High-frequency source localization in the Strait of Sicily

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Abstract— **One of the keys for a successful inversion of acoustic data using the Matched-field Processing (MFP) technique is the amount of environmental and geometric information available. When this information is missing or erroneous then one is in the presence of model mismatch.**

To work at higher frequencies provides better discrimination in range and depth but also increases the dependency of the inversion algorithm on mismatch which, in practice, leads to a tradeoff between discrimination and mismatch.

The ADVENT'99 sea trial took place in the area of the Adventure Bank in the Strait of Sicily during May 1999, with the objective of testing MFP techniques. A 62 m aperture vertical line array was deployed at 2, 5 and 10 km from an acoustic source. The source was emitting a series of multi-tone signals in the band of 800-1600 Hz.

This paper tests a two step MFP algorithm in the higher frequency band for the 2 and 5 km tracks: in the first step the data is pre-focused using genetic search where the environmental and geometric parameters are estimated and in the second step an exhaustive search is performed for source range and depth.

This method showed to be effective achieving a precise localization *during the whole recording of the 2 and 5 km tracks* **in the high frequency band. It is shown that the increasing MFP dependence on erroneous environmental information at high frequency and at longer ranges can only be accounted for by including a time dependent modelling of the water column sound speed profile.**

Keywords— **Source localization, focalization, high-frequencies, shallow water.**

I. INTRODUCTION

Matched-field processing (MFP) is an inversion technique that allows for locating a sound source in the ocean using acoustic data received on an array [1], [2] (see also reference [3] and references therein). Fundamentally, the technique consists in comparing the received acoustic field with replica fields generated for possible source locations using an acoustic propagation model. One key aspect in MFP is to quantify what is the necessary accuracy on the environmental data to obtain a correct and stable source location estimate. Another similar problem deals with the accuracy to which the geometry of the receiving array should be known in order to produce a meaningful MFP output [4], [5]. These problems induce what is generally called model mismatch. In classical MFP the environmental model is fixed since the search space includes only the parameters concerning the source location (typically range and depth when a vertical array is used).

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In order to combat model mismatch, a class of matched-field processors, including the so-called uncertain processors (OFUP) [6] and the focalization processor [7], emerged in the past decade. While classical MFP is conditioned on a fixed set of environmental and geometric parameters, these processors include both environmental and geometric parameters in the search space, hence reducing that conditioning [8].

MFP is also strongly dependent on frequency: increasing frequency means better discrimination in range and depth but also means a higher mismatch dependency. In practice there is a tradeoff between discrimination and mismatch that leaded to the fact that most of the experimental studies on which both classical MFP and focalization methods were applied was below 500 Hz.

The main issue to be addressed in this paper is to experimentally test whether MFP can be applied in a shallow water scenario at frequencies up to 1500 Hz and determine what are the most important causes of mismatch at those frequencies and for a source-receiver range of 5 km.

The NATO SACLANT Undersea Research Centre and TNO-FEL conducted the ADVENT'99 sea trial in order to acquire acoustic data on the Adventure Bank off the southwest coast of Sicily (Italy) in May 1999 using a vertical line array. One of the goals of this experiment was to test the performance of field inversion methods in shallow water under controlled conditions. During the ADVENT'99 experiment, the signals emitted were tones and LFM sweeps in the bands 200-700 Hz and 800-1600 Hz. A vertical array was deployed at ranges of 2, 5, and 10 km away from the source.

This paper reports source localization results achieved at 2 and 5 km range in the higher frequency band, with prior estimation of the geometry and the environment using a genetic algorithm (GA). This is done as a logical step in order to reduce the impact of the time variability of the geometric and environmental parameters and achieve more consistent correlation between measured and modelled data.

The results indicate that for this data set it is possible to achieve completely stable localization results for both tracks using multi-tones in the band 800-1500 Hz. In terms of focalization, this study shows that even at higher frequencies the number of parameters can be kept relatively low mainly by maintaining constant the seafloor parameters, and by following the environmental variability with a consistent parameterization of the sound-speed in the water column.

