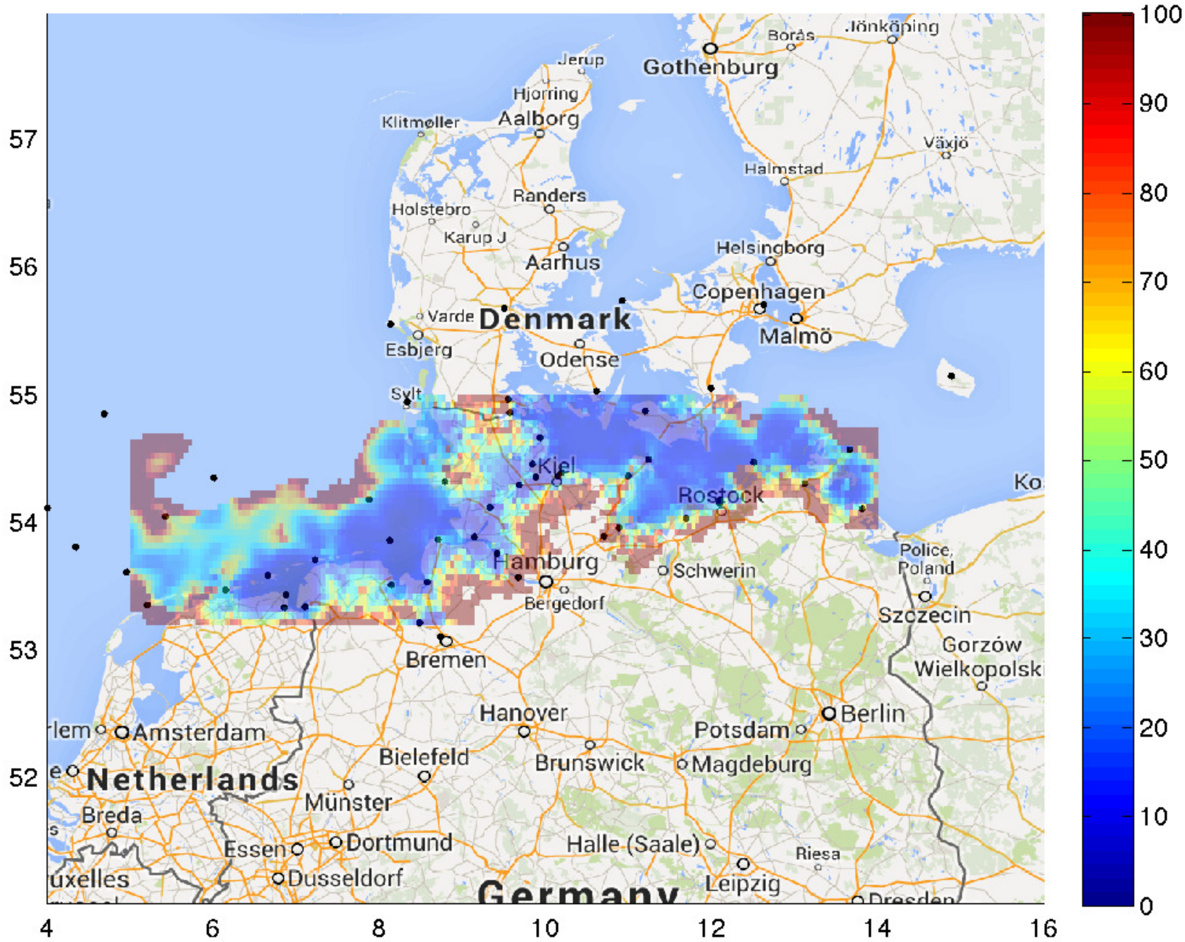

Figure 14: Predicted positioning accuracy (m) using the AIS signal.

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3.2.2 CW Signals in One or More Distinct VHF Channels

Figure 15 shows the results for CW phase tracking with 3 CW signals (2 VHF channels). Only base stations with a signal level > -117 dBm and within 75 km are used. If additional beat frequencies were used, the performance could be improved. However, this would be at the cost of increased VHF channels and receiver complexity. Conversely, if only one VHF channel (2 CW signals or one beat frequency) were used, performance would be worse than shown. For this analysis a receiver averaging time of 5 seconds was used.

