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Source localization based on matched field processing focalization using shallow-water experimental data

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Abstract

Matched field processing (MFP) is an inversion method that combines signal processing techniques with predictions of the acoustic field computed by numerical models and has been applied extensively to source localization. MFP's performance is dependent on accurate environment knowledge and degrades as the uncertainties about environmental parameters accumulate, resulting in model mismatch. To reduce model mismatch, the focalization technique can be used, by including environmental parameters in the search space in addition to source position, thus allowing the environment to be handled as a lens that can be focused. To this effect, a genetic algorithm is employed to efficiently optimize for multiple parameters simultaneously. This paper considers the inversion of experimental data from a shallow-water, mildly range-dependent track from the CALCOM'10 sea trial, which was not designed for source localization inversion and has multiple uncertainties for the accurate modelling of the channel. The experiment was run off the southern coast of Portugal, with an acoustic source being towed along various tracks and the signals acquired by a 16-element vertical line array deployed on a drifting buoy. Particularly, sound speed data is limited to low-resolution temperature measurements at receiver position. The results show that when a focalization step is included prior to MFP and the sound speed profile is incorporated into the optimization successful inversion for source range and depth is achieved.

Keywords: underwater acoustics, source localization, matched field processing, focalization.

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1. INTRODUCTION

Matched field processing (MFP) is an inversion technique that fundamentally involves comparing a complex pressure field measured on an array with a set of replica fields computed by an acoustic propagation model across a range of parameters [1]. Conventional MFP requires the systematic calculation of the replica fields for a range-depth grid of possible source locations and has seen widespread use for source localization.

MFP is a powerful technique because it explores the full-field complexity of waveguide propagation [2], but its greatest limitation derives from this very fact: if the model of the environment is not an accurate representation of it, a situation called model mismatch, MFP degrades and the inversion results will not be meaningful. Several robust processors that tolerate incomplete knowledge of the environment have been developed [3–5]. One particular technique introduced by Collins and Kuperman, termed focalization, includes environmental parameters in the search space along with source coordinates and simultaneously adjusts (focuses) the environment and localizes the source [6].

The inverse problem is inherently non-unique in the sense that there are multiple models that can provide adequate solutions [7]. As the parameter search space increases, its landscape becomes increasingly complex, with multiple local optima, therefore an efficient heuristic must be employed to try and find the best-fit model. Gerstoft was the first to use genetic algorithms (GA) in this context [8], reporting great results in treating the inversion problem as a global optimization one.

GA is inspired by biological evolution and is effective in searching a large search space because it employs a population of vectors instead of a single vector traversing the landscape. A population of model parameter vectors (individuals) is randomly initialized in the search space and the fitness of each one is calculated according to an objective function, for which the optimization is being carried out. The best-fit individuals in the population are selected as parents for the next generation. Information between them is exchanged through a crossover operator and random fluctuations in the next generation are in-

troduced by a mutation operator. The algorithm used in this paper is similar to the one described by Gerstoft [9], except for the absence of the temperature control parameter.

Results for experimental data [10] report improved performance for GA-based focalization over conventional MFP in uncertain or dynamic shallow-water environments, with consistent localization being achieved for up to 10 km at high-frequency bands [11].

This paper applies a GA-based focalization methodology to a short-range track of the CALCOM'10 sea trial, which involves a moving source in a range-dependent shallow-water uncertain environment. In addition to the GA, a stochastic hill climbing step was included to nudge the vector closer to the maximum of the region the GA was exploring in order to achieve a better-fit model than GA alone would be capable. Three strategies with different degrees of adaptiveness are compared to evaluate the benefit of focalization and its applicability to this experiment's data set, including: no optimization, optimization for geometric parameters only and optimization for both geometry and a parametrized sound speed profile (SSP). The latter is shown to achieve better localization results despite severe uncertainties in the environmental model.

The remainder of the paper is structured as follows: Section 2 describes the CALCOM'10 sea trial and its environment; Section 3 describes the three strategies used for source localization, model parameters and optimization techniques employed; Section 4 discusses the results of the application of this methodology to the selected track of the experiment; and Section 5 presents the conclusions and future work directions.

