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ORIGINAL ARTICLE

Concept, signal design, and measurement studies of the R-mode Baltic system

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Abstract

This article presents the work conducted in the R-Mode Baltic project, which aims to launch the R-Mode demonstrator in the Baltic Sea area. The article describes the concept of the Automatic Identification System (AIS) infrastructure and VHF Data Exchange System (VDES) signal utilization with respect to their potential role in the future R-Mode System. It also contains the analysis of the distance determination accuracy in the designed system based on calculation of the correlation between the received signal and the known transmitted signal, as well as the achievable ranges for various system configurations. Additionally, the paper discusses the implementation of the test-bed transmitter and receiver, the methodology of measurement campaigns carried out in the Baltic Sea on the Gdynia-Karlskrona route, as well as the obtained results. The collected measurement results were thoroughly analyzed and compared with theoretical values. The summary contains conclusions, as well as the plans for the next phase of measurement research.

KEYWORDS

e-navigation, maritime radiocommunications, ranging, r-mode Baltic, VHF data exchange system

1 | INTRODUCTION

Nowadays, Positioning, Navigation, and Timing (PNT) services are widely used in many areas. It is difficult to imagine the operation of many industries without access to this information. In some areas of application–especially in maritime applications–location information is crucial from a safety point of view. For this reason, basing the marine safety systems on only satellite systems poses a certain threat. The implementation of new systems and services for e-navigation should be the way to address this issue.

In recent years, various e-navigation services have been developed and tested as a part of international research projects (e.g., EfficienSea 2). One of the projects that concentrates around the PNT area is the Ranging Mode for the Baltic Sea (R-Mode Baltic). It is implemented in a consortium of 12 partners from the Baltic Sea region, including the National Institute of Telecommunication which is the organization of this article's authors.

Its main goal is the development of a new maritime system for PNT purposes which could serve as a backup for Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, Galileo, and Beidou. The main rationale behind such a goal is the fact that GNSS systems are highly vulnerable to jamming and interference and, at this time, no other system can take over the task of absolute positioning in the case of a local temporary loss of GNSS signal (e.g., due to jamming/spoofing), let alone in the case of a global outage.

During the work carried out in the R-Mode project, signal design as well as software and hardware implementation of the R-Mode system have been developed using Automatic Identification System (AIS) infrastructure and the VHF Data Exchange System (VDES) (ITU-R, 2015) signals. Subsequently, measurement tests in the maritime environment using ranging mode transmitter and receiver prototypes have been performed to verify the theoretical calculations and simulations.

The main purpose of this campaign was to analyze the influence of propagation conditions on ranging accuracy in the R-Mode. It was one of the first ever measurement campaigns of the R-Mode system conducted in its target environment (i.e., at sea using the maritime VHF radio channel) and the Baltic Sea is the first operational test area for this technology.

This article describes the entire process carried out during the development of the project, from theoretical analysis through implementation, and on to measurement tests.

2 | THE CONCEPT OF THE R-MODE BALTIC SYSTEM USING AIS AND VDES SYSTEMS

One of the main assumptions of the R-Mode project is the utilization of the AIS and VDES standard messages (alongside their respective infrastructures and physical layers) for the purpose of ranging measurements. The idea of R-Mode ranging is to send ranging sequences within the scheduled AIS or VDES messages and use the time of arrival (TOA) method to determine the distance between the terminal (ship) and the base station (shore).

This is accomplished taking into the account the following parameters: (a) the known precise time of the transmission start synchronized with 1 PPS signal from a rubidium oscillator, (b) the exact time frame structure, (c) the precise time of the correlation's peak calculated by the receiver, and (d) the speed of light. In this case, the accuracy of the method depends on the bandwidth, spectrum shape, and synchronization code length (it is recommended that it should be as long as possible).

On the other hand, the resources of maritime systems are limited and their use for purposes other than maritime safety should be kept to a minimum. Therefore, the project analysis and measurements were aimed at defining the appropriate structure of the R-Mode ranging sequence, which depended on the required R-Mode accuracy in the project set at a level of 10 m for the port approach case (i.e., the major R-Mode use case) and the maximum acceptable AIS and VDES systems' load.

It should be noted that the R-Mode system is designed to operate in harsh marine environments under low signal-to-noise ratio (SNR) conditions, using the narrowband AIS/VDES systems' standard messages. The R-Mode project assumption was to use the correlation technique which utilizes the pseudorandom ranging sequence allowing the usage of the entire signal energy in weak-signal areas at sea. In this environment, the other possible techniques, particularly the bit edge timing analysed in the feasibility studies of the ACCSEAS project (Johnson & Swaszek, 2014), would be less effective. There are a few reasons for that:

- Especially for the case of AIS, where Gaussian minimum shift keying (GMSK) modulation is used, the bit edges would not be very distinct, which contradicts the entire concept of the method
- The bit edge method is not very effective for relatively narrow bands and relatively small numbers of bits, especially at low SNR levels (which is the case in the R-Mode system)
- The efficiency of the bit edge method would deteriorate even further in the presence of multipath propagation

Therefore, it was decided not to address the bit edge method in the project or the corresponding paper.

2.1 | R-mode AIS concept

In case of the AIS system, it is necessary to select one of the message types already defined in the standard (ITU-R, 2014). The standard message in the AIS system has a length of 26.6 ms and transmits 256 bits within 1 slot, but some types of messages can utilize up to 5 slots. The multiple slot binary message 26, primarily intended for scheduled binary data transmissions, was identified for that purpose.

The AIS message structure depicted in Figure 1 consists of: training sequence (preamble), start flag, data, frame check sequence (FCS), a 16-bit cyclic redundancy check (CRC-16), end flag, and buffer.

The data field in message 26 contains an obligatory header with the source station identification and typically contains from 88 user data bits using 1 slot up to 984 user data bits using 5 slots (ITU-R, 2014). The project assumes

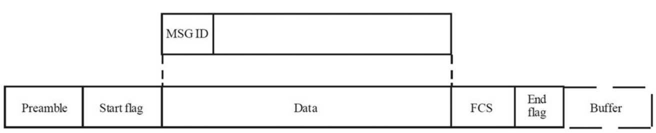

FIGURE 1 The Automatic Identification System (AIS) message structure (ITU-R, 2014)

that different lengths of the synchronization code and different forms (lengths) of message 26 would be used and that each AIS base station should be equipped with the precise time and frequency reference (e.g., GPS disciplined rubidium oscillator).

The AIS base stations regularly broadcast station reports via message 4, consisting of their position and Coordinated Universal Time (UTC). That information can be partly used for ranging calculations, but a few additional bits (up to 8) should be allocated in message 26 for current base station status information (e.g., real-time corrections or other variables not yet specified). As a result, the synchronization code length is approximately 80,300 and 970 bits, respectively, for 1, 2, and 5 slots in the AIS R-Mode ranging sequence.

The synchronization mechanisms in the AIS system (ITU-R, 2014) are based on the detection of the start and end flags[1] defining the beginning and end of the frame. To avoid matching the data bits with these flags, the bit-stuffing mechanism was introduced, and applies to the bit stream of the data portion and the frame check sequence (FCS). On the transmitting side, if five consecutive ones (1) are found in the output bit stream, a zero (0) should be inserted after them, and on the receiving side, the first zero (0) after five consecutive ones (1) should be subsequently removed. Therefore, the synchronization code cannot be arbitrary for the AIS R-Mode navigation message must be selected so that it is not supplemented by any additional bits that may adversely affect its correlation properties.

Since there is no forward error coding in the AIS system [only the non-return-to-zero inverted (NRZI) coding with CRC check], the signal transmitted within the message 26 structure can be almost entirely filled with a pure synchronization code without any changes, which allows it to maintain good correlation properties and keep a low signal processing delay on the receiver side.

2.2 | R-mode VHF Data Exchange System (VDES) concept

In case of the VDES system, as its standardization is ongoing, there have been no such restrictions such as in the case of the Automatic Identification System (AIS). The standard message type for the terrestrial component of the VDES system [VHF Data Exchange Terrestrial (VDE-TER)], presented in Figure 2 (IALA, 2019) was selected to be used in the R-Mode.

The number of net data symbols transmitted within one VDE-TER frame is much greater than in the AIS system. It depends on the VDES system bandwidth and is equal to 437, 917, and 1,877 symbols for 25 kHz, 50 kHz, and 100 kHz, respectively (IALA, 2019). The number of net data bits depends on the modulation scheme, which could be set to $\pi/4$ QPSK, 8 PSK, or 16 QAM[2]. For the R-Mode purposes, the $\pi/4$ QPSK modulation and 100 kHz bandwidth have been selected to achieve both long range and high throughput of the signal.

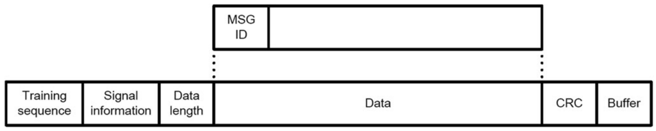

FIGURE 2 The VDE-TER message structure (IALA, 2019)

In the VDES system, the user data bits (payload) are appended with the CRC, then interleaved, encoded, scrambled, and finally mapped to modulation symbols. Subjecting the correlation code to these operations lower its length, which will require full processing on the receiver side (descrambling, decoding, interleaving, etc.) and will probably degrade the correlation properties of the code.

Therefore, the idea for the R-Mode is to send the unencoded correlation sequence within the full data payload in the VDE-TER message structure, similar to the AIS. The standardization work on the VDES standard is currently undertaken (on the IALA[3] forum) to introduce the possibility of employing such an approach in the actual system. It is also assumed that, like in the AIS, the VDES base stations will regularly broadcast station reports announcing their respective positions and UTC, therefore this type of data does not have to be included in the R-Mode message.

2.3 | R-Mode Synchronization code

When searching for the appropriate synchronization code, it was decided to use the Gold sequences and the long uplink scrambling code generator defined for the Universal Mobile Telecommunications System (UMTS) (3GPP, 2018). This code generator was constructed by two generator polynomials of 25 degrees and two output scrambling sequences obtained from the modulo-2 sum of two binary sequences generated using those polynomials. The resulting streams have bipolar values (+1 and −1) and constitute segments of Gold sequences. The nominal length of the UMTS scrambling code is 38,400 chips, but it can be easily shortened.

In order to determine the maximum length of the Gold code obtained using UMTS generator, all possible 2^{24} codes

[1] The start flag and end flag both consists of a 8 bit pattern: 01111110.

[2] QPSK - Quadrature Phase Shift Keying, PSK - Phase Shift Keying, QAM - Quadrature Amplitude Modulation

[3] IALA - International Association of Lighthouse Authorities

(over 16.7 million possible initial state combinations of the generator) have been searched to determine which codes can be used and would not require the insertion of additional bits by the AIS bit-stuffing mechanism. As a result of the simulations, the Gold codes that satisfy the bit-stuffing criteria for the AIS R-Mode navigation messages have been selected.

