Paper

Ranging and Positioning Accuracy for Selected Correlators under VHF Maritime Propagation Conditions

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Abstract — The article presents an analysis of the features of selected correlators impacting the accuracy of determining the receiver's range and position in VHF marine environment. The paper introduces the concept of various correlators – including the double delta correlator – and describes the proposed measurement scenarios that have been designed to demonstrate the effectiveness of those components. The entire work was performed as part of the R-Mode Baltic and R-Mode Baltic 2 projects, with our goals including analyzing the impact of multipath phenomena, changes in the sampling frequency or signal type on the determination of the received signal delay at the receiver. The measured data were processed in a signal correlation application and in a TOA-based tool in order to determine the receiver's position. This process made it possible to compare the selected correlating devices. The results presented in this article are to be used by IALA in developing a current version of the VHF data exchange system's (VDES) specification.

Keywords — correlators, e-navigation, maritime radiocommunications, positioning, ranging, R-Mode Baltic, VHF data exchange system

1. Introduction

Precise determination of location is a key factor in aquatic and marine environments. The process is based primarily on satellite systems. However, relying solely on satellite systems is risky due to GNSS jamming, spoofing or a potential global failure. Relying only on RTK or DGNSS fixes is not sufficient as well. Hence the development of e-navigation services, i.e. an approach that combines modern navigation and communication technologies, thus creating an accurate, safe and effective system that is expected to be available for use by ships of all sizes [1]. The necessity of such a solution is essential in coastal areas, where availability of security systems is limited and where satellite signals are often disturbed. Therefore, if satellite and terrestrial systems are used simultaneously for location purposes, the number of ranging signals observed is increased and the geometry is improved. All this ensures better positioning accuracy and shortens the positioning lead time.

Ranging Mode for the Baltic Sea – R-Mode Baltic [2] and R-Mode Baltic 2 [3] – is one of the projects dedicated to the emerging e-navigation services. It is carried out by a consortium of 12 partners, from the Baltic Sea region, including the National Institute of Telecommunications, Poland. The scope and results of this project are presented in [4]. As part of the R-Mode Baltic and R-Mode Baltic 2 projects – whose main goal is to develop a non-GNSS marine positioning system – selected correlators have been researched and implemented, which allowed for the determination of more precise pseudoranges from terrestrial transmitting stations, and thus – for more accurate determination of the receiver's position at sea. Based on theoretical analyses and simulations, a software tool was developed and implemented in an R-Mode positioning system demonstrator. It was also tested in a laboratory and used during a measurement campaign performed in the marine environment – using the VHF radio maritime channel. The aim was to select a specific correlator that exhibits the best efficiency under multi-path propagation conditions or in a scenario in which the quality of the received useful signal is poor.

The article describes the entire process of researching the correlators known from [5]–[7], starting with a theoretical analysis, through the implementation stage, laboratory tests performed under various measurement scenarios, all the way to measurement campaign tests conducted with the use of a prototype transmitter and receiver.

2. Selection of the Optimum Correlator for R-mode Baltic System

Signal correlators are a very important component of radiocommunication and navigation systems. They are used to determine the delays of RF signals reaching the receiver, based on which the receiver's position can be determined. Such devices rely on correlation methods that incorporate numerous measuring approaches, including analysis of noisy signals. By using the autocorrelation, it is possible to determine the extent to which signal values at a certain point in time will affect the signal at a given point in the future. These methods are also used for detecting and measuring parameters of periodic signals against the background of random interference, for detecting gravitational waves, as well as in space radar technology, in communicating with distant probes or in radio astronomy. Correlators are also used in transmittance and delay time measurements, in the prediction and filtering theory, in identifying energy and noise sources and in determining system properties based on specific input and output data. Their main advantages include the ability to analyze low-power signals which are additionally affected by noise from atmospheric disturbances or receiving devices [8]. The correlation technique is a relatively simple and effective method of detecting such signals. Due to very low power signals and the large amount of data that need to be collected and processed, this technique has specific features in radio navigation that distinguish it from other applications.

In correlators, two measurement signals are subjected to cross-correlation. The cross-correlation function of two stationary random signals $x(t)$ and $y(t)$ can be expressed by:

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_0^T x(t)y^*(t+\tau)\mathrm{d}t, \tag{1}$$

where T – observation time and τ – time shift.

Such a function brings out the similarity between $x(t)$ and $y(t)$. However, if $x(t)$ and $y(t)$ are independent, then for each value of τ, function $R_{xy}(\tau)$ takes the value equal to zero, provided that $x(t)$ or $y(t)$ has the zero mean value. This enables the measurement of random signals occurring against the background of random independent disturbances. Let us now consider the cross-correlation function of two disturbed random signals. Suppose we have z_1(t) and $z_2(t)$ containing a random useful signal $x(t)$ [8]:

$$z_1(t) = x(t) + n_1(t), \tag{2}$$
$$z_2(t) = x(t) + n_2(t), \tag{3}$$

where $n_1(t)$ and $n_2(t)$ are random disturbances present in $z_1(t)$ and $z_2(t)$, respectively. If $x(t)$ and $n_1(t)$, $x(t)$ and $n_2(t)$, as well as $n_1(t)$ and $n_2(t)$ are independent, then cross-correlation function of signals $z_1(t)$ and $z_2(t)$ is:

$$R_{z_1 z_2}(\tau) = R_{xx}(\tau), \tag{4}$$

where $R_{xx}(\tau)$ is the autocorrelation function of the useful signal. Function $R_{z_1 z_2}(\tau)$ reaches, at zero, a maximum equal to the mean square value $\overline{x^2(t)}$ of the useful signal. The measuring procedure based on formulas (1)–(4) consists in determining the cross-correlation function between two versions of the disturbed signal which was obtained, for example, as a result of amplification in two different paths of the measuring system. In real applications, the cross-correlation of signals hidden in noise and delayed against each other is the most interesting feature. Assume the transmitted signal $x(t)$ is a stationary random with a zero mean value. Let the received signal be a stationary random signal $y(t)$ with a zero mean value such that:

$$y(t) = ax(t - \tau_0) + n(t), \tag{5}$$

where: a – attenuation coefficient, τ_0 – delay, $n(t)$ – independent noise (disturbance) with zero mean value. The cross-correlation function of signals $x(t)$ and $y(t)$ is:

$$R_{xy}(\tau) = aR_{xx}(\tau - \tau_0). \tag{6}$$

The peak value of $R_{xy}(\tau)$ occurs at $\tau = \tau_0$ and is $a\overline{x^2(t)}$. This problem can be extended to a situation where each of the two signals is delayed, attenuated and disturbed, where the disturbances $n_1(t)$ and $n_2(t)$ are independent of the useful signal $x(t)$ and of one another [8]:

$$z_1(t) = a_1 x(t - \tau_1) + n_1(t), \tag{7}$$
$$z_2(t) = a_2 x(t - \tau_2) + n_2(t). \tag{8}$$

In such a case the cross-correlation function takes the following form:

$$R_{z_1 z_2}(\tau) = a_1 a_2 R_{xx}[\tau - (\tau_2 - \tau_1)]. \tag{9}$$

The peak values of $R_{z_1 z_2}(\tau)$ occurs for $\tau_0 = \tau_2 - \tau_1$ and is $a_1 a_2 \overline{x^2(t)}$.

