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VDE-TER R-Mode Measurements and Analysis

# Summary

The following paper focuses on measuring various VDE signals and analysing R-Mode for different maritime scenarios.   
As GNSS signals are not always reliable and subject to jamming and spoofing, it is desired to have alternative means of maritime navigation. One approach for that is to equip communication systems on the shore with the option to transmit ranging signals (R-Mode), which vessels can use to determine their position. The VHF Data Exchange System (VDES), which is currently in standardization, can be utilized for this R-Mode application. For that purpose, a ranging signal has to be chosen that will provide good time of arrival estimates. By using the Cramér-Rao-Bound (CRB) and the Ziv-Zakai lower Bound (ZZB), we investigate different options for this ranging signal. We find that optimising for high bandwidth is desirable at high Signal to Noise Ratios (SNR), while optimising for low autocorrelation side lobes is desirable at low SNRs. By utilizing a combination of both options, we are able to find a suitable ranging signal for any given noise level.

## Purpose of the document

The paper intends to document the dynamic progress of developing R-Mode in the VHF band to prepare R-Mode for the upcoming revision of VDE-TER as part IALA G1139 and ITU-R M.2092-1.

## Related documents

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3. Q. Hu, Y. Jiang, J. Zhang, X. Sun and S. Zhang, “Development of an Automatic Identification System Autonomous Positioning System”, doi:10.3390/s151128574
4. S. Gewies, A. Dammann, R. Ziebold, J. Bäckstedt, K. Bronk, B. Wereszko, C. RieckP. Gustafson, C. Eliassen, M. Hoppe, W. Tycholiz (2018) R-Mode Testbed in the Baltic Sea. In: 19th IALA Conference 2018. 19th IALA Conference 2018, Incheon, South-Korea
5. J. Šafár, A. Grant, P. Williams and N. Ward, “Performance Bounds for VDES R-mode”, THE JOURNAL OF NAVIGATION, doii:10.1017/S0373463319000559
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8. U.S. Executive Order on Strengthening National Resilience through Responsible use of PNT https://www.whitehouse.gov/presidential-actions/executive-order-strengthening-national-resilience-responsible-use-positioning-navigation-timing-services
9. IALA R-Mode Workshop, Saint-Germain-en-Laye, September 2019
10. "Stakeholder Requirements For R-Mode", September 6 2019 presented at [9]

# Background

Current position information of vessels is relevant for safety and navigation applications. The Automatic Identification System (AIS) utilizes the information by broadcasting it together with heading, current velocity and more detailed information about the vessel itself.

The Global Navigation Satellite Systems (GNSSs) are the primary systems determining positions and its derivatives, such as velocity and heading. Recent events have shown that the satellite based systems are a single point of failure to determine the location. Therefore, it is desirable to have an additional implementation method of localization for monitoring the integrity of the GNSS and as well for navigation with reduced accuracy in case the satellite system fails. Such failure could be a solar storm which primarily affects space based systems, but could also be a local event in case of intentional jamming or even spoofing. The demand for a resilient positioning, navigation and timing solution is reflected by the R-Mode Baltic Project which investigates in the MF and in the VHF band additional ranging sequences. Further, recently the U.S. white house announced an executive order to strengthen the resilience of existing PNT solutions by providing the required steps [8].

Therefore, the International Association of Lighthouse Authorities (IALA) discusses the need of a contingency or even backup system for GNSS. A backup system requires fulfilling similar performance requirements as the primary system, such as GPS. A contingency system has weaker performance requirements, especially the holdover time until the clock of the transmitters causes significant errors in determining the position. However, system requirements shall assure a safe travel of a vessel back to the harbour in case of a significant GNSS failure.

The proposal for such an alternative system is termed **Ranging-Mode** (R-Mode). R-Mode intends to utilize the shore based communication infrastructure, like Automatic Identification System (AIS) or VDE base stations [2] [9] with the existing housing infrastructure. Stakeholder requirements for R-Mode were discussed during [9] and documented in [10].

The accuracy of ranges between the base station on land and the vessel at sea, measured by means on the received radio signal, depends on the utilized bandwidth and of the received signal power versus the power of other noise sources.