2. THE CALCOM'10 SEA TRIAL

The CALCOM'10 experiment was set up to gather data to test the concept of “field calibration” as a tool for tuning the parameters of an acoustic propagation model for a region of interest [12]. The idea of this concept is that results from acoustic inversion could be used as parameters for the acoustic propagation model of a given region, even in face of scarce or absent geoacoustic and bathymetric data. Acoustic sea trials are

easier and quicker to carry out than geoacoustic or bathymetric surveys and such data can be used to predict transmission loss or noise distribution, thus reducing the need of extensive surveys of the area of interest. As a tool, this could be used in the early stages of planning for the construction of an offshore installation and the assessment of its impact. Martins, Felisberto and Jesus [13] demonstrates this application.

The experimental setup consisted of two free-drifting Acoustic Oceanographic Buoys (AOB), each carrying a vertical line array (VLA), and a Lubell 1424 acoustic source that was being towed at approximately 4 knots along various tracks while emitting a sequence of chirps and fifteen-seconds-long multitones in the 500-2000 Hz range. Only the 500 Hz data for a short-range track along a region of mildly varying bathymetry was used for source localization in this paper. The data was acquired by a single AOB with an array of 16 hydrophones evenly spaced (4 m) from 6.3 to 66.3 m. Figure 1 shows the VLA and source tracks on a bathymetric chart with the 8 transmissions used in this work marked.

VLA position was acquired from the GPS on the AOB. Source positions marked on Figure 1 were

obtained from the towing ship's GPS. In addition to the expected GPS inaccuracy and error due to the distance to the towfish, each position was recorded at the beginning of each one-minute-long transmission, of which the data used in this inversion comprised the last 15 seconds. A pressure sensor on the towfish recorded the source depth, which was kept at around 7 m for this track.

At each receiver position, there was a low-resolution (0.5 °C) temperature sensor installed. SSP was derived from these measurements by the Mackenzie equation, assuming constant 36 ppt salinity. As can be noted, only approximate low-resolution sound speed data at receiver position spanning about half the water column is available. This scarcity of reliable SSP data figures as a major source of uncertainty in the environmental model.

Accurate geoacoustic data for the seabed of the region is also absent beyond the mention that it is located on the continental shelf sedimentary cover, described as a thin (<10 m) cover of fine-grained sediment overlying a rougher erosive surface [14]. Preliminary modeling predictions were carried out, using the TRACEO Seismo-Acoustic ray based model [15], and the 500 Hz

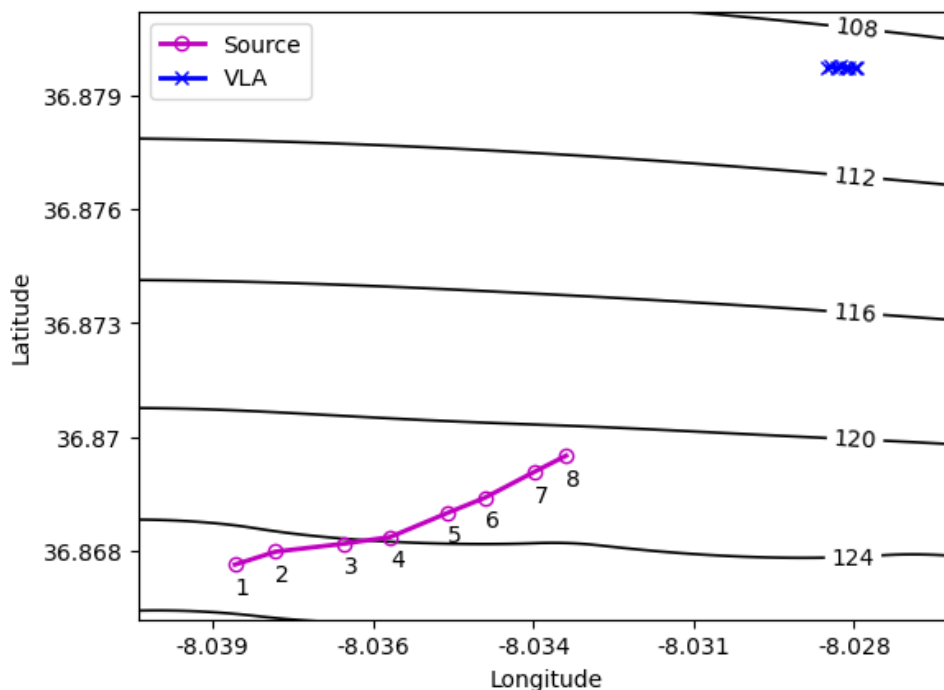


Figure 1: AOB and source tracks with the position of source at the start of each (numbered) transmission marked.



data showed better agreement with a harder bottom than the ones found by other works on the same dataset [12, 13]. Note, however, that those references used higher-frequency data, up to 2 kHz. Ray models with a single homogeneous bottom layer were also used, which means the parameters that were inverted are necessarily for an equivalent model of the real bottom [16]. At higher frequencies, the effective acoustic penetration depth is lower [17], so a softer equivalent bottom would indeed be expected in those cases.