A correlator based on the correlation function (9) is capable of obtaining appropriate synchronization. Under real life conditions, the main correlation peak of the correlation function may take a different shape (it may be either more jagged or smoother). This depends primarily on signal strength, noise power, multipath propagation, or the sampling frequency value used in the receiver. In order to obtain the most accurate information about the delay time of the signal reaching the receiver, three correlators were analyzed:

– basic correlator [5],
– narrow correlator [6],
– double delta correlator [7].

Figure 1 shows the baseband signal processing diagram for a single channel with particular emphasis placed on the correlators. Integrate and dump (I&D) blocks accumulate the correlators' outputs and provide their in-phase (I) and quadrature (Q) components. The number of correlator pairs depends on the specific type of the correlator used in the analysis of the correlation function [9]:

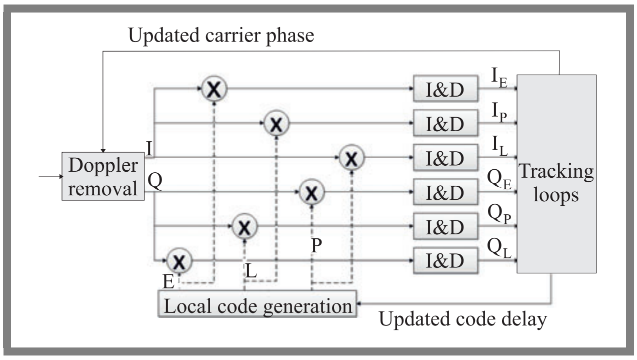

Fig. 1. Multicorrelators block diagram.

The basic correlator is the least complicated solution. Its output depends solely on the maximum sample value in main peak of the correlation function. In this solution, the correlator relies only on one locally generated code referred to as the prompt (P) replica [5]–[9]. When the code is correlated with the matched replica of itself, the correlation result reaches the maximum – meaning a high degree of autocorrelation. When the code is correlated with a non-aligned replica of itself – the correlation result is low. Real-time systems are very much prone to noise and the conditions always vary. As a consequence, the autocorrelation peak seems to change constantly, resulting in the need of adding continuous phase and frequency (Doppler) tracking to match the code replica.

A more in-depth analysis of the correlation function is performed by the narrow correlator. It uses the sample with the maximum value and a pair of adjacent samples. The correlator is based on three replicas of the local code: prompt (P), early (E) and late (L) [6]–[10]. The idea behind the narrow correlator is to reduce the spacing between E and L correlators, so that interference immunity and accuracy of ranging can be improved. In the narrow correlator the effect of multipath signals on the correlation function is least significant at the peak value. Thus, designing the correlators in the vicinity of the maximum value can effectively reduce the influence of multipath. Each of those correlators estimates the correlation function value for a different sequence offset. The P correlator calculates the value of the correlation function for the current phase of the sequence, while E and L correlators use the accelerated and delayed sequence with respect to the P correlator. Relative time shift of the sequence between successive correlators is usually half the duration of the sequence's elementary symbol (chip). The correlation function is shaped like a triangle within ± 1 chip around the maximum. The phases of the sequences in E, P and L correlators must lie within this triangle. If the values at either of the outputs of E or L correlators exceed the output of the P correlator, the phase of the locally produced sequence is updated (Fig. 2) [6].

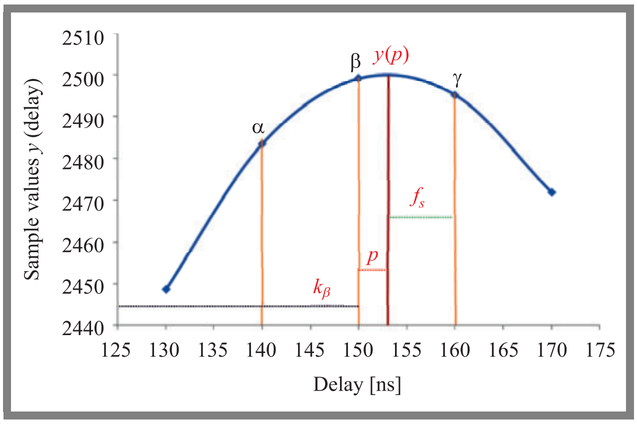

Fig. 2. Example of a correlation peak analyzed in a narrow correlator.

Having obtained the sample values of the correlation function at the output of the correlators, it is now possible to calculate the exact delay of the signals on the basis of the dependencies:

$$p = \frac{1}{2}\frac{\alpha - \gamma}{\alpha - 2\beta + \gamma} \cdot \frac{1}{f_s}, \tag{10}$$

$$k^* \triangleq k_\beta + p, \tag{11}$$

$$y(p) = \beta - \frac{1}{4}(\alpha - \gamma)p, \tag{12}$$

where: f_s – sampling frequency, p – calculated delay in relation to the maximum sample where the point with the highest value is located, α, β, γ – values of three consecutive samples of the correlation function, k_β – delay of the sample with the highest value, k^* – total delay of the point with the highest value, $y(p)$ – maximum value of the correlation function.

The double delta correlator is a more advanced solution. It uses two pairs of correlators (instead of one) in order to estimate signal delay with high compensation of multipath effects [7]–[11]. The correlator is based on five replicas of the local code: prompt (P), early 1 (E_1), late 1 (L_1) as well as early 2 (E_2) and late 2 (L_2). The double delta correlator introduces a correction term that can compensate variations of the rising and falling edges caused by multipath. E_1 and L_1 are one pair of output correlator with an earlier and later correlation peak (d_1 spacing), while E_2 and L_2 are the second output pair with an earlier and later correlation peak (d_2 spacing) [2]. The distance can be calculated as:

$$D = (E_1 - L_1) - \frac{1}{2}(E_2 - L_2). \tag{13}$$

Since the differences $E_1 - L_1$ and $E_2 - L_2$ can be interpreted as "narrow correlators", Eq. (13) can be:

$$D = \text{Narrow}\,(d_1) - \frac{1}{2}\text{Narrow}(d_2). \tag{14}$$

After the selection of the correlators, a full test campaign was performed on a π/4-QPSK signal generated by the VHF data exchange system (VDES) [13], [14] software simulator [15]. For testing purposes, a second signal was generated by shifting half of the sample from the first signal and by adding low-power noise. This helps to determine the effectiveness of the implemented correlators. On the receiving side, the correlation function was obtained. The sampling frequency of 10 MHz was used, where one sample relates to 30 m of distance.

Figure 3 shows the error in estimating correlation peak delay in relation to the exact value of the delay in which the peak is located. This error is expressed in meters – the result is the distance between the determined correlation peak and the real signal delay value. The graph has been presented as a function of the signal-to-noise-ratio (SNR) in order to verify the efficiency of correlators with respect to signal strength.