The longest code needed is for a 5-slot message and has a length of 968 bits. Only one such code has been found (initial state: 702 948). For a 2-slot message, over 200,000 usable codes of length 300 bits have been found and eventually, one code – featuring good autocorrelation capabilities – was selected from that list (initial state: 1 174 014). For a 1-slot message, over 10,000,000 codes of length 80 bits have been identified and eventually, one code – featuring good autocorrelation capabilities – was selected from that list (initial state: 4 872 582).

All three codes were constructed as a negative binary form (bipolar *1* denotes binary *1*, and bipolar *−1* denotes binary *0*) of the imaginary part of the generated Gold code. Using these synchronization codes, the AIS R-Mode navigation message 26 structure for 1, 2, and 5 slots was defined.

In case of the VDES system, the procedure for the correlation code selection was much simpler. Unlike the AIS system, there was no bit-stuffing mechanism in the VDE-TER, so the code didn't have to be custom selected, and moreover, due to the chosen modulation scheme ($\pi/4$ QPSK), it was possible to directly apply the complex Gold code (two codes: real and imaginary) generated by the UMTS uplink scrambling code generator, which has better correlation properties than the single code used in case of the AIS.

For the purpose of the R-Mode VDES navigation message, a single complex code (initial state: 103 462) of length 1,877 symbols has been selected from the list of codes with the best autocorrelation properties.

3 | DISTANCE DETERMINATION ACCURACY IN THE R-MODE SYSTEM

The accuracy of distance determination in the time of arrival (TOA) method is directly related to the duration of a single symbol, and thus to the transmission speed rate, bandwidth, and spectrum shape. Taking into consideration a very conservative half-wavelength accuracy assumption, data transmission rate in the AIS system is 9,600 bit/s, which gives an accuracy of approximately 15 km, whereas in the VDES system the symbol rate is 76,800 sym/s, which results in the accuracy of approximately 2 km.

Obviously, both of these values are unacceptable. By introducing oversampling of the signal, though, we can significantly increase this accuracy, as determined by the formula:

$$Acc = \frac{T_s \cdot c}{L_p \cdot 2} \tag{1}$$

where Acc is accuracy, T_S is symbol duration time, L_P is the number of samples per symbol, and c is the speed of light.

Obviously, the increase in accuracy due to the oversampling resulting from Equation (1) is only achievable under the condition that such correlation peak can be distinguished in the actual system under real conditions (e.g., in the presence of noise).

Assuming that both AIS and VDES signals will be oversampled (50 M Samples/s for AIS and 200 M Samples/s for VDES), according to Equation (1) it is possible to obtain the distance determination accuracy at the level of 3 m for AIS and 0.75 m for VDES. Of course, such accuracy can only be obtained at suitable received signal levels. In order to determine the dependence of accuracy on the received signal level, we should start by defining the limit of the received signal level (receiver sensitivity):

$$S = \frac{E_b}{N_0} + 10 \cdot log\,(R_s) + 10 \cdot log\,(k) + N_0 + NF \tag{2}$$

where S is the signal level in dBm, $\frac{E_b}{N_0}$ is the energy-per-bit to noise-power-spectral-density ratio, R_S is the modulation speed rate (9,600 sym/s for AIS and 76,800 sym/s for VDES), k is the number of bits per symbol (1 symbol for AIS and 2 for VDES at $\pi/4$ QPSK), N_0 is the noise power spectral density (−174 dBm/Hz), and NF is the noise figure [18 dB for the AIS and VDES receivers including man-made noise (ITU-R, 2019b)].

The noise variance σ^2 (i.e., noise power N) is given by:

$$\sigma^2 = \frac{S \cdot L_p}{k \cdot \frac{E_b}{N_o}} \tag{3}$$

Assuming that the synchronization code will have the symbol length of L_S, after its L_P-fold oversampling (L_P as the number of samples per symbol), we will obtain an extended synchronization sequence with the length of $L = L_S \cdot L_P$ symbols.

As per the normal distribution properties, the standard deviation σ_L of the sum of L independent normal distributions with a standard deviation σ is given by:

$$\sigma_L = \sqrt{L} \cdot \sigma \tag{4}$$

When calculating the autocorrelation function for the oversampled signal in the presence of noise, it should be remembered that the autocorrelation samples will be more and more correlated as time between samples decreases.

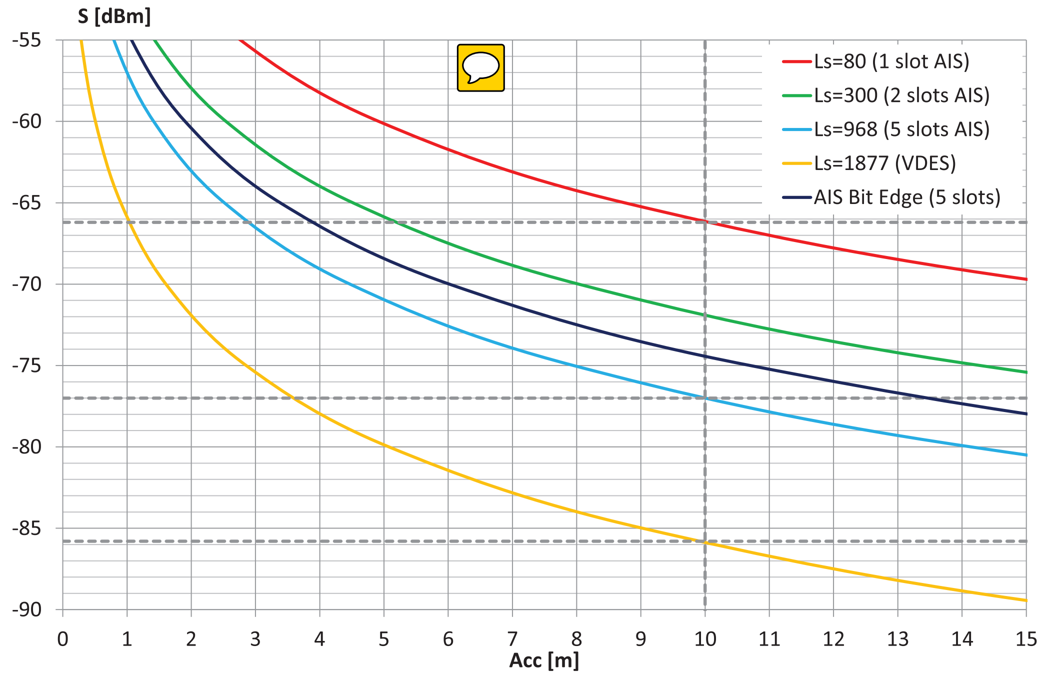

FIGURE 3 The relation between the determined distance accuracy and the received signal level [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

As a simplification, as well as for the analysis of the worst-case scenario, Equation (4) was used to calculate the standard deviation of the autocorrelation function samples.

The highest accuracy can be obtained when the maximum reduction of the synchronization code autocorrelation function value within one sample shift is greater than the correlation between the noise and the synchronization sequence. In simplified terms, the reduction of the autocorrelation function value can be estimated[4] as $q \cdot L_S \cdot S$, where: $q = 1$ for the pseudo-random sequence (Gold code) and $q = 2$ for the rectangular wave sequence [alternative sequence of consecutive 0s and 1s (i.e., 0101010…) planned for use in future considerations], L_S is the symbol length, and S is the received signal level. The edge dependence can be written as:

$$q \cdot L_s \cdot S = a \cdot \sqrt{L_p \cdot L_s} \cdot \sigma \cdot \sqrt{S} \tag{5}$$

where $a = \sqrt{2} \cdot Q^{-1}(10\%)$ is the coefficient corresponding to 90% of cases for which this condition is met for a normal distribution with a standard deviation σ_L, and $Q^{-1}(x)$ is the inverse Q function ($a = 1.813$).

By transforming Equation (1) to Equation (5), we can obtain:

$$Acc = \frac{a \cdot c}{\mathrm{q} \cdot 2} \cdot \sqrt{\frac{T_s}{L_s}} \cdot 10^{\frac{N_0 + NF + 10 \cdot \log(k) - S}{20}} \tag{6}$$

The preceding formula shows that the accuracy of the determined range depends on the received signal level and the length of the synchronization code.

For the selected lengths of the synchronization codes defined for the AIS and VDES R-Mode navigation messages, the relation between the determined distance accuracy and the received signal level was calculated on the basis of Equation (6) and is depicted in Figure 3. Figure 3 also shows the pseudo-range performance for the bit edge method, based on the assumptions of the authors of the feasibility studies of the ACCSEAS project (Johnson & Swaszek, 2014) defining the $\sigma_{GMSK\ bit\ edge}$ formula, corresponding to the 90% probability.

Figure 3 shows that the R-Mode required accuracy at the level of 10 m will be achievable at the received signal level in the range from approximately −66 dBm for the 1-slot AIS

[4] Let's use an example for a simplified rectangular wave. The value of the autocorrelation function of a two-symbol code oversampled four times ($L_S = 2$, $L_P = 4$): $\{\sqrt{S}, \sqrt{S}, \sqrt{S}, \sqrt{S}, -\sqrt{S}, -\sqrt{S}, -\sqrt{S}, -\sqrt{S}\}$ is equal to $8 \cdot S$. The value of the correlation function of the same code with the code shifted by one sample is equal to $4 \cdot S$. The difference between the correlation function values is $4 \cdot S$ which corresponds to $2 \cdot L_S \cdot S$, where $2 \cdot L_S$ is the number of samples that lowered the value of correlation function. In the case of the pseudo-random sequence, there are two cases: (a) when two adjacent symbols are different in which the decrease is the same as for the rectangular wave, and (b) when two adjacent symbols are the same in which there is no decrease of the autocorrelation function. Therefore, for the pseudo-random sequence, the decrease of the autocorrelation function should be estimated as $L_S \cdot S$.

