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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Table of Contents

Table of Figures

List of Tables

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1 Introduction

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. combining with eLoran or perhaps with GNSS measurements limited by urban canyons).

This report presents several AIS-based solutions to provide a Ranging Mode (R-Mode) Position Navigation and Timing (PNT) alternative to GNSS.

2 Description of the identified methods and approaches (LP2-210)

2.1 Analysis of the AIS Standard (LP2-110)

2.1.1 AIS Technical Characteristics

The technical characteristics of the AIS signal are defined in the International Telecommunications Union Radiocommunications Sector (ITU-R) Standard 1371 [1]. The relevant characteristics are:

- Very High Frequency (VHF) maritime mobile band, which consists of the frequencies 156.025-157.425, 160.625-160.95, and 161.5-162.025 MHz as defined in the Radio Regulations, App 18 [2]. Two channels have been designated for AIS use, 161.975 and 162.025 MHz (which are channels 87 and 88 [3]), although others are technically possible. This gives two simultaneous channels, but all base stations use the same two channels.
- There is 25 kHz of bandwidth (BW) for each channel; relative to the carrier frequency this is very narrow band.
- The frequency stability of the carrier frequency is required to be minimally ±500 Hz; the stability will be a function of the transmitter’s clock stability.
- The signalling rate is 9,600 bps.
- The bits are Non-Return-to-Zero Inverted (NRZI) encoded, which means that the signal has a transition at a clock boundary if the bit being transmitted is a logical 0, and does not have a transition if the bit being transmitted is a logical 1.
- The modulation is Gaussian-filtered or just Gaussian Minimum Shift Keying (GMSK), with a BT product of 0.4; this is a narrower spectrum than MSK, with lower side lobes (see Figure 1).
- The typical power level is only 12.5 W; however, the antennas at VHF frequencies are very efficient and typically have several dB of gain, so the radiated power is quite good.

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- The channels are shared using Time Division Multiple Access (TDMA); the system is organized into time slots (2,250 per minute), so in general the proposed ranging would be off of a time-limited signal.
- The AIS slots are time-synchronized to UTC, minimally to within 104 μsec of the UTC source; however, exact time accuracy is a function of the transmitter's clock synchronization accuracy.
- A single slot 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 flag, giving 32 known bits at the beginning of each message.
- Base stations transmit AIS message 4 (Base Station Report) at an interval of 10 seconds, alternating channels; if operating in semaphore mode, the interval decreases to 3.33 seconds.
- Base Station Reports contain the UTC time (to nearest second) and the slot number of

