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AIS R-Mode Trilateration for GPS Positioning and Timing Insurance

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ABSTRACT: Satellite navigation is the backbone of maritime navigation today. However, the technical vulnerability of on-board Global Navigation Satellite System (GNSS) receivers the satellite system greatly destabilizes maritime security due to the loss of ship's position and accurate time. This article devoted to study an alternative method for obtaining coordinates and accurate time based on the use of automatic identification system (AIS) radio channels, so-called range mode (R-Mode). We use other AIS ship stations with reliable position data as reference stations and determine time of arrival for received AIS transmissions. To improve the accuracy of measuring signal arrival instance in the time difference of arrival (TDOA), that we utilize for trilateration, it is proposed signal oversampling and applying the fast Fourier transform (FFT) to the product of quadrature components of the baseband Gaussian minimum shift keying (GMSK) signal in the window of AIS time slot. To take into account the movement of other ships, appropriate coordinate corrections are foreseen, which can be calculated by dead reckoning or by the inertial navigation system of our ship. The proposed method is fully compatible with the existing AIS signals and may be employed in critical situations of locally limited (jamming, spoofing) GNSS abilities. It can be implemented as a separate unit, working for receiving in parallel with the mandatory AIS transponder.

1 INTRODUCTION

Currently interferences, jamming and spoofing of GPS receivers are growing threats everywhere in modern technologies [14] including maritime shipping [1], [7], [10], [11]. Due to the low GPS received signal power, improvement of malicious interference technologies and scaling down the cost of corresponding devices, the concept of guaranteed positioning, navigation and timing (PNT) is seriously threatened [6].

Modern navigation depends on accurate, precise, and timely data that usually comes from external sources, mostly, GPS [9]. Nevertheless, contemporary realities testify to the significant vulnerability of the PNT concept, which in its basic configuration relies on the primacy of GNSS [3]. Two main alternative technological approaches exist to PNT implementation: relative PNT and absolute PNT. Relative PNT uses on-board sensors to track movements and calculate vessel's position as well as keep sharp time without using external signals. Relative PNT is not susceptible to jamming or spoofing. However, the cumulative effect of small errors in measuring movement degrades position accuracy over time. Absolute PNT relies on external information sources to determine vessel's position, for example, dead reckoning and inertial systems.

An example of a practical approach to implementing an alternative GPS navigation is AIS Range Mode (R-Mode) project [8]. This project is not relative PNT, nevertheless is free from GPS dependency. It intended to tackle the challenges related to the disturbances and develop a new independent of the GPS system that would allow a safe and more accurate positioning.

R-Mode refers to using AIS channels for measuring signal delay propagation from the coast beacon stations (available at least three simultaneously) to the vessel. R-Mode is a promising technology to support integrity of traditional positioning GNSS methods in emergency like GNSS failure of various scenarios.

The obvious tasks for the AIS R-Mode implementation are the need to create an appropriate coastal infrastructure and measure the propagation time of AIS signal.

In this article, we explore the possibility of temporal replacing the standard on-board GPS navigation in the case of GPS receiver failure or external local intervention, like jamming/spoofing attacks, leading to the functional inability of GPS receiver(s). The designed model in our study includes our ship under the loss of GPS navigation ability and other ship stations with a normally working GPS system and AIS channels. It is assumed that at least three other AIS stations simultaneously within VHF communications regularly transmit their own coordinates, which are used as the positions of reference stations.

The task is to restore the positioning of our vessel by using AIS data and additional capabilities of AIS channels for measuring signal delays and calculating our coordinates and time corrections using the trilateration method.

2 TRILATERATION

Trilateration for two-dimension means the determination of the location of a point based on its distance from three other known points. To measure distances Time of Arrival (TOA) and Time Difference of Arrival (TDOA) techniques. TOA method is based on knowing the exact times of transmitting from a references points and arriving the signal at a measured point, taking into account signal speed propagation (speed of light *c*). TDOA method does not require knowledge of absolute times at the transmitter and receiver but needs only the signal delay times from the reference sources with an accuracy up to a constant value. Moreover, it allows you to get the time correction for internal clock that is very important for safe navigation [16].