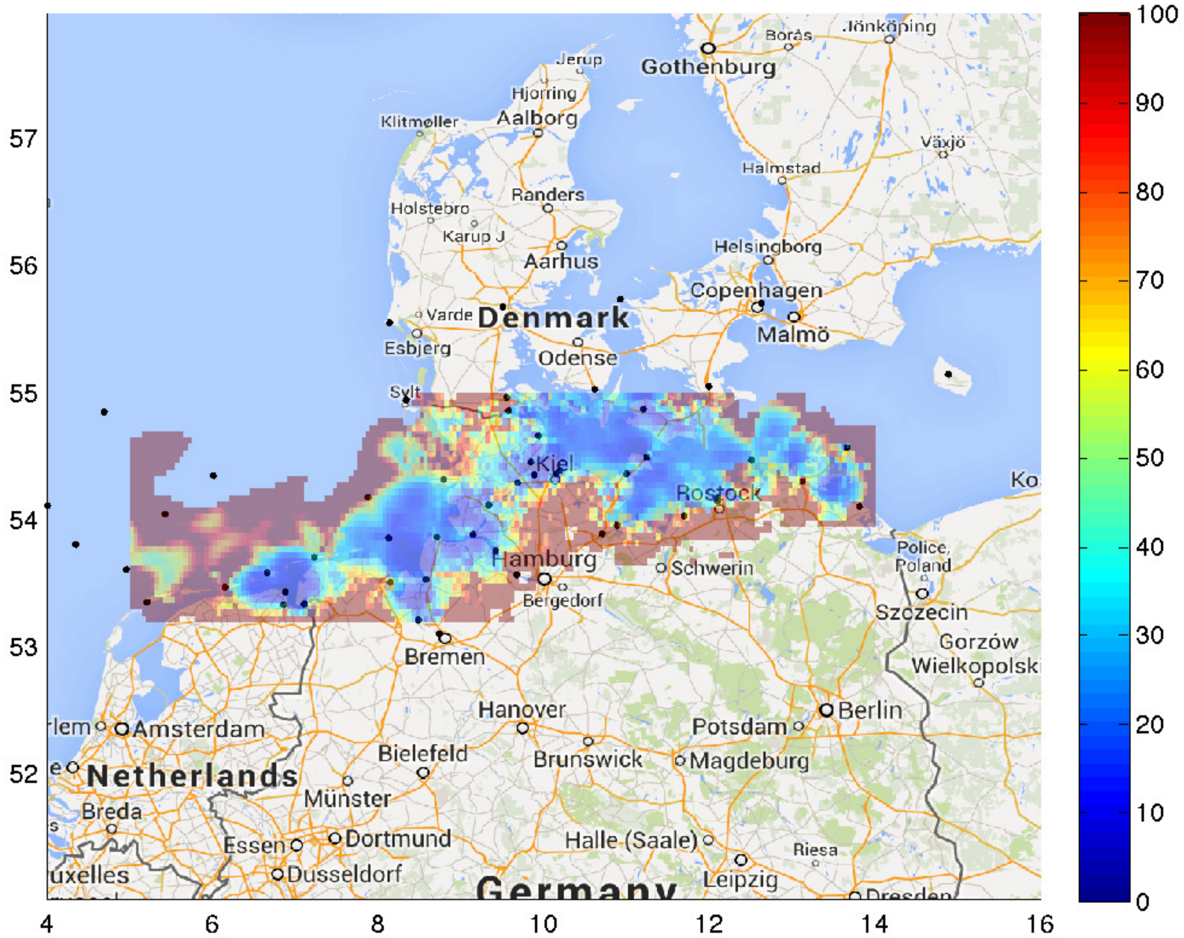

Figure 15: Predicted positioning accuracy (m) using CW signals.

3.2.3 Spread Spectrum Signal

Figure 16 shows the results for spread spectrum ranging using stations up to 50 km from the receiver with a uniform 12-meter accuracy standard deviation. Due to the reduced coverage area from each transmitter (50 km vs 75 km reduces the coverage area by more than 50%) the overall positioning coverage area is dramatically reduced; especially offshore.

