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Underwater Acoustics: Sonar performance modeling and verification. Applications to active and passive sonar

Optimization of active sonar parameters in a measured environment

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Sonar operation in coastal waters is challenging due to high false alarm rates and strongly varying sonar conditions. Optimal choices for sonar design and pulse characteristics depend strongly on target location and velocity, as well as the present environment. Given a description of the target and environment, acoustical models may estimate sonar performance for different sonar parameters. Updating sonar parameters to best meet shifting sonar conditions impose an unnecessary workload on operators and must be automated for unmanned systems. We suggest an optimization approach that takes into account both a variable environment and a random target. An acoustic ray trace model is run in all directions for a large number of different environment, target, and sonar realisations. Target parameters such as Doppler and aspect are modelled, and optimal sonar parameters are determined. The method is demonstrated for a littoral test case, where both the sonar design and its pulse parameters are optimized. The design takes into account whether the sonar is towed or hull-mounted, and its frequency. The pulse parameters include pulse length and pulse repetition time. The method can easily be extended to other sonar parameters, but the main intent here is to demonstrate the approach.

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1. INTRODUCTION

Active sonar detection of submerged targets in littoral and coastal waters is challenging. Underwater ridges, seamounts, and spatially variable sediments give rise to increased false alarm rate and complicated sonar conditions. In addition, coastal waters are characterised by highly variable oceanography. The optimal choice of sonar parameters, such as sonar depth and pulse parameters, depends strongly on the target location and velocity. Even for statistical approaches, the optimal parameters vary strongly from one target direction to another, as the sonar performance may be reverberation limited due to up slopes in one direction, while strongly noise-limited due to heavy shipping in the other. Constant updates of sonar parameters in order to best meet the shifting sonar conditions encountered during a sonar operation impose an unnecessary workload on the sonar operator. Furthermore, unmanned sonar operations are becoming increasingly relevant[1] and require algorithms to cover some of the traditional sonar operator tasks.

Beerens et al[2] developed a method called MSPOT for optimizing sonar parameters for detection of a specified target. The target is characterized both with target strength and expected Doppler. The coverage in terms of a weighted average of modelled probability of detection is maximized in the current environment by varying both the sonar depth and transmitted pulse type. Hjelmervik et al[3] suggested a statistical approach where both the sonar parameters, environment, and target parameters were varied using a Monte Carlo framework. The varied sonar parameters included pulse types and pulse parameters such as pulse length, bandwidth, and ping repetition intervals. The suggested algorithm came up with a set of optimal parameters for different types of environments, *e. g.* such as open and closed waters. They also employed the probability of track,[4] rather than probability of detection as a cost function in the optimization approach. This choice allows for comparison of sonar performance across different ping repetition intervals, as short intervals result in more frequent track updates and thus faster track initiation. On the other hand shorter ping intervals potentially also results in shorter detection ranges. Krout et al[5] studied the problem of optimal pinging strategies for multistatic buoy networks. They combined acoustic modelling and sonar detections with a Bayesian update equation in order to estimate a target presence probability map. The map was in turn combined with an acoustic model in order to determine an optimal ping sequencing of the buoy network.

Conventionally, during sonar operations, the sonar performance in a given environment is estimated by combining an acoustic model with the latest measurements of the present environment. Due to the environmental variability and uncertainties in the environmental measurements these estimates have associated uncertainties.[6] Monte Carlo simulations allow the inclusion of environmental uncertainty and variability in the calculations.[7]

Here we suggest an optimization approach that takes into account a realistic environment including its variability and uncertainty. Climatology and ocean model data are subjected to empirical orthogonal analysis in order to account for variability.[8] A topographic model is used to obtain 2D depth profiles in all directions from the analysed position. The fast, ray trace model Lybin[9] is run in all directions for a large number of different environments, targets, and sonar realisations. Target parameters such as Doppler and aspect are modelled statistically, while its location is handled using a 3D probability matrix similar to the probability map described by Krout et al.[5] This probability matrix may be determined from measurements using a Bayesian occupancy grid[10] or it may be based fully on an *a priori* knowledge of target behaviour, for example by using probability distribution for target depths.[2,3] Optimal sonar parameters are determined for the modelled environment. The cost function used is the modelled probability of track[4] integrated over all dimensions using the target probability matrix as weights in order to obtain a single scalar value of performance following the method proposed by Bøhler et al.[7]

The proposed method may be used both during a sonar operation for autonomous selection of sonar settings, but also as an objective approach for comparing the performance of different sonar designs in specified sonar operations. Here both of these applications are demonstrated in a brief example, where both the sonar design and pulse parameters are optimized for a littoral sonar operation.