It must be noted that the CALCOM'10 sea trial was not designed as a source localization experiment and the uncertainty in true source position and other environmental parameters contribute to make this an interesting test case for focalization.

3. FOCALIZATION AND SOURCE LOCALIZATION

Three strategies for locating the source at each transmission were considered:

1. Regular MFP over a baseline model.
2. MFP preceded by a GA-based optimization of geometric parameters of the model. For the first transmission, bottom parameters were included in this focalization step and held constant for the remaining transmissions.
3. Same as strategy 2, but with coefficients for a parametrized SSP included in the focalization step along with geometric parameters. Bottom was kept the same as strategy 2.

The Bartlett processor was used both as the correlator for measured and modeled fields for the MFP and as the objective function to be maximized at the focalization step. For a single frequency f , it is defined as [2]:

$$B(\Theta, f) = d(\Theta, f)^H C(f) d(\Theta, f) \quad (1)$$

Θ is a vector of model parameters. The focalization step is posed as an optimization problem: find the vector Θ that maximizes the objective function. The parameters included in this vector depend on the strategy being used. For the MFP step, only source range and depth are

changed according to a predefined search grid. d is the replica field, computed by the TRACEO ray model, normalized to unit norm. C is the sample covariance matrix of the data recorded on the hydrophone array, formed by averaging over a series of L snapshots. This is done to improve signal-to-noise ratio (SNR).

$$C(f) = \frac{1}{L} \sum_{l=1}^L e_l(f) e_l(f)^H \quad (2)$$

e_l is the normalized data vector, computed by fourier transforming the l -th snapshot of the measured field. The 15 seconds of data of each transmission were divided into 75 snapshots, the first and last of which were discarded in the calculation of the covariance matrix. The notation ^{H} denotes the Hermitian operator. The maximum attainable value for the Bartlett processor is unity, in the case the replica field identically matches the measured field, since both are normalized to unit norm.

3.1 The baseline model

A baseline environmental model was constructed based on the available information and is shown on Figure 2 for transmission 1. SSP used was based on temperature measurements at the beginning of transmission and was linearly extrapolated from the last two points to cover the entire water column. Bottom properties were kept constant between transmissions, with only SSP and geometric parameters being changed for each localization. This is reasonable, since it was noted that geoacoustic parameters show little influence on the acoustic field in the region [12, 13] and, once the bottom has been characterized, it can be considered time-invariant. A complete geoacoustic inversion is beyond the scope of this paper. From some preliminary testing with different sets of bottom parameters, it was found that properties for sand ($c_p = 1650$ m/s, $\rho = 1.9$ g/cm³, $\alpha_p = 0.8$ dB/ λ) [17] gave the best results.

No focalization step was done for the baseline model runs, only an extensive range-depth search for each transmission, with source range going from 500 to 2500 m (10 m step) and depth from 0 to 100 m (1 m step).