II. THE ADVENT'99 EXPERIMENT

The data were acquired on the Adventure Bank, off the southwest coast of Sicily (Italy), during the first three days of May of 1999. This area has a low range-dependence, and was found to be favorable for acoustic propagation. The measured water depth was 80 m. The acoustic source was mounted on a moored tower 4 m off the bottom at a depth of 76 m. The signals were received on an acoustic array of 31 elements with a total length of 62 m. Each day the array was deployed at different ranges of 2, 5, and 10 km. Broadband acoustic linear frequency modulated signals and multi-tones were transmitted every minute. To accomplish this, two sources were used, one for lower frequencies (200-700 Hz), and another for higher frequencies (800-1600 Hz). The transmission time was around 5 hours for both 2 and 5 km tracks.

For sound speed measurements a 49-element Conductivity-Temperature-Depth (CTD) chain towed by ITNS Ciclope with a data sampling rate of 2 s was used. The CTD chain spanned around 80% of the water column reaching a maximum depth of 67 m, and was continuously towed between the acoustic source and the vertical array (10 km track). See refs. [9] and [10] for a more detailed description of the experiment.

In order to check the variability of the array received acoustic signal through time, figure 1 shows the correlation of a reference signal received at time $t_0 = 0$ with the subsequent signals (in this case the LFM sweeps) given by

$$C(f,t) = \underline{x}(f,t_0)^H \underline{x}(f,t), \qquad (1)$$

where $\underline{x}(f,t)$ is an N-dimensional vector with the array measured acoustic pressure at frequency f and time t. The symbol ^{H} denotes transposed conjugation. It can be seen that the correlation time falls off as the frequency and range increases. Abrupt changes in the correlation values are noticed, especially for the longer range, where high correlation values last only for approximately 1 hour. Signal correlation tends to deteriorate faster at longer (5 km) than at shorter ranges (2 km). The abrupt changes in the correlation values suggest that within a few minutes there is a drastic change in the environmental properties. This suggestion is reinforced by the correlation range and frequency dependence where for larger ranges and at higher frequencies this environmental variability acoustic signature is more likely to occur.

III. PARAMETER ESTIMATION USING GA AND SOURCE LOCALIZATION

In order to achieve stable source location estimates in a highly time-variable environment, the processing was developed in two steps:

1. GA estimation of geometric and environmental parameters: in order to determine (focus) the geometric and environmental parameters to be used in the source localization step.
2. exhaustive range-depth source localization with parameters obtained in step 1.

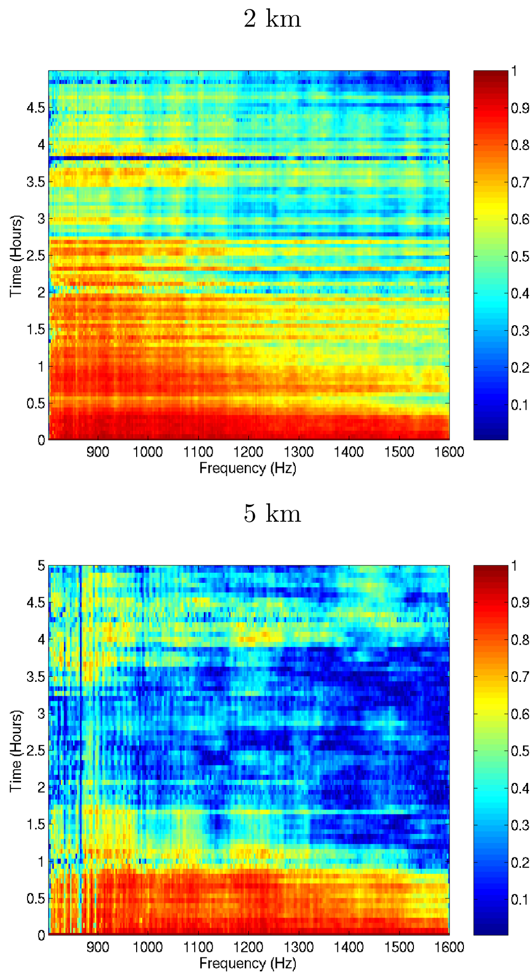

Fig. 1. Matched-field Correlation of the received acoustic signals with the signal received at time $t = 0$ as a function of frequency and time: the data are LFM chirps acquired during the ADVENT'99 experiment at source-receiver ranges of 2 and 5 km(from top to bottom) and 800-1600 Hz.

