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Comparison of

AIS R-Mode as proposed within the ACCSEAS feasibility study

with

True Heading Patent Application Publication
(A method for determining the timing of a radio message)

The following paper provides brief descriptions of the proposed AIS-R-Mode method, which was developed within the EU project ACCSEAS and a patent publication from True Heading regarding "a method for determining the timing of a radio message". Furthermore the document provides a direct comparison of both methods as well as a summary which provide the authors evaluation.

Inhalt

1. R-Mode via AIS

Within the ACCSEAS R-Mode Feasibility Study "AIS Transmissions (Part 2)" 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 R-Mode Feasibility Study "AIS Transmissions (Part 1)". Based on this evaluation it was agreed to further examine three potential solutions:

a) Existing AIS: this solution involves ranging off of the existing base station AIS messages, using Message #4 or #8 to increase the signal energy and duty cycle.
b) 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.
c) 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 the AIS Part 2 report. The recommended solution is the first, existing AIS including Message #4 or #8. With this solution 10m performance appears achievable using the existing system with no modifications other than adding some additional transmissions.

1.1 General description

Flowchart 1 provides a brief description how to derive a position based on transmitted AIS messages from an AIS base station which is controlled from an external precise timing source.

At transmitter site:

(1) Definition and configuration of AIS messages #4 or #8 for transmission from an AIS base station

(2) Connect an GNSS independant preceise timing source to the AIS base station

- 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.
- AIS message # 8 allow for longer, more frequent signal with a fixed form. More frequent transmission of longer, **known messages** increases signal energy which improves ranging performance and position update rate.

At receiver site:

(1) Demodulation and decoding of GMSK-Signals

(2) Estimation of carrier frequency ω_c, carrier phase θ and the time of bit transition τ_S

- GMSK receivers must be able to demodulate the transmission with high accuracy.
- Optimum decoding is 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 has to estimate the carrier phase θ, and the time of bit transition τ_S. Methods to estimate these parameters are described in [**13-28**].

(3) Determination of bit transition time τ_S, ambiguity resolution and underlying phase (see flowchart 2) to derive time delay Time of Emission (TOE) minus Time of Arrival (TOA).

(4) Determination of range measuremens based on TOA

(5) Combining 3 measurements for tri-lateration

Flowchart 1: General Process how to derive a position from AIS-R-Mode transmissions

1.2 Detailed description

The following flowchart 2 describes more in detail how to derive the bit transition time τ_S with an unknown time delay τ (the term of interest for ranging), and how to solve the ambiguity from AIS R-Mode transmissions based on AIS messages #4 and #8.

Solve ambiguity for bit transition

(1) one symbol period is 26.67 msec or, equivalently 31 km.

(2) within a maximum propagation range for AIS of about 100 km, the bit transition time has limited ambiguity to resolve

- The method to solve the ambiguity decribed in the study is to have a clear alignment between the start of each AIS message 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.

Determination of bit transition

(1) the study analysed the performance of two estimation algorithms for the time of bit transition of a GMSK signal[1)], based on

- a Modified Cramér-Rao Bound (MCRB), [9] "on the performance of any estimator of from the bit edges" and
- an analysis by Hosseini [29, 30] which assumes that **the data (within the message is known[2)]** and evaluates the CRB of the time of bit transition as a function of the message.

(2) Both methods are similar [3)]

- [1]) In both 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 with an unknown time delay (the term of interest for ranging), an unknown frequency offset (due to a mismatch of the receiver oscillator in the demodulation process), an unknown phase (due to the phase offset between the local oscillator at the receiver and the signal carrier), and additive white Gaussian noise (AWGN) with spectral density .

- [2]) This is a **similar technique to the one which is used in the True Heading patent**. Nevertheless these methods are described since years in the referenced literature.