2. METHOD

The low computation time of Lybin allows for Monte Carlo runs in order to map out the expected uncertainty and variation in the input parameters. These parameters and their uncertainty depend on the present environment, the target, and the sonar used. Following the steps described by by Bøhler et al[7] we represent both the target parameters and environmental parameters as stochastic state vectors, $\mathbf{M}$ and $\mathbf{T}$, respectively. We let the sonar state be described by the deterministic sonar state vector, S. All these state vectors are assumed to be statistical independent.

The modelled sonar performance is defined as $P(D|\mathbf{M},\mathbf{S},\mathbf{T})$, and represents the probability that the sonar, described by $\mathbf{S}$, detects the target (*probability of detection*), described by $\mathbf{T}$, in an environment described by $\mathbf{M}$. Each of the states $\mathbf{T}$ and $\mathbf{M}$ have associated probabilities given by $P(\mathbf{M})$ and $P(\mathbf{T})$. The probability that the target is detected in a given state is then given by,

$$P(D|\mathbf{M},\mathbf{S},\mathbf{T})P(\mathbf{M})P(\mathbf{S})P(\mathbf{T}). \tag{1}$$

This expression may be marginalized to estimate the marginal probability, $P(D|\mathbf{S})$, that the target is detected regardless of the environment and target for a given sonar state, $\mathbf{S}$,

$$P(D|\mathbf{S}) \;=\; \int_{\mathbf{M}}\int_{\mathbf{T}} P(D|\mathbf{M},\mathbf{S},\mathbf{T})P(\mathbf{M})P(\mathbf{T})d\mathbf{M}d\mathbf{T}. \tag{2}$$

If $P(\mathbf{M})$ and $P(\mathbf{T})$ are known, then $P(D|\mathbf{S})$ may be determined, as $P(D|\mathbf{M},\mathbf{S},\mathbf{T})$ for a single realisation of each of the states may be estimated using the acoustic model Lybin.[9]

$P(D|\mathbf{S})$ could be used as a cost function for determining the optimal choice of sonar parameters in the given environment. It is, however, not realistic that a detection from the sensor is sufficient in order to have a correct classification. A track initiation is also necessary. The probability of initiating a track depends on the track initiation rule used. Fewel et al[4] describes how this probability may be estimated when using the 3-in-5 rule. Here we apply Fewels equation on the estimated probability of detection, $P(D|\mathbf{S})$, in order to estimate track initiation probability, $P(I|\mathbf{S})$.

All possible combinations of sonar parameters are included and the sonar depth is uniformly distributed among all possible sonar depths. Fortunately, most pulse parameters influence the sonar equation only and does therefore not require a new estimate of the ray trace in Lybin. Sonar depth and centre frequency, on the other hand, require new runs as these parameters impact either the ray paths or intensities.

All possible target locations are organised in a discrete grid of target bearings, ranges, and depths. Lybin is a 2D model, so a single run covers all possible target ranges and depths within sonar range for one bearing. A new target bearing requires a new Lybin run to find all possible target ranges and depths in that direction. In order to limit the computational cost a relatively low resolution in target bearing is chosen compared to the target range and depth resolution. Target aspect impacts the target strength only, and this parameter is handled in the sonar equation. A high resolution in target aspect is therefore computationally cheap. Each of the target parameters have associated probability density distributions. The resulting probability of target state, $P(\mathbf{T})$, is then given by,

$$P(\mathbf{T}) \quad = \quad P(z) \cdot P(\mathbf{x}) \cdot P(v) \cdot P(\theta), \tag{3}$$

where $P(z)$, $P(\mathbf{x})$, $P(v)$, and $P(\theta)$ are the probabilities that the target is operating at depth z, geographic position, $\mathbf{x}$, speed, v, and at an aspect relative the sonar, θ. The probability of target location is here represented in Cartesian coordinates. On the other hand, the output from the acoustic model is represented in polar coordinates. A coordinate transformation is therefore required in order to compute (3) before inputting into (2). The target aspect influences both the target strength and target Doppler. Target strength is estimated using the TAP-model[11] assuming a target with a draft of 6 m and a length of 40 m.

