Design of a Cost Function for the Evaluation of Different SONAR Modes

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Abstract

A SONAR system can be operated in various configurations. The simplest mode uses just one projector and one hydrophone, which is called SISO (single input single output) processing. More sophisticated modes use multiple projectors or hydrophones. This is referred to as a MIMO (multiple input multiple output) system. The different modes, as well as individual variants, have advantages and disadvantages, for example in terms of hardware and software requirements or angular resolution. The choice of transmission sequences also plays an important role. With all these different SONAR modes, it is difficult to evaluate and compare their performance. This is usually done visually by analyzing the resulting plan position indicator (PPI) plot. To improve the reproducibility, an objective measure to evaluate different SONAR modes is developed in this contribution. This is done by establishing a cost function that considers different scenarios and targets in a harbor environment. The calculation is implemented in a real-time framework. For the evaluation, a realistic simulation of a harbor environment is used, in which the different SONAR modes are simulated and the respective cost functions are calculated. This allows a fair and reliable evaluation and comparison of the different modes.

SONAR Modes

There exist different SONAR modes, which vary in their complexity, e.g. the number of projectors and hydrophones used. Four basic modes are briefly described below. These will be used later in this paper to evaluate the cost function. In addition to SISO and MIMO, MISO (multiple input single output) and SIMO (single input multiple output) are available. The former mode uses multiple projectors and one hydrophone, the latter mode one projector and multiple hydrophones. With SISO it is not possible to steer a beam in any particular direction. Only the distance of a target can be estimated, but not its angular position [1]. However, it is a very low cost system. MISO and SIMO can be used for transmit respectively receive beamforming. Both systems are more complex because more projectors or hydrophones are needed, but they are also more accurate because both distance and angular position can be estimated [1]. The most complex mode is MIMO, where multiple projectors and hydrophones are used. If each transmitter sends different signals that are orthogonal to each other, transmit beamforming at the receive side can be performed. This allows both the transmit and receive beamformers to steer in exactly the same direction, increasing accuracy [2].

Harbor Environment

To calculate the cost function for the different SONAR modes, a simulation in the Kiel Real-time Application Toolkit (KiRAT) is used. This simulation of a digital ocean is as detailed as necessary and as simple as possible. A distinction is made between two cases, using either a 1D or a 2D target. Figure 1 shows the harbor environment used for the 1D case. The seabed with small ridges and depressions is modeled in brown and the undulating water surface in blue. The seabed is static, while the water surface changes over time according to the set wind speed and direction.

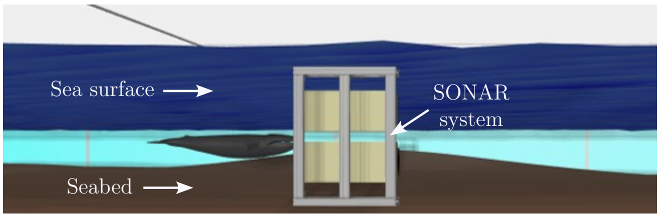


Figure 1: Simulation environment for the evaluation of the cost function in the 1D case in KiRAT.

A monostatic SONAR system is used in this simulation. This means that the projectors and hydrophones are located in the same place. The SONAR array can be seen at the front of Figure 1. In the case of a single input or output, a single projector or hydrophone is used. For the multiple inputs or outputs, 16 projectors or hydrophones are chosen. The 1D point target is visualized as a whale and is placed at a distance of 82.5 m and in a direction of $-14°$ from the transducer arrays. The depth of -10 m is the same for the target and the arrays. The target has a reflection strength of -10 dB.