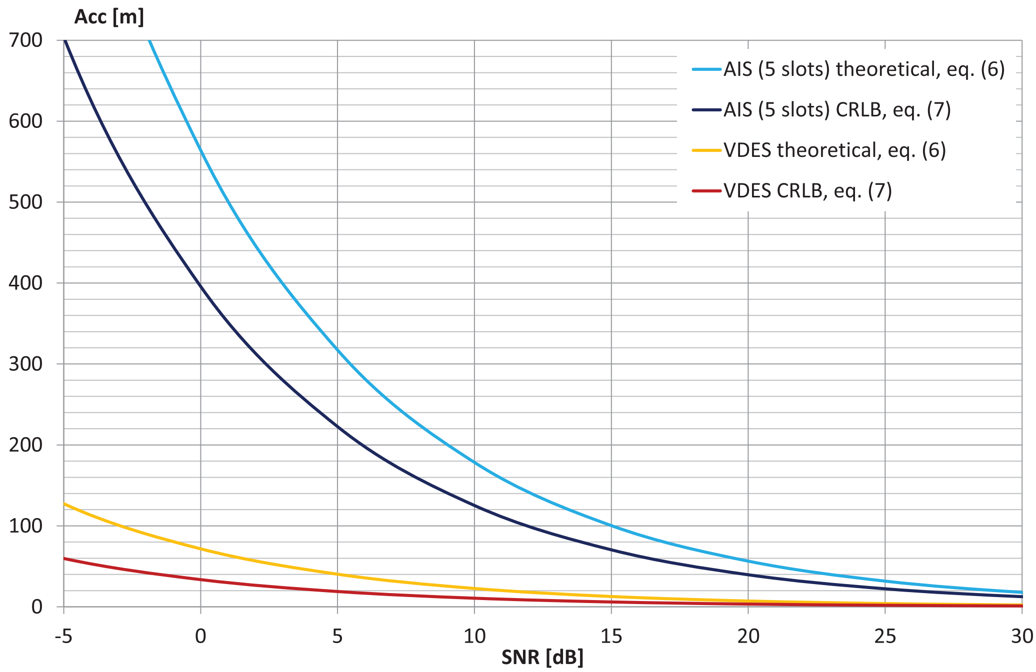

FIGURE 4 The relation between the determined distance accuracy and the signal to noise level [The Cramer-Rao lower bound (CRLB)] [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

message, to approximately −77 dBm for the 5-slot AIS message, and approximately −86 dBm for the VDES.

For comparison, the limit of the AIS and VDES range is typically −107 dBm, so it is expected that the range of the R-Mode will be much shorter than the ranges of those systems. The comparison of the correlation technique with the bit edge timing for the AIS system cannot be made/interpreted directly from Figure 3. The presented curves show an approximate 3 dB difference at the 10 m accuracy level, which may lead to better quality of the correlation-based approach proposed in the article in practice, but requires appropriate comparative measurements.

The accuracy of TOA (measurement error) can also be analyzed using the Cramer-Rao lower bound method (Kay, 1993; Van Trees, 1968). In ideal propagation conditions, with no multipath and interference phenomena considered, the ranging accuracy can be defined as a function of the signal-to-noise ratio and the effective signal bandwidth:

$$Acc_{CRLB} = \frac{c}{\sqrt{8\pi^2\beta^2 SNR}} \tag{7}$$

where c is speed of light and $\beta^2 = \frac{\int f^2 S(f)df}{\int S(f)df}$ is the squared equivalent bandwidth. The signal to noise ratio SNR can be calculated from the ranging signal energy E_r to noise ratio:

$$SNR = \frac{E_r}{N_0} - 10\,log_{10}(B) + 10\,log_{10}(R_r) \tag{8}$$

where B is the system bandwidth (25 kHz for AIS and 100 kHz for VDES), and $R_r = 1/T_r$ and T_r is the ranging frame length (130 ms for 5 slots AIS and 26 ms for VDES).

Figure 4 shows the comparison of accuracy determination for the two mentioned methods [using the engineer formula in Equation (6) and the Cramer-Rao lower bound theory in Equation (7)].

As can be seen from the VDES system, both methods provide similar results. For the AIS system, the observable differences are due to the simplification adopted in the analysis (e.g., the real AIS spectrum shape in the Cramer-Rao method). For the purpose of the deeper analysis, the R-Mode range accuracy will be compared to the Cramer-Rao lower bound (CRLB) method. It has to be stated that this method is particularly effective for high SNR values (above 15 dB); if used for lower SNRs, however, the CRLB may be less accurate[5] and may introduce higher error [see Rezaiesarlak and Manteghi (2015)][6]. This theoretical assumption will be confirmed later in the paper during the analysis of the measurement data.

In the next stage, the dependence of the determined distance accuracy from the AIS and VDES base station ranges were analyzed. To do so, the results of radio planning carried out using the ITU-R P.1546-6 propagation model (ITU-R, 2019a), assuming the typical configuration

[5] with respect to higher SNR values.

[6] The Ziv-Zakai bound is more accurate for low-SNR, but as a simplification it was not considered.

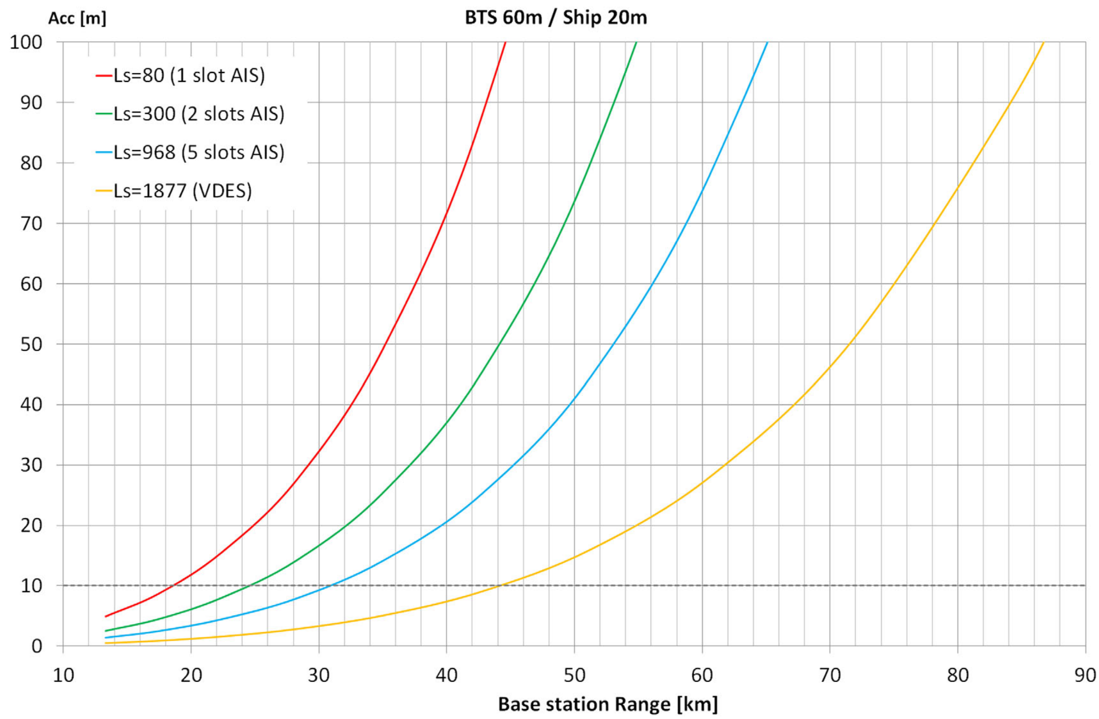

FIGURE 5 The relation between the determined distance accuracy and AIS/VDES base station range for the base station antenna height 60 m ASL and ship antenna height 20 m ASL [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

of the AIS/VDES base station (EIRP power 46 dBm and the 162 MHz frequency). The analysis has been conducted for different heights of the base station antenna (30 m and 60 m ASL) and of the ship terminal antenna (4 m, 10 m, and 20 m ASL). Figure 5 presents the results of the analysis for one of the scenarios: 60 m ASL base station antenna height and 20 m ASL ship terminal antenna height.

The full set of the ranges calculated for different base station and ship antenna height configurations has been presented in Table 1.

Having analyzed the above results, it can be concluded that the accuracy of 10 m can be achieved in the R-Mode system for the ranges from about 7 km up to about 31 km in the AIS system and for the ranges from about 21 km up to about 44 km in the VDES system. Of course, the R-Mode system will work for greater distances as well, but it should be noted that the observed accuracy will decrease with distance for both AIS and VDES system.

TABLE 1 R-Mode ranges for 10 m accuracy

Acc = 10 m		AIS	AIS	AIS	VDES
BTS	Ship	$L_S = 80$	$L_S = 300$	$L_S = 968$	$L_S = 1877$
30 m	4 m	7.5	10.5	13.5	21.5
	10 m	9.5	14.5	19	29
	20 m	14.5	19	24.5	36
60 m	4 m	9.5	13.5	17.5	27
	10 m	14	19	24.5	36
	20 m	18.5	24.5	31	44

4 | R-MODE SYSTEM IMPLEMENTATION

The R-Mode system was implemented using the software developed by the article's authors in C++ language and the LabVIEW environment. There are two main hardware elements that have been selected for the purpose of implementation works: the first one is the Universal Software Radio Peripheral (USRP) hardware platform provided by National Instruments, while the second component is a GPS-disciplined rubidium time and frequency reference. In the following sections, the structure of the R-Mode testbed system is characterized.

4.1 | AIS and VDES segment's physical layer

The physical layers of the AIS (ITU-R, 2014) and VDES (ITU-R, 2015) were implemented in the software for USRP platform. In case of the VDES system implementation, the main changes with respect to the AIS system were the utilization of the $\pi/4$-QPSK modulation (instead of GMSK) and the root raised cosine (RRC) filter with a roll-off factor = 0.3 for the 100 kHz band (Bronk et al., 2019a; IALA, 2019; ITU-R, 2015). The latter is used to reduce the modulated signal bandwidth and to minimize the intersymbol interference (ISI).

The simplified process of the AIS and VDES R-Mode signal generation can be described as follows:

- AIS: the real Gold code is inserted into the AIS message number 26 and encoded using a 17-bit polynomial-based CRC generated and appended to the end of the Gold code. After that, the NRZI encoding with bit stuffing is applied, followed by sampling and the Gaussian minimum shift keying (GMSK) modulation. Finally, the modulated signal is multiplied in the time domain by the Hann window, converted to RF, and transmitted in the radio channel
- VDES: the complex Gold code is inserted into the VDES frame (in this case, no CRC, FEC, or scrambling are applied). After the sampling process, the signal is modulated using the $\pi/4$-QPSK modulation with the RRC filter (roll-off factor = 0.3 for the 100 kHz band). Finally, the modulated signal is multiplied in the time domain by the Hann window, converted to RF, and transmitted in the radio channel

The essential units of the AIS and VDES software segment are the ones responsible for synchronization and reception of signals. The reception process starts in the signal power detector, where the average received signal power is compared to the designated threshold. When the receiver detects a signal, it is then possible to determine the position of the transmitted frame. As soon as there are enough samples of the signal in the receiver's memory, the time synchronization algorithm initiates its operation. The received signal is then correlated with a known reference signal (Bronk et al., 2019b).

4.2 | Hardware implementation

The concepts of the transmitting and receiving parts of the test-bed for VDES transmission are illustrated in Figures 6 and 7, respectively.