The environmental parameters include for instance wind speed, sound speed profiles, and bottom properties. All changes in the environment require new Lybin runs and are therefore computationally expensive. For this reason a slightly different approach than the exhaustive approaches for the target and sonar parameters is used. The environmental parameters in each environmental realisation are picked randomly based on specified distributions. The sound speed profiles are modelled using an empirical orthogonal function scheme that combines climatological and modelled oceanographic profiles for realistic capture of the oceanographic variations.[12]

The marginalised version of the probability of initiating a track on the target, $P(I|\mathbf{S})$, is then maximized in order to find the optimal set of sonar parameters, $\widehat{\mathbf{S}}$,

$$\widehat{\mathbf{S}} = \max_{\mathbf{S}} \left(P(I|\mathbf{S}) \right). \tag{4}$$

3. RESULTS

The proposed method is demonstrated for a compact, towed or hull-mounted sonar used in a shallow and partly closed environment. The sonar vessel could be a part of a larger force, for instance a single unit in a small group of unmanned surface vehicles (USV) as described by McCutcheon.[1] It has been assigned to locate a submerged target in an area within 6 km of its position. The vessel is moving at a speed of 6 m/s.

The intent of this example is to demonstrate how the proposed method may be used to evaluate both the choice of sonar design and sonar settings for a specific sonar operation. In order to limit the analysis, only four different sonar designs are tested. All four sonars have the same physical aperture, but differing frequencies and therefore variable beam widths and directivity indexes. The frequency bandwidth varies with frequency, so the first listing of the bandwidth in the table corresponds to the first listing of the frequency, etc. Both hull mounted and variable depth sonars are tested. All sonar systems are modelled with a source level of 215 dB and a duty cycle of

Parameter	**Variation**
Pulse types	{FM, CW}
Sonar depth, z_s	{3, 50, 150} m
Centre frequency, f	{3, 6, 12, 24} kHz
Pulse length, T	{250, 500, 1000} ms
Range setting, R	{4, 6, 8} km
Bandwidth, B	{1000, 1500, 2000, 2000} Hz
Vertical aperture	1 m
Horizontal aperture	1 m

Table 1: Sonar parameters used in the optimization. The same parameters are used for both the FM and CW pulse, although the bandwidth parameter only applies for the FM pulses.

10%. All sonars are modelled as planar arrays with both 1 m height and width. Each sonar design is assumed capable of transmitting both continuous wave (CW) and frequency modulated (FM) pulses with various pulse lengths. The different designs are described in Table 1.

The sonar is operated in a fairly shallow, littoral environment. The position of the sonar vessel is shown in Fig. 1. The topography is highly variable with sea floor depths ranging from 0 to 400 m. Fig. 2a and Fig. 2b shows the sound speed profiles used. The method is applied for sound speed profiles both from spring and autumn. The wind speed is modelled as a Gaussian distribution variable with an estimate of 7 m/s and a variance of 1 $\mathrm{m}^2/\mathrm{s}^2$.

The target is randomized using the parameters shown in Fig. 2c. This corresponds to a target that intends to close the distance to the sonar vessel. Aspects of 0° correspond to target headings directly towards the sonar vessel. The target depth distribution used is uniform between 30 m and 150 m. No prior information on the target's location is known, therefore the horizontal distribution is defined as uniform in the area within 6 km of the sonar vessel.

Employing the method described in section 2 for the spring and autumn sound speed profiles yields the results shown in Figs. 3 and 4. These statistics are useful for analyzing the general behaviour of sonar performance for varying sonar parameters and designs.

The design parameter with the largest impact is towing depth. A towed sonar (50 m or 150 m depth) clearly outperforms the hull-mounted design (3 m depth) in both the spring and autumn environment. This is partly attributed to the strong surface channel that captures a significant amount of the transmission in the upper layers above the target depth (autumn), and partly due to the strong sound channel centred at approximately 50 m depth that also contains the most probably target depths (spring). Regardless, the ability to account for the vertical structure in the sound speed profile makes a towed sonar a better design choice than a hull-mounted sonar.