For the 2D target case, almost the same simulation environment is used. The only difference is the type of target. Instead of a point target, a 2D wall is simulated, as shown in Figure 2. The wall is 50 m to the right of the array and starts at a distance of 20 m with a total length of 180 m and a depth of 20 m. It is simulated with 100 randomly generated points, which differ in each frame of the real-time processing. Each point has a reflectivity

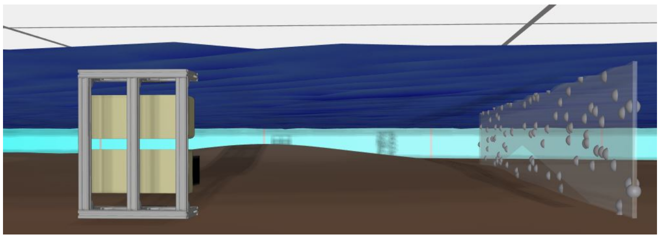


Figure 2: Simulation environment for the evaluation of the cost function in the 2D case in KiRAT.

of −10 dB. In addition, background noise is simulated, which includes shipping, wind, turbulence and thermal noise. For this purpose, the models mentioned in [3] are used.

Design of the Cost Function

In order to compare different SONAR modes, a cost function is to be defined. For this, it is necessary to consider the parameters that can be taken into account. There are two important parameters that determine the accuracy of the target position: angular and distance resolution. The angular resolution can be analyzed using the beampattern, which is characteristic for the different modes. The beampattern shows the received power of the different directions for a fixed distance. Those of the four modes are shown in Figure 4. The main lobe with the most energy points in the direction of the target. The beampattern also contains a number of side lobes, caused by constructive and destructive interference. For the distance resolution the distance plot shows the received power of the different distances for a fixed direction. The highest peak is at the distance where the target is located. The distance plots can be seen in Figure 5. Other parameters of interest are the power of the reflection on the target and the power of the background noise.

In order to express this in one number, a ratio can be formed. Usually the signal-to-noise ratio (SNR) is calculated. In this context, it is difficult to determine the signal power because it is overlaid by noise. Therefore, the input-to-noise ratio (INR) was chosen:

$$\mathrm{INR} = \frac{\mathrm{I}}{\mathrm{N}} = \frac{\mathrm{S}+\mathrm{N}}{\mathrm{N}} = \frac{\mathrm{S}}{\mathrm{N}} + 1. \qquad (1)$$

I is the input power, which is the sum of the signal power (S) and the background noise power (N). The result therefore includes the SNR but takes into account that the signal power cannot be accurately determined.

Realization of the Cost Function

The calculation of the INR is implemented in the processing part of KiRAT. This can then be tested with the simulation described above. Figure 3 shows the graphical user interface for the cost function.

At the top left is the PPI plot. Two different areas can be selected here – one for the input power and one for the noise power calculation. This can be done by clicking on the outer boundaries, in this case in the shape of a cake slice. These boundaries can also be set using an initialization file. The input area is marked in pink and the noise area, which may include the input area, in blue. As an additional option to the cake slice shape, which is easy to implement due to the use of polar coordinates, the areas can have the shape of a rectangle. This is closer to the shapes found in a harbor environment, such as harbor walls. The distance resolution plot is shown at the top right. The angular direction to be displayed can be selected in the PPI plot by clicking with the mouse. It is indicated by the orange line. The input area can be selected in the distance plot. The boundaries are marked with the vertical pink lines. These should be placed around the largest peak as this is where the energy reflected from the target is located and therefore the input power required to calculate the INR. All values outside the limits belong to the noise area. The beampattern is shown at the bottom left. The distance at which the beampattern is to be displayed can also be selected by clicking on the PPI plot. It is marked with the yellow half circle. For the INR calculation, the input boundaries can be set in the same way as for the distance plot. Again, the boundaries should be set around the main lobe, as this is where the input power reflected from the target is located. Similarly, all values outside the limits are part of the noise area.

To calculate the INR for the 1D case, the distance plot and the beampattern are considered. Two values are therefore calculated, but only applied to the previously defined direction and distance. To calculate the INR in the 2D case, the two-dimensional matrix shown in the PPI plot with the selected input and noise areas is used. Many directions and distances are therefore included and only one value is calculated. The calculation of the input and noise power is the same for the 1D and 2D case. There are two ways to determine the input power. The first is to use the maximum of the input area and the second is to calculate the average of the input area. There are also two ways of calculating the noise power. Either the average of the noise area or the average of the noise area plus the input area is determined. The INR is calculated once for each SONAR ping. A smoothed average is formed over a pre-defined number of pings so that short-term fluctuations do not have a large effect.