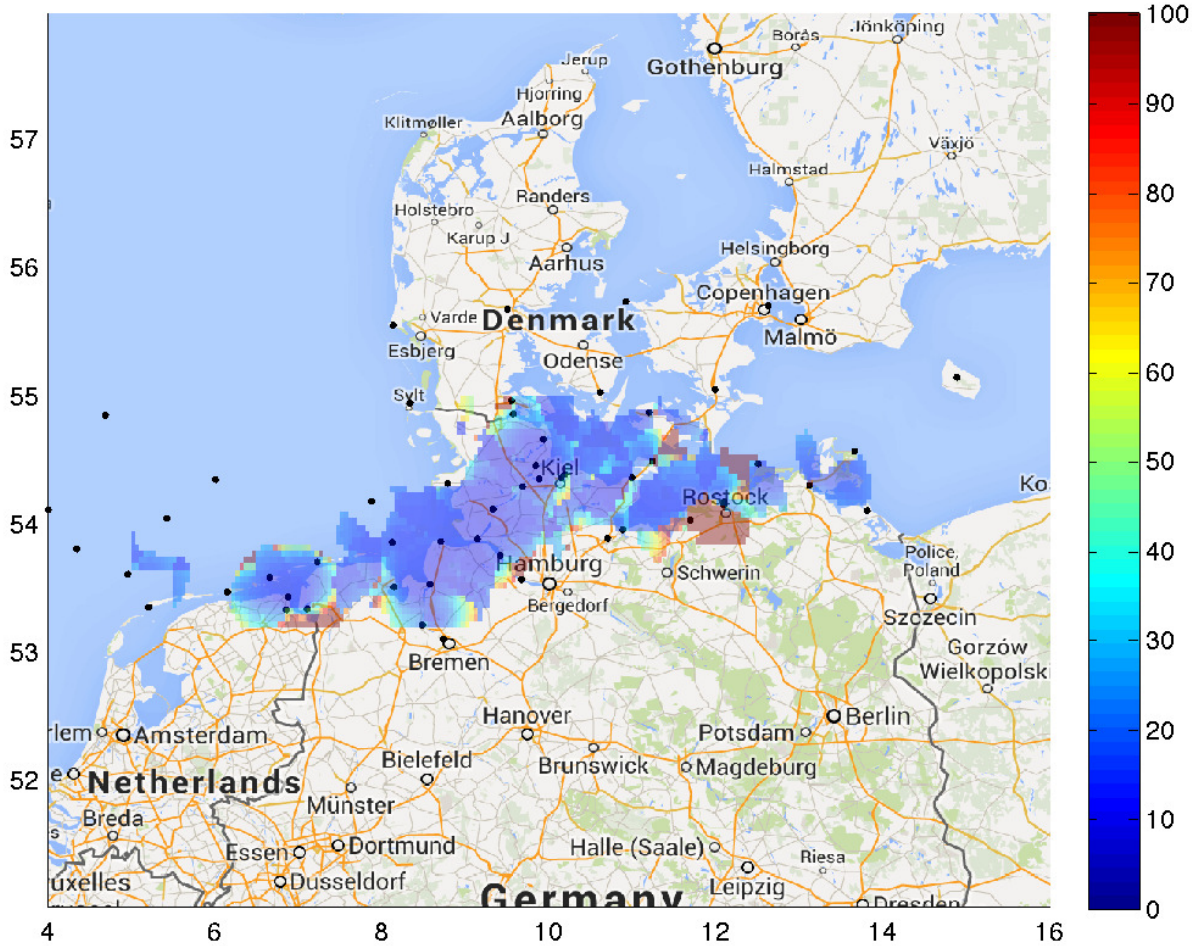

Figure 16: Predicted positioning accuracy (m) using spread spectrum.

3.3 Critical Waterways

The results above assumed that all AIS base stations locations were available to transmit ranging signals and focused on the entire area. However, the reality is that some portions of the area are more important than others; for example, the critical waterways of the Kiel Canal and the Elbe River as far as Hamburg. For this secondary analysis we have focused on these waterways inside a boundary box of 8.5 – 10.5° E and 53.4 – 54.5° N. For this analysis we have included the AIS base station at Hamburg (operated by the Port of Hamburg) and added in additional sites to improve performance to a uniform level of better than 20m along the critical waterways.

To achieve the desired 10m performance, stations were added at Seevetal and Tangstedt to improve performance near Hamburg, at Büsum to improve performance at the mouth of the Elbe, at Nienborstel to improve performance in the middle of the Kiel Canal, and at Strande to improve performance at the entrance of the Kiel Canal to the Baltic Sea. The site selection was accomplished by selecting locations that appeared to provide good geometry and then assessing performance; in some cases several different locations were tried before arriving at the final recommendation. In addition, two sites were converted from sectorized antennas to omnidirectional antennas (Eckernförde and Kiel-Wik). We then eliminated those sites that did not impact that performance (at total of 13 stations).

As an example using AIS bit edges (option 1), Figure 17 shows the optimized set of transmitters (cyan circles are those used as-is, yellow triangles are used as omni sites, green diamonds are added sites, red squares are the sites eliminated). The positioning performance for this set I shown in Figure 18. This can be compared to Figure 14; it should be emphasized that the site selection was done to optimize performance along the critical waterways within the boundary box and serves as an example. Some of the sites eliminated could be very necessary for performance coverage in other areas.

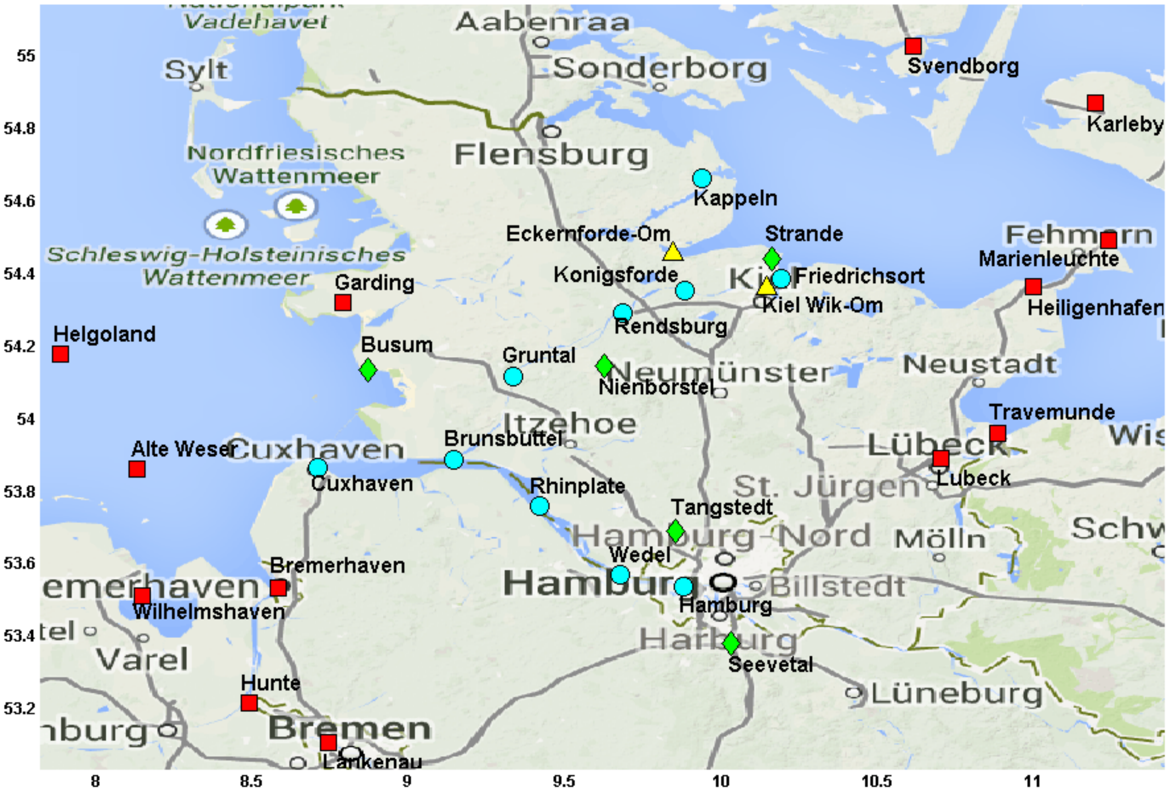

Figure 17: Optimized set of AIS transmitters for critical waterways.