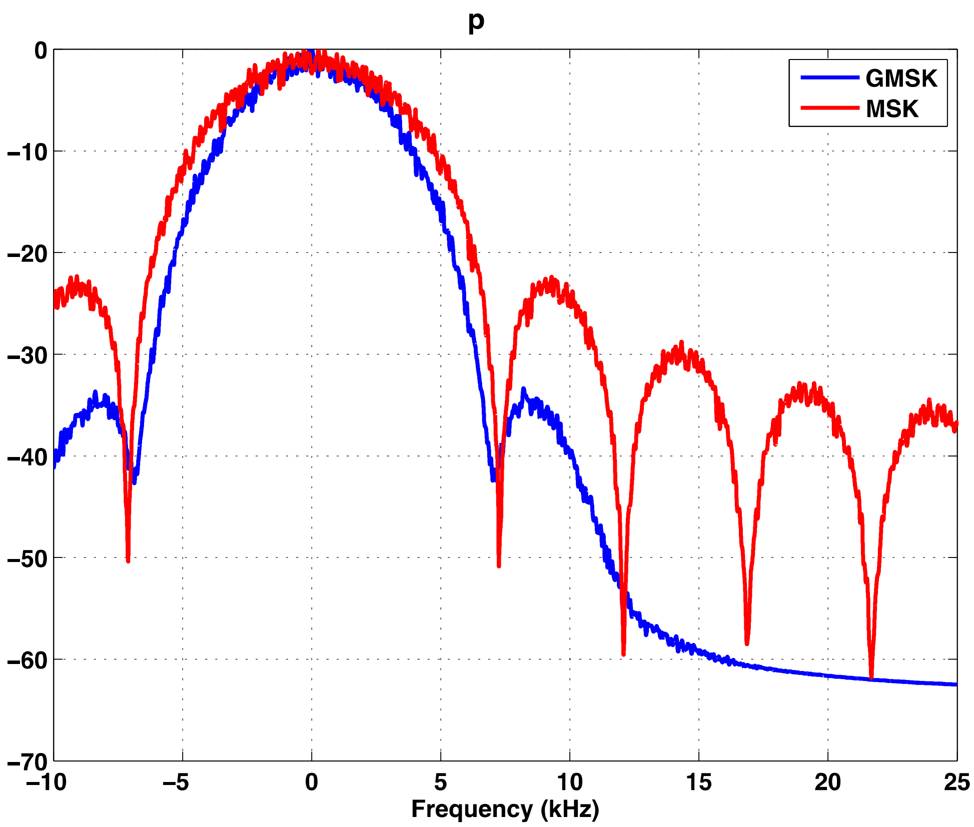

Figure 1: GMSK vs. MSK Spectrums at 9,600 bps.

2.1.2 The GMSK Signal

The AIS transmission uses GMSK, an example of a more general modulation technique called Continuous Phase Modulation (CPM), and is somewhat more narrow band than MSK [4-6] (MSK is also a CPM signal). The functional form of a binary CPM signal can be written as

$$s(t) = A\,sin\left(\omega_c t + \pi \sum_k b_k q(t - kT_s)\right)$$

in which A is the signal amplitude, 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

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

For GMSK the frequency response is

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

with B a design parameter ($BT_s \approx 0.4$ for AIS; typically *L* = 4 or 5 for GMSK) and $\mathrm{Q}(x)$ is the Gaussian tail probability

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

A variety of GMSK demodulation approaches have been considered in the communications literature (see e.g. [7-9]). In its use as a communications system transmission, three parameters of this signal are typically estimated at the receiver: the carrier frequency, the carrier phase, and the time of bit transition. The performance of any estimator for these parameters can be lower bounded by a modification of the Cramér-Rao Bound [10].

2.1.3 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 the 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. Figure 2 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.

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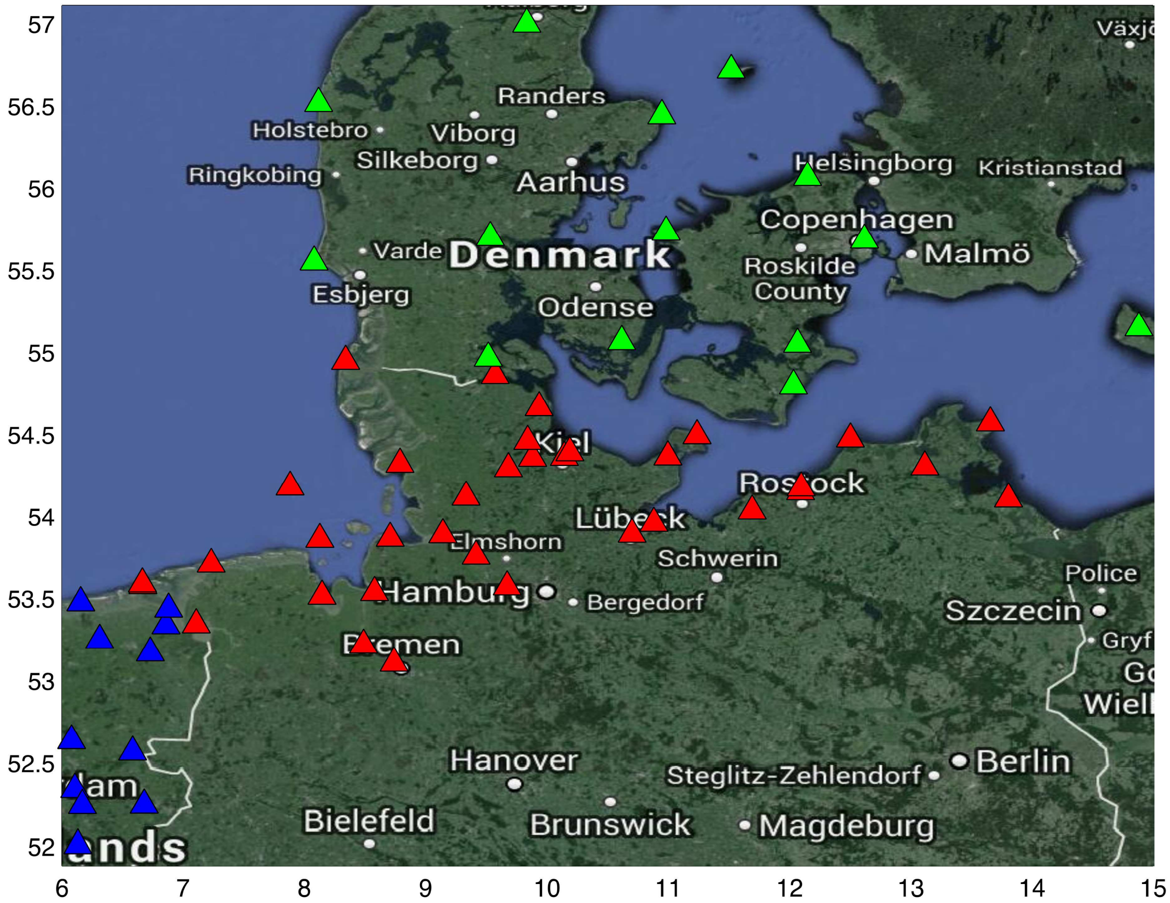