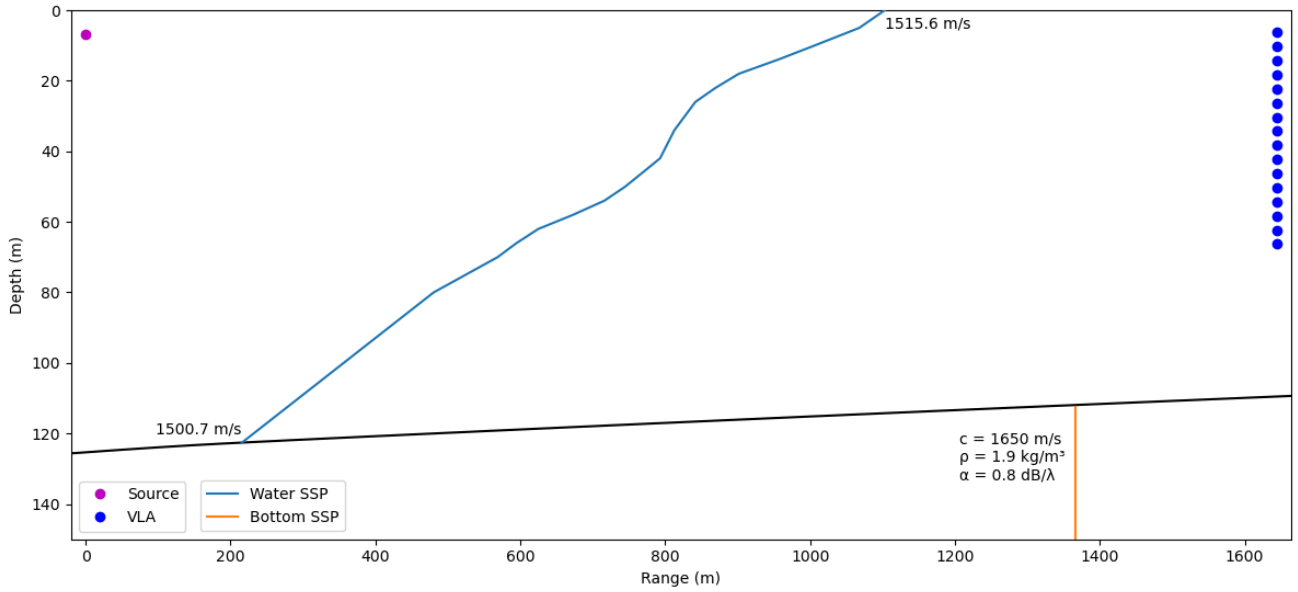


Figure 2: Baseline model (transmission 1).

3.2 Focalization: geometric parameters

For the second and third strategies, a focalization step was included prior the extensive range-depth search to calibrate the environmental model. At first, only parameters respective to the geometric arrangement of the model were optimized, which included nuisance parameters such as array depth offset and tilt. The parameters included in the search, as well as their bounds, are shown in Table 1. Source range and depth were included in the optimization within a margin of uncertainty defined *a priori*. Azimuth from receiver to source was assumed known, but was included as a way to introduce slight variations to the bottom slope, accounting for the water depth range-dependency.

The search for the best model vector Θ was carried out by a combination of genetic algorithm and first-choice stochastic hill climbing [18]. GA and hill climbing are complimentary, in a sense. While the first has the power of parallel exploration of the search space, with exchange of information through the crossover operator, its progress tends to slow down as it converges to a solution. Hill climbing, as a greedy search algorithm, makes quick progress in finding new solutions, but tends to get stuck in local maxima, particularly in problems in which the landscape of the search space isn't convex or is too complex, as is the case in acoustic inversion. Starting the hill climb near the solution helps in avoiding this problem without the need for random restarts. Therefore, GA was used to explore the

Table 1: Model parameters included in the focalization step. Bottom parameters, marked with (*), were included only for the first transmission and then held constant.

Parameter	Lower bound	Upper bound
Source range (m, ref. GPS position)	−150	+150
Source depth (m)	5	9
Source azimuth (ref. GPS position)	+0°	+2°
Array tilt (rad)	−0.026	0.026
Array offset (m)	−2	+2
Bottom offset (m)	−5	+5
Bottom sound speed (m/s) (*)	1500	1650
Bottom density (g/cm ³) (*)	1.2	1.9
Bottom attenuation (dB/λ) (*)	0.2	1.0



search space and stochastic hill climbing, with very small steps, was used to reach the maximum of the region the GA had converged to, in order to achieve the best-fit model. Since there is always a chance the GA will converge to a local maximum, 3 independent populations were used. All optimization hyperparameters are shown in Table 2.

Table 2: Hyperparameters used for focalization.