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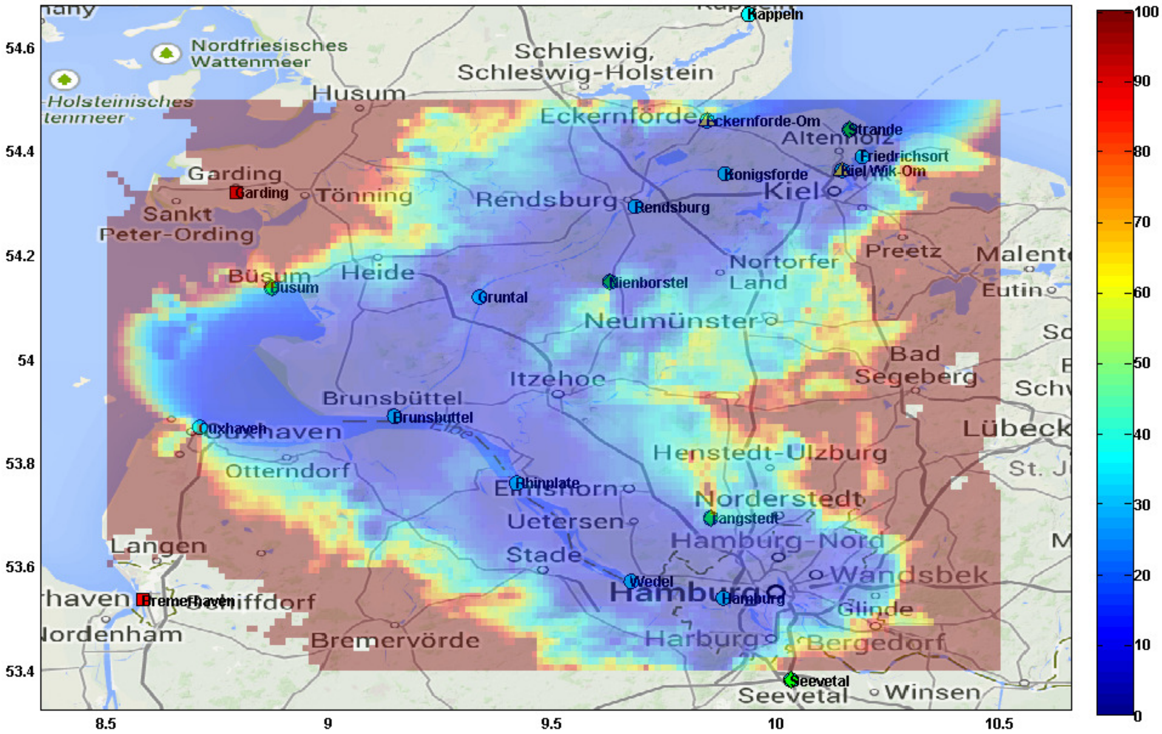

Figure 18: Position performance for the optimized set of transmitters.

3.4 Pros/Cons of Solutions

Table 1 contains a summary of the Pro's and Con's of the three solutions.

Table 1: Pro's and Con's of Three Solutions (recommended solution in BOLD).

Solution	Pro's	Con's
Existing AIS	**1. No change to existing transmit systems.** **2. 10m performance appears achievable using the existing system.** **3. Performance can be increased with more bits used – this could be from additional messages (such as Message 8s and Message 17s that are already being transmitted).**	**1. Addition of Message 8's adds (slightly) to VDL loading.**
CW Aiding	1. CW phase estimate is easier to implement than GMSK bit edge tracking. 2. Carrier phase estimate at this frequency can provide sub-meter accuracy.	1. Cycle resolution is difficult due to the small wavelength; multiple beat frequencies would be needed. 2. Requires addition of multiple CW signals; with different sets of signals for adjacent sites. This requires the use of 1 or more additional VHF channels (4 CW signals and 2 VHF channels for performance equivalent to that of option 1).
Spread Spectrum	1. Provides the ranging service re-using existing spectrum as an overlay. 2. Concept is well-understood.	1. System design is not mature. 2. Performance severely range-limited due to Near-Far problem.

Recommended solution is #1: Existing AIS. Potential AIS performance looks good, can be optimized for excellent coverage along critical waterways

4 System Modifications

4.1 Reference Station Modifications

4.1.1 Standard AIS Transmissions Including Message 8's

No hardware modifications are required for this solution. The modulator's software must be modified to create and send frequent Message 8's to the transmitter (see Figure 19, red is used to clearly show additions to the existing equipment). While this and future diagrams show "Synchronized Rubidium Clock" for the timing source, the clocks at all of the broadcast sites must be synchronized via a non-GNSS source for the trilateration algorithm to correctly predict performance. If synchronization is impossible, the relative offsets of each transmitter must be provided to the receivers (perhaps as part of the message payload).