Figure 2: Study coverage area with German AIS stations (red triangles), Danish AIS station (green triangles) and Dutch AIS stations (blue triangles).

2.1.4 AIS as a SoOP

The Milestone 1 report described several challenges that face SoOP positioning systems. Specific issues from that report especially relevant to employing AIS as a SoOP are:

- Time synchronization of the transmissions. While it is possible to implement a positioning system using unsynchronized SoOP signals, such an approach requires a system of monitor receivers to identify the time offsets between the SoOP signals and a communications channel to broadcast those time offsets to users, in real time. As part of its definition as a TDMA communications link, the AIS transmissions are synchronized; specifically, the base stations derive time from GNSS signals, or by using a network time protocol, and the vessels derive time either directly from their own observed GNSS signals or indirectly from other AIS signals. Since a SoOP positioning system would only exploit the base stations' already synchronized transmissions, a monitor network appears to be unnecessary. However, this issue needs further exploration as it is unknown at this point if the network-based synchronization provided to the base stations is sufficiently accurate for the ranging/positioning goal in the absence of GNSS.
- Coverage area. While widely distributed along coastlines, the locations of the AIS transmitters and their coverage areas will greatly affect potential SoOP positioning performance. The coverage is predominantly a function of the line-of-sight propagation

path, due to the signal being in the VHF range, and the potential directionality of the base stations' transmitter antennas; the signals are typically not power-limited.
- Algorithms. While the AIS transmission has obvious timing characteristics that could be exploited for ranging (carrier phase and times of bit transitions), the complexity of the signal structure and its resulting narrow band nature make the development of effective algorithms difficult. The high frequency AIS carrier can provide sub-meter positioning accuracy; however the ambiguity resolution of the carrier cycle is an issue that must be addressed.
- Signal propagation. At VHF frequency there are no ground propagation effects or sky wave to be concerned about.

2.2 Literature Review (LP2-120)

As noted above, the AIS signal consists of GMSK modulation. We note the following facts with respect to the relevant literature:
- GMSK is a narrow band communications technique, narrower than MSK (see e.g. [4-6] and Figure 1).
- For use as a SoOP, we would be interested in the carrier phase and symbol timing of this GMSK transmission. Bounds on the accuracy of estimates of these parameters are available for the GMSK signal [10].
- Algorithms, within the communications context, to estimate these parameters as part of the demodulation operation have been considered in [7-9].
- Discussions of AIS as a SoOP are non-existent. Specifically, while references [11, 12] have promising titles, they have no content relevant to the problem at hand.
- There appears to be no literature on using GMSK signals, in general, for ranging.

2.3 Author Proposed Methods (LP2-130)

In this section of the report we list and briefly describe potential methods to yield high performance ranging utilizing the AIS signals. We realize that for many of these ideas the existing signal's realities dramatically limit their feasibility. The intent, however, is to be all-inclusive before focusing in on just a few ideas for further investigation.

Below we separate the proposed methods into four categories: (A) the status quo, using the existing AIS signals, (B) considering the effect of employing a third VHF channel, but dedicated to ranging instead of AIS, (C) adding signals to the current AIS channels, and (D) exploiting the entire VHF maritime band (portions of the 156-162 MHz band listed in 2.1.1) with a spread-spectrum transmission. We note that the ideas might not be mutually exclusive; two or more might be used together synergistically.