The platforms presented in these pictures have also been employed in the R-Mode/VDES (AIS) measurement campaigns that will be described later in the paper.

As mentioned in the introduction, the main goal of this campaign was to examine the propagation environmental influence on distance measurements. It was also assumed that while preparing for the measurements, all other types of errors (except those due to propagation environment) would be minimized to the greatest extent possible. That assumption was considered critical when the hardware platforms were designed and developed. In Table 2, the list of those identified types of errors is presented alongside the hardware elements or procedures which were used to minimize each of them.

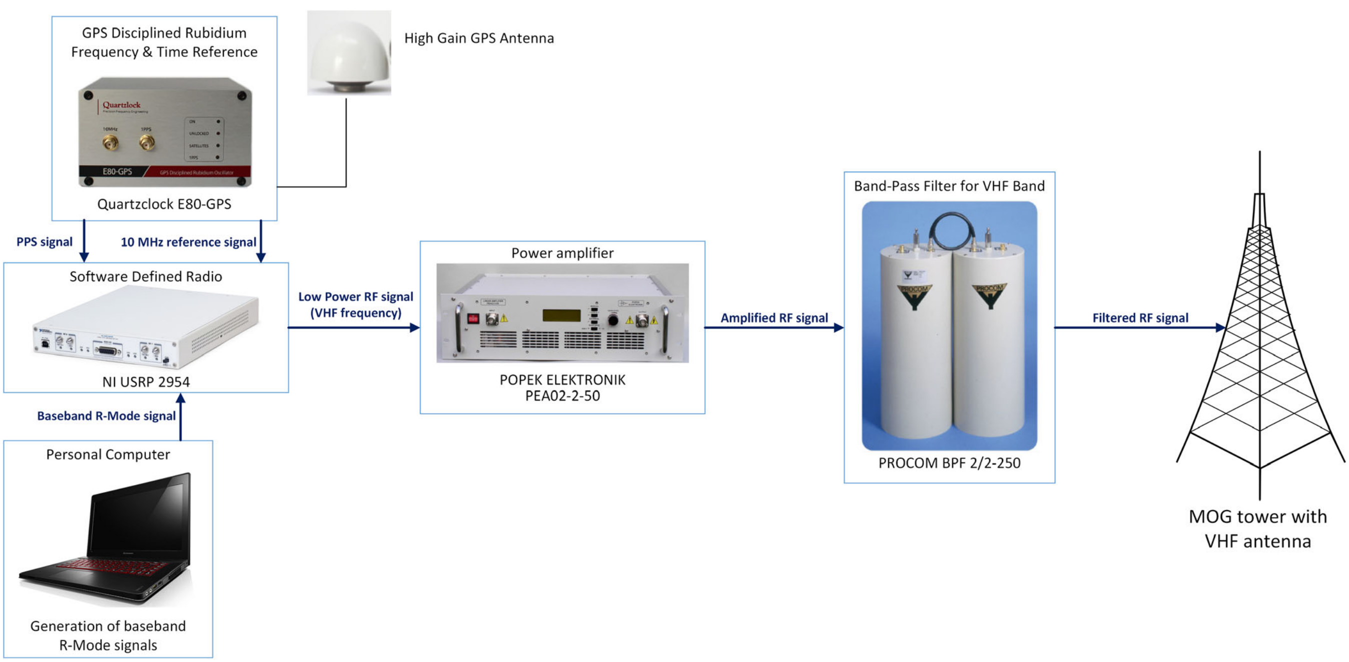

FIGURE 6 Test-bed transmitter diagram for the VDES transmission [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

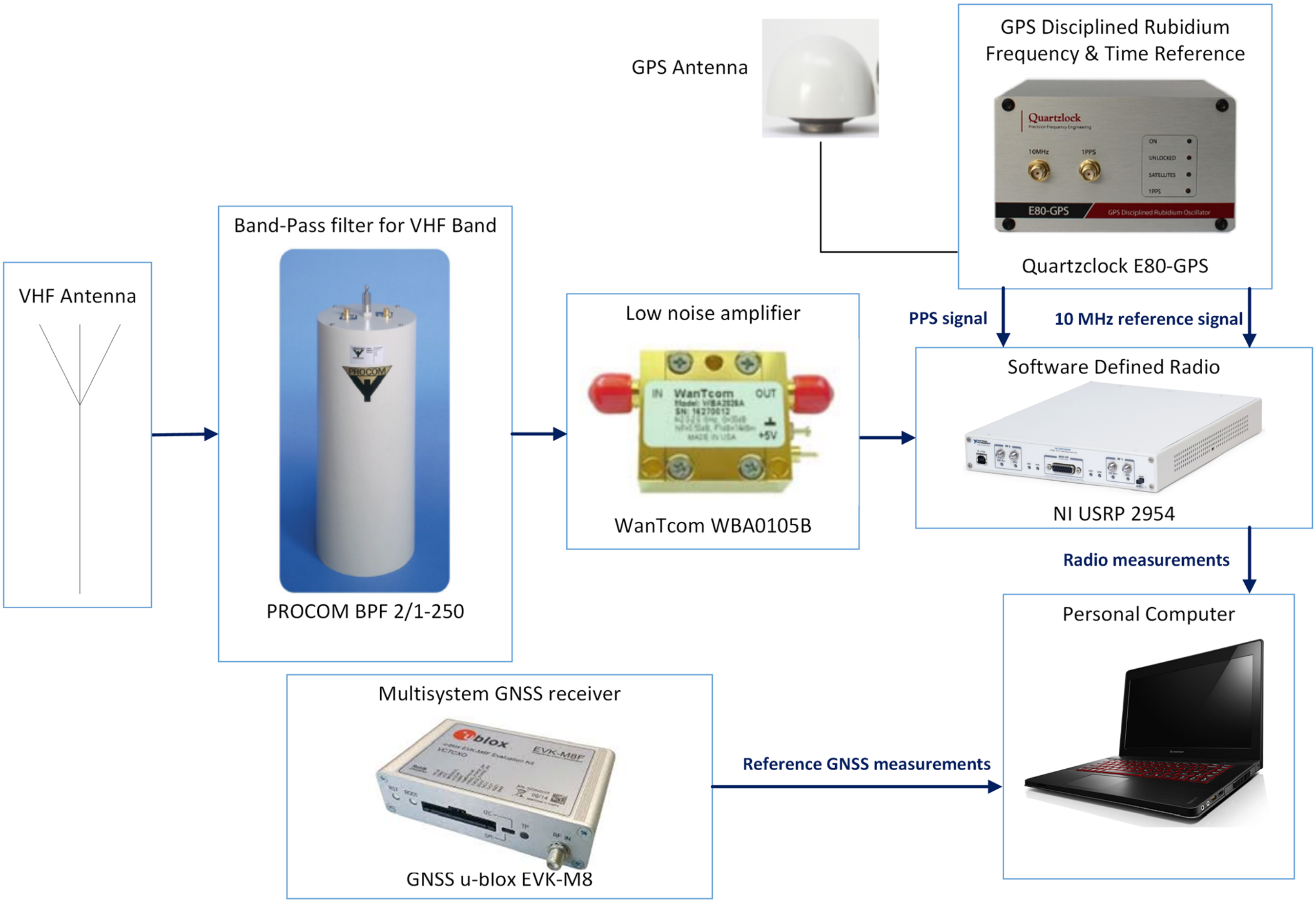

FIGURE 7 Test-bed receiver diagram for the VDES transmission [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

TABLE 2 Measures to minimize the anticipated errors that may occur during measurements

Error to be minimized	Utilized measures
Clock errors	Rubidium disciplined oscillator
Delay on the transmitter and receiver sides	Calibration measurements; see below
Error of the station's position determination	Position determined with a real-time kinetic (RTK) receiver
Error of the ship's reference position	Reference ship's position determined via GNSS + EGNOS
Errors due to noise and interference	Filters and LNA

Generally, the main elements of the developed measurement system are National Instruments Universal Software Radio Peripheral (NI USRP) software defined radios [USRP 2920 (National Instruments, 2012) for AIS and Universal Software Radio Peripheral (USRP) 2954 (National Instruments, 2017) for VDES transmission], responsible for transmission and reception of the generated test signals, as well as external rubidium Quartzlock E80 GPS oscillators (Quartzlock, 2017) that provide a stable source of frequency and time. This is particularly important for the ongoing studies involving the measurement of radio signal propagation time. External oscillators are also used to synchronize the transmitter and receiver parts of the system. In addition to these elements, the measuring sites consisted of: appropriate bandpass filters, a power amplifier on the transmitter side, a low noise amplifier (LNA) on the receiver side, and antennas.

4.3 | Signal correlator application

As part of the implementation activities, a simulator of the AIS and VDES systems was developed. An advanced signal correlation module was also created, on the basis of which the distance from the transmitting antenna can be determined. The correlator is based on the oversampled *I* and *Q* signals and the peak-to-sidelobes ratio detection algorithm. In this module, the correlation is calculated and after that, the correlator searches for the main peak. This allows us to determine the distance between the