The worst results were observed for the basic correlator. Therefore, the correlation function based on just one correlation peak is not capable of providing reliable data. A lot of information is lost regarding the exact delay of the received signal. Hence, this method is not suitable for beacon services due to the potentially significant pseudo-range errors. On the other hand, narrow and double delta correlators with the second pair spacing $= 0.15$ chip allow for a more precise delay estimation, as shown in Fig. 3. Better immunity to multipath propagation phenomena and the larger spread of the correlation function around the maximum value peak makes the double delta correlator a proposal that is most suitable for navigation applications.

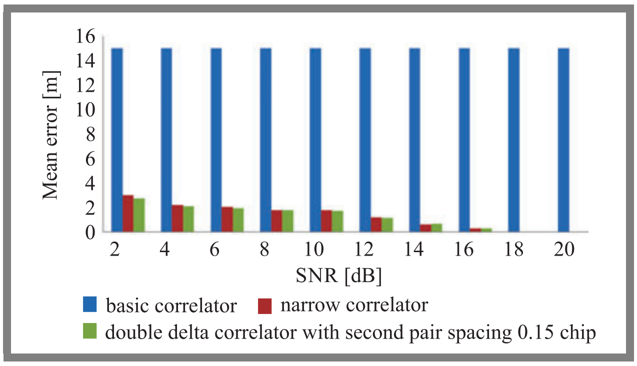

Fig. 3. Error of the determined correlation peak delay as a function of signal strength.

3. Multipath Propagation Impact on the Effectiveness of Correlators

The propagation conditions of a given radio channel depend on the properties of the wave itself, i.e. its length and polarization, as well as on the features of the environment in which the wave propagates. These include, for example, the topography and the type of the surface – radio waves propagate differently in areas covered with water, in forests, in urban or in open areas. Multipath transmission is a phenomenon that substantially impacts the signal in a given radio channel. The term "multipath" means that the signal – subjected to diffraction, refraction, scattering and reflection – reaches the receiver as a sum of many signals with different delays, phases, and amplitudes [16], [17]. Additionally, in the proximity of the receiver, each of the signal components is dispersed into other N components. If the receiver is in motion, the carrier frequency of each scattering component is shifted based on the Doppler effect.

The delay of multipath signals depends on the additional distance traveled by the reflected signal, with the said distance being longer than that of the direct path. During the measurement campaign organized by the National Institute of Telecommunications, the transmitter was installed in the Gdynia harbor, where, for the initial short-range measurements, the multipath effect was caused by nearby objects or buildings. On the other hand, for measurements at sea, the signal could also propagate to the receiver through reflections from maritime infrastructure, e.g. ships, ports or breakwaters. The presence of land (Hel Peninsula) along the line of sight also impacted the reflected signals reaching the receiver. The next important phenomenon is the tropospheric waveguide (duct) channel (Fig. 4) [18]. This is a specific type of radio propagation that tends to occur during periods of stable, anti-storm weather only.

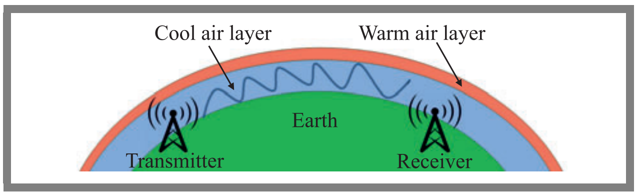

Fig. 4. Phenomenon of tropospheric ducts.

When instead of a normally expected drop, an RF signal encounters an increase in temperature at high altitudes (temperature inversion), the higher refractive index of the atmosphere will cause the signal to bend. Especially favorable conditions for the formation of tropospheric ducts occur mainly in the second half of the year [19]. Migrations of high-pressure areas observed in autumn, a large load of moisture in the atmosphere and the daily temperature fluctuations have a beneficial effect as well. Tropospheric ducts affect all radio frequencies, and signals amplified by this phenomenon are capable of reaching locations up to 1300 km away.

Radio waves that reach the receiver as multipath signals are superimposed (with a slight delay) on the main signal, which causes an abrupt unevenness in the shape of the correlation peak. If, on top of that, noise is also present along the propagation path, these distortions are even larger. Consequently, the calculation of the transmitter – receiver range can be difficult. The application of a correlator with an additional pair of correlators might be an efficient solution to that problem. Choosing appropriate spacing between additional correlators will cause the irregularities of the correlation peak to be covered along the entire range of the correlator's operation and, consequently, the impact of the multipath phenomenon will be significantly reduced and the quality of pseudo-range determination will be improved.

As part of the research concerning the effectiveness of the proposed method, a simulation was carried out in which the signals reaching the receiver were delayed relative to each other by such a value that the distorted correlation peak was located between the first and second pair of the correlators.

The reflected signal reached the receiver 25 ns later and with less power compared to the one received directly. In Fig. 5, the effectiveness of the analyzed types of correlators for the above simulation test is shown. Signals with $\pi/4$-QPSK modulation and a sampling frequency of 10 MHz were used.

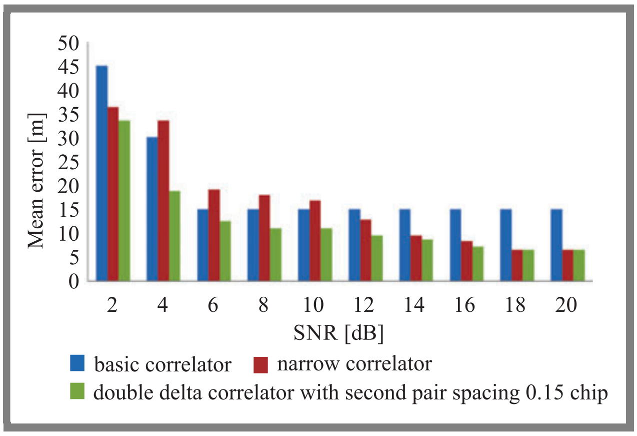

Fig. 5. Error of the correlation peak delay determined for the measurement scenario.

The results show that even for signals with a low SNR, the double delta correlator with a second pair spacing of 0.15 chip determines the delay of the transmitted signal more accurately compared to other solutions. It takes into account the distortion of the correlation peak due to the delay of the signal's replica. This means that it is an effective concept that can be used in a multipath environment to reduce the error in determining the time of arrival of a useful signal to the receiver.

4. Impact of Correlators on the Real R-mode Signal

In this section, correlators used under real conditions are presented and their influence on the accuracy of determining the receiver's position in maritime VHF channels is discussed. While many ships are equipped with sensors and assistance systems for positioning and navigation, collisions and groundings are still taking place. To reduce the risk of such incidents, a test stand was built under the R-Mode Baltic project for a ground-based positioning system called Ranging Mode (R-Mode) in the Baltic Sea [20]. This new system enables positioning even when Global Navigation Satellite Systems (GNSS) fail or are unavailable. The provision of reliable position, navigation and timing (PNT) information is key to safe navigation and is also essential to the development of new marine e-navigation applications. As part of this project, the effectiveness of selected correlators was evaluated as well.