The AIS system offers *25* kHz of bandwidth and uses a GMSK modulated signal. Currently, IALA defines the VHF data exchange system (VDES) that comprises of the existing AIS, and an additional application message service (ASM) and the VHF data exchange (VDE). VDE has a terrestrial and a satellite component. The terrestrial component offers in the up- and downlink 100 kHz each.

AIS and VDE have already been investigated regarding R-Mode. The authors in [3] investigate the AIS system and its existing infrastructure and how to use for ranging and positioning. A key aspect that was stressed is the impact of the geometric dilution of precision and is limited to coastal areas. It was concluded that because of cost issues that a precise clock on the vessel seems unfeasible. An additional secondary factor was applied which increased the performance by an order of magnitude. However, the proposed site requirements are challenging to cope with the limited bandwidth of AIS to achieve *10* m.

The concept of using AIS as a ranging source was further proposed and addressed in [4]. The concept described the application of R-Mode in the Baltic Sea which covers relevant areas with a favourable geometric dilution of precision (GDOP). The concept is expanded further to the MF frequency band to increase the coverage of individual transmitter sites. Therefore, a joint R-Mode system concept utilizing AIS and MF was proposed. The MF-R-Mode has significant advantages by using only limited infrastructure as the propagation conditions during day time can reach several hundred km. However, during the night the sky wave effect causes severe multipath errors which prohibit a night-time use of MF-R-Mode.

In [5] the authors derived for AIS, ASM and VDE the Cramér-Rao bounds considering the different bandwidths of all three systems. They also considered five successive time slots in AIS and three successive time slots for ASM to improve the ranging performance and to compete with the terrestrial 100 kHz VDE system. The authors applied the ITU-R P.1546-5 channel model with distinct antenna heights to provide realistic assessments about the expected range. The authors concluded that the focus should be on VDE because of the superior performance results.

In this paper we follow the path to apply VDE for ranging, and in addition shape the waveform by a dedicated sequence to improve the performance and utilize the existing bandwidth further. This follows the concept of [6] that optimized the Cramér-Rao bound to improve the ranging performance.

# VHF Data Exchange System (VDES)

The VHF Data Exchange System (VDES), which is currently in standardization, comprises three different systems: AIS, ASM and VDE link. The VDE link system is expected to be a general purpose data channel for shore to ship and ship to ship communication offering a higher data rate than existing terrestrial maritime radio applications. It differs from the existing Automatic Identification system in several key aspects. The most important difference that it has a four times higher bandwidth of 100kHz available for data transmission.   
Furthermore, VDE link utilizes a linear modulation scheme instead of Gaussian Minimum Shift Keying (GMSK), and introduces forward error correction. Compared to GMSK modulation, linear modulation has the drawback that it is not a constant amplitude modulation scheme. Therefore it has a significantly higher Peak to Average Power Ratio (PAPR), which means that amplifiers for the signal will have to be designed for a higher peak power when the same average transmit power should be achieved. As this additional expense is a concern, VDE implements the -QPSK symbol mapping, which mitigates this effect to some degree as consecutive symbols can never be on opposite positions of the constellation. In order to determine the range between the vessel and a land based VDE base station, the base station needs to transmit a known signal whose time of arrival can be accurately estimated at the receiver. As the VDE system is intended to be used, these signals should conform to the VDES physical layer, so they can be used without disrupting equipment which is unprepared for their existence.

# Theoretical Bounds

To assess the ranging performance of the signals under investigation, we consider theoretical lower bounds on time of arrival estimation errors.

Under the assumption of a received signal where (s(t) is the transmitted signal, and (w(t) is additive white Gaussian noise with a noise power spectral density . We are interested in estimating the parameter which is the delay between the transmission of the signal and its arrival at the receiver. Together with the propagation speed *c* of the signal, an estimation of the distance between transmitter and receiver can then be easily calculated from the estimation . The first bound which we consider is the Cramér-Rao-Bound (CRB). For the given problem of estimating the time of arrival of a known signal, the CRB states

Where the total energy of the transmitted signal is, is the noise power density, and is a measure of the mean square bandwidth of the signal.