- [3]) This result is quite similar to the MCRB (the difference in the denominator constant, about 2dB, 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)

Flowchart 2: Detailed Description how to estimate bit transition time within a future R-mode receiver based on standard AIS messages #4 or # 8

As shown in flowchart 2 the main topic of AIS-R-Mode is to solve for the "**Bit edge**" or "**Bit transition time**". The methods described in the ACCSEAS feasibility study are based on analyses which already were published in various documents (see references) years ago. The range performance at the end is based on following estimation (full derivation available in the study):

Standard AIS Signals including Message 8s

Pseudorange performance using bit edges is bounded by:

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

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

1.3 References (copied from ACCSEAS feasibility study)

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[29] E. Hosseini and E. Perrins, "The Cramer-Rao Bound for Training Sequence Design for Burst-Mode CPM," Communications, IEEE Transactions on, vol. 61, pp. 2396-2407, 2013.

[30] S. M. E. Hosseini, "Synchronization Techniques for Burst-Mode Continuous Phase Modulation," PhD Dissertation, Department of Electrical Engineering & Computer Science, University of Kansas, 2013.

2. True Heading Patent Application Publication

The published patent on “a method for determining the timing of a radio message” describes use cases, principles, methods, devices and a system “how to derive timing information from radio messages”. The main use case is the validation of reported positions, speed, heading[1], etc. from standard AIS messages (e.g. AIS position report). In the described use case the validation will be performed from a central unit. The general principle is based on time measurements from at least three shore/mobile receiving sites to a transmitter to perform a triangulation[2]. The principle is therefore comparable to the method of an “inverse R-Mode”. The methods and principles described in the patent are applicable to radio receiver and transmitter equipment whereby the examples and details are focused on AIS. The paper will describe briefly the following main topics of the patent:

- the general measurement principle,
- the method how to derive the timing from radio transmissions (AIS),
- the use cases, and
- the main claims.

2.1 General measurement principle

The main measurement principle is based on a triangulation[2] between at least three receivers (at a known location) and one transmitter site (which location should be derived) as shown in figure 1 (Fig 3 in patent). The receivers are synchronized (preferably to GPS) and receive the transmission of TX1 at different times. The triangulation calculations are performed by a central computer which is connected to the receivers (Rx1, Rx2 and RX3).

[1] The patent describes the possibility to validate the heading as one of the monitored parameters derived from up-following positions. To my opinion this is not possible. They may derive speed and course from up-following positions.

[2] To my opinion the principle is based on **trilateration** because there are using time measurements which normally used to derive ranges. The patent describes and claims a **triangulation** method which is typically based on angular measurements. It seems this is an error in the patent publication