During the measurement campaigns, the transmitting R-Mode station was located in the Gdynia harbor, while the receiving station was aboard the "Stena Baltica" ferry, with the exception of the stationary measurements when it was at a fixed location in the harbor of Jastarnia (as part of the R-Mode Baltic 2 project). All these prototype stations were developed by the authors of the article at the National Institute of Telecommunications.

Figure 6 presents a block diagram of the R-Mode demonstrator and the received signal processing path relied upon in order to obtain the most accurate receiver position. The purpose of operating and synchronizing the R-Mode VDES system has been described in detail in [4].

The R-mode system demonstrator presented in Fig. 6 consists of the following modules:

- RF module – which receives radio transmissions from the R-Mode stations and stores the I/Q samples,
- external rubidium oscillator,
- signal correlation application – which reads files with I/Q samples, correlates them and, thereafter having information about the coordinates of the stations, determines the pseudoranges,
- GNSS receiver – which provides the UTC time, GNSS position, speed, and track angle. The first two parameters are used for accuracy comparison purposes, while the other two are fed to the Kalman filter,
- R-Mode real-time positioning application – which determines the position based on the calculated pseudoranges to the R-Mode stations and additionally uses Kalman filtration. It also determines positioning errors with respect to GNSS position.

The deployment of this system made it possible research the correlators' effectiveness with respect to determining pseudoranges and position accuracy. The selection of the best correlator and its configuration will allow to obtain more accurate location results in the upcoming measurement campaign, in the final R-Mode Baltic 2 demonstration.

4.1. Spacing Between Correlator Pairs, Sampling Frequency and their Impact on Efficiency

As part of the research, a number of modifications were introduced to the selected transmission signal and sampling frequency, which gave us the opportunity to increase the accuracy of the determined range. The aspect of changing the sampling frequency is particularly important due to the ability of building the target VDES R-Mode receiver with the use of software-defined radio technology, using off-the-shelf components. A number of scenarios have been verified during the measurement campaigns performed in the point-to-point mode, i.e. with the VDES R-mode base station located in the Gdynia harbor and with remote access to the receiving station installed in the harbor of Jastarnia.

Initially, all tests and measurements were carried out at a sampling frequency of 200 MHz and using a correlation sequence which consisted solely of the Gold sequence with a length of 1877 symbols. This resulted in a large number of files with the recorded samples and, consequently, longer time of processing the signal by correlators. The subsequent tests were conducted with lower frequencies and various correlators, which allowed to choose the optimal combination presented in Table 1. There is a summary of the root mean square error (RMS) of the determined distance accuracy in relation to the actual distance between the transmitter in Gdynia and the receiver in Jastarnia. In the case of the double delta correlator, the second pair spacing was set to 0.15 chip.

Tab. 1. Determined RMS error for selected correlators depending on the sampling frequency.

Sampling frequency [MHz]	RMS for the basic correlator [m]	RMS for the narrow correlator [m]	RMS for the double delta correlator with the second pair spacing of 0.15 chip [m]
200	98.17	93.31	92.22
100	90.32	91.81	90.19
50	94.35	93.12	91.04
10	90.74	84.25	81.41
1	100.53	82.2	79.65

The values presented in Table 1 have been obtained for the specified sampling frequency and for the Gold sequence signal. The tests for each sampling frequency were performed on a group of 1,000 recorded files with samples. The basic correlator utilizing a single correlation peak produced the worst results. With each decrease in the sampling frequency, the error resulting from the inaccuracy of one sample was higher. Narrow and double delta correlators produced the best results, with the latter being slightly more accurate. The high power of the received signals impacted the shape of the correlation peak, making its slopes smoother and, therefore,

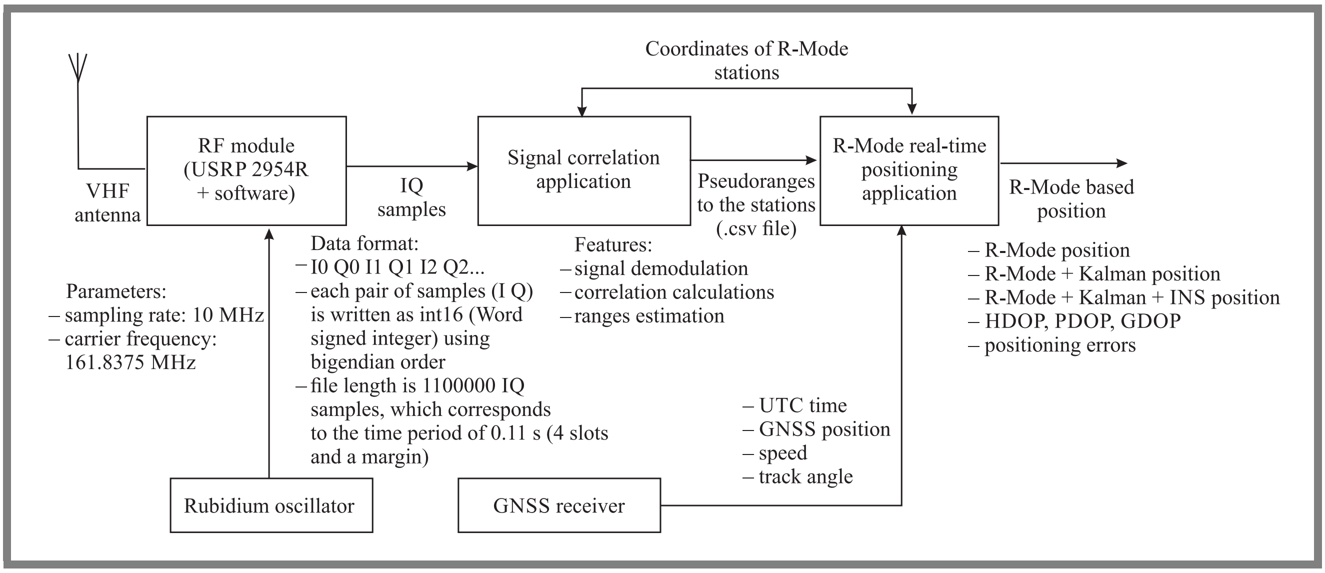

Fig. 6. Block diagram of the R-Mode positioning system demonstrator.

preventing the multicorrelators from exhibiting any major range determination deviations.

Next, we conducted the measurements, with varying transmitted signals. Each of the 4 emulated stations sent, once per second, a known ranging sequence as a part of the payload data [21]. In this case, the ranging sequence was a combination of two sequences (defined below) to customize the required performance based on two given scenarios:

– shorter distances between shore station and ship,
– longer distances between shore station and ship.