In the descriptions below we will assume that the transmitters are provided with a high quality clock and are all synchronized to a common timing source (synchronizing both times of bit transitions and carrier frequency and phase as well as appropriate parameters of any other signals being transmitted). The elimination of this assumption might be possible for some of the methods, but would likely require monitor stations and the use of some of the message bandwidth to disseminate the monitor information. It is also important to keep in mind that there are two AIS channels; all base stations normally must share the same two channels leading to limits on signal availability for positioning (AIS is a time division multiplexed system). And finally, although it might be possible to add direction-finding capability to the receiver so that the receiver could employ both pseudo-range and bearing estimates in its positioning algorithm, this idea is not investigated further at this time.

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A. Status Quo

1. Use the existing GMSK signal as it is – 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 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.
2. Use additional messages (Message 8's) – similar to the first method (A1), 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. An obvious disadvantage of this approach is that it reduces the throughput of the entire AIS system as these longer, more frequent messages require their own time slots. AIS Message 17's could also be used, but introduce the difficulty of demodulating the data first in order to have a known signal.

B. Use Other VHF Maritime Channel(s)

A request could be made to the competent authority for the use of separate VHF channel(s) that would transmit signals for ranging. Depending upon the specifics of the signal, this might be possible on a VHF channel(s) shared with other users or might require a channel(s) dedicated to ranging. Such methods could use one or more VHF channels for each base station and the specific channels could be different for different base stations. The sharing of the same channel(s) would require some sort of time diversity protocol across adjacent base stations; different VHF channels for different base stations would eliminate this and would also yield the advantages of frequency diversity in the estimation process. Potential signals include:

1. A pulsed signal – for good ranging we would want a pulse shape such that the peak of its autocorrelation function is both narrow and unique. However, given the narrow band nature of the VHF maritime channels (25 kHz at 160 MHz), any pulse shape will locally appear to be sinusoidal in nature and experience cycle ambiguity in its autocorrelation function. Resolution of this ambiguity is necessary for ranging and would depend on whether one or more VHF channels are available for ranging:
    a. With one channel, one could time sequentially transmit bursts of sinusoidal signals at fixed, but different, frequencies. The receiver could then beat[1] the sinusoids together to generate sinusoids of lower frequencies that would allow for coarse and fine lane estimates from the signals' phase estimates. For example, bursts of two different sinusoidal signals at a frequency spacing of 3 kHz (with this spacing both could be in the same VHF channel) would yield a beat signal with a lane width of 100 km; estimation of the phase of this signal could yield a range with precision of better than 1 km. Combining this signal with the AIS

[1] Superimposing two sine waves of different frequencies will result in components at the sum and difference of the two frequencies. These new frequencies are called heterodynes. Typically only one of the new frequencies is desired, and the other signal is filtered out of the output of the mixer. Heterodynes are related to the phenomenon of "beats" in acoustics.

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carrier (estimated using idea A1 and/or A2 above) could potentially provide a smaller lane estimate with its ambiguity resolved from the first set of signals.

b. With two or more distinct ranging channels, bursts of sinusoidal signals in each channel could be transmitted. As these bursts would be further apart in frequency, the beating of them could lead directly to fine resolution of the ranges and ambiguity resolution from a pair of bursts in the same channel.

As noted above, different base stations could conceivably use different VHF channels, or could use the same channel(s), but send bursts of different frequencies to allow for simple station identification.

2. CW signals – an alternative to a sinusoidal burst is to continuously broadcast sinusoidal signals (continuous wave, CW, modulation), potentially at a lower power level, within one or more VHF maritime channels and use the same concepts of ambiguity resolution from the beat signals. 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, especially if the employed channel(s) has low duty cycle of alternative usage.
3. Two-tone modulation – in [13] we introduced a method called two-tone modulation to perform data wipe-off on MF DGNSS transmissions so as to aid in ranging applications. Specifically, it required a second, simultaneous transmission of identical and complementary data on the two MSK channels. This concept would also work for AIS transmissions (since the modulation method, GMSK, has similar characteristics) and the second signal could be transmitted on the alternative VHF channel.

C. Signals Added to the Existing Channels

The ideas of section B could, conceivably, be implemented on the existing AIS channels; however, this would require a standards change that is most likely not feasible:

1. Add a pulsed signal on the AIS channels – see B1.
2. Add CW signals to each AIS channel – see B2.
3. Two-tone modulation – see B3; the additional GMSK signal would be sent simultaneously on the second AIS channel.