One of the difficulties associated with any MFP study is the choice of the environmental model to represent the real environment where the acoustic signal propagates. That model - that we refer to here as the *baseline model* - contains a mathematical description of the real environment that heavily conditions the attainable set of solutions.

A. The Baseline Model

The baseline model consists of an ocean layer overlying a sediment layer and a bottom half space, assumed to be range independent, as shown in Fig. 2. For the purposes of the inversion the forward model parameters were divided in two subsets: geometric parameters and water column parameters. The geometric parameters include source range, source depth, receiver depth, array tilt and water depth. The parameterization used for the water column parameters will be explained later. The baseline sediment and bottom properties used for the experimental site were those estimated by Siderius [11] using the low frequency data set. Figure 2 shows an example of sound speed profile measured close to the vertical array, at 5 km distance from the sound

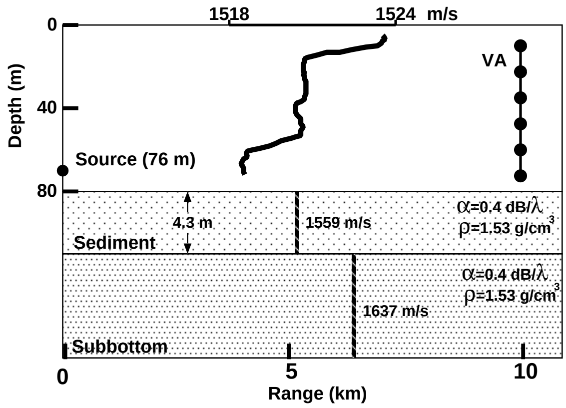

Fig. 2. Baseline model for the ADVENT'99 experiment. All parameters are range independent. The model assumes the same density and attenuation for sediment and sub-bottom.

source, in May 02 at 06:38. This is a typical sound speed profile with a double thermocline at 10 and 55 m depth with isovelocity layers in between.

B. The objective function

The focalization of the environment and geometry (step 1) was posed as an optimization problem, that is to find a vector of parameters $\underline{\theta}$ that maximizes an objective function, which in this case is the conventional incoherent broadband processor defined as

$$P(\underline{\theta}) = \frac{1}{N}\sum_{n=1}^{N} \underline{p}^H(\underline{\theta},\omega_n)\hat{\mathbf{C}}_{XX}(\omega_n)\underline{p}(\underline{\theta},\omega_n), \qquad (2)$$

where $\hat{\mathbf{C}}_{XX}(\omega_n)$ is the sample cross-spectral matrix obtained from the observed acoustic field at frequency ω_n, N is the number of frequency bins, and $\underline{p}$ are the replica vectors to be matched with the data. All factors in (2) have norm equal 1, hence the maximum attainable value of $P(\underline{\theta})$ is 1.

The cross-spectral matrices were computed out of the time series received at the 31 hydrophones for the tones' higher frequencies (800, 900, 1000, 1200, 1400, 1500 Hz). Each ping of 10 s was divided into 0.5 s non-overlapping segments, where the first and last segments were discarded, giving a total of 18 segments. Then the 18 data segments were Fourier transformed, the bins corresponding to the multi-tone frequencies extracted, and the sample cross-spectral matrices computed. This procedure was repeated every 28 minutes for the 2 km track and at every 32 minutes for the 5 km tracks, for a total of 12 estimates for each track. Note that, for convenience and perceptibility, the ambiguity surfaces shown throughout this paper are only the odd numbered surfaces out of the 12 estimates.

C. Model parameter estimation and source localization

In order to cope with the time-variability of the acoustic field for each range track the source-receiver geometry and the environmental parameters were optimized using genetic algorithm (GA) search. The GA parameters were adjusted as follows: the number of iterations was set to 40 with 3 independent populations of 100 individuals; crossover and mutation probabilities were set to 0.9 and 0.011 respectively. Note that these GA parameters were slightly readjusted as necessary.