The system of trilateration equations can be written in the compact form as:

$$\|x - p_i\| - r_i + \Delta t\, c = 0 \qquad i = 1,2,3, \tag{1}$$

where

$\|...\|$ – denotes Euclidian norm (distance from reference object to the point to de determined;

$x = (x_1; x_2)$ – vector-column of coordinates to be determined (in MatLab notation);

$p_i = (p_{1i}; p_{2i})$ – known positions of reference stations:

$r_i = c\tau_i$ – pseudo ranges calculated on the base of TDOA delays τ_i;

Δt – unknown time correction of internal clock at the receiver point.

Equation system (1) presents the system of three nonlinear equation with unknowns $x_1, x_2, \Delta t$.

General approach to solve such equation is iterative least squares method, or Gauss-Newton method [15]. Author of this paper criticizes various attempts to outperform Gauss-Newton method by means different iterative and closed form algorithms. Likely MatLab has imbedded function "fsolve" to solve system of nonlinear equation using Gauss-Newton algorithm in one form or another. Tic-toc procedure in MatLab, ver. 9.5 (R2018b) gives the computation time 0.19 seconds for solving Eq. (1) at hardware processor Intel(R) Core(TM) i5-1035G4 CPU, 1.50 GHz, with Windows 10 Pro.

Some simulation results for trilateration process are shown in Fig. 1 under the following scenarios: Coordinates of reference points: p_1(0,2); p_2(5,3); p_3(2,0), measured pseudo distances: *r*=[1.3; 1.8; 1.6]]. Calculated point is *x*(2.226; 2.594) and time error converted in distance Δ*tc* =-1.007 (clock is ahead). This situation is demonstrated in Fig. 1 a). Three circles (blue, red, yellow) with centres in the points p_i and radii *r* touch the forth one (violet), centred in point *x*=(x_1;x_2), and having radius abs(Δ*tc*)=1.007. The violet circle is outside the other three circles. Fig. 1 b) plotted for exact clock – when three circlers are intersected in point *x*; and Fig. 1 c) plot corresponds to late clock when the forth circle centred in *x* touches another three circles, being inside each of them.

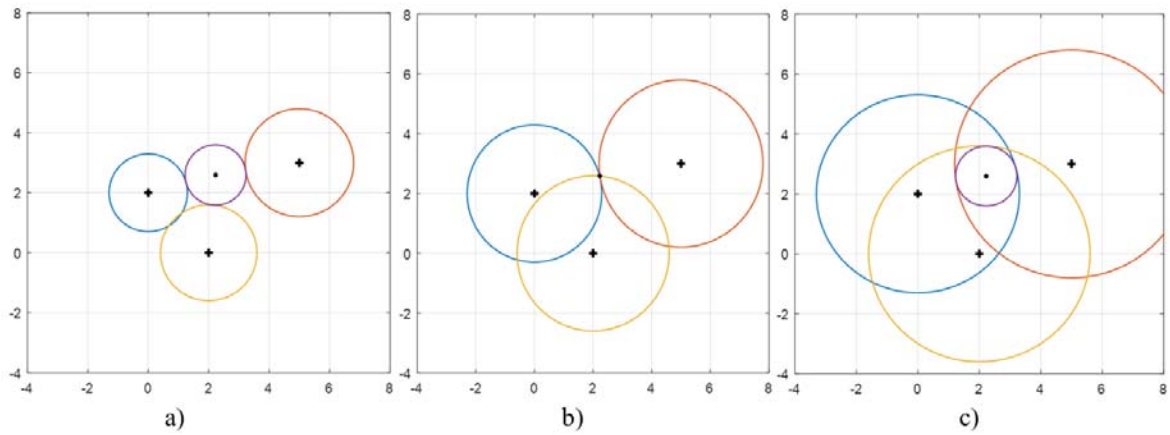

Figure 1. Trilateration circles: a) clock is ahead; b) exact clock; c) late clock

An example of root-mean squared (RMS) error of functions (1) in dependence from coordinates x_1, x_2 is shown in Fig. 2. Minimum of RMS error is achieved at point x_1=2.226; x_2=2.594.