D. Wideband modulation

1. Spread spectrum (CDMA) signalling – the VHF maritime band which contains the AIS signal is quite wide, approximately 6 MHz, comparable to the GPS L1 band, although not all of the band is dedicated to maritime (there are two contiguous blocks of ~1MHz each allocated to maritime). Conceivably, the AIS base stations could broadcast a very low level CDMA signal, effectively a terrestrial GPS akin to Locata[2], with similar ranging capability.

3 Evaluation and comparison of the identified methods (LP2-220)

3.1 Comparison and evaluation of identified methods (LP2-140)

Each of the ideas presented above (A1-2, B1-3, C1-3, and D1) has been evaluated using the following metrics:

[2] www.locata.com

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- Spectrum requirement – simply, does the method fit within the two existing AIS channels or is additional spectrum required?
- Compliance with standards – are any modifications to the existing standards required?
- Transmitter complexity – as all new modulations would be implemented using a separate transmitter, this metric attempts to evaluate the complexity of that transmitter.
- Impact on legacy AIS users.
- Technical feasibility of the idea.
- Ambiguity resolution – being based on narrow band signals, the ideas in groups A, B, and C should all provide good accuracy, within an RF cycle (the frequency of which depends upon the method), but will require resolution of the cycle ambiguity; hence, this metric assesses how well we think the system will be able to resolve that ambiguity.
- Channel sharing for positioning – a position solution requires the reception of non-interfering signals from multiple base stations; this necessitates having some form of time, frequency, or code diversity. This metric assesses how effective the method is at providing the required diversity.
- Implementation cost.

We note that none of the ideas require changes to the AIS modulation itself; any new signals/modulations would either be instead of or in addition to the AIS signal. Further, in all cases a new R-Mode receiver would need to be designed/implemented; this is assumed to be equally difficult for all options so is not included as a metric.

This evaluation is tabulated into Pros and Cons in

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Table 1; Pros and Cons are relative to method A1, the status quo with higher quality time synchronization of the transmissions (this is assumed for all methods). Next,

Table 2 presents a comparison of the metrics above in a Green-Amber-Red (GAR) chart. In this table, each column is a different metric with the criteria for Green, Amber, or Red listed in Table 3. Complete details on how each method was scored on each metric are provided in Appendix A.

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Table 1: Pros and Cons of each of the proposed methods.

#	R-Mode Option	Pros	Cons
A1	Use existing AIS signal as is (range on MSG 4's) - range on single slot (msg is known/predictable).	1. No changes to current system. 2. No impact to legacy users.	1. Frequency of position solutions is limited by the MSG 4 transmission rate. 2. Ambiguity resolution is a problem for carrier tracking, so positioning is only possible using bit transitions at lower accuracy. 3. Would not be able to do simultaneous ranges from all base stations.
A2	Use existing AIS signal with a special ranging message (MSG 8, perhaps multislot) transmitted more often.	1. No changes to current system. 2. Longer and more frequent messages should improve performance (both accuracy and position update rate). 3. No impact to legacy users.	1. Decreases AIS throughput as additional slots are used for the longer and more frequent messages. 2. Ambiguity resolution is a problem for carrier tracking, so positioning is only possible using bit transitions at lower accuracy. 3. Would not be able to do simultaneous ranges from all base stations.
B1	Transmit a pulsed signal on a third dedicated channel.	1. More signal results in improved ranging and more frequent position updates. 2. No impact to legacy user (since pulses not on AIS channels). 3. Pulses could also be data-carrying.	1. Need 3rd VHF channel assigned and standards would need to be modified to allow pulsed signal. 2. A new modulator would be needed for the third channel. 3. Ambiguity resolution would still be difficult due to the limited bandwidth. 4. Would not be able to do simultaneous ranges from all base stations.
B2	Transmit CW signal(s) on the third channel.	1. Ranging on phase of CW is easier. 2. Continuous signal allows for more averaging and continuous positioning. 3. More BW available for multiple CW signals - could use the 3rd channel in conjunction with other 2 channels (method A1) to provide additional signals for ambiguity resolution. 4. No impact to legacy users.	1. Need 3rd VHF channel assigned, but this could be shared with other uses, standards would need to be modified to allow the CW signals. 2. An additional, new modulator would be needed for the third channel.
B3	Two-tone concept – duplicate AIS1 and AIS2 transmissions on third channel (simultaneous transmission).	1. Provides for data wipeoff to simplify parameter estimation. 2. Additional transmitter is standard AIS base station. 3. No impact to legacy users.	1. Need 3rd VHF channel assigned and authorized for AIS. 2. An additional base station modulator would be needed for the third channel. 3. Would not be able to do simultaneous ranges from all base stations.