The GA optimization was carried out using a varying number of environmental parameters depending on the track. Throughout this paper it will be explained which environmental and geometric parameters were included in each inversion, but only source localization results are reported.

Table I shows the geometric parameters of the forward model and their respective search bounds for each range track. Note that source and receiving array depth are coupled to water depth, and therefore referred to as bottom height.

Forward models were computed using the SACLANTCEN normal mode propagation code C-SNAP [12].

C.1 The 2 km track

The 2 km data set was optimized using the search intervals shown in Table I and the sound-speed profile was linearly extrapolated down to the bottom using the two deepest sound speed values. No optimization was performed for the water depth since no significant water depth changes were expected in the relatively short range of 2 km. Range-depth ambiguity surfaces were computed for source ranges varying from 1 to 3 km, and source depth between 10 and 80 m using the baseline environmental parameters and the previously GA estimated geometry. Figure 3 shows only the odd numbered ambiguity surfaces, and Table II summarizes the results obtained through time in terms of mean and standard deviation. The time elapsed between surfaces is 28 minutes except between surfaces 2 and 3 (where transmissions were interrupted). It can be observed that all surfaces show a relatively stable ambiguity pattern with a clear peak outstanding from the background at the correct source position. The standard deviation is low for the source parameters and the Bartlett power has a mean of 0.57 (Table II). A full optimization including all seafloor parameters has shown little dependence of the acoustic field in this frequency band, and therefore it is not worth to include those parameters in the search space.

C.2 The 5 km track

Having obtained stable results on the 2 km data set, the next step is to study the effect of a larger source range (5 km). The first step included the optimization of the geometric parameters using the higher frequency data set, according to the search intervals of Table I, and with the geoacoustic parameters of the baseline model. The sound-speed profile was that measured close to the vertical line array. Using the previously estimated optimized parameters, ambiguity surfaces were computed for the higher frequency multi-tones data set (Fig. 4). In this case the algorithm completely failed to localize the source. Close observation of the surfaces, reveals that in the first half of the run there is an ambiguity structure (peaks and sidelobes of maximum

Parameter	**2 km**		**5 km**	
	min	max	min	max
source range (km)	1.8	2.6	4.7	5.8
source height (m)	1	10	1	10
array height (m)	1	15	1	15
array tilt (rad)	-0.025	0.025	-0.025	0.025

TABLE I

Search bounds for the GA optimization of the geometric parameters: source and array last receiver height are measured from the water-sediment interface and are therefore coupled with the water depth search parameter.

Parameter	**2 km**		**5 km**	
	mean	std	mean	std
source range (km)	2.23	0.041	5.44	0.048
source depth (m)	76.5	0.22	75.6	0.37
Bartlett power	0.57	0.072	0.60	0.047

TABLE II

Summary of the source localization results for the 2 and 5 km track in terms of mean and standard deviation. The data are the higher frequency multi-tones (800-1500 Hz).

correlation) close to the expected structure, and also that surfaces (4) and (5) have the peak at the correct location (surface (4) not shown in Fig. 4). The structure that appears in surface (1) to (6) disappears in surfaces (7) to (12) and this causes the true source location to be completely missed. This result suggests that somehow there is misadjustment of the environmental model that leads to a complete mismatch in the second half of the run.