Algorithm works as well for solving overdetermined systems of equation when its number exceeds number of unknowns. The overdetermined system generally allows getting solutions that are more accurate.

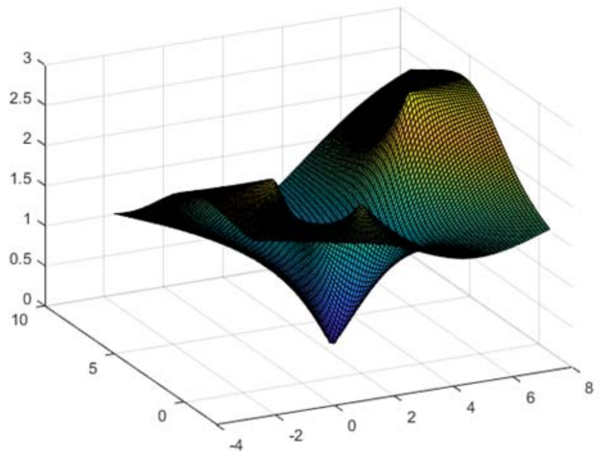

Figure 2. 3D function of RMS error

3 SYNCHRONIZATION

TDOA method requires connecting of transmissions from reference stations to the exact time. AIS uses time division multiple access (TDMA) protocol to share common frequency VHF channels, usually Ch 87B, 161.975 MHz and Ch 88B, 162.025 MHz [12]. All AIS transmissions connected to the beginning of time slot of duration 26.667 ms.

Standard AIS transponder has imbedded GPS receiver that outputs pulses per second synchronized with coordinated universal time (UTC). AIS station which has direct access to UTC timing with the required accuracy indicates this by setting its synchronization state to UTC direct (Sync state = 0). We use only UTC directly synchronized AIS stations.

Another issue to be solved it is estimation of arriving signal moment at the receiving AIS station. AIS uses Gaussian minimum shift keying (GMSK) baseband signal. GMSK parameters relating to physical layer, which is responsible for the transfer of a bit-stream from the source to link layer [12], are:

Channel bandwidth	25 kHz
Bit rate	9600 bit/s ±50 ppm
Training sequence alternating zeros and ones (0101....)	24 bit
Start flag 01111110 (7Eh)	8 bit
Slot length	256 bit/26.667 ms
Transmit BT product	~0.4
Receive BT product	~0.5

GMSK modulation handles data transfer very well but it poorly suitable for time arrival measurements. That is why R-Mode project assumption was to use the correlation technique, which utilizes the pseudorandom ranging sequence to utilize all signal energy for ranging improvement [2]. Importance of correct synchronization of base stations is studied in paper [13]. Another approach to obtain the time of arrival values proposes timestamp detection of GMSK signal using the differential peak detection and zero-crossing detection in cooperation with rather sophisticated Orthogonal Matching Pursuit (OMP) algorithm [5].

Instead, we propose a solution while staying within the ITU-R M.1371 standard. The essence of the proposal is as follows. Modern GMSK demodulator electronic is based on the representation of the GMSK baseband signal in the form of two components: in-phase *I(t)* and quadrature *Q(t)* components [4].