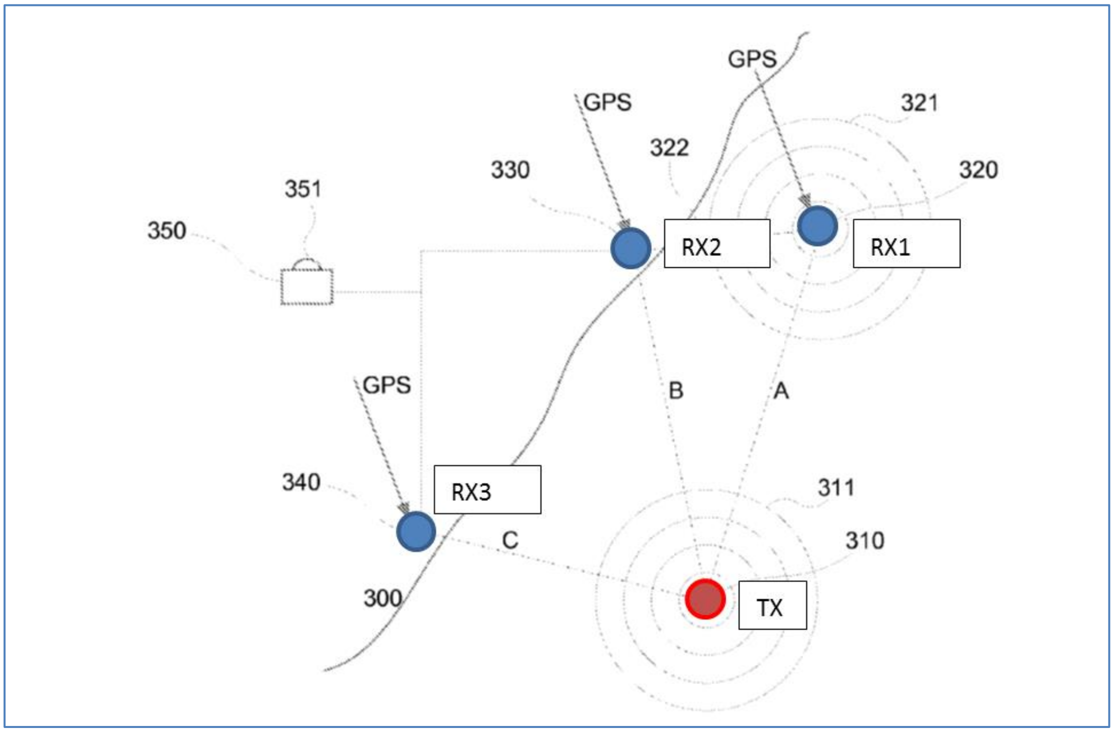

Figure 1: General measuring principle and use case

2.2 Method to derive the timing

The method described in the patent can be divided into the transmitter and receiver part. The transmitter part is shown in flowchart 1, the receiver part in flowchart 2.

Transmitter site:

The transmitter according to the prefered embodiment comprises means for assembling and periodically transmitting AIS messages for at least one predetermined type which could be received and read by an AIS receiver.

- The transmitter device should follow AIS specifications for class A, class B, base stations, , AtoN and SART.

The transmitter comprises

(1) a **sensor** to detect that AIS messages (of predetermined type) is to be sent based upon the time frame allotted to the TX device or based upon CSTDMA

(2) a **digitally message assembly means** to assemble, digitally store and calculate a checksum for a predetermined AIS message[3)].

(3) **Filtering means** (analog or digital) to perform preferable GAUSS filtering of the binary coded signal and enabling GMSK modulation

(4) **Modulation** preferably using frequency modulation of the filtered signal on a carrier wave which is then amplified and fed to the antenna.

- [3)] Information to be transmitted are received from a data source. Such data could be geographic position or ID of the transmitter.

Flowchart 1: Functional elements within the transmitter device of the True Heading patent

Receiver site:

The receiver according to the prefered embodiment comprises means for receiving radio signals which comprises a data stream, which include predefined signal elements. The receiver comprise means to receive, demodulate, sample, decode and correlate the received signal element with a localy stored constructed predefined signal to derive and correct the time of receiption.

The Receiver comprises following main functional parts

(1) **Antenna** to receive an incoming radio siganl as described in the transmitter part to achieve an analogue electrical signal.

(2a) **Demodulator** which demodulates the analogue electrical signal. This demodulated analogue signal is fed to an **A/D converter**.

(2b) The patent describe an alternative configuration where the electrical analogue signal from the antenna is first sampled in an **A/D converter**. The output could then directly used for a later correlation and/or digital demodulated and decoded. All signals could be used for the later correlation with a construced signal.

(3) **Decoder** to determine the AIS message data content, based on the demodulated signal, as a stream of data bits[4)]. The received and decoded messages are forwarded also via an **interface** for the publication of the message

(5) The **predetermined signal** has been defined beforehand. The prefered method in the patent is the use of the "front edge" or "trailing edge" of the field "start flag" based on an AIS message.

(6) The **timing determination device** is the core element to derive the time of receiption of the received signal. The main functionality is a ***correlation*** of the received predetermined signal element which position in the message is being known in advance, (S_i) and the constructed comparison signal element which is digitally stored in the receiver (J_i). The correlation function is known as cross correlation of two signals[5)]. As described in the patent it is more an autocorrelation because the two signals elements are more or less equal to each other.

(7) The output of the timing determination process is a time variable which is used to **correct the time of receipt**.

(8) variuos optimization methods are described by using interrupt signals and an internal clock which is prefered to be synchronized to GPS.

- [4)] The decoding device as decribed in the patent is preferably an AIS standard modem, which may also comprise the demodulator.
- [5)] The cross correlation of the two signals is conform to the convolution of the signals S_i and J_i. (See [0058] in the patent).