The first part of the ranging sequence was based on the $\pi/4$-QPSK modulation alphabet with alternated constellation points (the so-called "alternating sequence") [21]. The second part of the ranging sequence was a Gold code ($\pi/4$-QPSK modulation). The length of each sequence is based on the weighting factor γ. This means that the length of the entire correlation sequence (1877 symbols) is multiplied by the appropriate weighting factor associated with the sequence type. Both sequences were weighted and merged with each other. To be more precise – the alternating sequence was multiplied by a weighting factor of $\gamma = 0.7$ for short distances (higher SNR) and $\gamma = 0.3$ for larger distances (lower SNR). The Gold code was multiplied by a weighting factor of 0.3 for short distances and 0.7 otherwise. Figure 7 shows the principle of creating such a correlation sequence.

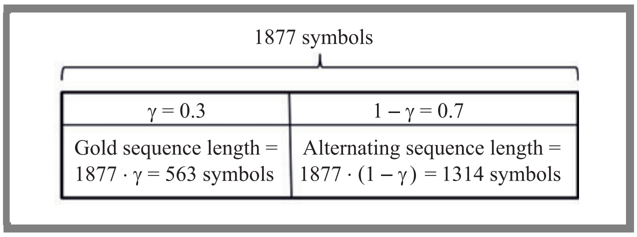

Fig. 7. A method of creating a correlation sequence consisting of two different types.

Table 2 shows the RMS values obtained for different γ coefficient and the correlator type for both transmitter and receiver side. The obtained RMS was also analyzed in the context of the correlation of signals with different values of γ.

Tab. 2. RMS determined for selected correlators depending on the γ coefficient.

Factor γ	**RMS for the based correlator [m]**	**RMS for the narrow correlator [m]**	**RMS for the double delta correlator [m]**
$\gamma = 0.7$ (TX) correlated with $\gamma = 0.7$ (RX)	48.15	18.67	17.58
$\gamma = 0.3$ (TX) correlated with $\gamma = 0.3$ (RX)	50.37	20.88	20.54
$\gamma = 0.7$ (TX) correlated with $\gamma = 0$ (RX)	84.22	45.12	44.68
$\gamma = 0.3$ (TX) correlated with $\gamma = 0$ (RX)	70.7	45.01	44.52

The combination of the Gold signal and the alternating sequence is characterized by very good correlation properties. It can be noticed that this sequence improved the ranging accuracy by approximately 50 m compared to the scenario in which the Gold sequence was used solo. That is a significant improvement compared to previous studies. Again, the double delta correlator offered the best results, slightly better than those of the narrow correlator. The solution presented in [24] is one of the methods for evaluating the effectiveness of the correlator. This approach involves the calculation of the S-curve, the code multipath envelope and the thermal noise. Here, the authors propose a single universal model for the double delta correlator used in the marine environment. In order to select the most effective configuration, tests were carried out on a number of signals transmitted and received under marine environment conditions. For the purpose of furthe research, the effectiveness of the double delta correlator was tested depending on the spacing width of the second pair of correlators (Fig. 8).

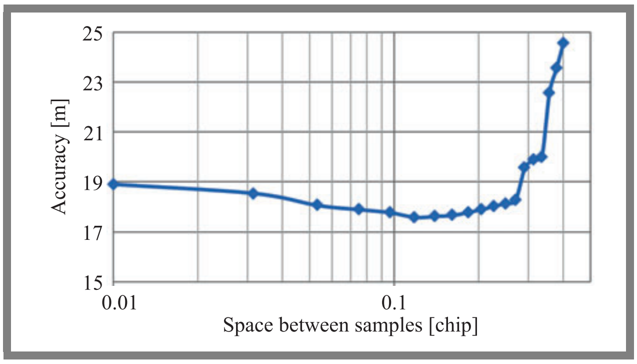

Fig. 8. Range estimation accuracy as a function of the spacing of the second pair of correlators in the double delta correlator.

Based on 1,000 received waveforms, the simulation of accuracy was performed by varying the spacing of the second pair of correlators. The most effective spacing width is approximately 0.1–0.2 symbol duration between the E_2 and L_2 correlators. Using a larger spacing is not rational, because samples that go beyond the correlation peak are taken into account and introduce additional errors.

To recapitulate, one may state that due to the possibility of analyzing a wider range of samples included in the correlation peak, double delta correlator is the best choice for large-scale applications in the marine environment. At the same time, the basic correlator was found not to be suitable for such purposes.

4.2. Correlator Type vs. Accuracy

After the selection of the best signal in terms of correlation properties, it was possible to research the selected correlators' of pseudo-range accuracy. In order to finally calculate the receiver's position using the calculated ranges, a measurement scenario was used where additional base stations were emulated[1]. The coordinates of the emulated stations were chosen in such a way so that their respective distances from the receiver in Jastarnia were exactly the same as the distance between Jastarnia and the "real" transmitting station in Gdynia (Fig. 9). It is also worth noting that tests were performed in the Gulf of Gdańsk, in a line-of-sight (LOS) marine environment.

During the tests, a 4-slot message was transmitted and was recognized by the receiver as four signals from the emulated transmitters. Using the collected data sent via the VHF marine channel, the RMS factor was determined for:

– basic correlator,
– narrow correlator,
– double delta correlator with the second pair spacing of 0.1 chip,

[1]Since only one "physical" base station exists so far (installed in the Gdynia harbor), the emulation of other stations was necessary. Otherwise, we would not be able to calculate the receiver's position, because at least three stations are required.

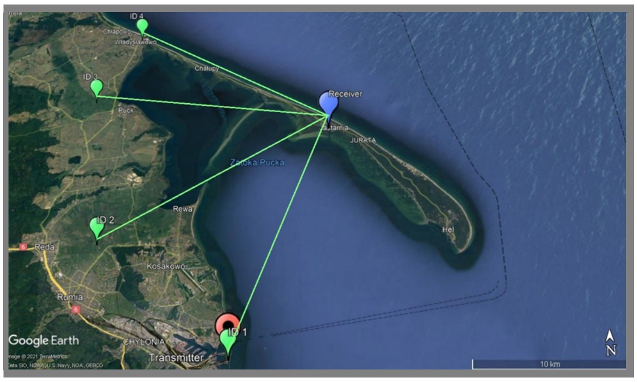

Fig. 9. Measurement scenario for four emulated broadcasting stations.

– double delta correlator with the second pair spacing of 0.2 chip.

All analyses, including digital signal processing, were carried out using a signal correlation application that was developed in-house.

The application includes various data processing modes: offline, useful for processing the collected data, or online, where samples are processed in real time, e.g. during the measurement campaign on a ship. The application allows to select the correlator to be used, with the possibility to set the required spacing in the double delta correlator. After measurements and signal processing, the accuracy of the determined distances of selected correlators was compared. Table 3 shows the RMS error values for each correlator based on approximately 3,000 measurements.

Tab. 3. RMS determined depending on the selected correlator.