For a given signal, the CRB is often a fairly good indicator for achievable estimation performance at sufficiently high Signal to Noise Ratios (SNR), however, the achievable estimation performance is usually much lower than what is indicated by the CRB. Up to a certain SNR value, no useable estimation is possible. This is known as the threshold effect. To take this phenomenon into account, the Ziv-Zakai Bound (ZZB) is considered in addition to the Cramér-Rao-Bound. Unlike the CRB, the ZZB can predict this phenomenon to some degree. The ZZB is based on a comparison of the estimation problem with a detection problem. The ZZB for time of arrival estimation is given by the formula [7]:

where is uniformly distributed between and is the probability of an optimal detector making an error in the decision between the signal and and is based on the Q-function that uses the normalized autocorrelation function of is .

As the CRB states, the mean square bandwidth is the defining factor for good time of arrival estimation. Therefore, it is desirable to maximise this parameter. The signal with the highest possible mean square bandwidth for a given amount of spectrum available would be a continuous wave signal. In frequency domain, this would correspond to two Dirac impulses at the edges of the available channel. Such a signal has a mean square bandwidth of, where is the frequency of the continuous wave signal. For a total available bandwidth of *B* the maximum frequency that can be chosen is. The VDE communication system utilizes a linear single carrier modulation scheme. Thus the transmitted signal *s(t)* can be described by where is the transmitted data symbol and is the root raised cosine pulse shape with being the duration of one data symbol.

To calculate the ZZB, we use with the signal energy . As we are using a PSK signal for all possible symbols, and g(t) is normalised and . The autocorrelation of the pulse shape is a root raised cosine pulse, its autocorrelation is a raised cosine pulse.

This form of the signals normalized autocorrelation can be evaluated numerically without having to perform numerical integration. The resulting ZZB according depends on the transmitted data symbols and the parameters of the root raised cosine pulse. As the pulse parameters are given by the VDES standard to be a roll of factor of and symbol duration of, they cannot be changed. To influence the ranging performance, the data symbols have to be used.

VDES utilizes and an alternating between opposite constellation points is not possible. To achieve a high mean square bandwidth under the constraints of the modulation, it is possible to approximate this alternating pattern. This approximated alternating data sequence consists of multiple repetitions of the constellation points and is visualized in Figure 1.