Evaluation

The evaluation considers all four SONAR modes described above and should clarify if reasonable values are calculated with the proposed cost function. For each mode, the INR of the 1D and 2D case is calculated. The transmission signal is white noise with a center frequency of 52 kHz and a bandwidth of 15 kHz. The length of the transmission sequences is 10 ms. The total measurement time is 30 s with a ping duration of 1 s, resulting in 30 measured pings. The smoothed average over 5 pings is calculated. For the input power the maximum is chosen, while for the noise area, the average excluding the signal area is calculated.

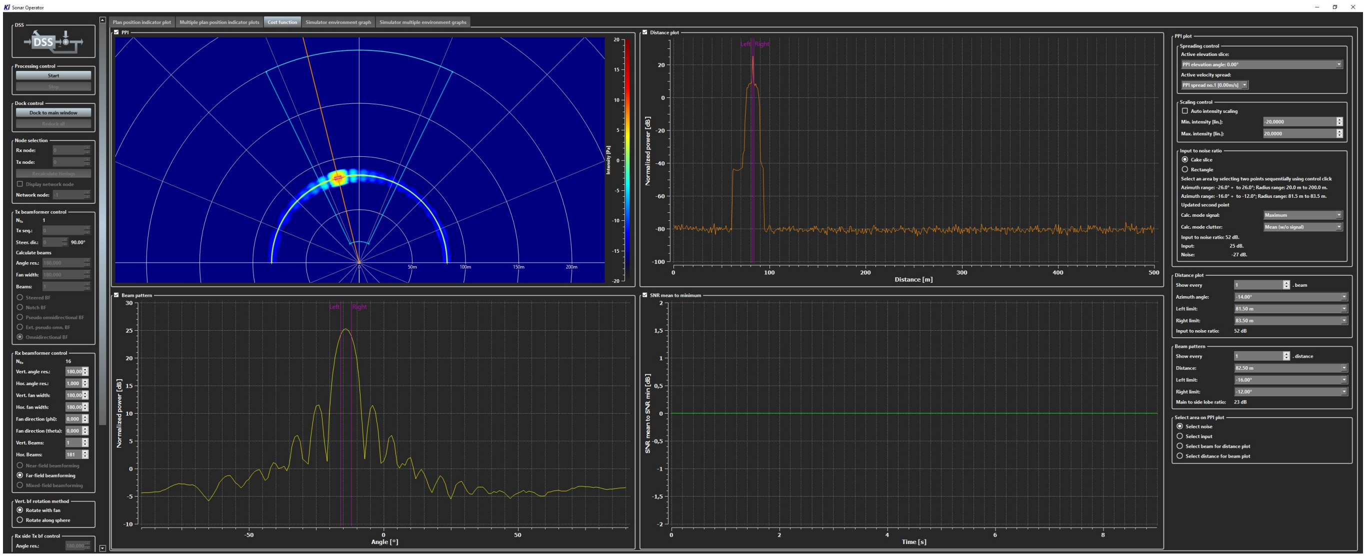


Figure 3: Graphical user interface for the cost function in KiRAT.