I(t) and *Q(t)* signals for binary data sequence 01111110 are simulated in Fig. 3. Signals are presented in the time scale according to AIS specification (data bit duration T_b=1/9600=0.104 ms). The product of these signals *I(t)Q(t)* is shown in black. The periodicity with the frequency 4800 kHz for the product signal is clearly manifested. To improve the accuracy of bit edge detection, we make oversampling of baseband signal and perform the FFT over the entire time slot. Local area of amplitude spectrum are presented in Fig. 4 for the next parameters:

Sampling frequency f_s	19.66 MHz
Signal-to-Noise Ratio	0 dB
FFT size N	524288
Length of data in GMSK signal	256 bit

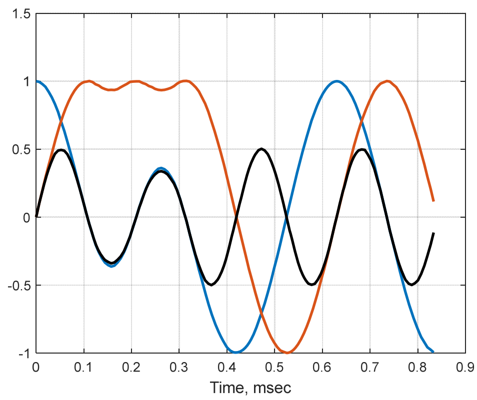

Figure 3. GMSK baseband signals: *I(t)* red, *Q(t)* blue, *I(t)Q(t)* black for Start flag sequence

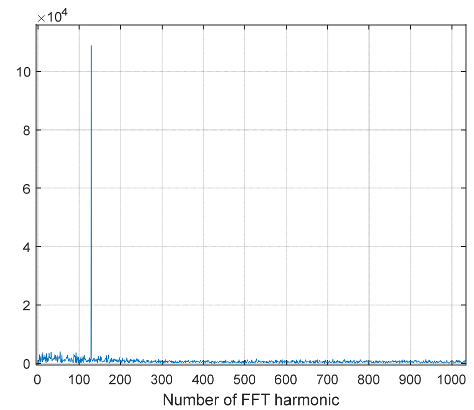

Figure 4. FFT amplitude spectrum, harmonic number 128 (frequency 4.8 kHz)

Despite the impressive sample size (500 M), the FFT procedure is completed in 0.01 seconds under above mentioned soft and hardware conditions.

Clearly visible harmonic number 128 even under SNR = dB corresponds to half down data rate of 4800 kHz.

Taking into account the cyclic shift property of discrete Fourier transform *x(n)↔X(k)*, which states that a circular shift by *m* samples of the input sequence in the time domain corresponds to multiplying the output in the frequency domain by a linear phase:

$$x(n-m) \leftrightarrow X(k)\exp\left(-\frac{2\pi j}{N}km\right) \quad (2)$$

Using this formula, we get the expression for the time delay for our case in the form:

$$t_{Rx} = \frac{\varphi}{\pi R} \quad (3)$$

where
φ – the measured phase in rad of the 4.8 kHz harmonic;
R = 9600 bit/s – standard data rate.

2Pi phase periodicity should be regarded in formula (3).

It should be noted that the phase measurement errors caused by the influence of electronic circuits and other systematic factors for signals from different reference sources will be the same and therefore do not affect the accuracy in the TDOA method.

Practically the accumulation of signal samples should be performed from the beginning of time slot (according internal clock of our ship). The on-air delay of the signal comes to a shift of the signal samples, but not in the manner of a cyclic shift, but simply to the right. The beginning of the sequence is filling with a possible buffer signal of the previous time slot. According to specification [12] signal transmission must be ended to the time T3 = 24.167 ms and falling down to zero power within the next 1 ms. So, in general we have some zeros encapsulation and cutting the end buffer of the transmitted slot. Such variation from formula (2) do not principally affect the availability of the proposed method.

Noise influence on the delay measurement accuracy was simulated using stochastic modelling for various data sequence lengths from 16 to 256 bit. The results are presented in Fig. 5. As expected, the length of data sequence significantly affects the measurement accuracy. In all calculations, the sampling rate was taken equal to f_s = 19.66 MHz. Oversampling is necessary for achieving the necessary measurement accuracy. The length of bit sequence (ndata) expresses the width of the window.