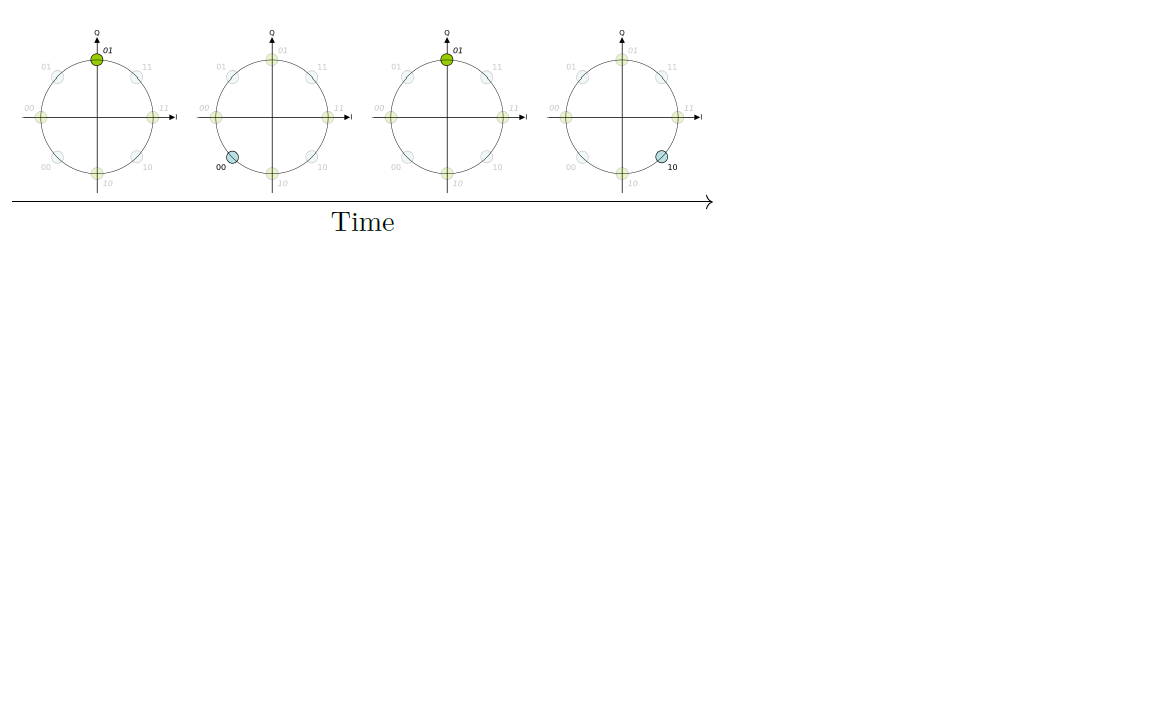


Figure : Generating alternating sequence according to the VDE standard.

While the mean square bandwidth determines the ranging performance at good signal to noise ratios, the performance at lower signal to noise ratios is determined by the side lobes of the signals autocorrelation level, as it is likely that a side lobe is mistaken for the main correlation peak. The previously mentioned approximated alternating signal, however, has higher correlation side lobes, as the signal shifted by one period strongly correlates with the original signal. To reduce the level of side lobes in the signals autocorrelation function, a pseudo-noise sequence can be chosen for its good autocorrelation properties. The pseudo-noise sequences however a lower mean square bandwidth has, and therefore performs worse at higher signal to noise ratios than the previously described signal. The normalized autocorrelation for both types of signal are being shown. It can be seen that the pseudo-noise signal has much lower side lobes, and thus a much lower side lobes that could be confused for the main lobe at lower SNRs. But the approximated alternating signal has a narrower correlation peak, which can be estimated with higher accuracy at good SNRs.

To find a compromise between these two design goals, a combination of the two signals can be used. The most straightforward way of combining both signals would consist of a linear combination, such that. An alternative approach with lower PAPR would be to concatenate both sequences, such that for for the alternating sequence and otherwise. The spectrum of the joint sequences is shown in Figure 2.

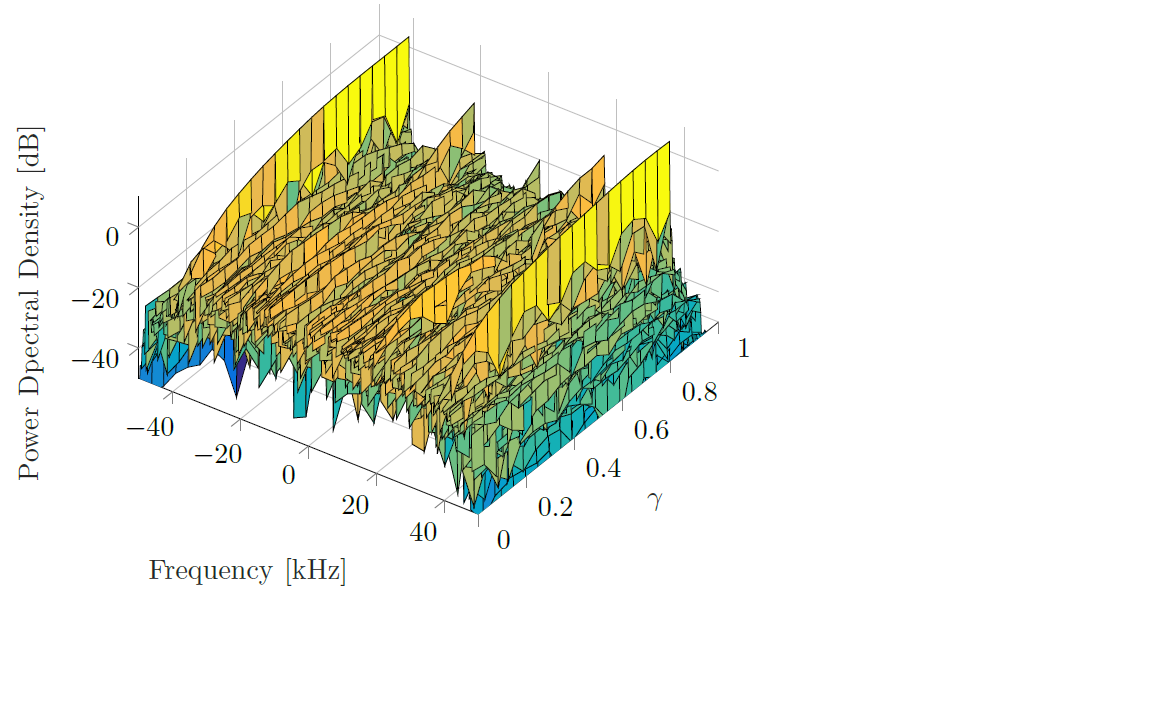


Figure : Power spectral density of the signal for different values of .