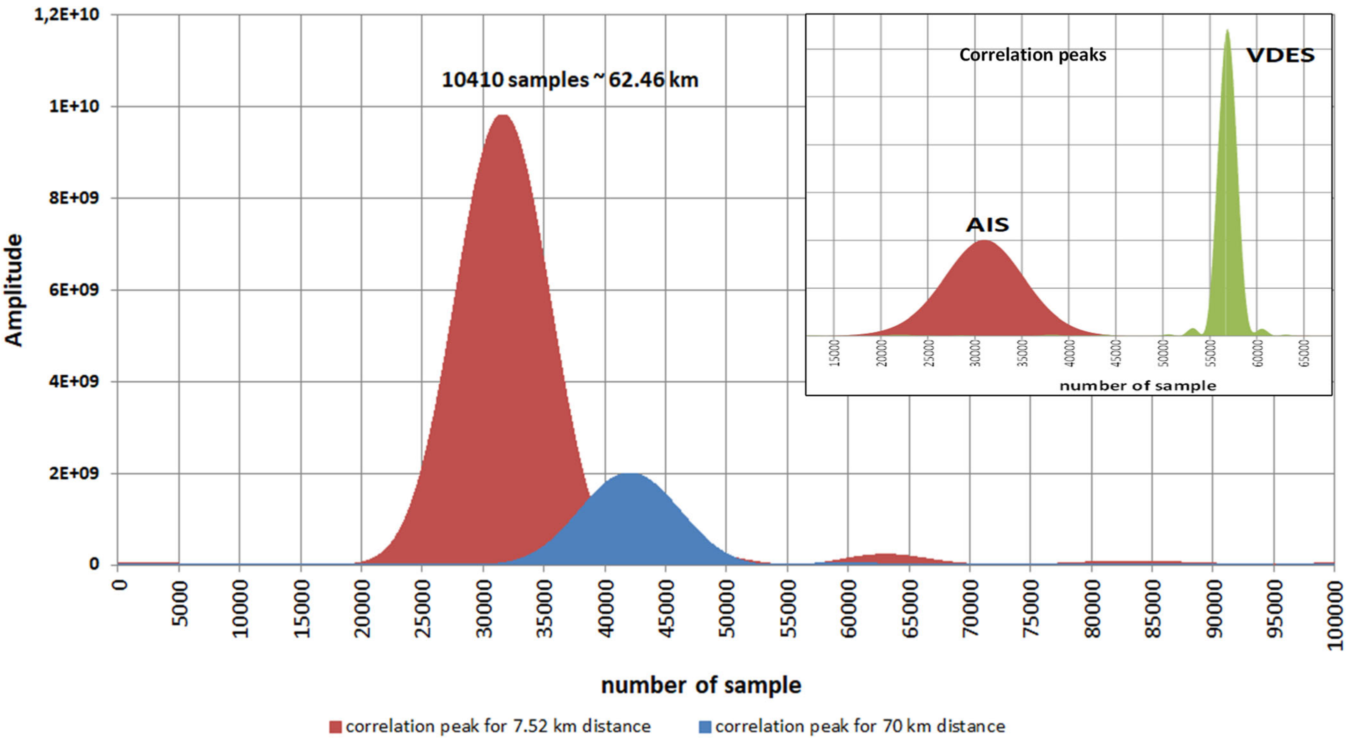

FIGURE 8 Correlation peak found (100,000 samples) as an example for AIS. Correlation peaks for both AIS and VDES systems are also presented for comparison [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

transmitter and the receiver with the accuracy of one sample (i.e., ±3 meters for the AIS system and ±0.75 meters for the VDES system).

In addition, the Hann window was employed for both cases of modulated signals. The main reason to use that window is the reduction of spectral leakage, but on the other hand, this solution results in a power loss of 4 dB. The low-pass filter reduces the noise energy in relation to the signal strength and thus increases the SNR, but the consequence of narrow bandwidth is smoothing of the correlation/peak function.

The sample correlation charts obtained in the signal correlation application for the AIS signal are presented in Figure 8. It is also shown that the correlation's peak width will decrease 8 times compared with AIS (see the inset) due to the fact the VDES physical layer will allow it to achieve an 8-fold increase in data rate.

5 | MEASUREMENT STUDIES

The 2019 measurement campaigns at sea were carried out in cooperation with the Maritime Office in Gdynia (MOG). For the purpose of the measurements, the MOG provided its VHF antenna installation located on the tower near the entrance to the port of Gdynia. This specific location was used for the R-Mode testbed's transmitter (Tx) installation. The aim of the measurements was to test the designed system in real conditions as well as its possibility to determine the distance between the terminal at sea and the base station on the shore.

Before the campaign, the precise location of the transmitting antenna was determined via RTK measurements (within a 1 cm accuracy). An important element of the measurements was the logging of the vessel (receiver) position obtained using the GNSS receiver with European Geostationary Navigation Overlay Service (EGNOS) corrections (within about 1-2 m accuracy). The fixed position was converted to the distance to the transmitting station and was the reference value for the collected measurement values. It allowed us to determine the final ranging accuracy of the R-Mode test-bed. For this purpose, the GNSS u-blox EVK-M8 (multisystem GNSS + EGNOS receiver) was used on the receiver side, registering the most important parameters such as: UTC time (time tag derived from GNSS), coordinates, velocity, course, and dilution of precision (DOP) values.

The receiving (Rx) station was installed on the Stena Line ferryboat *Stena Baltica* operating between Gdynia, Poland, and Karlskrona, Sweden. The measurements were collected in both directions.

Two measurement campaigns have been carried out as of March 2020:

- June 17-18, 2019, based on AIS transmission
- November 15-16, 2019, based on VDES transmission

The main differences between these campaigns were as follows:

- AIS signal covered 5 time slots, while VDES covered only 1 slot
- the single transmission measurement file size in VDES was larger than in AIS (due to higher IQ rate and better ADC resolution)
- there was a different frequency of receiving messages—due to higher performance of the USRP 2954, the recording of VDES transmission samples performed every 1 second (and every 4 seconds for the AIS transmission). The measuring signal was transmitted in both cases every 3 seconds. So, for VDES, the useful signal was recorded in 1 of 3 samples, and for AIS, the useful signal was recorded in 1 of 12 samples

5.1 | Base station technical parameters

During the tests, four 25-kHz neighboring channels provided for the VDES system (ITU-R, 2015) were utilized (channel numbers 2024, 2084, 2025, and 2085, with center frequencies from 161.800 MHz to 161.875 MHz). The National Institute of Telecommunications obtained a temporary permit from the President of the Polish Office of Electronic Communications (Decision No. DZC.WML.5101.3255.2018.2) to use the above-mentioned radio channels for testing the R-Mode system in the Bay of Gdansk area and in the Polish territorial waters of the Baltic Sea.

Table 3 contains the most important technical parameters of the R-Mode test station.

Calibration and test measurements were carried out in a few stages: The first stage was targeted to validate the correctness of the generated AIS and VDES signals and their spectra. The second stage was dedicated to the calibration of the delay introduced by the transmitter/receiver circuits and by other hardware components. The main part of the measurements took place in the port of Gdynia, in the vicinity of the transmitter station. The last stage of the calibration process was conducted on the selected site on the Hel Peninsula.

TABLE 3 Technical parameters of the R-Mode test station

Location	N 54° 31′ 45, 36″ E 18° 33′ 34,48″
Height of the antenna	28 m ASL
Frequency of the transmitter	161.8375 MHz
Antenna type	Radmor 32812/1
Antenna radiation pattern	Omni-directional antenna
Antenna gain	2.15 dBi
Cable and filters attenuation	8.5 dB
ERP power	14.8 dBW

5.2 | Analysis of the results from the AIS measurement campaign

Following the successful output of the calibration measurements, it was possible to start the actual testing campaign. The measurements of the AIS system took place on June 17-18, 2019. During the ferry route from Gdynia to Karlskrona and back, almost 2,000 distance measurement samples using the R-Mode AIS signal were collected. On the basis of those, further analysis was made.

Figure 9 shows the distance from the transmitting antenna in Gdynia to the receiving antenna located on the ferry, obtained using the R-Mode compared with the distance determined by the GNSS with EGNOS.

Figure 10 shows the obtained accuracy error superimposed on the ferry route.

It can be seen that the charts overlap up to 20 km, where the obtained accuracy of distance measurement was the highest. Beyond the 20 km range, however, some deviations became noticeable and the measurement's accuracy degraded.

A similar conclusion can be drawn from Figure 11 which presents the distance error obtained for the AIS R-Mode measurements with respect to the GNSS with EGNOS measurements.

Again, we can observe a decrease in signal strength and the impact of the terrestrial environment behind the Hel Peninsula (which caused a large increase in accuracy errors beyond the 20 km range). This anomaly can be explained by taking into account the path propagation conditions that were dealt with on the specific parts of the ferry route.

The first 20 km from Gdynia is clearly a line-of-sight (LOS) sea path. Beyond this mark, the influence of the Hel Peninsula starts to become more prominent, and the propagation path transforms into a mixed one (sea and land). This is where the accuracy begins to deteriorate.

Several kilometers further, the transmitter gets fully obscured by the Hel Peninsula, and from then on, the path type changes into non-line-of-sight (NLOS[7]). The theoretical distance at which we move from LOS into

[7] The term *NLOS* in this case is a simplification introduced for the clarity of the text. Indeed, NLOS was a dominant scenario in that zone, however at times, a LOS-like behavior could also be observed there, especially around the 50 km mark.

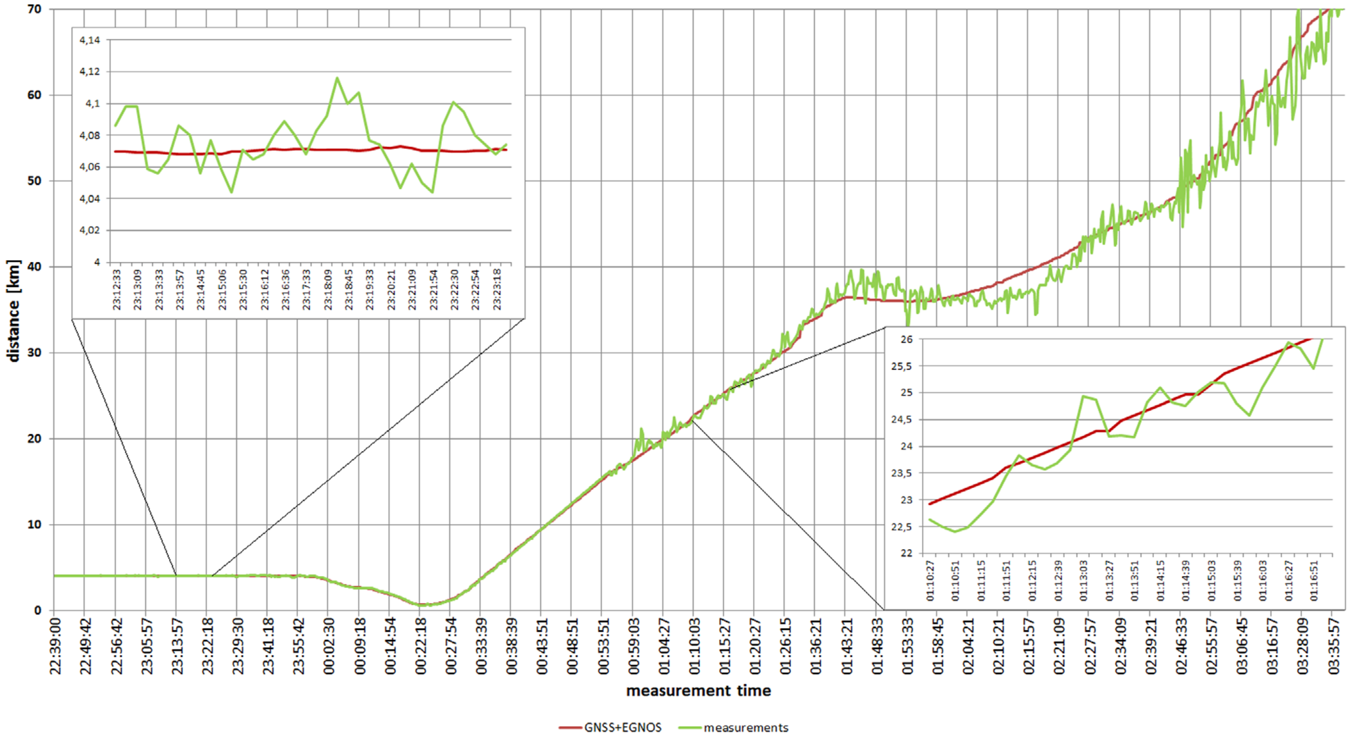

FIGURE 9 The distance calculated by the AIS R-Mode system compared with the distance determined by the GNSS with EGNOS [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