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#	R-Mode Option	Pros	Cons
C1	Interleave a pulsed signal with the AIS transmissions on the same channel (still TDMA, so not too many pulses are possible).	Relative to B1: 1. Does not need additional channel	Relative to B1: 1. Limited number of slots are available for pulses on the existing channel, so improvement in performance might be small. 2. As this pulse might be a totally different signal, transmitter and receiver modifications might be quite difficult; there might be impact to legacy users. 3. Would require an AIS standards modification to allow pulsed signal interspersed in standard GMSK.
C2	Overlay CW signal(s) onto the AIS transmission – this could be done on both AIS channels.	Relative to B2: 1. Does not need additional channel	Relative to B2: 1. CW overlay might impact legacy user; but is there sufficient BW to resolve ambiguity? 2. Would require an AIS standards modification to allow CW overlay.
C3	Simultaneously transmit two copies of the GMSK signal on the two channels – the “two-tone” concept.	Relative to B3: 1. Does not need additional channel	Relative to B3: 1. Transmitting same message on both channels would double the slot usage.
D1	Transmit a spread spectrum (CDMA) signal using the entire VHF maritime band.	1. Spread spectrum provides accurate ranging system based on known technology (GPS). 2. Spreading should keep the signal in the noise level to other users of the band so should be minimal impact to legacy users. 3. Ambiguity resolution is not an issue. 4. Simultaneous ranges from all base stations possible.	1. Uses the entire (or a large part of the) marine band so would require a standards/frequency authorization change, but should not be a performance impact. 2. A new modulator would be needed but this would not require changes to the existing AIS modulator; also this new modulator is based on known technology.

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Table 2: GAR Chart for AIS Ranging Ideas.

R-Mode Option	Spectrum Reqmts	Standards Compliance	Transmitter Complexity	Impact to Legacy Users	Technical Feasibility	Ambiguity Resolution Ability	Channel Sharing for Positioning	Implementation Costs		Select
A1	Green	Green	Green	Green	Green	Red	Yellow	Green	Grey	Red
A2	Green	Green	Green	Green	Green	Red	Yellow	Green	Grey	Red
B1	Yellow	Yellow	Yellow	Green	Yellow	Red	Yellow	Yellow	Grey	Red
B2	Yellow	Yellow	Yellow	Green	Green	Green	Green	Yellow	Grey	Green
B3	Yellow	Yellow	Green	Green	Green	Yellow	Yellow	Green	Grey	Yellow
C1	Green	Red	Red	Yellow	Red	Red	Yellow	Red	Grey	Red
C2	Green	Red	Yellow	Yellow	Yellow	Red	Yellow	Yellow	Grey	Red
C3	Green	Green	Green	Green	Green	Red	Yellow	Green	Grey	Red
D1	Yellow/Green (hatched)	Yellow	Yellow	Green	Yellow	Green	Green	Yellow	Grey	Green

Table 3: GAR criteria for each Metric.

Metric	Red Level	Amber Level	Green Level
Spectrum Reqmts		Amber = needs additional channel(s)	Green = fits in existing AIS channels
Standards Compliance	Red = Low - requires changes to AIS standard that are not likely	Amber = Medium - requires change to VHF frequency allocations	Green = High - no changes required
Transmitter Complexity	Red = High	Amber = Medium	Green = Low
Impact to Legacy Users	Red = Legacy will not work	Amber = Degrades performance	Green = No Impact
Technical Feasibility	Red = Low	Amber = Medium	Green = High
Ambiguity Resolution Ability	Red = Low	Amber = Medium	Green = High
Channel Sharing for Positioning		Amber = channel sharing method requires sequential ranges	Green = channel sharing method allows for simultaneous ranges
Implementation Costs	Red = High	Amber = Medium	Green = Low

4 Recommendation for further investigation (LP2-230)

Based on our analysis we would recommend the following options for further investigation:

- The best of the Additional Channel options appears to be B2 – CW signals onto one or more distinct VHF channels.
- The Wide band option, D1 – spread spectrum signal across the available portions of the VHF marine band, also should be investigated as it shows promise.
- As a reference baseline, A2 – standard AIS transmissions including Message 8s, could be investigated. Although high precision is probably not possible due to the inability to resolve carrier ambiguities it would be possible to do positioning at lesser accuracy using bit edges, which are at a known time.

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Appendix A

See attached Excel spread sheet.

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