The obtained simulation results fit the theoretical Cramer-Rao bound on the variance of the estimated parameter φ: $\text{var}(\hat{\varphi}) \geq \sigma^2/n$, where in our case n = ndata.

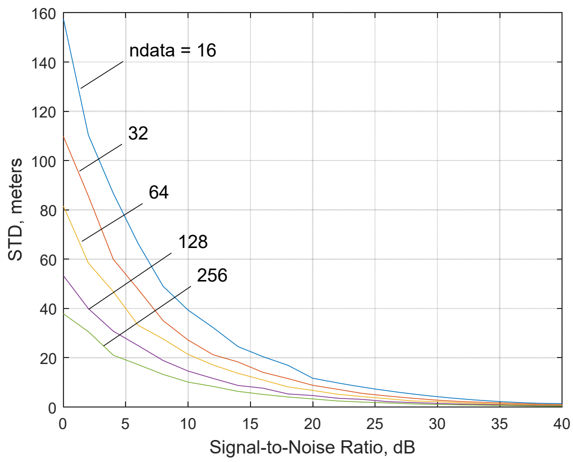

Figure 5. Dependence of RMS error (STD, meters) in measurement of GMSK signal delay time on signal-to-noise ratio (dB) and signal length in bits (ndata = 16, 32, 64, 128, 256)

4 DEAD RECKONING

It is ideal to transmit signals from the different reference stations in TOA/TDOA methods simultaneously. However, the AIS TDMA mode does not allow this because the AIS stations alternately transmit their data in the different time slots. This transmission time separation does not prevent achieving correct time delay measurements if the transmissions are synchronized with the direct UTC time source of the AIS reference stations. We study our model on this basis. The movement of our vessel during the time between adjacent time delay measurements must be taken into account, for example, by dead reckoning using log and gyrocompass data. Inertial navigation system can be used also.

Time separation of transmissions from another AIS stations can be taken into account by modifying equations (1) by entering adding appropriate corrections, caused by vessel's movement. The detailed form of the equations (1), taking into account the corrections, is presented in the following view:

$$\begin{cases} \sqrt{(x_1 - p_{11})^2 + (x_2 - p_{21})^2} - c(\tau_1 - \Delta t) = 0, \\ \sqrt{(x_1 - \delta_{12} - p_{12})^2 + (x_2 - \delta_{22} - p_{22})^2} - \ldots \\ \qquad - c(\tau_2 - \Delta t) = 0, \\ \sqrt{(x_1 - \delta_{13} - p_{13})^2 + (x_2 - \delta_{23} - p_{23})^2} - \ldots \\ \qquad - c(\tau_3 - \Delta t) = 0, \end{cases} \quad (4)$$

where

x_1, x_2 – coordinates of our ship at the moment of first measurement;
p_{1i}, p_{2i} – coordinates of reference AIS stations, i=1,2,3;
δ_{1i}, δ_{2i} – corrections (latitude, longitude), i=2,3;
τ_1, τ_2, τ_3 – measured time delays the reference AIS stations;

Δt – time correction for our ship;
c – speed of light.

AIS stations transmit scheduled position reports (message 1) at 6 second intervals (ship moving with speed 14-23 knots). Position report, among other data, contains: latitude and longitude in 1/10 000 min, position accuracy flag (high, ≤10 m /low, >10 m). Preference must be given to AIS stations with the best performance.

Delay measurements τ_1, τ_2, τ_3 are made in the following sequence. First we get the value τ_1 and treat the coordinates of the first AIS reference station to the slot beginning, at time, say, t_1. The second measurement τ_2 will be obtained at the moment t_2 of receiving a suitable slot from the vessel with coordinates p_{1i}, p_{2i}, i=2, and the third measurement τ_3 will be obtained at the moment t_3 for coordinates, p_{1i}, p_{2i}, i=3. Appropriate corrections δ_{1i}, δ_{2i}, i=2,3, are believed, to be calculated by means dead reckoning. As a result of solving the system (4), we obtain the coordinates x_1, x_2 of our ship and time correction Δt at the time t_1.