To evaluate the suitability of this concatenated signal for ranging, the ZZB was evaluated for multiple values of . The resulting bounds on the square root of the minimum ranging variance for different . Therefore, for low SNRs, the bound converges to a value equivalent to estimating the time of arrival in the a-priori interval which corresponds to about 75 km. Figure 3 shows for high SNRs that the curves with a high value of allow a higher accuracy than those with a lower one, while at low SNRs lower values of give better results. Thus, for optimal performance, the parameter has to be chosen depending on the SNR of the signal at the receiver. Figure 4 shows the optimal value depending on the given SNR.

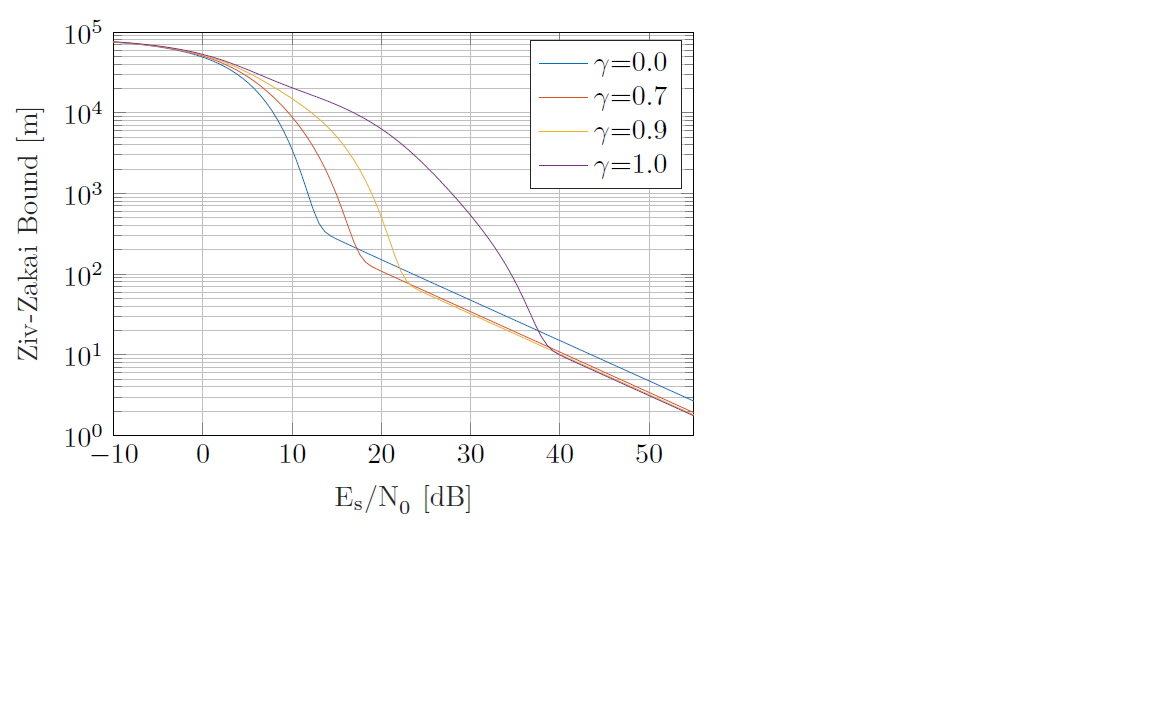


Figure : Ziv-Zakai bounds for different values of

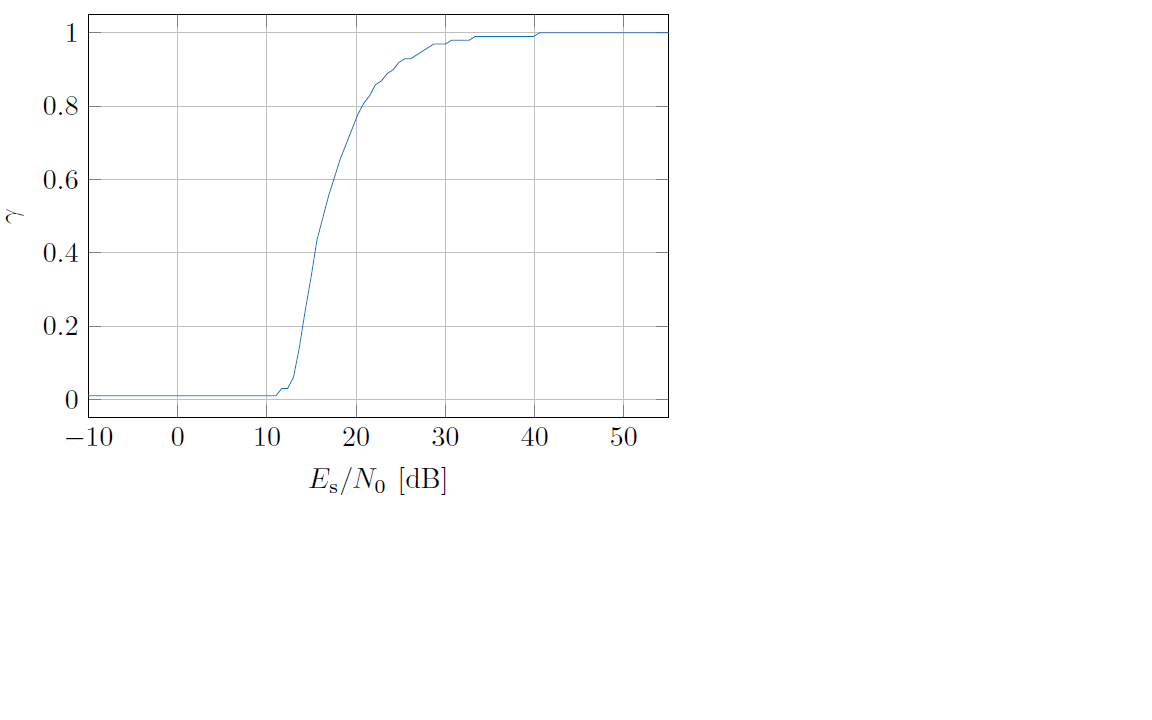


Figure : Optimal values of for a given .

# Measurements

To validate the results obtained by considering estimator bounds, a measurement campaign was performed. The measurement setup consisted of a transmitter on the land side and a receiver on a vessel on the lake. Both sides utilised Software Defined Radio (SDR) hardware to transmit or receive the different signals to be evaluated. The location of the measurement was the Lake Ammer in Germany and Figure 6 shows the route that we used to measure the different R-Mode signals.

In addition to the same SDR hardware, as used on the receiver side, the TX side setup also included a power amplifier to allow transmission of the signal with a power of 1 W. A higher power was not approved by the regulatory agency. The transmitter antenna was mounted on top of a car; however, the car remained stationary during the entire measurement. In order to