The next attempt was to increase the degrees of freedom of the environmental model by parameterizing the sound speed profile in order to capture the time variability of the acoustic signal in the high frequency data set. It is possible to parameterize the sound-speed profile using one or several parameters that can be searched as free parameters and combined with site measurements. Since at sea, it is impossible to keep track of the exact depth of most of the deployed devices, one of the included search parameters was the depth of the CTD chain used for measuring the temperature in the water column. This was motivated by the fact that the CTD chain was towed by ITNS Ciclope, giving rise to inevitable up and down accelerations due to wave action and ship navigation. A search interval of 4 m was therefore included in the depth of the sound speed profile measurements used in the model. Another parameter included in the search space was the gradient of the sound speed profile in the portion between 67 m and the bottom, which is a region of the water column not covered by actual measurements. This is possibly very important for predicting the acoustic field since the sound source was located near the bottom at 76 m depth. For the 2 km track, the sound speed profile was completed by extrapolating the two deepest sound speed values down to the bottom which may lead to incorrect sound speed values. In this case, including the gradient as a search parameter, implicitly assumes that the sound-speed behaves linearly as the depth increases. Even if this is a simple and crude assumption, this parameterization was judged sufficient to model the last values of the sound-speed close to the bottom. The third and last attempt to track the time variability of the acoustic data in the 5km-high frequency data set, was to include a full parameterization of the sound speed profile evolution through time using a set of data based Empirical Orthogonal Functions (EOFs). EOFs are shape functions [13] that can be obtained from a database and are very efficient to reduce the number of data points to be estimated. If historical data is available, an efficient parameterization in terms of EOFs leads to a faster convergence and higher uniqueness in the optimal solution since a large amount of information is already available and the search is therefore started close to the solution. For this purpose, EOFs are constructed from representative data by sampling the depth dependence of the ocean sound speed. The EOFs can be obtained from a singular value decomposition of the sample covariance matrix, together with an approximation criteria that is used to obtain the number of EOFs required to accurately represent the sound-speed. The criteria used here was to take the number of required EOFs such that they represent more than 80% of the total energy in the water column. In the case handled here, using a database of sound-speeds measured close to the vertical array, the number of representative EOFs was set to three. By trial and error, the search interval for the coefficients combining the (previously normalized) EOFs was chosen between -5 and 5.

The total number of parameters included in the focalization step is now 9, four concerning the geometry, and five concerning the sound-speed in the water column, corresponding to a search space with size 2×10^{15}. Regarding the GA optimization and in order to cope with this larger search space, the number of iterations was set to 40, the number of individuals was set to 140, and the number of independent populations was three which corresponds to

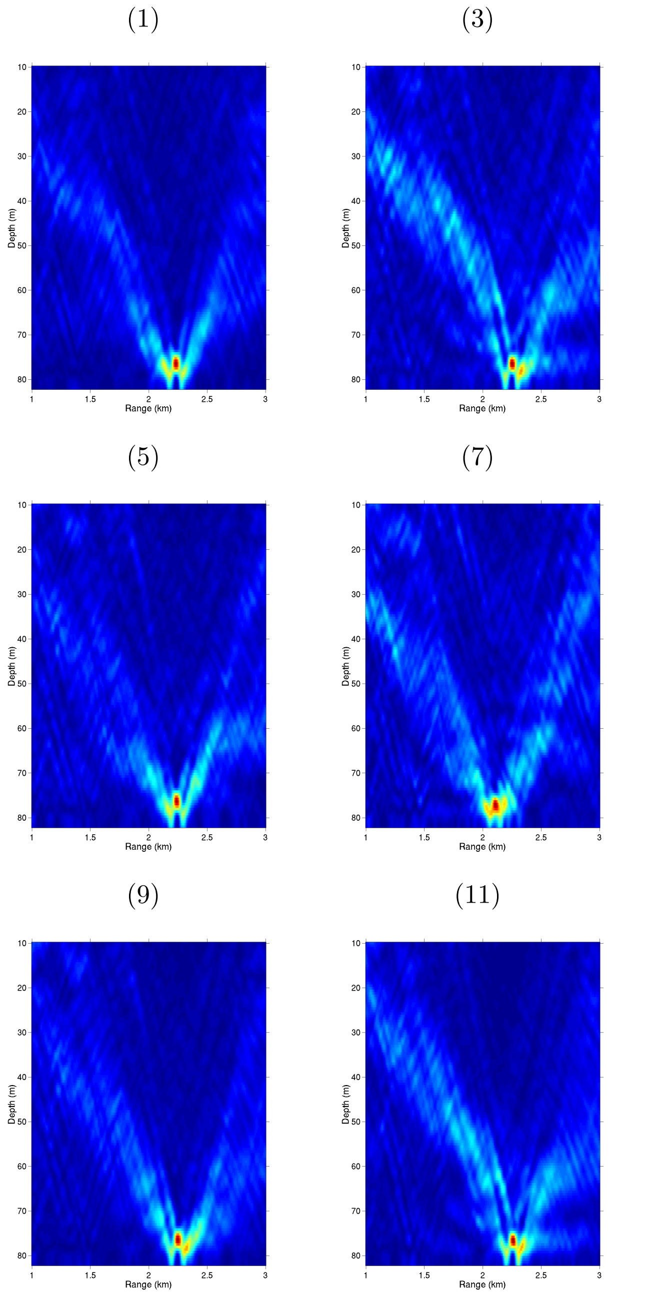

Fig. 3. Incoherent Bartlett ambiguity surfaces obtained for the 2 km track using 6 multi-tone frequency bins in the band 800 to 1500 Hz.