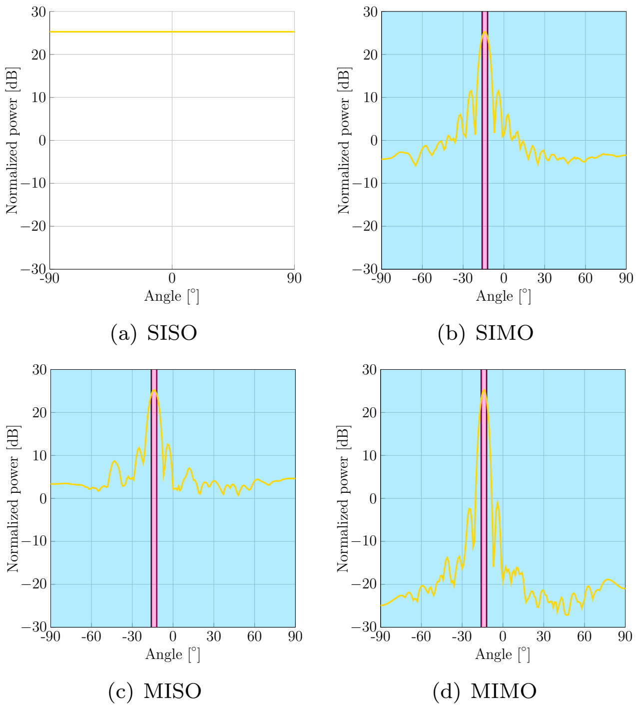
Table 1 shows the results for the 1D case. These are the $\mathrm{INR_{BP}}$ of the beampattern, the $\mathrm{INR_{Dt}}$ of the distance plot and the total $\mathrm{INR_T}$ which is the sum of $\mathrm{INR_{BP}}$ and $\mathrm{INR_{Dt}}$.

Table 1: INR results for the 1D case.

Mode	$\mathrm{INR_{BP}}$ [dB]	$\mathrm{INR_{Dt}}$ [dB]	$\mathrm{INR_T}$ [dB]
SISO	x	52	x
SIMO	23	52	75
MISO	19	42	61
MIMO	34	42	76

The four corresponding beampatterns are shown in Figure 4. With SISO it is not possible to form a beam, so $\mathrm{INR_{BP}}$ cannot be calculated and the beampattern shows a straight line. Therefore, no value is entered in the table. In the other three plots, the limits of the input areas are set to $-12°$ and $-16°$ because the target is at $-14°$. It can be seen that the main lobes are at $-14°$, as expected. The input areas are highlighted in pink. The side lobes of the beampatterns are also visible, which are undesirable and should be kept as small as possible. These noise areas are highlighted in blue. The beampatterns differ in the width of the main lobe and the height of the side lobes. Both are smallest in MIMO mode, which reflects in the highest INR of 34 dB.

The distance plots of the four modes are shown in Figure 5. The target peak can be clearly seen at 82.5 m in each plot. The limits are set at 81.5 m and 83.5 m. The distance plots differ in the height of the noise floor around the target, which is lowest for the SISO and SIMO modes, and the height of the noise floor of distances away from the target, which is lowest for the MIMO mode. This is also reflected in the INR values, as SISO and SIMO achieve higher results for $\mathrm{INR_{Dt}}$.

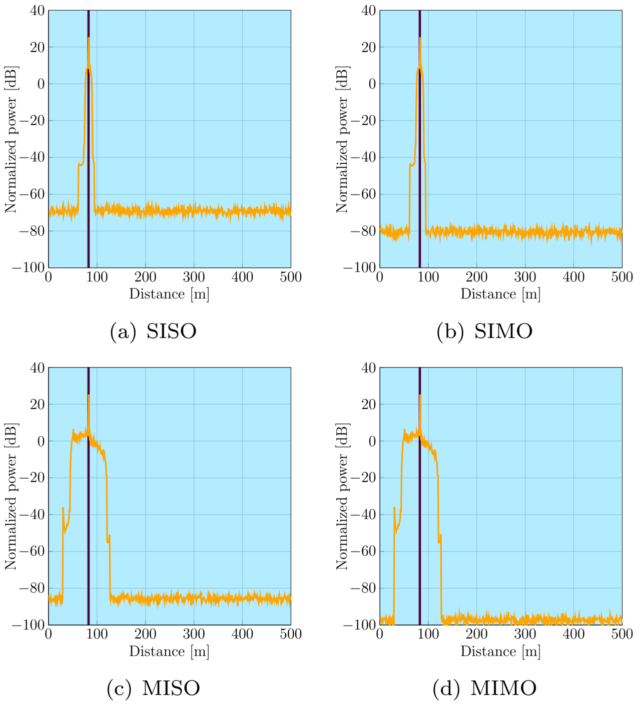


(a) SISO (b) SIMO (c) MISO (d) MIMO

Figure 4: Beampatterns of the four SONAR modes for the 1D case at a distance of 82.5 m.