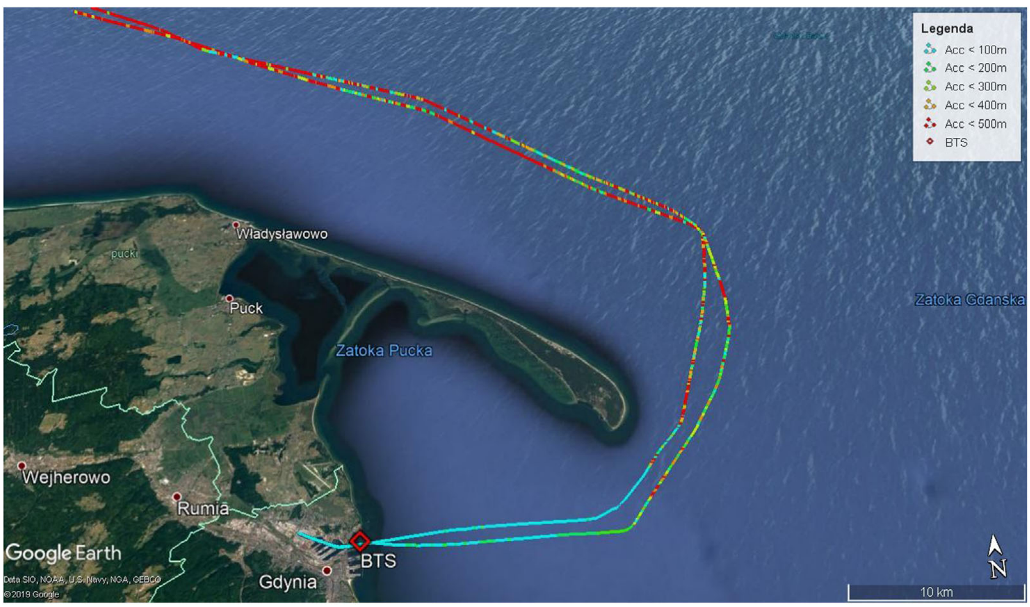

FIGURE 10 Ferry route versus distance accuracy error for AIS system [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

NLOS can be calculated using the well-known formula for radio horizon:

$$d_{LOS} = 4.12 \cdot \left(\sqrt{h_{transmitter}} + \sqrt{h_{receiver}}\right) \tag{9}$$

where $h_{transmitter/receiver}$ is the antenna height of the transmitter and receiver, respectively.

If we substitute $h_{transmitter} = 28$ m ASL and $h_{receiver} = 25$ m ASL into Equation (9), we can calculate the theoretical radio horizon limit as $d_{LOS} = 42.4$ km.

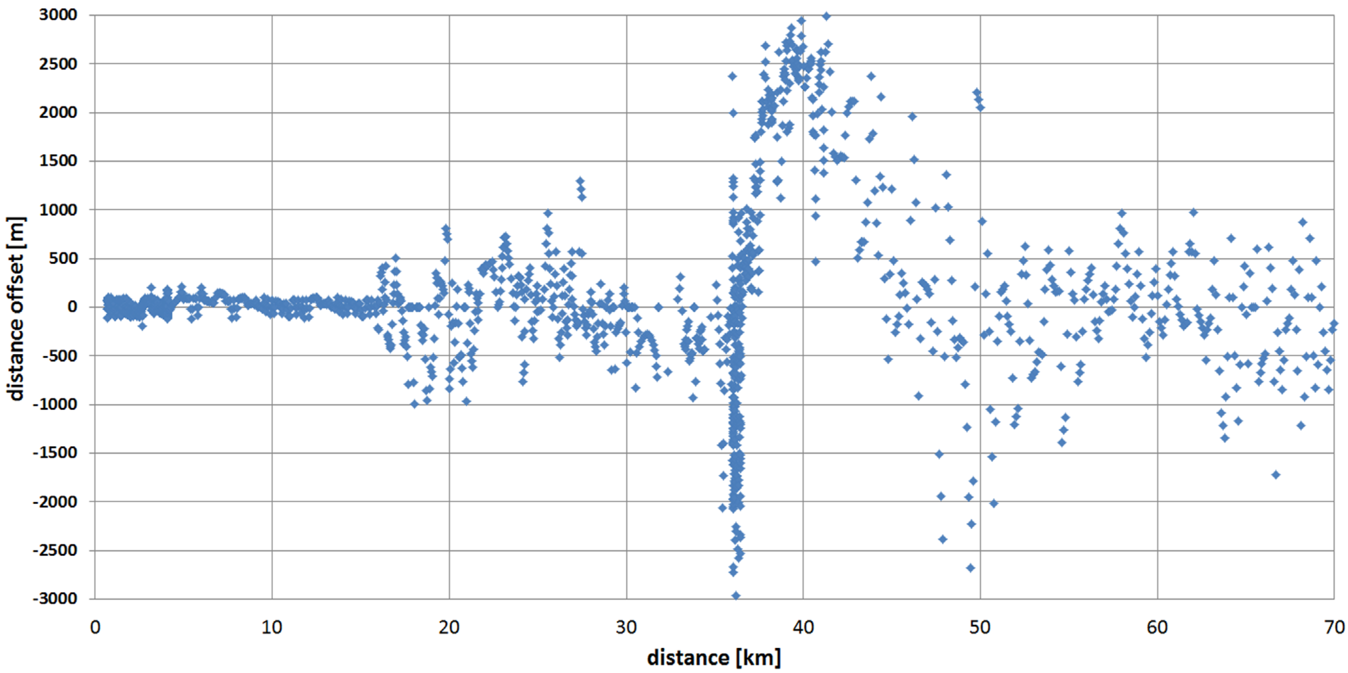

FIGURE 11 Distance error for the AIS R-Mode measurements [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

Figure 11 shows that around the 37 km mark, the observed error is the highest, reaching the level of nearly 3,000 m. On the basis of the above analysis, we can conclude it was probably caused by the transition from LOS to NLOS zone and by some specific features of the terrain along the edge of the Hel Peninsula (such as forests and buildings) which temporarily made the transmission conditions unusually difficult.

The presented results also demonstrate that the maximum achieved range of the AIS R-Mode system is about 72 km. Up to this point, the signals were correlated and it was possible to calculate the distance from the transmitting antenna. Above that range, the receiver correlation was unable to clearly distinguish between the signal peak and noise.

Figure 12 shows the obtained signal-power-to-noise ratio (SNR) values on the Gdynia – Karlskrona route for the AIS measurements. This graphic clearly demonstrates that the application of an additional digital low-pass filter reducing the signal bandwidth resulted in an extra gain of 6 dB

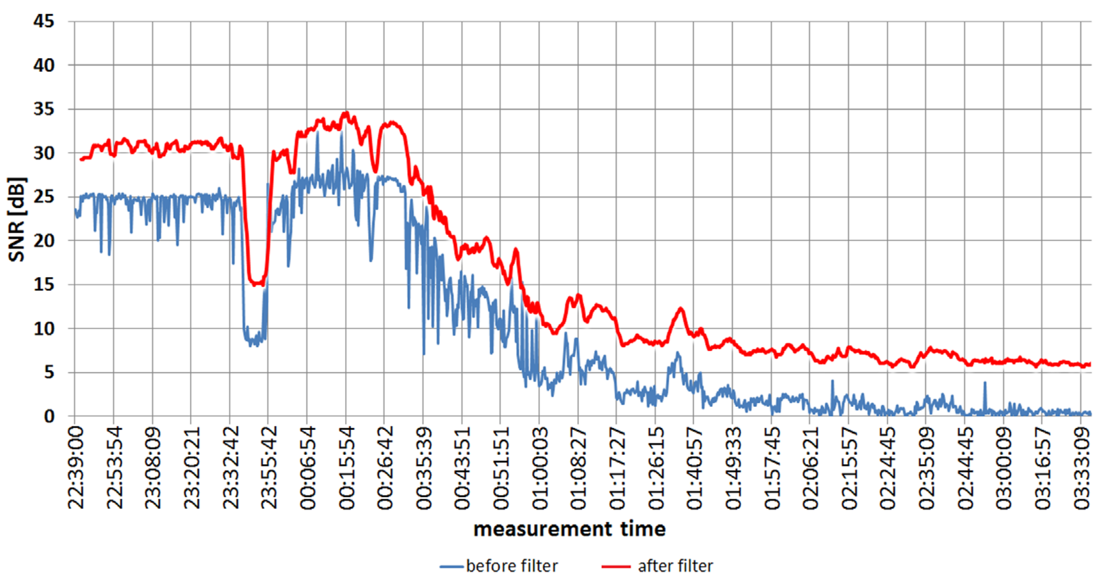

FIGURE 12 Measurements of the signal-to-noise ratio (SNR) for AIS system [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

(due to the 4-time reduction of the noise bandwidth with respect to the physical filter). The signal strength decrease recorded just after passing the Hel Peninsula is also visible.

The SNR drop observed at the beginning of the measurements was caused by the broadcast voice marine weather forecast from Witowo Radio, transmitted in one of the channels used during measurements.

Further analysis of the recorded measurement data also shows there was dependence between the ratio of the main correlation peak to side peaks and the distance. It was observed that this value was gradually going down as the distance increased. The higher the value of this ratio, the better distance accuracy can be obtained based on the correlation.

5.3 | Analysis of the results from the VDES measurement campaign

The measurements for VDES system were taken on November 15-16, 2019. During the ferry route from Gdynia to Karlskrona and back, almost 9,000 distance measurements using the R-Mode VDES signal were collected. The most important results and observations will be presented in a similar fashion as in the case of the AIS measurements to make the results comparable.

Figure 13 shows the distance from the transmitting antenna in Gdynia to the receiving antenna located on the ferry, obtained using the R-Mode compared with the distance determined by the GNSS with EGNOS. Figure 14 presents the obtained accuracy error superimposed on the ferry route.

As can be seen in Figure 13, the range of 70 km has been observed for the VDES system. Beyond this range, signals could no longer be correlated. In this case however, the discrepancies between the R-Mode VDES and the GNSS + EGNOS are much smaller than was previously observed for the R-Mode AIS signal, even after entering the NLOS zone behind the Hel Peninsula.

Figure 15 presents the distance error obtained for the VDES R-Mode measurements compared to the GNSS and EGNOS measurements.