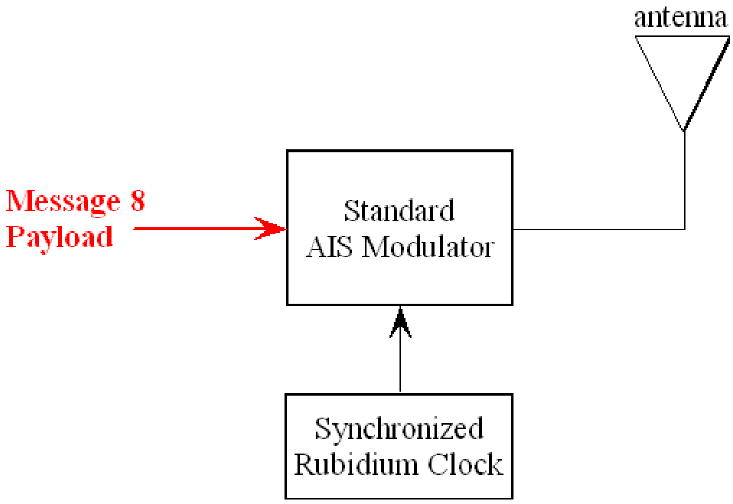

Figure 19: Transmitter for AIS ranging.

4.1.2 CW Signals in One or More Distinct VHF Channels

A new CW transmitter, including a new antenna, is required for this solution (see Figure 20); its precise details depend upon the number of CW signals being generated (2 or 3) and their specific frequencies. Each CW signal must be synchronized to a common clock (UTC). If the channel(s) are not dedicated to ranging, then the CW modulator works in a time switched mode. It is expected that the existing AIS tower would be used for the second antenna.

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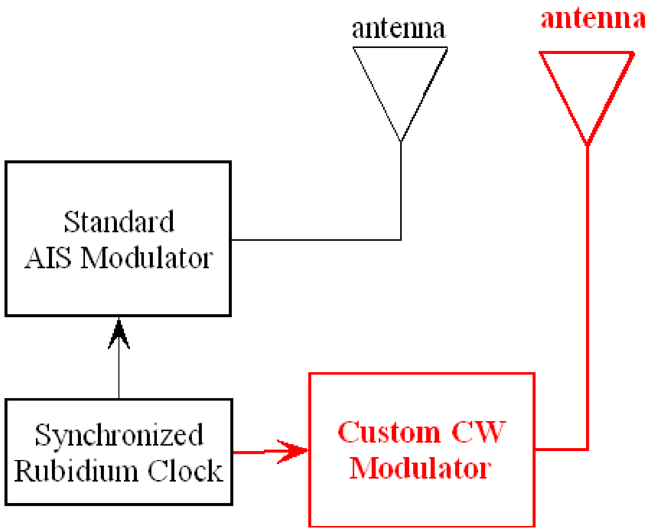

Figure 20: Transmitter for CW ranging.

4.1.3 Spread Spectrum Signal

A new spread spectrum modulator and transmitter, including a new antenna, is required for this solution (see Figure 21); its precise details depend upon the RF bandwidth, chipping codes, desired data carrying capacity (if could carry a limited amount of data such as clock offset), etc. The signals must be synchronized to a common clock (UTC). It is expected that the existing AIS tower would be used for the second antenna.

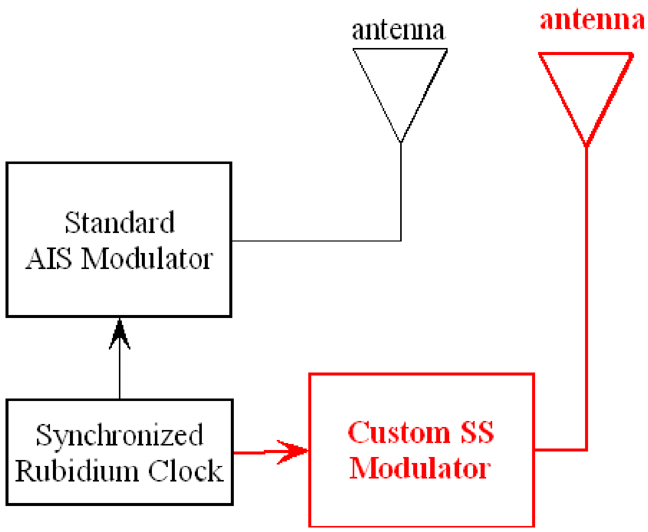

Figure 21: Transmitter for spread spectrum ranging.

4.2 AIS Mobile Receiver Modifications

For all of the three options, an R-Mode receiver would be implemented separate from an existing Class-A AIS radio. It would not be feasible to modify an existing radio to do ranging.

4.2.1 Standard AIS Transmissions Including Message 8's.

Figure 22 contains a block diagram of a receiver to implement ranging from existing AIS signals, which consists of the following:

- The AIS front end/mixer removes out-of-band noise and interference and converts the VHF signal to an intermediate frequency (this could be baseband).
- The analog-to-digital converter (ADC) samples the signal for digital processing.
- The AIS pseudorange estimator implements algorithms to estimate the pseudorange. The output of this block is the estimated pseudorange and an estimate of its error variance (for weighting in the position solution). Note that this block, one for each AIS channel, processes AIS signals from all AIS base stations visible. Since these are transmitting in separate time slots, there is no overlap of processing.
- Finally, the pseudoranges from each AIS channel and their associated weights are combined into a position solution. The output should be a standard NMEA string.