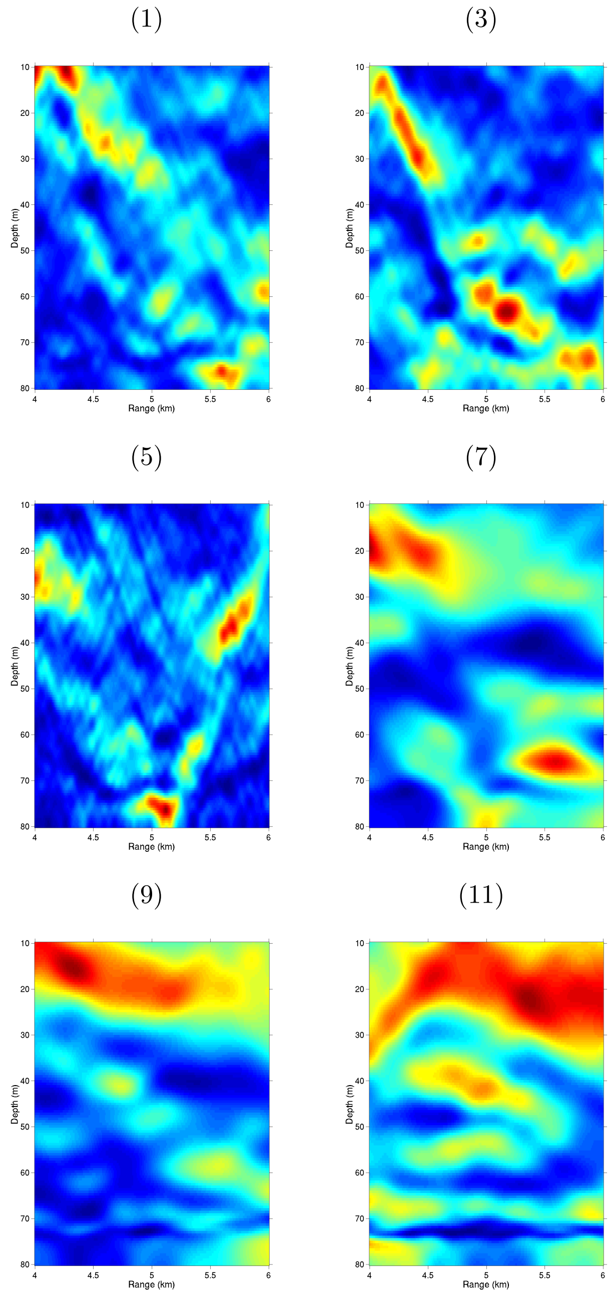

Fig. 4. Incoherent Bartlett ambiguity surfaces obtained for the 5 km track using 6 multi-tone frequency bins in the band 800 to 1500 Hz.

about 1.5×10^4 forward models to be computed.

Observing the ambiguity surfaces obtained after accomplishing the focalization step, (Fig. 5) it can be seen that the main peak is always nearly at the correct location, within negligible variations, and the ambiguities are largely suppressed. In Table II it can be seen that the variability of the source parameters is in the same order of greatness as those obtained for the 2 km track and that the mean Bartlett power is even higher than that obtained for the 2 km track. The parameterization chosen for the sound speed allowed for modelling the environment such that localization results of high quality could be obtained for the high frequency data set.

IV. CONCLUSION

Acoustic data were collected in a 80 m depth mildly range-dependent shallow water area of the Strait of Sicily, during the ADVENT'99 sea trial in May 1999. A vertical line array was deployed at three different ranges of 2, 5 and 10 km from an acoustic source mounted on a tower 4 m off the sea-bottom. A series of multi-tones and LFM sweeps were transmitted in two frequency bands of 200 to 700 Hz and 800 to 1500 Hz.