		Emulated station			
	Correlator type	**ID 1**	**ID 2**	**ID 3**	**ID 4**
RMS [m]	Basic	31.798	33.816	38.122	33.771
	Narrow	24.228	24.324	24.352	24.264
	Double delta with second pair spacing of 0.2 chip	21.898	21.996	21.940	21.915
	Double delta with second pair spacing of 0.1 chip	21.580	21.675	21.593	21.597

As we can see, for the double delta correlator, the spread of the second pair of correlators translates into the achieved accuracy range. The narrow correlator generated narrow correlator generated less accurate results, which may be due to the fact that one pair of the correlators is not able to detect all the distortions that may have occurred in the correlation peak. Therefore, an additional pair of correlators allows to include all useful information contained in the correlation peak, which facilitates the determination of a more precise pseudo-range. With 0.2 chip spacing, however, the samples that were beyond the range of the correlation peak could potentially be included in the processing stage, which might have negatively impacted the results obtained. Uncorrelated noise that falls within the scope of the correlator analysis may also impair range determination outcomes. In this case, due to the high signal level, the such differences were low, but under less favorable conditions i.e. with a higher noise level and with the shape of the correlation function not being as smooth, the impact may by significant. With theoretical research and the simulations performed taken into consideration, the optimum value of spacing between the second pair of samples is 0.1 chip. This reduces the multipath phenomenon and the impact of uncorrelated, additional noise. The results obtained with the use of the basic correlator were characterized by the lowest level of accuracy, as stated in the previous analyses. This confirms that for a lower sampling frequency, the error that results from the accuracy of one sample is too large, which makes this type of correlator unsuitable for use in navigation services.

In the next step, data from each of the four correlators was transferred to the software application for determining the position based on the obtained pseudo-ranges (this specific tool also was created by the authors, in-house). Based on the conducted research, it will be possible to determine the manner in which the selection of the correlator affects the determination of the receiver's position in a marine VHF channel.

The application allows to determine the position using the time of arrival (TOA) method [22], based on the measured pseudo-ranges from reference stations with known locations. The application displays the coordinates of the calculated position, positioning error, DOP coefficients, the number of visible reference stations, the calculated receiver clock bias, speed and course [23]. The map shows the calculated and actual positions of the receiver and the reference stations.

For each correlator, three scenarios were assessed in order to take into consideration different numbers of reference stations and varying geometries. Table 4 lists these scenarios along with the information on the number of reference stations used, HDOP values, with ID numbers referring to Fig. 9, while Fig. 10 visualizes the specific scenarios. The reference stations are marked in green, while the receiver is marked in blue. In each case, the position was calculated 2,741 times for each correlator. The same set of recorded samples was used as input for each of the correlators. This allows to assess the dependence of the positioning accuracy on the correlator applied, regardless of the noise level present in the channel.

Tab. 4. Positioning scenarios.

	Number of stations	HDOP	Emulated stations ID
Scenario 1	4	3.392	1, 2, 3, 4
Scenario 2	3	3.731	1, 2, 4
Scenario 3	3	9.199	2, 3, 4

For a clear visualization of the obtained results, Fig. 11 shows the detailed data for scenario 2 only, while Table 5 lists the RMS values obtained for each tested correlator for all scenarios.

The largest difference in terms of position determination accuracy was observed between the basic correlator and

Fig. 10. Position reference stations used in the campaign: a) scenario 1 – four stations and good geometry, b) scenario 2 – three stations and good geometry, c) scenario 3 – three stations and poor geometry.

the remaining types. Regardless of the number of stations and the HDOP coefficient, all three correlators (narrow and two variants of double delta) performed significantly better than the basic correlator. As expected, the positioning error value increased for each of the correlators if the geometry of the reference stations deteriorated and if their number was decreasing.

Simultaneously, no significant differences in terms of position determination accuracy were observed between these three correlators. In each case, the RMS values were sim-

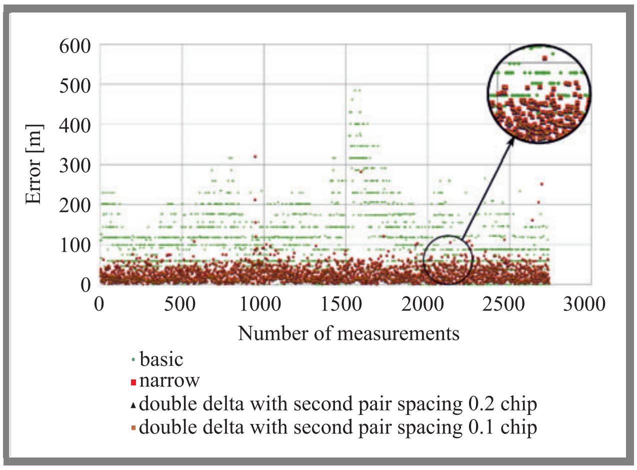

Fig. 11. TOA positioning error for scenario 2 for: basic correlator (green), narrow correlator (red), double delta correlator with second pair spacing of 0.1 chip (blue), and double delta correlator with second pair spacing of 0.2 chip (orange).

Tab. 5. Determined RMS of positioning error.

Correlator	RMS [m]		
	Scenario 1	Scenario 2	Scenario 3
Basic	130.443	133.053	271.791
Narrow	30.146	32.807	80.564
Double delta with second pair spacing of 0.2 chip	30.135	32.795	80.537
Double delta with second pair spacing of 0.1 chip	30.135	32.975	80.537

ilar. Nevertheless, since the differences in the accuracy of pseudo-range determination were small, the lack of ability to achieve an improvement in positioning accuracy may result from the emulation, because only one real reference station was used in the campaign. We can assume that if the reference signals from each of the stations are completely independent of each other (e.g. different propagation paths), the benefit of using a double delta correlator will become noticeable.

4.3. Type of the Correlator and the Accuracy of the Determined Range in the R-mode Campaign

Paper [4] presents a detailed analysis of the results obtained by the authors during the measurement campaign with the use of the VDES system and the basic correlator. As follow up, another measurement campaign was performed in June 2020 on the Gdynia-Karlskrona route, with a VHF transmitting antenna located in the Gdynia harbor and the receiver placed aboard a Stena Line ferry.

Figure 12 shows a graph presenting the ranging errors observed during the measurements. The red line shows the distance between the receiver and the transmitter. The blue points represent the error resulting from the difference between the correlator's output and the reference measurement (by EGNOS + GNSS). For better visualization, the chart is divided into three parts in which the measurements took place: LOS – i.e. the part of the measurements carried out in the Gdańsk Bay, mixed sea + land path – i.e. measurements that took place when the ship was behind the Hel Peninsula and measurements in the NLOS environment – i.e. with the ship outside the 50 km zone from the transmitter and out at sea.