It can be seen that the accuracy of the determined position is about 50 m for a range up to 20 km (i.e., in the LOS zone). Above this distance (as we transit from LOS to NLOS), the accuracy error begins to gradually increase. For distances beyond 40 km this error is about 400 m and at the edge of the range (near the 70 km mark), the observed errors are about 600 m.

It has to be recalled that for the AIS case, the observed errors on the system's edge were much higher—around 3,000 m (compare with Figure 11)—which shows the indisputable advantage of the VDES system over AIS in this respect.

This may be related to the occurring multipath propagation, the impact of which will be tested in the next measurement campaign with the use of a double-delta multi-correlator using two pairs of early and delayed

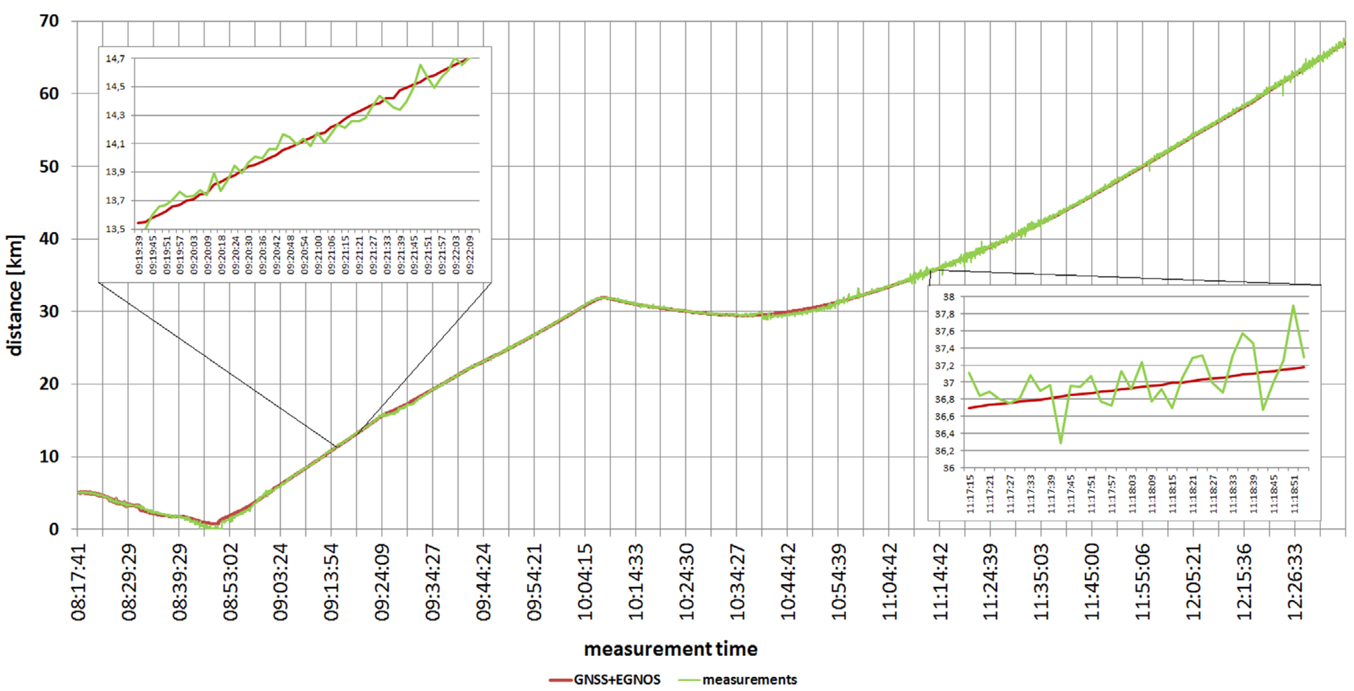

FIGURE 13 The distance calculated by the VDES R-Mode system compared with the distance determined by the GNSS + EGNOS [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

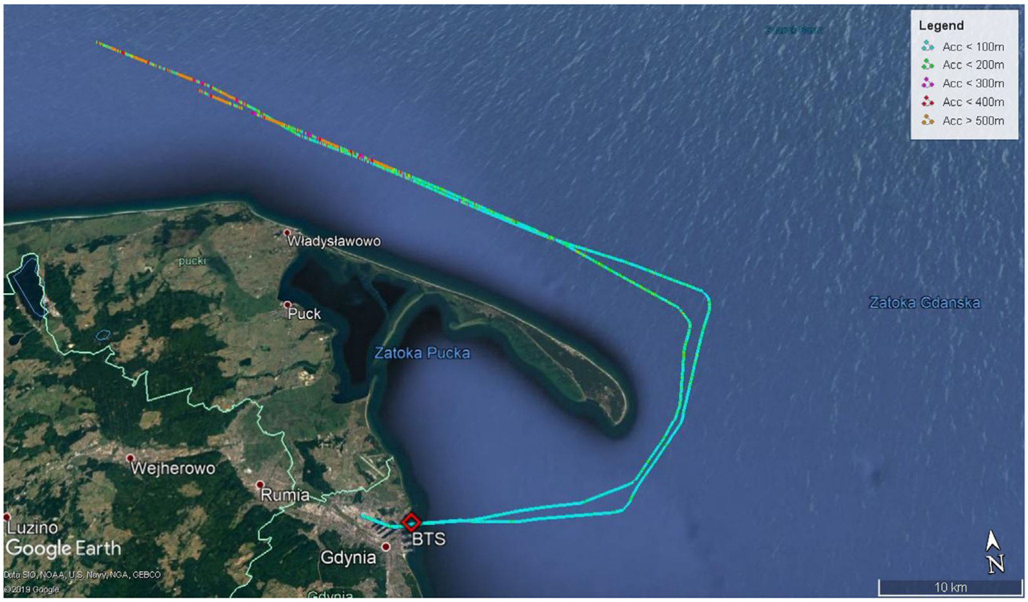

FIGURE 14 Ferry route versus the distance accuracy error for VDES R-Mode system [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

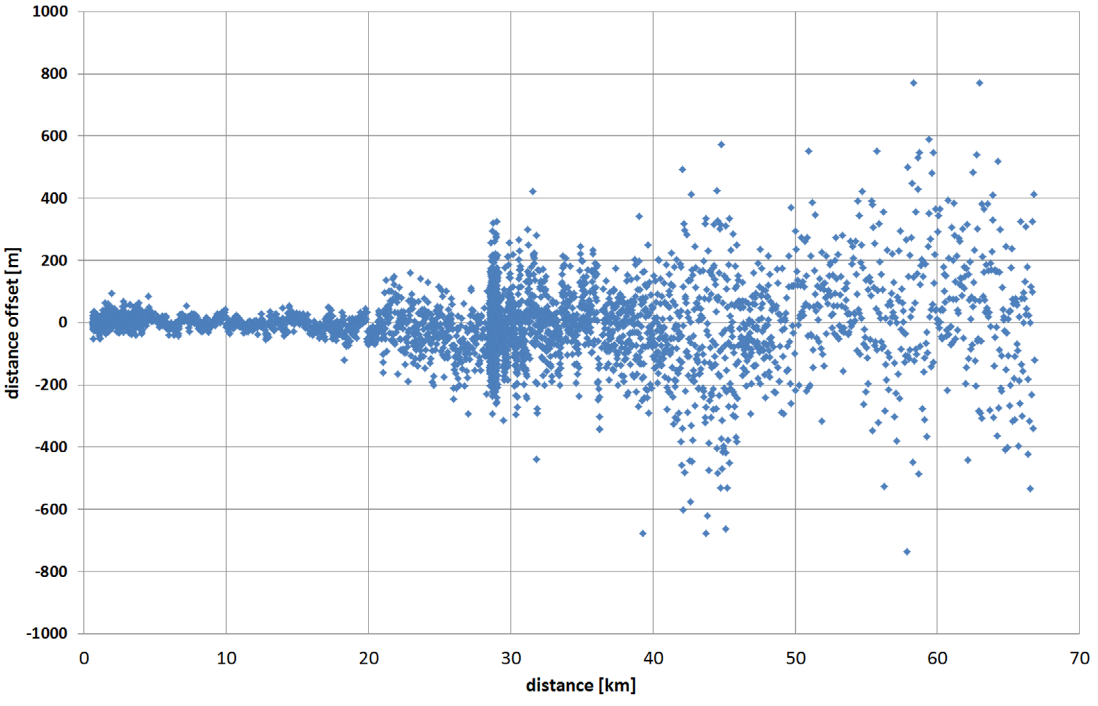

FIGURE 15 Distance error for the VDES R-Mode measurements [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

correlation function samples with different intervals in the time domain (European Space Agency, 2014; Phelts, 2001; Qu et al., 2016).

The characteristic contained in Figure 16 presents the obtained SNR values; again showing the benefit of the 6 dB gain due to the additional digital low-pass filter reducing the signal bandwidth can be easily noticed here. Similarly to the AIS case (see 5.2), this gain is a result of the 4-time reduction of the noise bandwidth with respect to the physical filter.

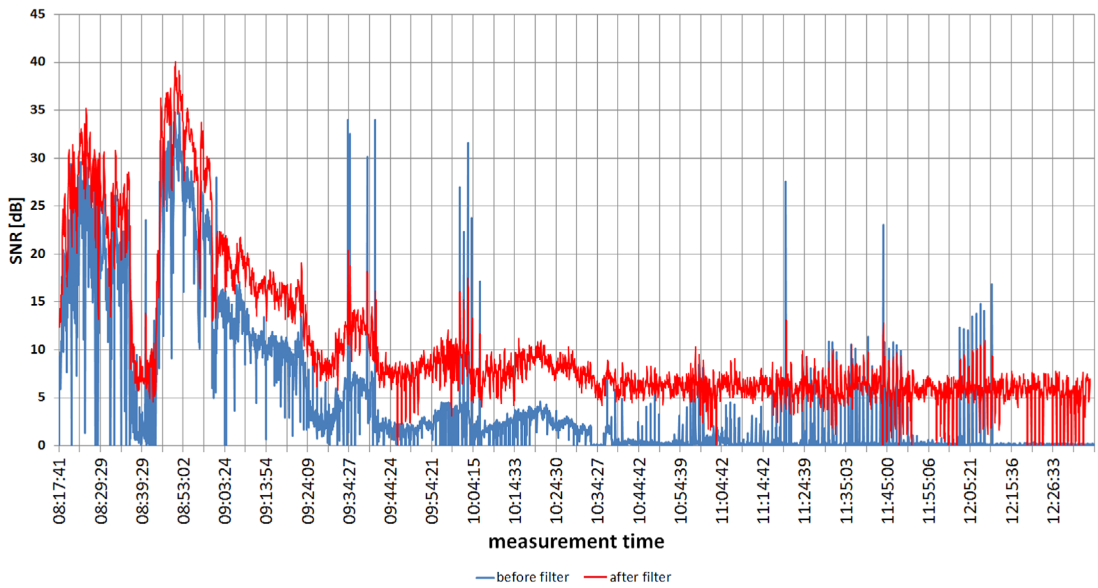

FIGURE 16 Measurements of the signal-to-noise ratio (SNR) for VDES R-Mode system [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

5.4 | AIS and VDES measurement results versus theory

As it was predicted, the R-Mode VDES measurements gave better results than those for the R-Mode AIS. Most notably, the observed accuracy of the determined ship (receiver) position was significantly higher.