Hyperparameter	Value
No. of independent populations	3
Population size	150
No. of generations	60
Crossover rate	0.9
Mutation rate	0.015
No. of bits	10
No. of hill climbing iterations	1000
Hill climbing step	0.1% of parameter search space

3.3 Focalization: geometry and SSP

In addition to the parameters in Table 1, the third strategy included a parametrized SSP in the focalization step. The parametrization was done by means of empirical orthogonal functions (EOF) decomposition of the measured profiles [19]. EOF analysis is useful when historical data is available, leading to better convergence and uniqueness of the solution [20]. Here, it is used to overcome the lack of both historical data and comprehensive *in situ* measurements. This means the SSP parametrization is used to better adjust the model to the measured field, as this is the basic concept of focalization, and may in fact lead to highly unrealistic profiles. EOF representation is shown on Figure 3. Due to the low resolution and short time span of the data, variability of the profiles is low and the first three EOFs are responsible for over 99% of the variance.

The modeled SSP was constructed as:

$$c(z) = \bar{c}(z) + \sum_{i=1}^3 a_i v_i(z) \quad (3)$$

where $\bar{c}$ is the mean profile and v_i is each of the EOFs. The three a_i coefficients were included in the optimization, with values ranging from -3 to 3 . The gradient below the last measurement depth was also included, ranging from -0.09 to 0 m/s/m. Therefore, a total of 10 parameters are used in the focalization step for this third strategy. The optimization hyperparameters were kept the same as they were already dimensioned for a larger search space.

4. PRELIMINARY RESULTS

After the focalization procedure, replicas were computed on the same 200×100 range-depth grid to generate the ambiguity surfaces. Only some of them are shown on Figure 4, which were considered to be representative of the results. A successful localization was defined as the source being found within the same bounds used for focalization for both range and depth. Error in range and depth is referenced to towboat GPS position and source pressure sensor, respectively. The rows correspond to transmissions 1, 3 and 6, in this order, while each column corresponds to one of the strategies employed (regular MFP, geometry optimization, geometry and SSP optimization).

The ambiguity surfaces for the transmissions displayed in Figure 4 show the ways in which focalization improved the results. Where the baseline model had succeeded in locating the source, focalization provided a better adjusted model, demonstrated by higher Bartlett power (transmission 1). In the cases where localization failed for the baseline model, focalization managed to suppress sidelobes and adjust the model enough that localization was made possible (transmission 3). Although the baseline model was initially well matched to the environment, it was not tolerant to temporal and spatial variability. However, optimizing for the geometric parameters only was not always enough for a successful localization, and SSP parametrization was made necessary due to the unavailability of accurate data in this regard (transmission 6). The bottom, inverted from the first transmission, was found to be very close to the one used in the baseline model, with properties $c_p = 1630.91$ m/s, $\rho = 1.88$ g/cm³ and $\alpha_p = 0.79$ dB/λ.

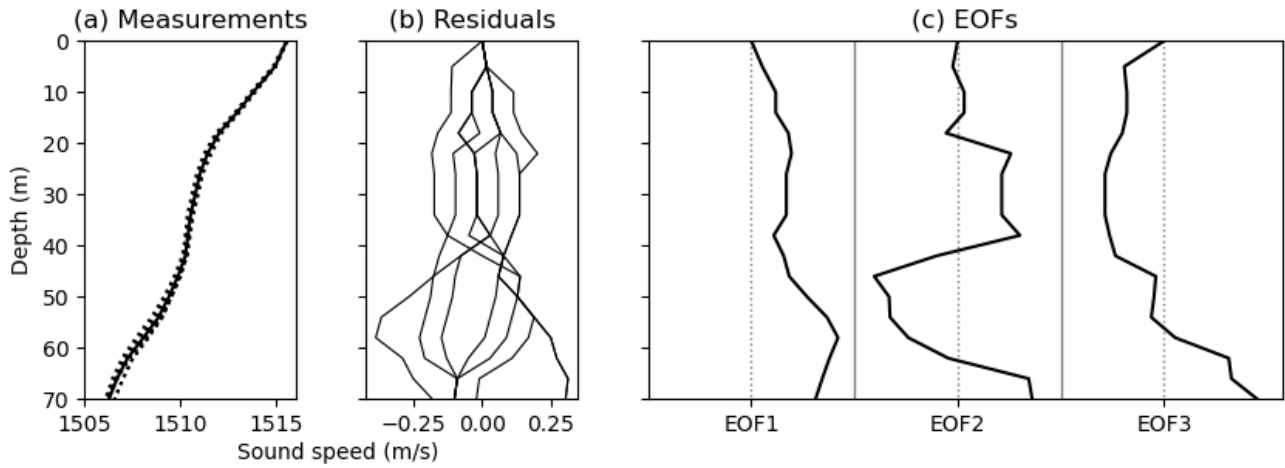


Figure 3: EOF analysis of the SSP. (a) Temperature measurements converted to sound speed. (b) Sound speed residuals. (c) First three EOFs.