Frequency is also an important design parameter. For the specified environments, mid-frequency choices of 6 or 12 kHz outperforms both the lower frequency option of 3 kHz and the high-frequency option of 24 kHz. A notable exception is the CW-pulse in the spring condition that exhibits significantly improved performance at 12 kHz even compared to 6 kHz. This suggests that the relatively small acoustic aperture of the 3 kHz design is a significant drawback when compared to its higher frequency cousins. Likewise, the choice of a high-frequency design (24 kHz) is impeded by the strong thermal attenuation expected at those frequencies. The latter is particularly

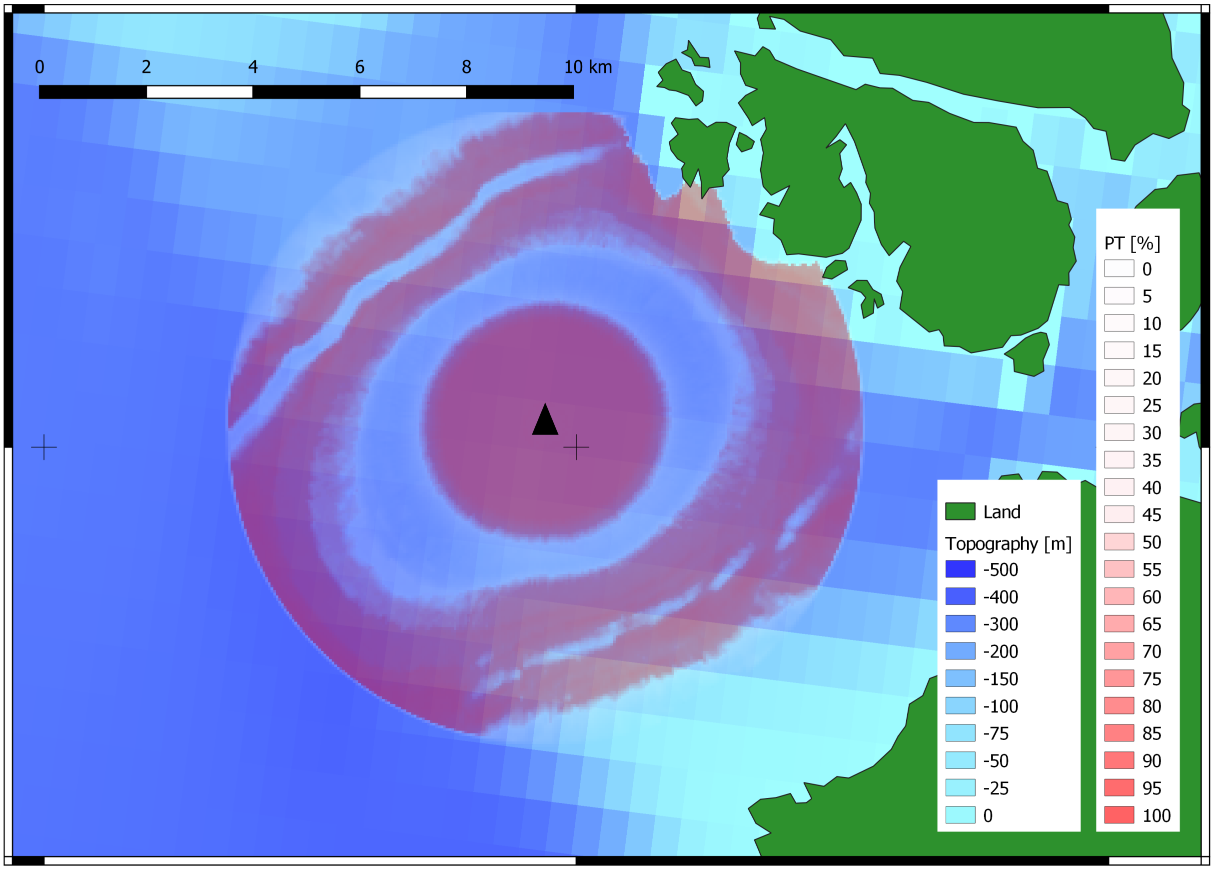
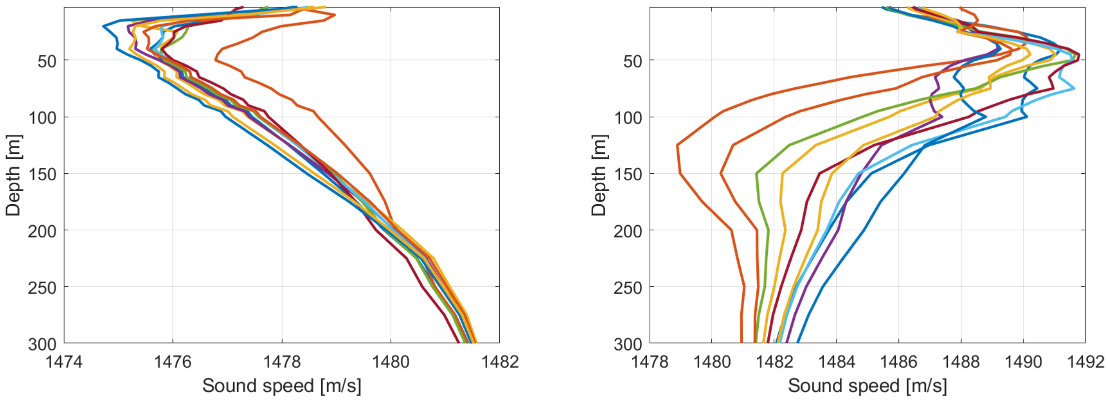
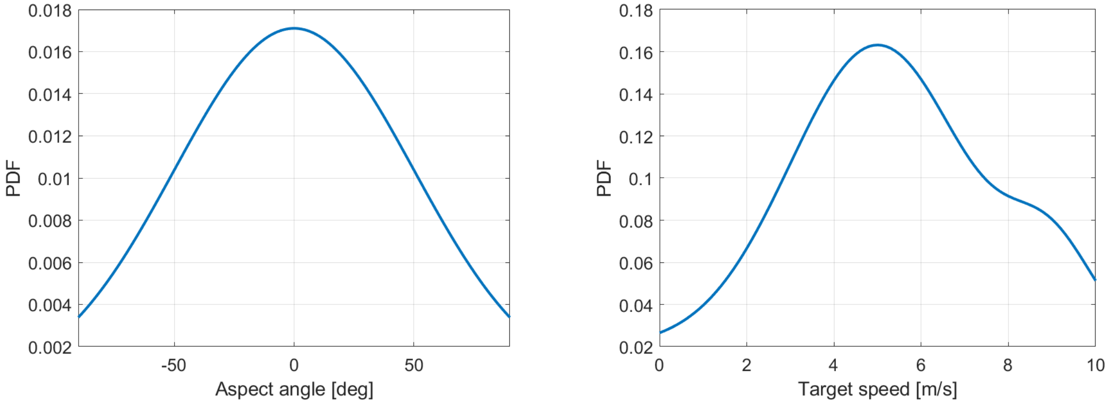