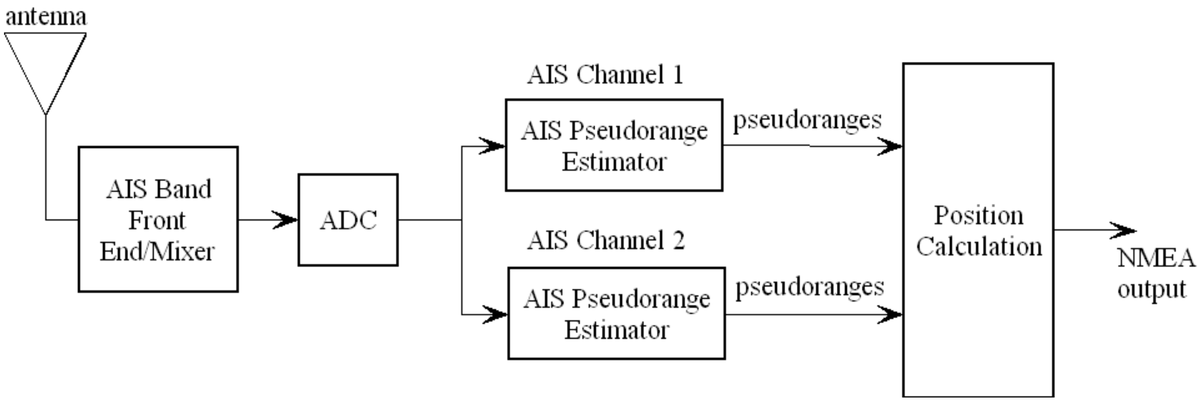

Figure 22: Receiver for AIS ranging.

4.2.2 CW Signals in One or More Distinct VHF Channels

Figure 23 contains a block diagram of a receiver to implement CW ranging, which consists of the following:

- The CW front end/mixer removes out-of-band noise and interference and converts the VHF signal to an intermediate frequency (this could be baseband). Details on this unit depends upon which VHF channel(s) are being employed.
- The ADC samples the signal for digital processing. If the channel is not dedicated to ranging, then only those time periods in which the CW signals are present are converted.
- The block labelled Beat Signal includes band pass filters, multipliers, and additional band pass filters to produce a sinusoid at the beat frequency.
- The CW phase estimator block implements standard algorithms to estimate the phase of the beat signal.
- Ambiguity resolution on the second phase estimate is determined from the phase estimate of the first (lower frequency) beat signal. The result is a pseudorange to the CW transmitter. An estimate of the accuracy of each pseudorange is also provided for the least squares position solution.
- Finally, the pseudoranges from each CW transmitter and their associated weights are combined into a position solution. The output should be a standard NMEA string.

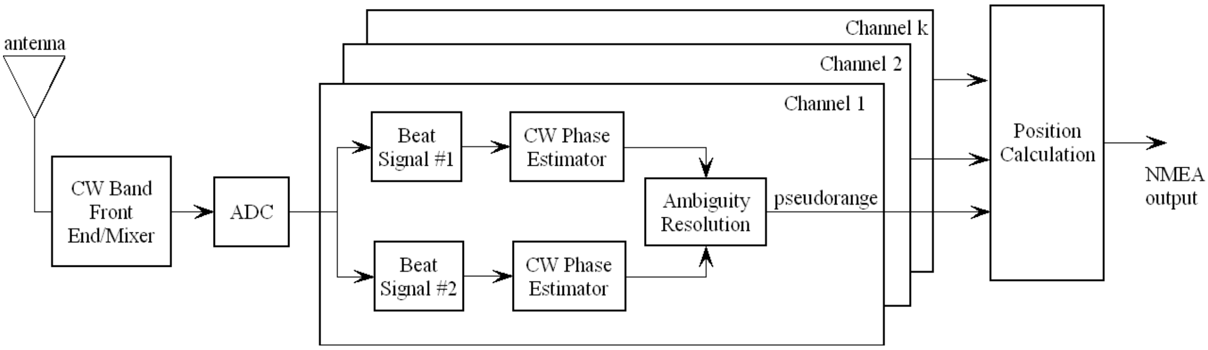

Figure 23: Receiver for CW ranging.

4.2.3 Spread Spectrum Signal

Figure 24 contains a block diagram of a receiver to implement spread spectrum (SS) ranging, which consists of the following:

- The SS front end/mixer removes out-of-band noise and interference and converts the relevant portion of the VHF signal to an intermediate frequency.
- The ADC must be sufficiently fast to record the entire SS band as one signal for synchronous signal processing.
- The SS receiver dispreads the signal, demodulates any data bits, and generates the pseudorange. An estimate of the accuracy of each pseudorange is also provided for the least squares position solution.
- Finally, the pseudoranges from each SS signal and their associated weights are combined into a position solution. The output should be a standard NMEA string.