allow a fair comparison between the different ranging signals, they should be transmitted in close temporal proximity, such that the channel conditions are comparable. In our measurement, this was done by transmitting each signal of interest in succession with a guard interval in between.

Each block of transmitted signals was sent at the full second mark. Thus, the update rate for the measured range was 1 Hz. A reference Pulse-Per-Second (PPS) for precise timing of the transmitted signal was provided by a GPS disciplined oscillator (GPSDO) module in the SDR hardware. The carrier frequency was also derived by a 10 MHz signal provided by the GPSDO. On the receiver side, the same type of SDR and GPSDO was utilized. This way, both sides had access to a common GNSS based time base. While the purpose of R-mode is to be independent of satellite based systems, the purpose of this measurement was only to evaluate the possible ranging signals. After the reception of each signal block, it was tagged with a time stamp and written to disk in the form of I/Q baseband samples. As a reference for the true range between transmitter and receiver, both sides were equipped with GNSS receivers. Evaluation of the recorded signals was done in a post-processing step. As each signal was tagged with the time of reception, the data could be associated with the appropriate position as recorded by the GNSS equipment. The true range could then be calculated. To determine the estimated range from the measurements, first the appropriate time slot within the one second block of recorded samples was cut out. Then a coarse synchronisation was performed by determining the maximum of the cross correlation of the received signal with the transmitted signal.