Figure 1: The test case is located in the Norwegian Trench on the South-West coast of Norway. The sonar vessel (black triangle) is heading North at a speed of 6 m/s. The estimated probability of track initiation (P_T) is calculated using the autumn sound speed profiles. It is based on 20 different environmental realisations and has an angular resolution of 1° and a range resolution of 100 m.



(a) Spring sound speed profiles used. The sound speed profiles are based on both climatology from the World Ocean Atlas and data from the Norkyst800 ocean model distributed online by The Norwegian Meteorological Institute.[13]

(b) Autumn sound speed profiles used. The sound speed profiles are based on both climatology from the World Ocean Atlas and data from the Norkyst800 ocean model distributed online by The Norwegian Meteorological Institute.[13]



(c) Target aspect distribution. 0° aspect corresponds to the target setting a course directly towards the sonar vessel.

(d) Target Speed distribution

Figure 2: Descriptions of target and environmental parameters for the modelling of the test case.

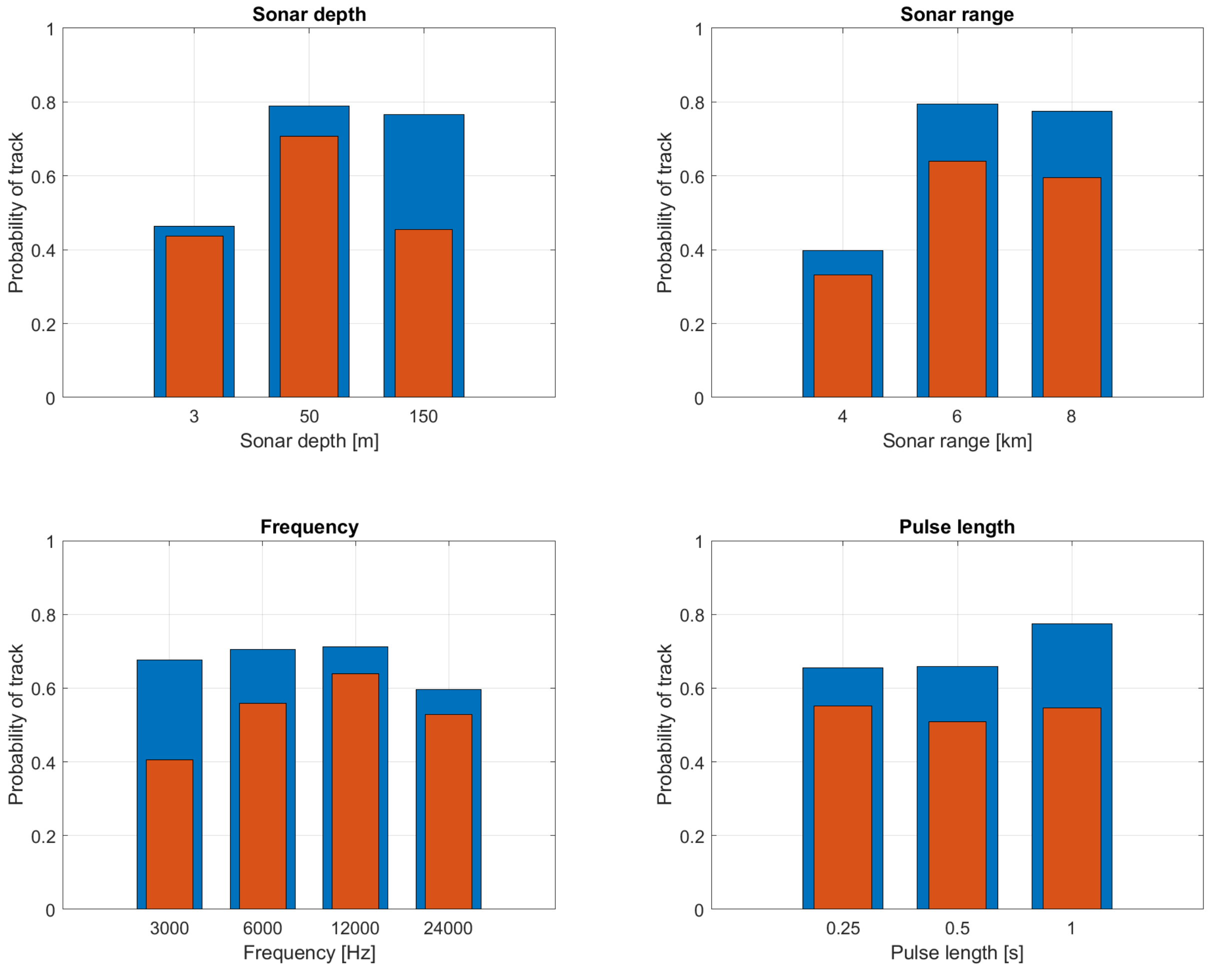


Figure 3: Average probability of track initiation on the target for the FM (blue) and CW (red) pulse for the spring sound speed profiles. Each bar represents a single sonar parameter design choice, but is integrated over all other possible sonar parameters, as described in section 2.