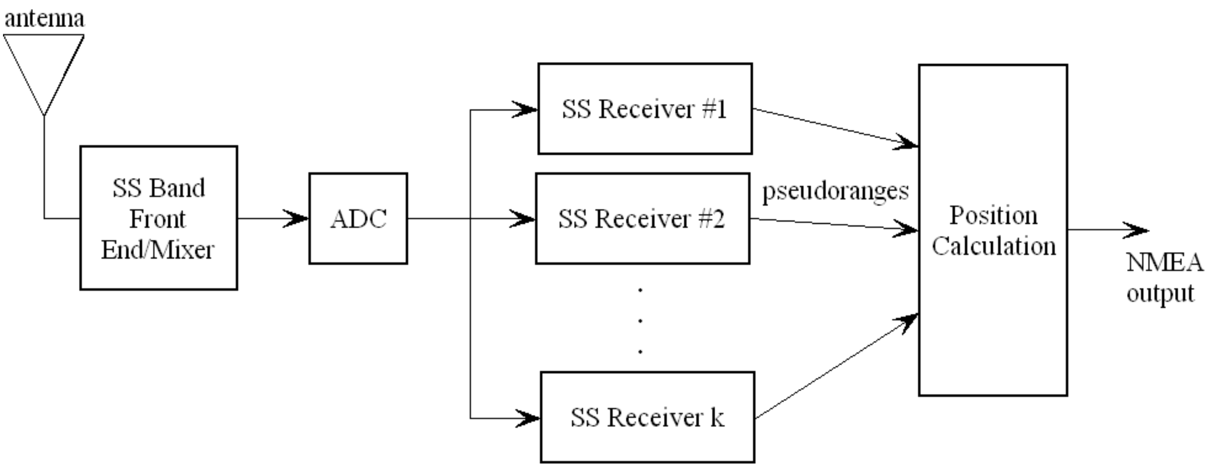

Figure 24: Receiver for spread spectrum ranging.

4.3 Clock Specification

There is a trade-off between accuracy, cost, complexity, and coverage area. Probably the best recommendation would be to install Rb clocks at the AIS sites to provide the short-term signal stability and use a UTC time base to synchronize the clocks (this is already done for the German AIS sites). This would provide R-Mode positioning coverage throughout the area at a level of accuracy limited by the clock synchronization accuracy (50-100ns). The other option (and maybe the easiest option for test bed use) would be to use the existing internal (GPS) timing receivers as the UTC reference, accepting the limited holdover time in the loss of GPS. Caesium clocks would provide much longer holdover time, but are an order of magnitude more expensive than Rb clocks.

Minimum frequency accuracy: 5×10^{-11}

Minimum Stability: 1×10^{-10}.

Minimum UTC synch accuracy: 50 ns.

4.4 Potential Improvements

An array of directional antennas would improve performance for the CW and spread spectrum solutions, reducing interference from the other continuous transmissions. Since the direct AIS solution is already time-slotted, there is no obvious gain there.

5 Test Bed Concept

Detailed description of the concept for testing the R-mode for AIS transmissions in a real testing ground.

5.1 Field Test Concept Study

The goal for the future AIS test bed was to identify locations using either German stations or German stations in conjunction with those from other countries. Another goal was to be able to implement a test bed using a small number of stations (3-5). Two potential test areas have been identified: one using solely German AIS stations and one using German and Danish AIS stations. In each case a variety of transmitters were tested and the combinations that gave the best, predicted performance have been selected. Figure 25 shows the proposed German-only test bed and Figure 26 shows the proposed German-Danish test bed. Of the two test bed sites, the German-Danish one has the advantage of a ferry route running through the middle of the test area; the ferry could be a convenient data collection platform.

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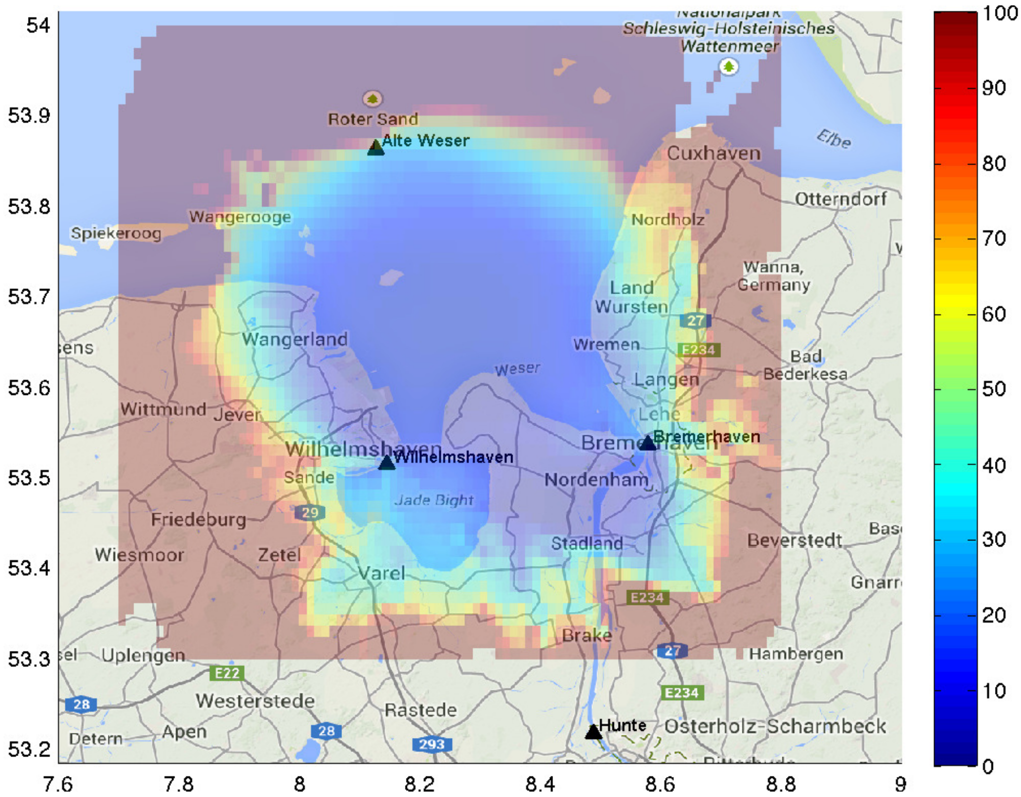