As a sampling frequency was used, the result of this estimation is quantized to steps of , which corresponds to a range of 489.5 m. This is obviously unsatisfactory for the purpose of a ranging system. Therefore, an additional fine estimation step is necessary. As the fine synchronisation needs to determine the time of arrival of the signal with a better accuracy than the sampling time, it is necessary to interpolate between the recorded samples. This can be achieved by the means of a Discrete Fourier Transform (DFT). A cyclic shift in time domain corresponds to a multiplication with the complex exponential function in frequency domain. Thus a time shift can be achieved by multiplying the frequency domain representation of a sufficiently zero padded signal with an exponential function, and transforming the signal back to time domain. For the purpose of determining the maximum correlation, it is possible to omit the inverse DFT and perform the correlation in frequency domain.

For a dedicated part of the route we analysed the RMSE of the ranging performance for different bandwidths and also included the performance of AIS as reference. Figure 5 shows the ranging performance at a distance of about 2.5 km from the transmitter including blockages by trees on the shore.

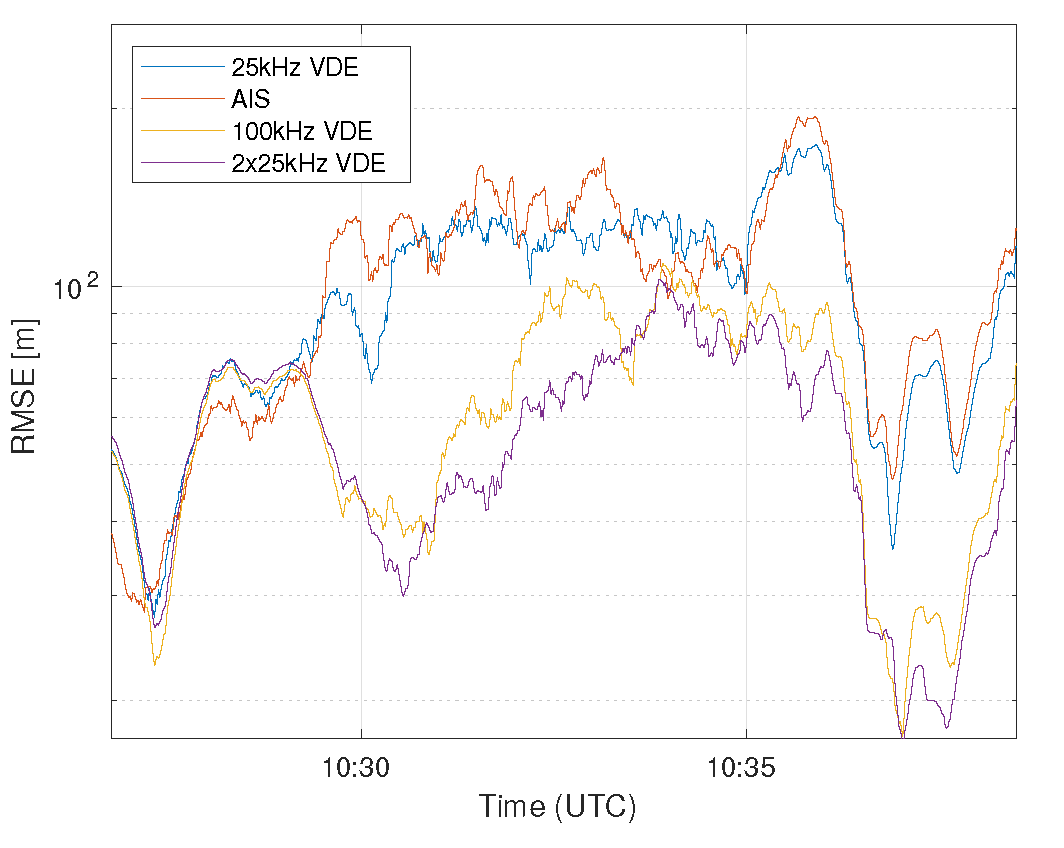


Figure : Ranging performance for different bandwidths utilizing VDE and the alternating sequence comparing to AIS.