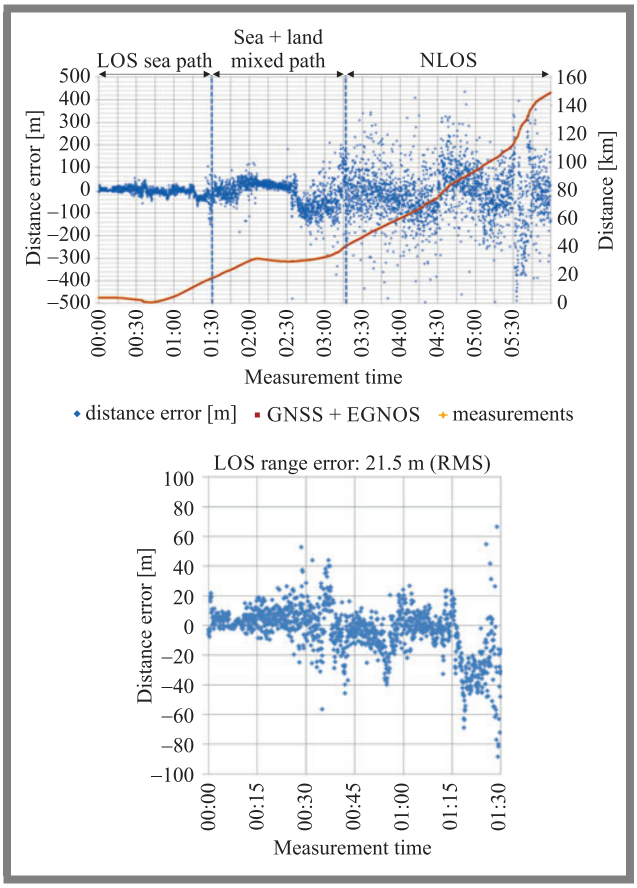

Fig. 12. Ranging errors in the VDES 2020 measurement campaign for the double delta correlator with second pair spacing of 0.1 chip.

Due to some modifications applied to the hardware configuration in the second measurement campaign, it is not possible to clearly assess the degree to which the double delta correlator contributed to the improvement of the calculated RMS. To be more specific, compared to the first VDES measurement campaign, the following changes were made, which could have an impact on the final results:

– using VDES signal without Hann window – to improve transmitted signal power,
– setup transmission without physical VHF filter – to improve transmitted signal power,
– using amplifier with higher output power levels,
– incorporating different LNA and filter configuration on receiver side.

For example, in the case of the LOS environment, an RMS of 20 m was obtained with the double delta, whereas in the previous measurement campaign these values were over 30 m. Figure 13 shows a map presenting the measurement campaign's route with the applied errors.

For short distances, it can be seen that the ranges provided by GNSS almost coincide with those calculated by the sig-

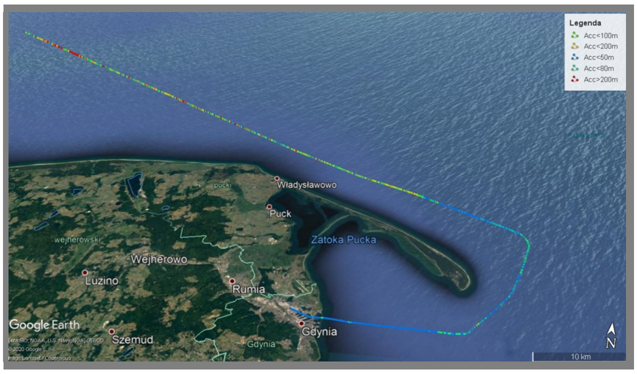

Fig. 13. Map of the 2020 Gdynia – Karlskrona measurement campaign.

nal correlation application. Such results allow for calculation of the exact position of the receiving station. This is very important, especially in ports where accurate, precise navigation is critical. For long distances (over 66 km) the error of positioning is approximately 180 m. This is a very good result compared to previous measurement campaigns. It should also be added that at a distance of approximately 120 km, these accuracies were in the order of 300 meters, which is still a satisfactory value. The RMS curve for the basic and double delta correlator for the second VDES measurement campaign is shown in Fig. 14.

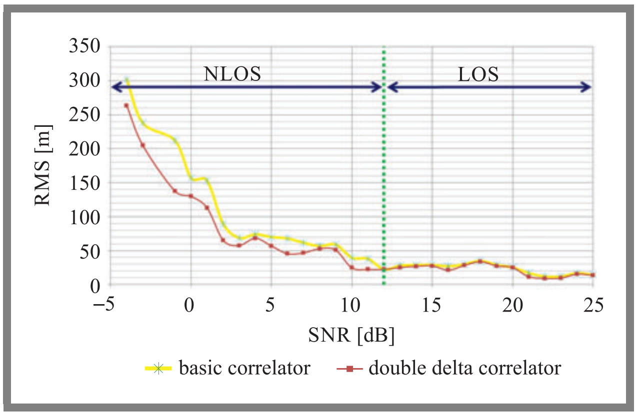

Fig. 14. RMS curve for second measurement campaign.

In another step, a comparison of the efficiency of basic and double delta correlators in the second VDES measurement campaign was researched using samples recorded at a sampling frequency of 200 MHz. The difference between the obtained RMS is presented in Fig. 15.

For the LOS zone, the differences in the calculated distances are imperceptible, due to the high sampling frequency. In contrast, for NLOS, the double delta correlator has a higher RMS value resulting from multipath propagation. e.g. in the area behind the Hel Peninsula, where there are many obstacles. In relation to the basic correlator, this improves the determination of distances, allowing to achieve accuracy of up to 30 m. Future plans assume that four transmitting stations will be set up in the Baltic Sea. Then, it will be possible to fully verify the effectiveness of the double delta correlator in determining the receiver's position.

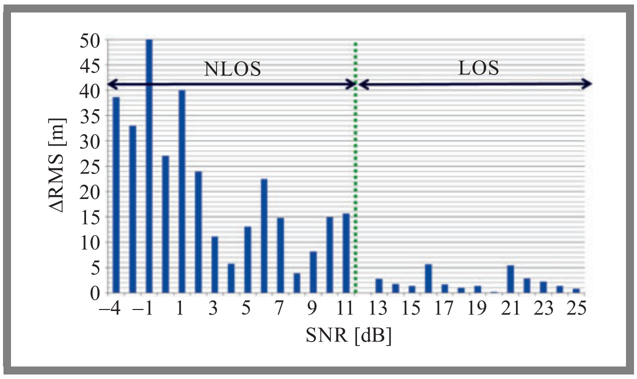

Fig. 15. Difference of the RMS between the double delta and the basic correlators.

5. Long-term Stationary Measurements Using a Best Correlator

As a follow up to the R-Mode Baltic project (ended on 03/31/2021), the authors continued their research within the framework of the Ranging Mode Baltic Sea test bed evaluation project (R-Mode Baltic 2). The main goal of the R-Mode Baltic 2 project is a long-term evaluation of the R-Mode Baltic test stand and additional testing of new R-Mode concepts. To achieve that goal, the project consortium will increase the monitoring capabilities of the R-Mode Baltic test stand and equip vessels with R-Mode-ready receivers and marine applications from the R-Mode Baltic project. This expanded network of static and dynamic monitoring stations will be used for extensive R-Mode performance studies over a project period of nine months. The results are essential for the further development of the proposed solution and will facilitate its ultimate transformation into a reliable and internationally recognized backup maritime navigation system.