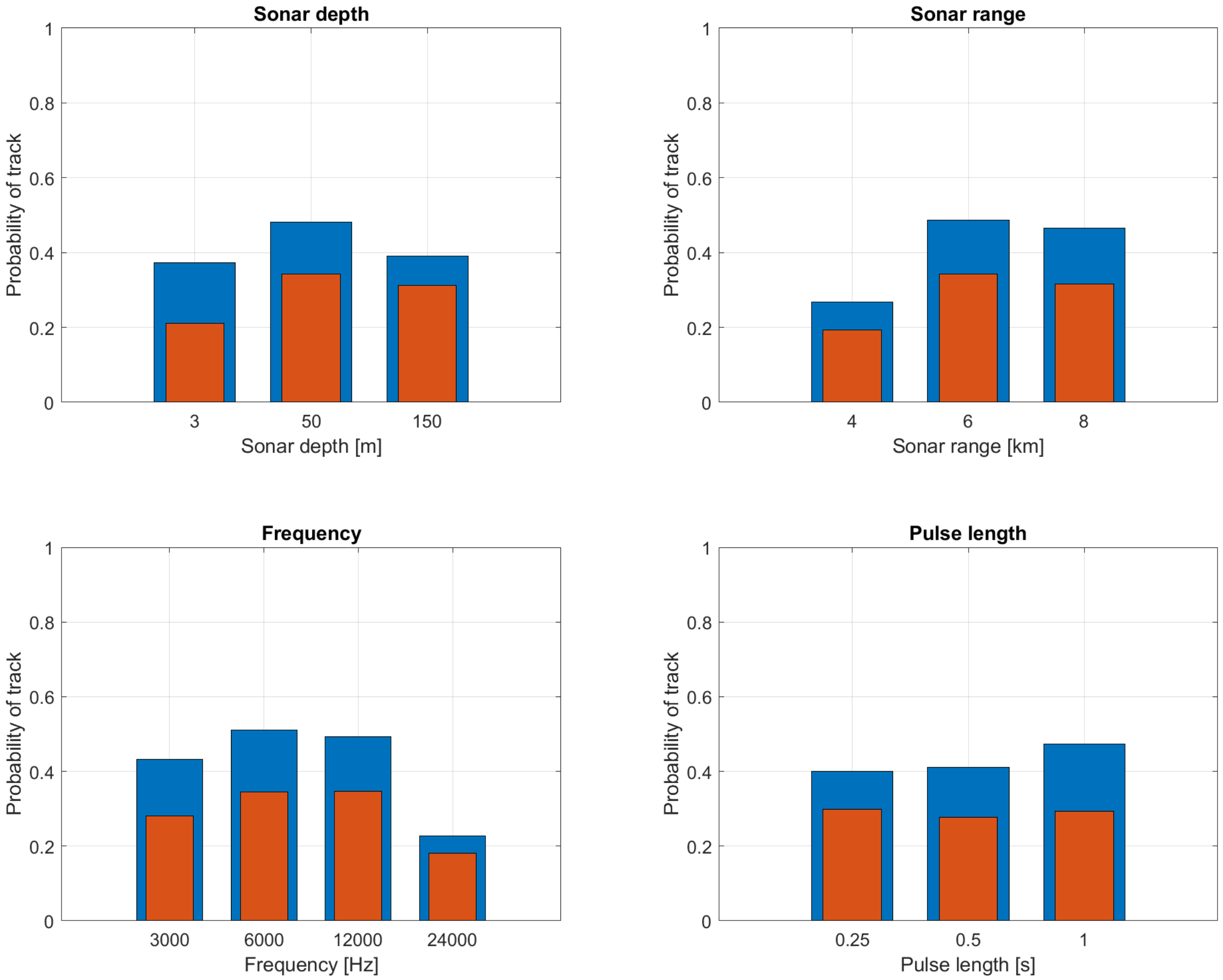


Figure 4: Average probability of track initiation on the target for the FM (blue) and CW (red) pulse for the autumn sound speed profiles. Each bar represents a single sonar parameter design choice, but is integrated over all other possible sonar parameters, as described in section 2.