This analysis confirms, that the calculated INR values match those that were expected for the 1D case.

The INR values of all four SONAR modes are again calculated for the 2D case, summarized in Table 2. The corresponding PPI plots are shown in Figure 6. The input area is highlighted by the pink rectangle. It is set to match the dimensions of the wall. Similarly, the noise area is marked with a blue rectangle. Here, the dimensions are set in relation to the wall to create a rectangular area that is mirror-symmetrical to the center of the array.



(a) SISO (b) SIMO

(c) MISO (d) MIMO

Figure 5: Distance plots of the four SONAR modes for the 1D case at a beam of $-14°$.

Table 2: INR results for the 2D case.

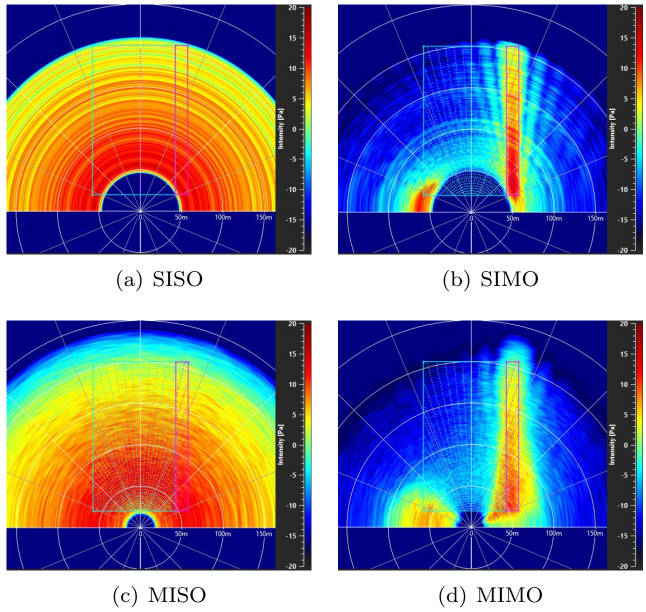
Mode	INR [dB]
SISO	12
SIMO	31
MISO	7
MIMO	21

It should be noted that in SISO mode, the signal and noise areas are almost the same because there is only one beam. They only differ slightly in distance. The SISO and MISO PPI plots cannot really display where the wall is placed. This results in very small INR values of 12 dB and 7 dB. In the SIMO and MIMO plots the wall is clearly visible and the INR values of 31 dB and 21 dB are much higher.

This analysis also confirms, that the calculated INR values correspond to those expected for the 2D case.

Summary and Outlook

A cost function for the evaluation of SONAR modes has been introduced in this publication, which can be used as an objective measure to compare different modes. Therefore, the INR is calculated, distinguishing between the 1D and 2D cases. This was realized in the real-time framework KiRAT, where the limits for the input and noise areas can be flexibly set in the graphical user interface and the values are calculated in real-time. In addition, the cost function was evaluated with four basic SONAR modes. It was shown that reasonable values



(a) SISO (b) SIMO

(c) MISO (d) MIMO

Figure 6: PPI plots of the four SONAR modes for the 2D case.

were calculated, reflecting the advantages and disadvantages of each mode. The cost function can therefore be used in the future to compare different, more advanced SONAR modes. Different parameterizations (e.g. number of transducers, transmission sequences) of the same mode can also be compared. This is intended to provide an objective measure to support the selection of the appropriate SONAR mode for specific applications.

In the future, it should also be possible to select circular areas for the 2D case, as there are many circular objects in a harbor environment, such as bollards. The 3D case should also be considered for applications where 3D beamforming is used. One way to improve the comparison is to take additional parameters into account. For example, a measure of how well two targets can be discriminated could be used.

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