Such an approach allows to study the features of the double delta correlator and check its effectiveness and stability by means of long-term measurements conducted in various weather conditions. The preliminary results that were obtained from the 11-day campaign are presented here. The transmitter was installed in the Gdynia harbor. The EIRP power was 25 W and the antenna height was 28 m above sea level. The receiver was located in the harbor of Jastarnia – approx. 20 km away, with its antenna positioned at 17 m above sea level. The transmission between the stations took place under LOS conditions and entirely over a sea-covered area. Both stations were equipped with rubidium oscillators. The receiver was also equipped with a low noise amplifier (LNA) (noise figure of 0.6 dB) and a VHF bandpass 3 dB filter. Fig. 16 shows the results obtained at the beginning of the measurements.

The RMS is presented for two cases: when the mean error from the measurements was subtracted every day and when it was subtracted just once on the first day of the campaign. From Fig 16, the potential accumulation of the mean error could be observed, which confirms the stability of the measurements. The graph indicates the atmospheric factors (wind direction,

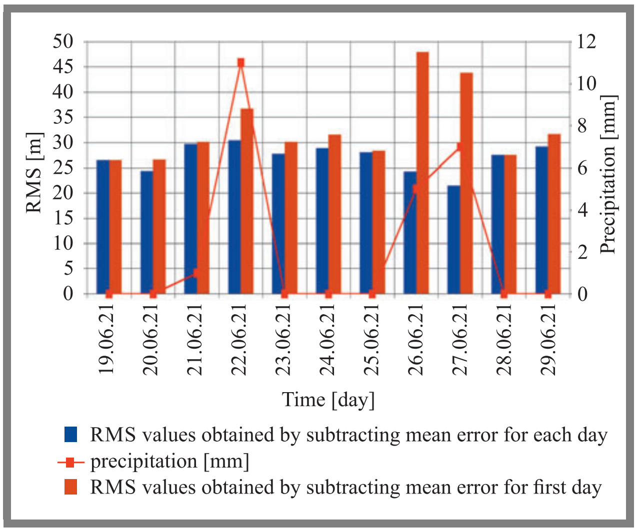

Fig. 16. Analysis of the observed RMS depending on the weather conditions.

precipitation) that could affect the results. The phenomenon of ducts, introduced in Section 3, can be observed in Fig. 17.

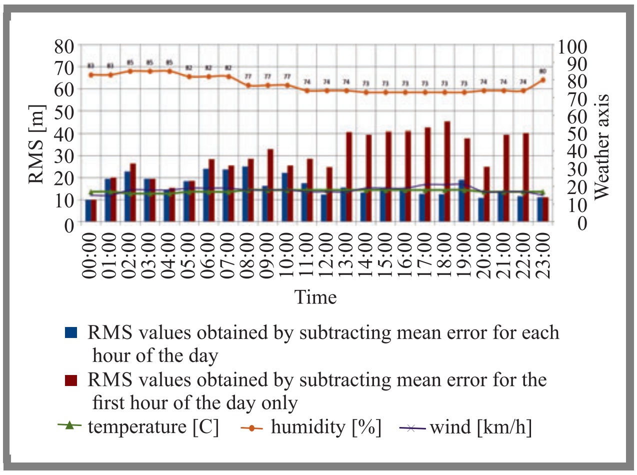

Fig. 17. The phenomenon of radio ducts visible during the measurements conducted on 26th June 2021.

Additionally, Fig. 16 presents the impact of rain on signal attenuation resulting in the ducts phenomenon, which shows a clear temporary increase in the accumulated RMS. One may also see, however, that it did not affect the RMS values obtained by subtracting the mean error for each hour. By the end of the project, it will be possible to collect a large amount of data, thanks to which it will be possible to analyze the measurements obtained from the double delta correlator in terms of RMS changes depending on the season of the year or time of the day. In addition, the National Institute of Telecommunications is preparing a research focusing on time and frequency synchronization of the R-Mode system with optical fibers. Thanks to such an approach, an opportunity would arise to compare stationary measurements using a rubidium oscillator with measurements obtained in a scenario in which synchronization is achieved by means of a fiber optic solution. This would ensure the elimination of time error sources, thus greatly enhancing the quality of data.

6. Conclusions

It is the double delta correlator (with the second pair spacing = 0.1 chip), selected for signal propagation on the VHF channel, that offers the highest level of accuracy in terms of range and position determination in the marine environment. The analysis conducted has shown the sheer number of factors that influence the results of the studied correlators. These included multipath propagation, sampling frequency, selection of signal modulation and its structure, spacing between pairs of correlators, and weather conditions prevailing during the measurements.

The research campaign was divided into a theoretical phase, followed by a series of simulation tests and concluded with measurement campaigns relying on the VDES R-Mode system demonstrator. The double delta correlator displayed the best properties as far as the analysis of the correlation function was concerned. For signals received along the Gdynia-Jastarnia route (with the distance equaling approx. 20 km), where the SNR of the received signal was about 2 dB, the accuracy of the calculated distance was 21.58 m. The results obtained with the use of the double delta correlator, with the spread of the second pair of samples equaling 0.1 chip, was 30.135 m. Because the measurements were static with an almost constant SNR value, the differences in accuracy between the correlator with sample spacing of 0.1 and 0.2 were hardly visible and amounted to approx. 0.3 m. This is due to the fact that positioning errors result from the superposition of distance errors. We assume that the advantages resulting from applying the double delta correlator with the spread of the second pair of samples $= 0.1$ chip will be noticeable in real conditions, i.e. for different propagation paths and for different SNR values. However, confirmation of this assumptions requires that another measurement campaign be conducted. Furthermore, during the measurements, the phenomenon of tropospheric ducts could be observed. The double delta correlator showed an RMS that was increased even by 20 m compared with the measurements performed with the duct phenomenon not being present. The software implemented by the authors allowed to conduct an in-depth analysis. It included an application for the correlation of signals, determining pseudo-ranges, and software determining positions based on distance measurements from several R-Mode reference stations using the TOA method in LOS and NLOS environments.

7. Future Work

The selected optimal correlator will be used primarily in the next measurement campaign, the purpose of which will be to demonstrate the capability of the VDES R-Mode system and its usefulness for the PNT sector in marine conditions. The received data will be processed on the survey ship in real time and the highest achievable level of accuracy will be required. These tests will show the effectiveness of the selected double delta correlator in marine navigation applications. The data that has been already collected with the use of the Gdynia–Jastarnia setup will allows to check the effectiveness of the double delta correlator, but also to evaluate the operation of the entire VDES R-Mode positioning system in the long term. It will also allow to assess the dependence of the calculated RMS on the various weather conditions. Long term plans assume that the time and reference clock will be synchronized with the use of optical fibers connecting the transmitter with a common central time standard. This will allow to separate the system from sources of time errors and will help compare the positioning errors with the results obtained in the course of previous campaigns, where time synchronization was based on rubidium oscillators. All of these factors will help improve the R-Mode test bench and eventually transform it into the most accurate positioning and navigation system that will provide reliable data, even in a scenario in which the GNSS is not available. These activities contribute to increasing the level of protection and safety in the Baltic Sea by improving the technical capabilities of the broadly understood maritime sector.

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