Flowchart 2: Functional elements within the receiver device of the True Heading patent

2.3 Use cases

Within the True Heading patent the following main use cases are addressed:

- **Monitor AIS transmissions:**
    - to provide an improved control ability of a receiver with respect to the information transmitted by a vessel, such as position, speed and heading.
    - to detect whether a particular AIS signal is emitted by one and the same transmitter

  The application is based on 3 receivers with known positions as illustrated in figure 1 and the use of a central PC unit which monitor the transmission. The accuracy of such a method is estimated of a few hundred meters.

- Provide **secondary synchronisation** capability as an alternative to the AIS standard supported synchronisation process.

- **Jointly agree on a common time basis** between two or more transmitters/receivers. Such a time synchronisation between two devices can be used to agree on a common secret "sense of time" without any other nearby devices being able to gain knowledge.

2.4 Main Claims

The following main claims are outlined in the patent publication:

Claim 1: Determining time of receipt by a radio receiver based on a correlation between a predefined signal element transmitted from a sender and a constructed signal element in the receiver (**method**).

Claim 2: According to claim1but using analogue modulation.

Claim 3: According to claim1 but using filtering of the predefined signal before modulation by the sender. The constructed comparison signal will be filtered in the same way.

Claim 4: According to claim1wherein the constructed comparison signal will be filtered to match deviations arising from analogue frequency and/or phase response of the receiver.

Claim 5: According to claim1 wherein the A/D converter sends out at least one interrupt signal and uses an internal clock to improve timing performance.

Claim 6: According to claim 5 wherein the A/D converter sends out a number of interrupt signals to perform averaging to further improve timing performance.

Claim 7: According to claim 5 wherein the clock comprises a local oscillator which is synchronized to GPS.

Claim 8: According to claim 1 wherein the location of the sender is known by the receiver and wherein a common point of time is synchronized between the sender and receiver.

Claim 9: According to claim 7 wherein at least three receivers with synchronized clocks receive one and the same radio signal from a sender, where each receiver applies the method of claim 1 to determine time of reception and where the location of the sender is determined by triangulation. (**The main application**)

Claim 10: According to claim 9 wherein the calculated location of the sender and/or heading and /or velocity has been calculated based upon several consecutive calculations. The calculated parameters will then be compared against thresholds and a warning will be issued when thresholds are reached.

Claim 11: Receiving device arranged to use the methods described in claim 1-7 (**The receiver using the method)** and a configuration as described in claim10 and claim 9

Claim 12: **System** for determining the location for a sender by using the methods (claim 1-7).

3. Comparisons of AIS R-Mode with True Heading Patent

The following table provides an overview about similarities and differences between both described methods to derive timing from AIS transmissions.

Differentiator	AIS R-Mode as proposed within the ACCSEAS feasibility study	True Heading Patent Application Publication (A method for determining the timing of a radio message)
Used principle	**Trilateration** within an AIS mobile receiver using at least 3 AIS transmitting sites (typically shore installations)	**Triangulation**[3] within a central unit based on reception from at least 3 shore or mobile sites (of known position) receiving the same signal from one transmitter
Used time measurement method	Bit transition time (bit edge) based on already described methods (see literature)	Cross Correlation between received and constructed signal elements (entire signal)
Achievable accuracy level	10 m	100 m
Main field of application	GNSS independent range measurements to provide Resilient PVT	1. Monitor AIS position report with respect to position, speed and heading[4] from consecutive measurements 2. enable secured time synchronisation between AIS transmitter/receivers of known position
Claims	No	See 2.4 especially Claim 1, Claim 9, Claim 11 and Claim 12
Similarities	- General Principle is based on standard AIS transmissions and known message content referred to bit edge - Position method is trilateration	- General Principle is based on standard AIS transmissions and known message content referred to entire signal - Position method is triangulation[3)]

[3] The patent claims triangulation. To the authors view this is a failure because the measurements are based on range measurements instead of angular measurements.