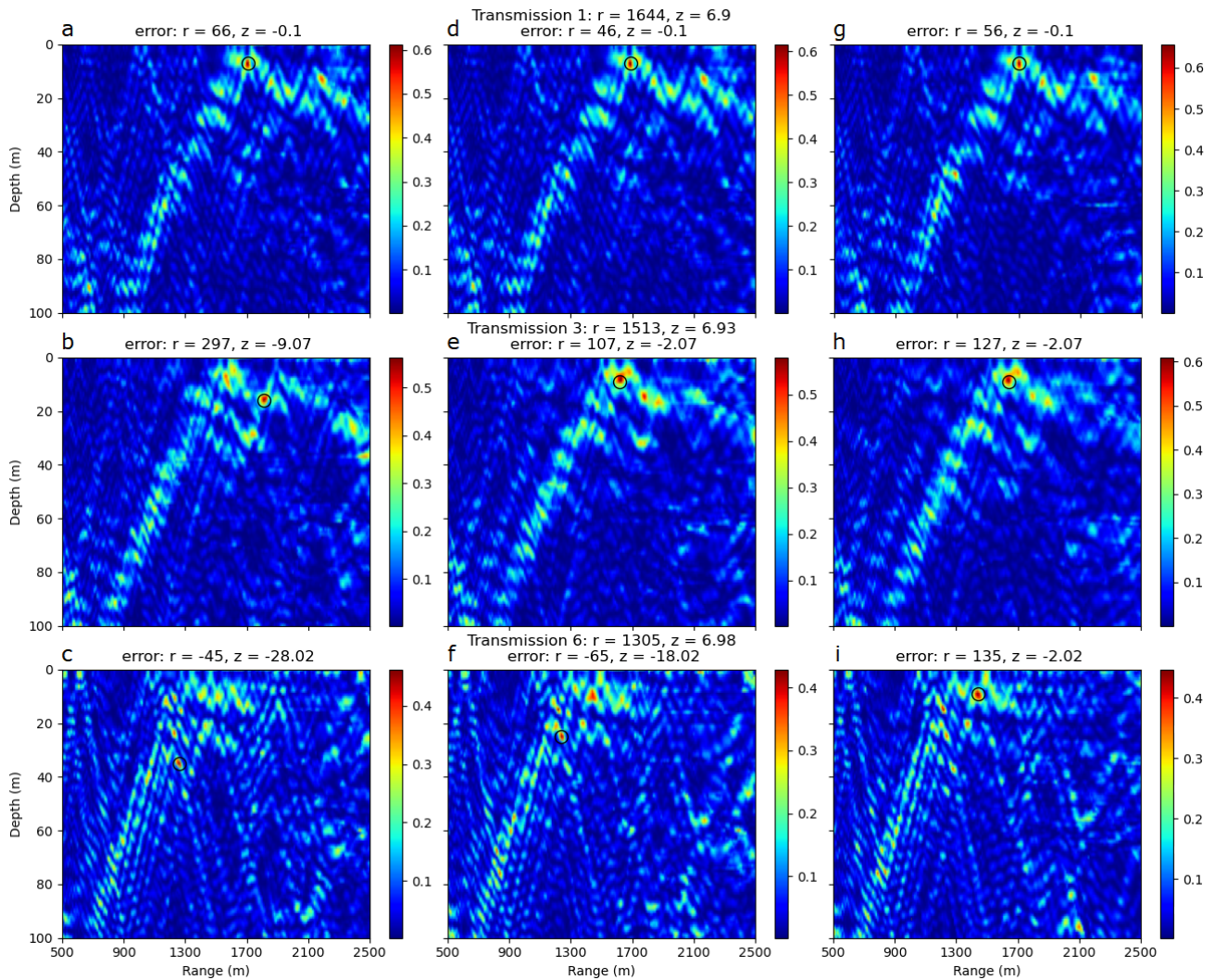


Figure 4: Ambiguity surfaces for transmissions 1, 3 and 6. Peak Bartlett is marked with a black circle. (a-c) Baseline model. (d-f) Focused geometry. (g-i) Focused geometry and SSP. Error for range (r) and depth (z) in meters, referenced to towboat GPS position and source pressure sensor, respectively.