This conclusion is further confirmed by the RMS analysis which was performed for all measurements. The chart presented in Figure 17 includes both theoretical and measurement curves for the AIS and VDES systems.

In Figure 17, the results obtained in the measurement campaigns were compared with the theoretical curves

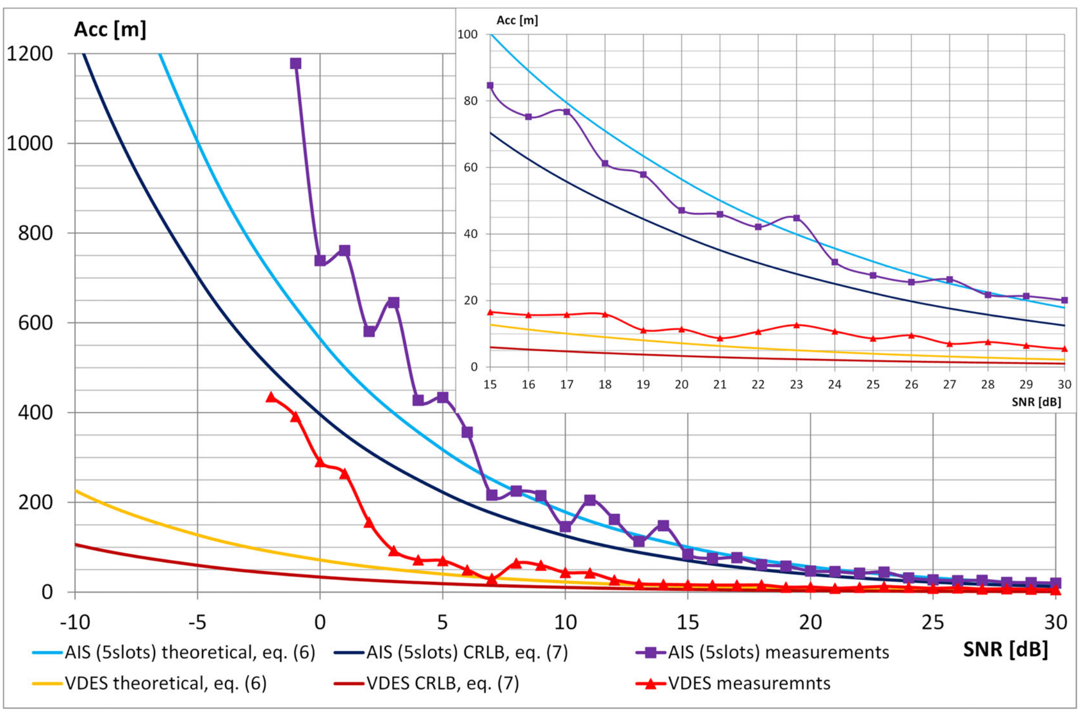

FIGURE 17 RMS curves for all measurements with an enlarged graph showing the calculated RMS values for high SNR [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

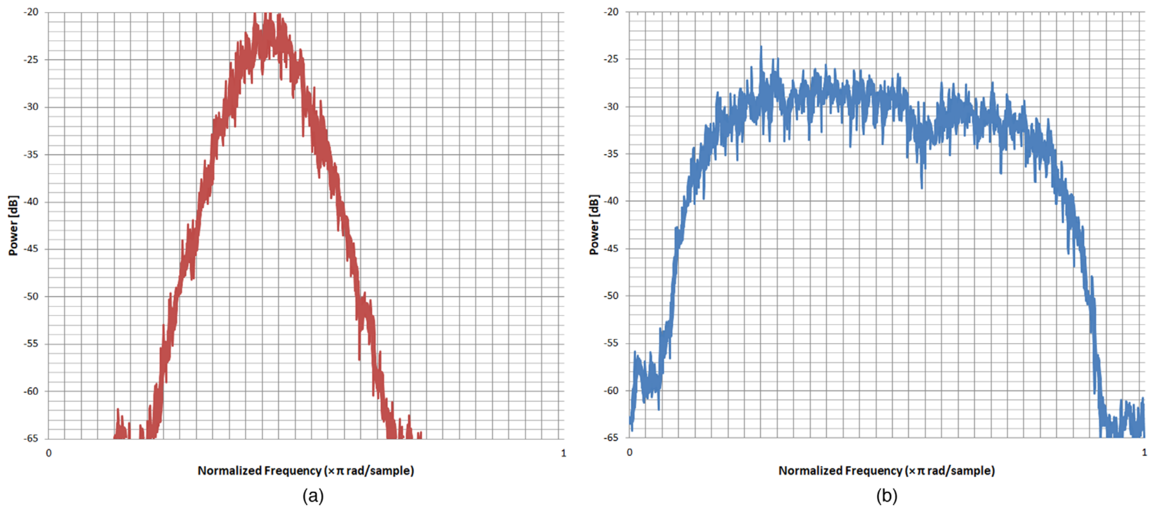

FIGURE 18 a) AIS spectrum, and b) VDES spectrum [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com and www.ion.org]

calculated on the basis of both methods presented in the paper [see Equation (6) and Equation (7)].

It has to be emphasized yet again that the Cramer-Rao lower bound (CRLB) method constitutes the ultimate lower limit of the RMS which cannot be exceeded under any circumstances. This is clearly visible in the figure, where the measurement curves and the theoretical ones [see Equation (6)] are always above the CRLB.

As can be seen, for very low SNR values, the discrepancy between the theoretical CRLB and the measurements was significant at low SNR (< 5 dB), but the correspondence between theory and measurement improved as the SNR increased.

The fact that, for lower SNR values, the accuracy of the calculated distance was not satisfactory for both analyzed systems confirms the limitation of the Cramer-Rao method mentioned earlier in this article. On the other hand, the discrepancy between the measurements and the theoretical curves drawn on the basis of Equation (6) was less severe, particularly for low SNR values. However, there is still significant differences between Equation (6) and measurements below 0 dB.

It can also be seen that in the low-SNR region, the measurement results for the AIS are closer to the theoretical curve obtained from Equation (6) than for the VDES. In this case, the differences between the systems might be caused by different shapes of the spectra (Gaussian versus rectangular), which has not been directly addressed in this method.

On the other hand, the results obtained for high SNR values almost coincided with the theoretical curves generated for the AIS and VDES systems, with the exception of the nearly constant 10 m difference of the RMS error (see the inset in Figure 17).

This difference might be caused by the multipath propagation which can be particularly problematic for the wideband VDES system. This observation is further confirmed by the comparison of the respective systems' spectra presented in Figure 18: in case of the VDES (Figure 18b), the frequency selectivity caused by multipath fading is clearly visible, while the spectrum of the narrowband AIS (Figure 18a) is much more resistant to the negative effects of the multipath propagation. It should be noted that both spectra in Figure 18 were measured at exactly the same location and in exactly identical hardware configuration.

Other possible sources of errors resulting in the behavior observed in Figure 17 which caused some deviation between theory and measurements have been identified and listed in Table 4. It should be noted that some of these

TABLE 4 Sources of errors applicable for low and high SNR region

Source of error	Applicable for low SNR region	Applicable for high SNR region
Possible impact of residual clock errors	yes	yes
Errors caused by the presence of the Hel Peninsula	yes	no
Errors that can be caused by lack of EGNOS and/or high HDOP	yes	yes
Ship's speed too high	yes	yes
Weather conditions	yes	yes
Error resulting from passing the LOS distance (beyond the 42.4 km mark)	yes	no
Sampling rate	yes	yes

errors only apply to the low-SNR region, while others are valid for the entire SNR range shown in Figure 17.

6 CONCLUSIONS

The results for our designs obtained in the maritime environment indicate that the utilization of the novel VDES system for VHF ranging is more promising than the AIS system. Most notably, the accuracy of the positioning for the VDES system design is better than for the AIS system design, according to theoretical assumptions and the actual measurement data.

It should be noted, however, there are some differences between the theoretical curves and obtained measurement data, likely due to the fact that the results were largely affected by the errors mentioned in the previous section. The usage of the Gold code sequence provided satisfactory results in a harsh marine environment under low SNR conditions. Additionally, the topography and NLOS propagation have influenced the results, which can be seen particularly for the Hel Peninsula (see Figure 17).

Besides the measurements already described in the paper, yet another campaign was held on June 29 – June 30, 2020, whose goal was to confirm the feasibility of the VDES-based solutions for the purpose of the planned R-Mode system.

The results of this campaign are currently being analyzed. The following changes (on the hardware and software sides) were made for the purpose of this campaign:

- VDES signal without Hann window to improve transmitted signal power
- transmission without physical VHF filter to improve transmitted signal power
- noise reduction in the receiver as utilization of another LNA and filter type were being considered
- low noise amplifier with less gain to eliminate the need for an attenuator at the USRP input
- reconfiguration of the ublox GNSS receiver module (reference positioning system) to maximize the number of the GPS and Galileo satellites used

One more measurement campaign is (initially) scheduled for spring 2021. The new sequence will be used this time, which will be comprised of Gold-code-based ranging code (1st slot) and alternating sequence-based ranging code (2nd slot):

- The alternating sequence, as the name suggests, contains an alternating stream of repeating *0*s and *1*s (in a rectangular wave sequence) and provides more correlation peaks than the Gold-code-based sequences
- The station transmitting such signal has already been established
- The measurements will allow to compare the performance of these types of ranging sequences in real maritime environments

During this campaign, different types of correlators will also be compared. It is planned to utilize two receiver sets: one with high sampling frequency, and the other, with low sampling frequency. The study of new correlators will help analyze the impact of multipath transmission on the results and will enable reducing the sampling frequency in the receiver.

It is planned to maintain the R-Mode test station installed in the Port Gdynia until the end of the R-Mode Baltic project and, possibly, throughout its extension (until 2021).

All measurement results obtained will be utilized in the implemented positioning software based on the distance measurements from several reference R-Mode stations using TOA method. This software is critical for further evaluation of the R-Mode system capabilities because it will ultimately allow us to analyze not only ranging accuracy but also to estimate the actual positioning errors, which otherwise would not be possible as currently we only have one R-Mode station. That being said, in the future there are plans to develop a multi-station test bed in the R-Mode project as well.

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