[4] To the authors view measurement of heading is not possible from consecutive position measurements

Differences		
- General principle	Trilateration	Triangulation[3)]
- Main application	GNSS Backup Ranging (R-Mode)	Monitoring (Inverse R-Mode)
- Users	Navigators (Resilient PNT)	Administrations (e.g. replace direction finder)
- Time determination method	Bit transition time based MCRB	Cross correlation of known signal content
- Location of positioning	Within a mobile AIS receiver	Within a central site (PC)
- GNSS dependant	No	YES

4. Published work

The following chapter will summarize published documents according to AIS-R-Mode and publications with respect to the claimed methods and concepts by the True Heading patent.

4.1 Published work regarding AIS R-Mode

First publication were made in 2008 (ENAV and EUPOS Conference)

- J.-H. Oltmann, M. Hoppe, "Contribution to the IALA World Wide Radio Navigation plan (IALA-WWRNP) / Recapitalization of MF DGNSS Systems, ENAV4-7.10A, Shanghai, 2008.
- J.-H. Oltmann, M. Hoppe, "Contribution to the IALA World Wide Radio Navigation plan (IALA-WWRNP) / Recapitalization of MF DGNSS Systems, ENAV4-7.10B, Shanghai, 2008
- Jan-Hendrik Oltmann, Michael Hoppe "Maritime Terrestrial Augmentation and Backup Radio Navigation Systems - State of the Art and Future Developments", EUPOS2008 International Conference, Berlin November 2008

Further publications were made during the ACCSEAS project in 2014

- G.W. Johnson, P. F. Swaszek, Part III "Feasibility Study of R-Mode using AIS transmissions", May 2014, ACCSEAS homepage www.accseas.eu
- G.W. Johnson, P. F. Swaszek, Part IV "Feasibility Study of R-Mode using AIS Transmissions", August 2014, www.accseas.eu.

4.2 Published methods claimed in the patent

The patent claims an algorithm to correlate the received AIS signal (digitized) with a constructed version of the transmitted signal so as to estimate the time of arrival. Such methods are well known.

Available textbooks that show the use of a correlator to estimate time of arrival:

- "Detection, Estimation, and Modulation Theory, Part I" by H. Van Trees, Wiley, 1968, p. 276-278 (this is the continuous time version of the problem)
- "Fundamentals of Statistical Signal Processing, Estimation Theory" by S. Kay, Prentice Hall, 1993, p. 192 (this is a discrete time version)
- "Detection of Signals in Noise" by A. Whalen, Academic Press, 1971, p. 222-223 (this is also continuous time, with the extension to discrete time on p. 225-227)

Further the measurement principle claimed in the patent publication, to locate a vessel using pseudorange measurements received by multiple base stations, is well known and is used e.g. in underwater tracking systems.

4.3 Published methods described in the ACCSEAS AIS-R-Mode concept

The concept used for AIS-R-Mode described in the ACCSEAS feasibility study is mainly based on published material as given below:

- U. Mengali and A. N. D'Andrea, Synchronization Techniques for Digital Receivers: Springer, 1997.
- E. Hosseini and E. Perrins, "The Cramer-Rao Bound for Training Sequence Design for Burst-Mode CPM," Communications, IEEE Transactions on, vol. 61, pp. 2396-2407, 2013.
- S. M. E. Hosseini, "Synchronization Techniques for Burst-Mode Continuous Phase Modulation," PhD Dissertation, Department of Electrical Engineering & Computer Science, University of Kansas, 2013.

5. Conclusion

The paper provides a brief description of deriving timing from AIS transmissions. The concept of the AIS-R-Mode, developed in the ACCSEAS feasibility study, is based on a method where AIS messages (#4 or #8) are transmitted typically from AIS shore installations. An onboard AIS receiver will calculate a position based on range measurements to at least 3 transmitting sites. The method to derive range is based on the determination of the bit transition of received AIS messages #4 or #8.

The True Heading patent publication describes a method which is based on a correlation principle between a predefined signal element transmitted and a constructed signal element stored in the receiver. The focus of using the time determination is to monitor AIS position reports from a central site (such a system was already described years ago as “inverse R-Mode”). To the authors view both concepts are only similar in the way that known AIS transmissions are used to determine time of reception within a receiver. The detailed methods, the application and the measurement principle are quite different.

Finally it is important to note that the time determination methods of a digital radio communication system using continuous phase modulation techniques (like GMSK) are well known and issued since years in many publications.