Figure 5 shows the range and depth results for all transmissions. Focalization of both geome-

try and SSP managed to consistently result in a correct localization, except for transmission

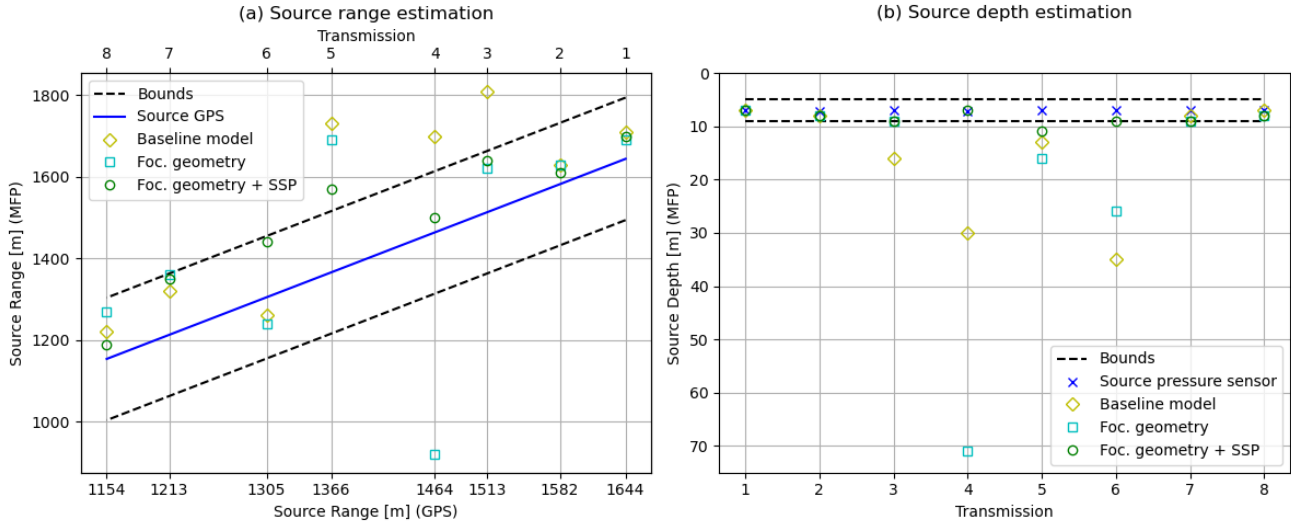


Figure 5: Localization results in (a) range and (b) depth.

5. Transmissions 4 to 6 remained with several sidelobes and lower overall Bartlett powers, as can be seen in Figure 6. This might be due to some transient effect that selectively affected the SNR of the frequency which was being analysed or could not be modeled within the constraints of the optimization step. To test this, an ambiguity surface was computed for transmission 5 using the 759.9 Hz bin. Figure 7 compares the ambiguity surfaces for both frequencies. No optimization was done for the 759.9 Hz tone, i.e., the same model as for 500 Hz was used. For this frequency, a satisfactory localization was produced. This result suggests broadband processing might be useful in this case in further suppressing ambiguities and improving the localization accuracy.

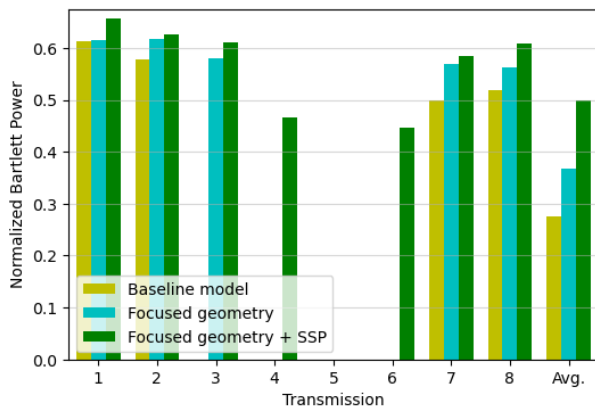


Figure 6: Peak Bartlett power comparison between strategies. Only successful localizations are shown.