A two stage MFP algorithm was applied throughout the processing of the higher frequency data: a first stage for environmental focalization using genetic algorithms to search

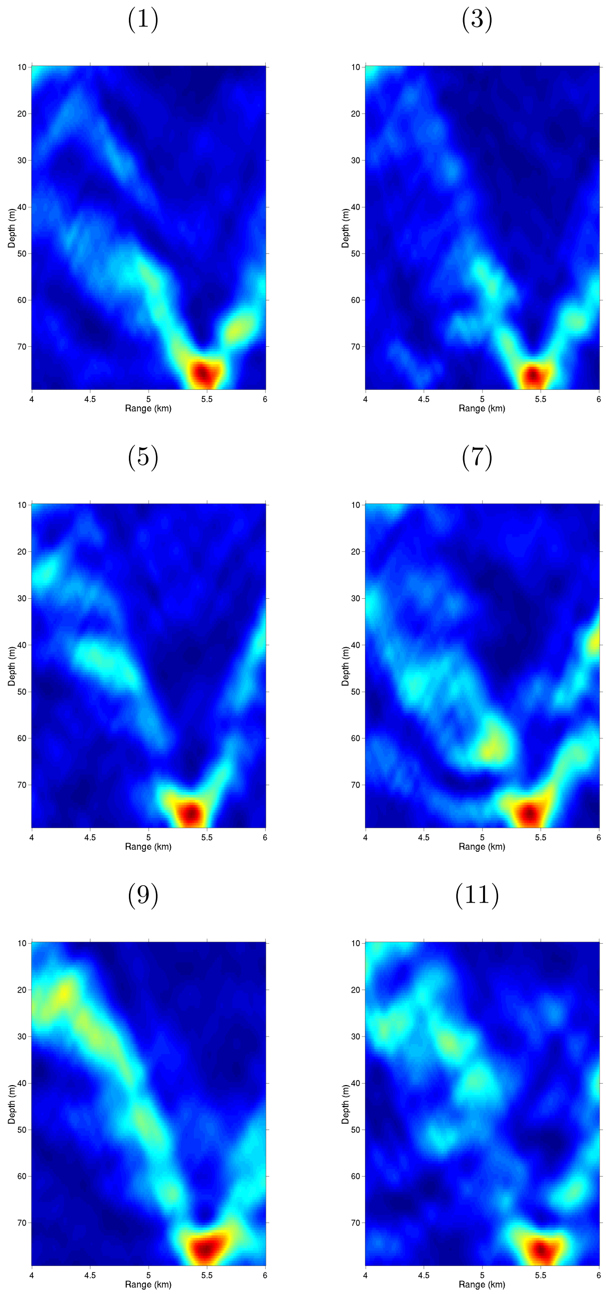

Fig. 5. Incoherent Bartlett ambiguity surfaces obtained for the 5 km track using 6 multi-tone frequency bins in the band 800 to 1500 Hz. The focalization step included estimation of the sound speed profiles via EOFs.

for the parameters giving the best Bartlett fit and then a second stage for computing the MFP ambiguity surfaces in range and depth for source localization.

Concerning the analysis of the ADVENT'99 data, one of the conclusions in reference [11] is that the environmental variability at longer ranges destroys coherent processing and propagation prediction of acoustic data. This paper completes reference [11] with the following conclusions: first, is that the bottom parameters could be estimated from the short range 2 km track and hold constant for the 5 km range; second, it was found that, as the range was increased, the water column variability became more important to obtain correct matches - with particular difficulties due to the short wavelength; third, that water column variability could be modeled using an EOF expansion of the sound speed profile which coefficients could be estimated with the focalization process; fourth, with a full sound speed model focalization, precise MFP localizations could be obtained at all ranges working at frequencies up to 1500 Hz.

The results reported in this paper indicate that under controlled conditions and in a mildly range-dependent shallow water environment, it is possible to accurately model the acoustic field for a range 5 km and frequencies up to 1.5 kHz to correctly localize an acoustic source over time if the optimized modelling process has into account possible time variabilities in the water column.

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