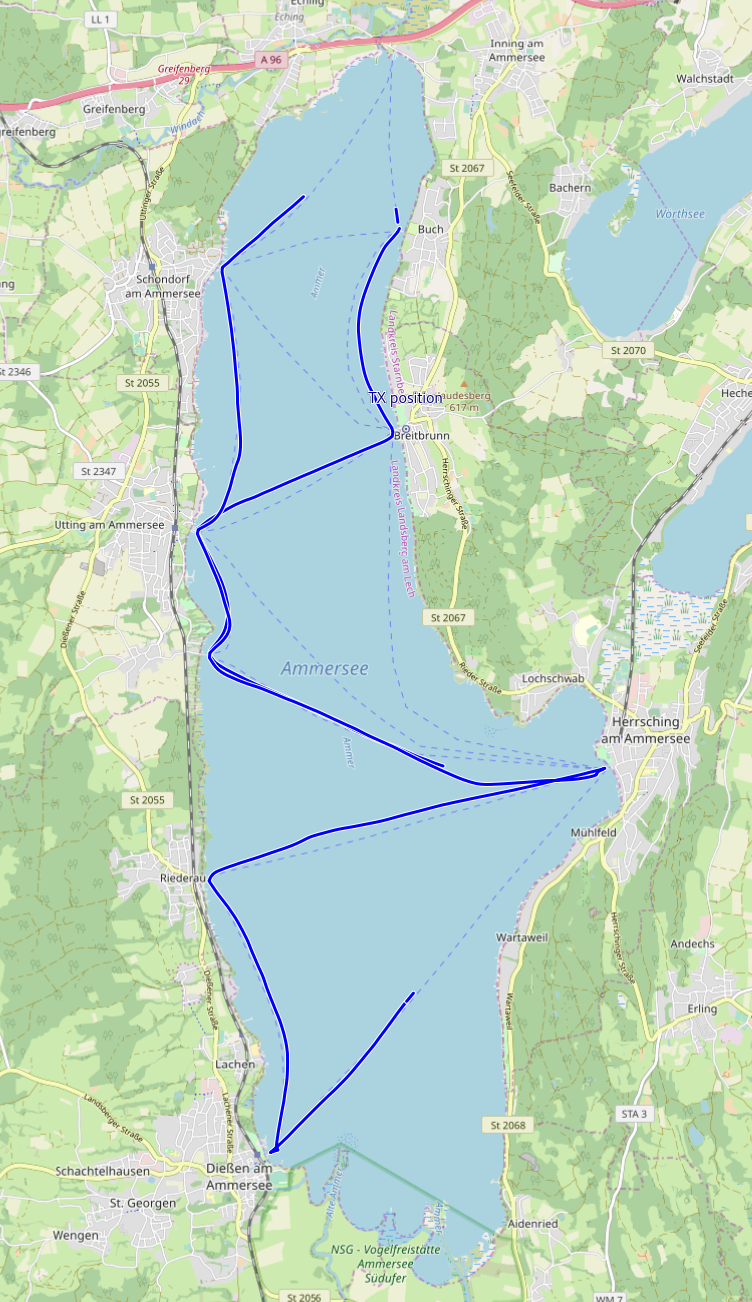


Figure : Map of the Lake Ammer where the measurements were performed.

# Summary

By having evaluated the Ziv-Zakai bound for different potential ranging signals, we find that optimizing the VDES ranging sequence by either mean square bandwidth or by low side lobe levels only gives results that are suboptimal for either low or high SNR values. Therefore we designed a concatenation of two signals which each optimize one of the given criteria. For high SNR values, optimizing the mean square bandwidth results in the best possible ranging performance, while at low SNR values, a signal with low autocorrelation side lobes allows ambiguity free determination of the signals time of arrival. However, neither of those signals are a good choice for intermediate SNRs. Therefore, we propose to utilize a combination of both signals which consists of a concatenation with variable ratios of the two signals.

# Action requested of the Committee

The Committee is requested to review the information and take appropriate action.

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