Figure 25: AIS test bed using 3 German stations.

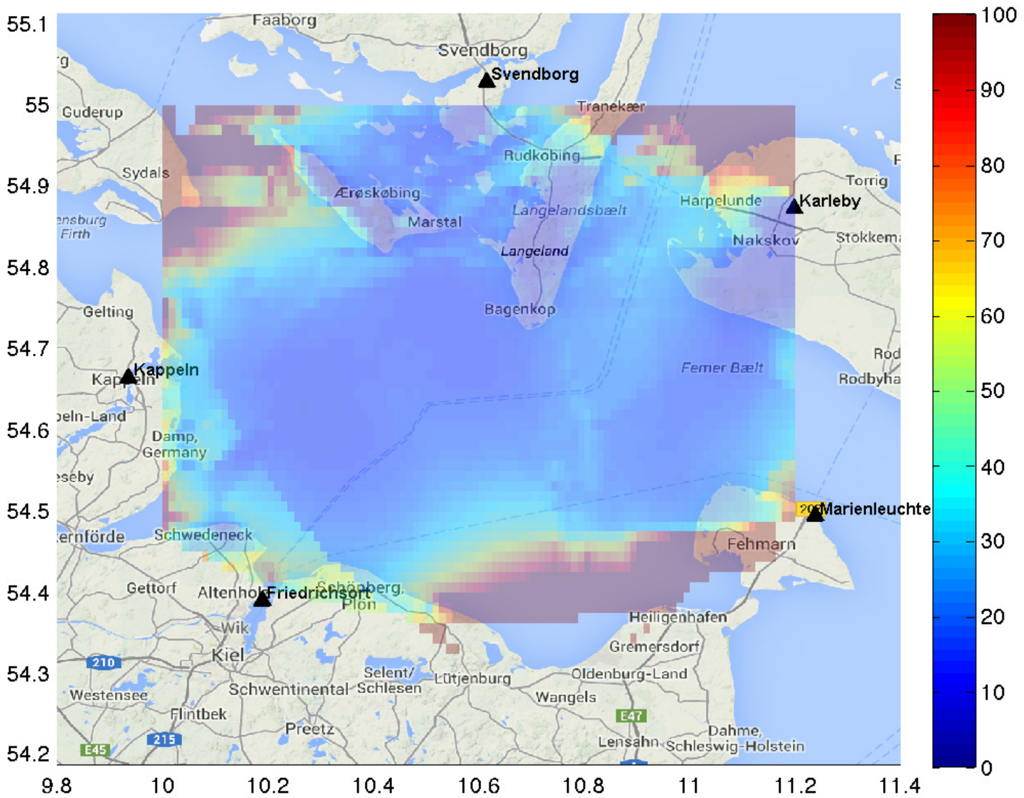

Figure 26: AIS test bed using 3 German and 2 Danish stations.

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6 Conclusions

Although all three proposed ranging methods could yield good results, it appears that ranging off of the standard AIS signal is the most feasible. It appears that quite good accuracy (less than 100m and less than 20m in some areas) can be achieved using the existing AIS signal with a small impact to the VDL. The analysis has been done using just 60 slots per minute, which is only 1.3% of the total VDL. Performance can be increased by allocating additional slots for ranging messages. This could be additional message 8's or message 17's. If the stations are used for DGNSS corrections already, there are an additional 30 slots per minute per GNSS system (per IALA guidelines [61]) of message 17's that could be used for ranging without adding any additional VDL load. In addition, since performance is a function of number of bits used, better performance (meaning better positioning accuracy or increased coverage or shorter averaging window) could be achieved using more message bits (more messages) and possibly a higher bit rate on one of the proposed new AIS or VDES channels.

The CW method can yield sub-meter accuracy due to the small wavelength of the signals, but the ambiguity resolution is not easy. It would require multiple CW beat frequencies (requiring at least one additional VHF channel) in order to get to equivalent performance. And even more beat frequencies (and an additional VHF channel) to get to the sub-meter performance level.

The spread spectrum concept is the least mature of the three and thus there would be more risk in going forward. It appears to have the possibility of achieving 100m or better accuracy; however, the distance from the stations is limited by the near-far problem, which greatly reduces the coverage area. There are also some technical challenges to solve as well as regulatory hurdles. Although there appears to be precedence within ITU regulations for a system such as this, it would require some effort. The spread spectrum concept might have more appeal as a short-range communications overlay; in this case the near-far problem would not exist and it could provide an additional channel suitable for local communications such as ship to boat, using existing spectrum.

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