Parameter	**CW, spring**	**FM, spring**	**CW, autumn**	**FM, autumn**
Sonar depth	50 m	50 m	50 m	50 m
Centre frequency, f	12 kHz	12 kHz	12 kHz	12 kHz
Sonar range, r	6 km	6 km	6 km	6 km
Pulse length, T	250 ms	250 ms	250 ms	500 ms
Bandwidth, B	N/A	2000 Hz	N/A	2000 Hz
Probability of track initiation	97.5%	98.4%	53.0%	72.5%

Table 2: Optimum sonar parameters found from optimization.

obvious in the relatively poor sonar conditions in autumn. Note however, that these results are based on a test case where each sonar vessel is allocated a search area within 6 km of their position. Higher frequency systems require less power and a smaller handling system. Such systems also allow smaller and cheaper USVs than for lower frequencies, which, in turn, means that the swarm could be larger and the area of coverage per unit could be smaller.

The same method can also be used to optimize the choice of pulse parameters, here represented by sonar range (pulse repetition time) and pulse length. Sonar ranges of 6 or 8 km, both of which covers the desired area, perform approximately equally well in all cases. Shorter ranges result in lower ping repetition times and therefore allows for more frequent transmissions and thus a higher probability of initiating a track. Longer ranges means longer ping repetition times, which subsequently allows for longer pulse lengths due to the limited duty cycle of the sonar. Longer pulse lengths increase the matched filter gain and therefore also the probability of track initiation, but also increases the blanking zone of the direct blast from the sonar. All in all, the longer pulse length statistically outperforms the shorter pulse length for the FM-pulse, while all pulse lengths have equivalent performances for the CW-pulse.

For a towed sonar the same method could also be used to find the optimal depth. In the present study only three depths are assessed in order to support the design analysis part of the paper. However, by applying the method on a dense grid of towing depths, the optimal depth for this specific environment could also be determined.

Table 2 lists the set of sonar parameters resulting in the highest probability of track initiation for both the CW and FM pulse. For the spring case, both pulses achieve a probability close to 100%, much due to the present sound channel and relatively short range. Surprisingly, the method suggests the shortest pulse length. This minimizes the blanking zone due to the initial blast, however an increased pulse length could potentially increase the performance at long ranges. Clearly the modelled signal-to-noise ratios at the longest ranges (6 km) is sufficiently high, regardless of the choice of pulse length. The remaining choices coincide well with the statistical comparisons presented in Fig. 3.

For the autumn sound speed profiles, the lack of a sound channel at the target depths strongly degrades the performance of the different sonar designs, see Fig. 4, but except for a longer pulse length the optimized sonar parameters remain the same. Increased pulse length is recommended because the inferior sonar conditions are then sufficiently improved by the increased matched filter gain to counter the increased blanking zone at short ranges.

It is reassuring that the method recommends the same sonar design for both the poor sonar conditions met in autumn and the excellent spring conditions. For this specific case with these conditions, the method recommends a medium frequency, towing or dipping sonar in the range of 6-12 kHz. Fig. 1 shows the probability of detecting the target when using the sonar parameters optimized for the autumn conditions.

This study only scratches the surface of the diverse conditions littoral sonar operations may encounter. For proper quantification of the performance of different sonar designs, the study should include different locations that are representative to the type of sonar operation the sonar is designed for. A wider range of different oceanographic and meteorological conditions should also be included. The proposed method supports this widening of the environmental base. The main objective of this paper is to demonstrate the capability of the method to objectively assess the performance of different sonar concepts and designs in realistic environments. The present study is therefore limited to a single location and the sonar design parameters are restricted to frequency and pulse parameters. An extended study should also assess the size and power consumption of the sonar, as well as other design choices, so as to give a fair comparison of the different concepts.

4. CONCLUSION

This work proposes a method that can be used during sonar operations to optimize sonar settings and is here demonstrated for a littoral sonar operation. We have used a quantitative approach for comparing different sonar designs for a specified environment. The method is demonstrated by optimizing a sonar design in the mid- to high-frequency range (3 - 24 kHz), where the objective is to detect a moving, submerged target.

Especially in high intensity scenarios, the optimization process described here may improve the decision basis for a sonar operator and the ability to use the sonar system in the most optimum way, in order to detect underwater targets.

The approach can also be used as input to the substantial work put into designing and specifying the next generation autonomous sonar systems. In the future the tasks normally handled by sonar operators for manned systems, will require autonomy for unmanned vessels.

The example shown in this paper is not an in-depth analysis, but included in order to demonstrate the applicability of the method. The intention of the paper is to propose an objective and quantifiable method for comparing different sonar designs in varying sonar conditions for different target types and behaviours.

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