The focalization step was carried out assuming a certain amount of *a priori* knowledge about the

source position to demonstrate that the model could in fact be adjusted to provide a correct localization even in face of severe lack of environmental data. Bayesian approaches, such as marginalization [21], can provide this information about the source position, in the form of marginal probability distributions over source range and depth. While marginal probability distributions allow the constraint of the search space for focalization, they don't reflect the coupling between parameters, therefore an optimization heuristic such as the one presented in this work must be employed in order to achieve a best-fit model.

5. CONCLUSIONS AND FUTURE WORK

Acoustic data from a shallow-water area with mildly range-dependent bathymetry from the CALCOM'10 experiment was successfully inverted for source location. A single frequency bin of 500 Hz and a ray-based model were used in this inversion. There was significant uncertainty about all parameters in the experiment, from source position to seabed parameters, but, mainly, the water column SSP information was limited to low-resolution approximate data.

Three strategies for localization were considered: the first was regular MFP with a fixed baseline model constructed from the available information, while the other two included a preliminary focalization step based on genetic algorithm optimization followed by stochastic hill climbing to

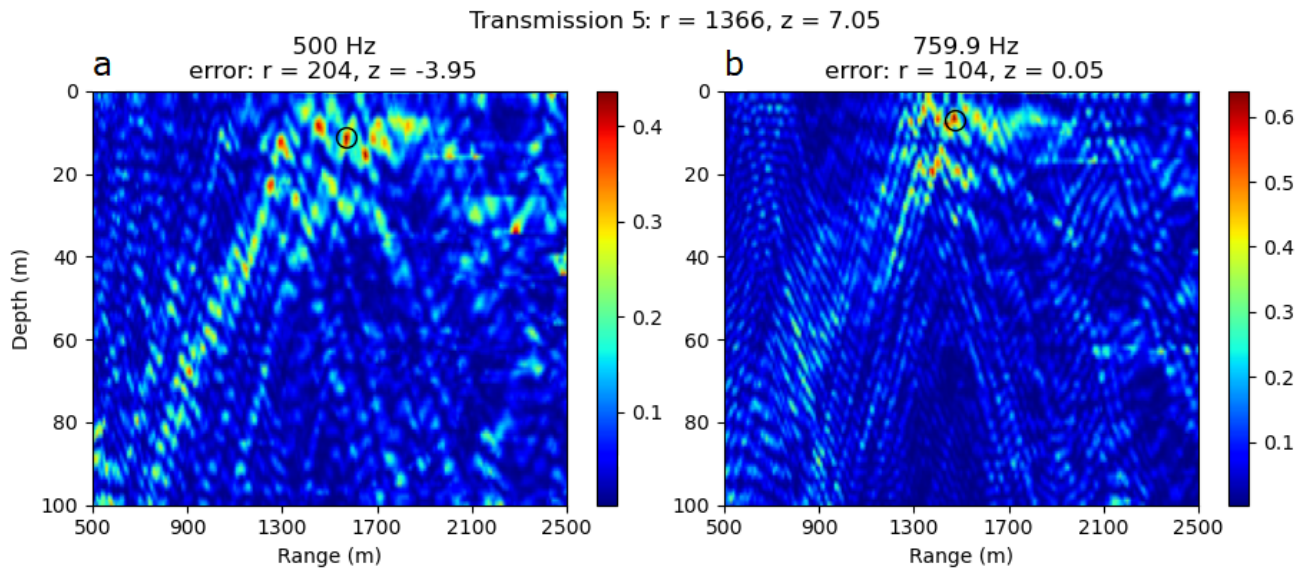


Figure 7: Ambiguity surfaces for transmission 5 optimized for geometry and SSP. (a) 500 Hz. (b) 759.9 Hz.

obtain the best Bartlett fit. For the first focalization strategy, optimization was carried out only on geometric parameters of the model, while the second included a full parametrization of the SSP in the search space by means of EOF decomposition of the very limited data.

The results show that focalization improved the MFP performance, particularly when SSP parametrization was included to overcome the limitations of the data, achieving a nearly stable localization along the track. One transmission resulted in a miss for the 500 Hz data, while two other transmissions succeeded with lower than average peak Bartlett values. Further investigation into broadband processing and the duration and number of snapshots used for the computation of the covariance matrix is required. Furthermore, there are several other tracks of the CALCOM'10 experiment, all with longer-distance, more range-dependent environments, on which this methodology remains to be tested.

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