Overdetermined system (4), when $i > 3$, is also appropriate and gives more accurate solutions for positioning x_1, x_2 and timing Δt in accordance with the of least squares method for the Gauss-Newton algorithm.

5 CONCLUSION AND DISCUSSION

GPS-based positioning and timing functions on board the ship should be supported by alternative backup methods. This article proposes a method for replacing satellite navigation during its possible rejection due to GNSS jamming in the local area around our vessel by means the use of AIS channels and reliable position data from other ships, which are not under jamming influence.

In our study, we address scenario when another vessels (at least three) are located within the VHF communication, equipped appropriate AIS station, which having direct GPS time synchronization and reliable positioning. Such scenario is quite likely on traditional sea routes. Based on the use of 2D trilateration, the TDOA ranging method, and the application standard AIS channels as defined by Recommendation [12], the following main sources of errors in positioning and timing can be listed and identified in the next manner:

1. time uncertainties of AIS transmissions from other vessels, which are used as reference stations;
2. errors in measuring the moments of signal arriving on our ship;
3. errors caused by the instability of our clock between transmissions from other ships;
4. errors caused by reckoning;
5. error caused by the "poor" positions of other ships relative to our ship (poor geometry).

The main problem that we clearly realize is the time uncertainties of transmissions from other AIS ship stations (item 1). Here we rely on the requirements of the de facto AIS standard in the form of Recommendation ITU-R M.1371-5, in particular, concerning the signal requirements at the physical layer of AIS interconnection model. This standard defines bit timing from AIS slot beginning [11, Table 6] not pointing the tolerance to time shift. Herewith slot time borders are tied to the absolute time of GPS accuracy under the condition of direct GPS synchronization. Namely AIS stations with direct synchronization we use as reference ones. The question whether bit transmission accuracy by AIS transponders from different manufacturers practically corresponds to above mentioned parameters is opened and may be the direction of subsequent researches.

The task of arrival moment measurement (item 2) is settled by the next manner. Firstly we stay in the frames of using standard baseband GMSK signal according with demands to signal on physical layer [12]. To estimate time of arrival we apply sampling frequency to GMSK signal $f_s = 19.66$ MHz and FFT processing of in-phase and quadrature components product over a time slot of duration 26.67 ms. In this case, the internal clock is used without pulses per second (PPS) synchronization, which is impossible in jamming conditions. Simulation results yields a 10 m RMS distance error under a signal-to-noise ratio of only 10 dB (see Fig. 5). Application of TDOA method eliminates systematic errors in the time delay signal measurements for different vessels.

After the loss of GPS synchronization due to jamming, the internal clock is obliged to work without PPS correction. Time gap between consecutive measurements of signal delay leads to an error 3) of the list above under internal clock instability. The system of equations (4) includes the same time error Δt of the internal clock to be corrected for all three measurements. Ideally all delays measurements should be done for all simultaneously transmitted signals. However, AIS time-division transmission protocol does not allow to realize this. Taking short-term stability of a crystal oscillator 10^{-9} and the time interval during which signals from three ships can be received 10 seconds (with transmission intervals of 6 s for AIS message 1), we obtain a deviation within 0.01 μs (in terms of a distance it corresponds to 3 m).

Dead reckoning errors (item 4) in the corrections δ_{1i}, δ_{2i} in the system of equations (4) are determined by the accuracy characteristics of the gyrocompass and log.

And, finally, the error caused by the poor relative position of the vessels (item 5) is calculated in accordance with the concept of horizontal dilution of precision (HDOP).

Technically, the proposed method can be implemented as a separate unit, working for receiving in parallel with the mandatory AIS transponder. A certain computational burden should not be an obstacle to the device implementation in the conditions of modern software and technological level.

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