MATCHED FIELD PROCESSING: ENVIRONMENTAL FOCUSING AND SOURCE TRACKING WITH APPLICATION TO THE NORTH ELBA DATA SET

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Abstract: *Experimental results on the localization of a moving sound source in shallow water are presented. Genetic algorithms (GA) are used to first intensively estimate the environment from a fixed source part of the data. Then, assuming the stationarity of the environment, localization is carried out in the moving source part of the data. Comparison with results obtained previously on the same data set shows that the source range error is reduced by 75%, while the source depth error is reduced by approximatelly 50%. Further, using a band of 20 Hz instead of a single frequency conducts to more stable source location estimantes.*

I- Introduction

The SACLANT Undersea Research Centre has conducted a sea trial on North of Elba Island in October 1993. The objective of that sea trial was to collect data to verify the performance of geoacoustic and geometric parameter estimation methods based on the inversion of acoustic field observations received on a vertical array of sensors. The data set made available to the authors comprises one period of time where the source is being held fixed and another period where the source is moving away from the receiving array. In a first publication Gingras *et. al.* [1] have obtained simultaneous estimates of environmental and geometric parameters using a single frequency Bartlett processor in the stationary source data. A global search procedure based on genetic algorithms (GA) was used for parameter optimization. Source tracking was then carried out in the moving source data using the previously estimated environmental parameters. Later on, on a second publication [2], the same scheme has been followed using two frequency bands. A range-dependent adiabatic normal mode code was used as forward model and it could be shown that at lower frequencies range dependence was not required while a better model fit was obtained at higher frequencies when range dependence was included. The same data set was used by Krolik [3] to test various Minimum Variance (MV) adaptive beamformers. Single frequency data was used and the environmental parameters were assumed to be within the same interval as in [1]. Among the proposed processors, the MV-EPC†[1] achieved the best source tracking performance and similar to that obtained in [1] with, however, a much less intensive computation load, since no environmental search was performed.

The goal of the present work is to estimate the position of a moving source and demonstrate that the accuratness to which that estimate can be obtained mainly depends on the environmental parameter set used in the forward model processor. The novelty of the work presented in this paper is that the estimation of that environmental parameter set is performed through an intensive GA search - mainly by increasing the population size. It is also shown that using a broadband processor, in a 20 Hz band around 170 Hz, the variance of the source location estimator is reduced, when compared to the single frequency processor. In order to make a fair comparison, a single frequency source tracker was used and the results compared to those of Gingras *et al.* [1]. It is shown that the source range error is reduced by 75% while the source depth error is reduced by approximately 50%.

II- Environmental Parameter Estimation

A- *Theoretical Background* Matched-field processing (MFP) can be briefly reviewed as follows. The acoustic pressure is measured in an array of sensors. Then, an accurate acoustic model, fed with an appropriate environmental and geometrical model candidate, is used to compute the predicted acoustic pressure replica field. Then a variety of methods is available which, in general, involve some kind of correlation and serves the purpose of comparing the measured and replica fields. Each comparison may be called the MFP response to the environmental and geometric model candidate, and finaly the parameter set with the best response is selected. This is an inverse problem, and may be posed as an optimization where the objective function is the MFP response to be maximized. In this case

[1] †Minimum Variance with environmental perturbation constraint

the goal is to find a model vector $\underline{\vartheta}$ that maximizes the objective function, which may be written as the Maximum Likelihood estimator:

$$L(\underline{\vartheta}) = -\sum_{j=1}^{J} \ln \mathrm{tr}[(\mathbf{I} - \mathbf{P}(\omega_j, \underline{\vartheta}))\hat{\mathbf{C}}_X(\omega_j)], \qquad (1)$$

where $\mathbf{P}(\omega_j, \vartheta) = \underline{H}(\underline{H}^H \underline{H})^{-1} \underline{H}^H$ is a projection matrix of the measured data into the subspace spanned by $\underline{H}$ at the frequency ω_j, $\underline{H} = \underline{H}(\omega_j, \vartheta)$ is a vector with the replica field predicted by the forward model, and $\hat{\mathbf{C}}_X(\omega_j) = \frac{1}{N}\sum_{n=0}^{N-1} \underline{X}_n(\omega_j)\underline{X}_n(\omega_j)^H$ is the sample spectral density matrix at frequency ω_j.

B- *The Baseline Model* The baseline model used for simulations is depicted in Fig. 1 and corresponds to that used by Gingras [4]. It consists of a 127 m depth ocean layer overlying a 2.5 m thick sediment over a half space subbottom. The parameters to be estimated were subdivided into three subsets: the geometric subset (source depth, source range, water depth, array depth), the sediment subset (upper compressional speed, lower compressional speed, density, thickness, attenuation), and the subbottom subset (compressional speed, density, attenuation). The environment was considered range independent.

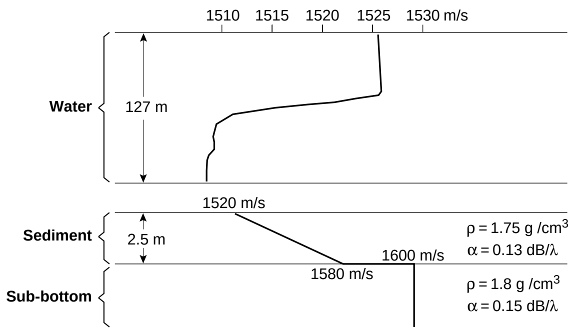

Figure 1: Measured sound speed profile and historical geoacoustic parameters for the North Elba experiment site.

C- *Model parameter estimation* The goal is to obtain estimates of the source locations in the moving source portion of the data. For this purpose the environment is first estimated from the fixed source data and then supposed stationary during the moving source part of the data. The sampling frequency was 1 KHz and the FFT block-size was 1024. The sample spectral density matrices were computed in the frequency interval 161.1 to 179.7 Hz, as the average of 10 cross-spectral matrices computed from a time epoch of aproximately 1 second each. This procedure was repeated every minute of data. Before starting optimization with the GA a few parameters have to be adjusted: the population size was 270, the number of iterations to 100, the crossover probability was 0.7 and the mutation probability was equal to 0.00875. The final environmental parameter vector estimate over the 10 minutes of data was taken as the mean of the best GA candidates from 5 independent runs on each 1 minute data segment. For comparison purposes the whole procedure was done for a single frequency (169.9 Hz) and in a 20 Hz bandwidth centered in 170 Hz as explained above. The parameter search space was the same as that of Gingras *et al.* [1], except for the source range interval that was much larger in our case, ranging from 5 to 8 km. Another difference is that, instead of estimating sediment and subbottom compressional speeds directly, as done in [1], the water-sediment interface compressional speed is taken as reference and then only the differences between that value and the sediment-subbottom interface and subbottom half-space velocities are estimated. Also, those differences are assumed to be always positive, which puts an additional constraint into the search. To give an idea of the computational effort involved in the search procedure, it is sufficient to say that the total search space contains about 10^{24} points, while for each inversion only about 10^6 of those points were explored.

Table 1 shows the results of the narrowband (NB) and broadband (BB) processors. The results given by those two processors are only slightly different. The two last lines of table 1 show the normalized Bartlett peak powers in dB, for the NB and the BB estimated models. These four numbers represent the adjustment - or misadjustment - of the estimated NB and BB models to the data. As it can be noticed, the model adjustment is poorer when measured at one single frequency with the BB model than with the NB model. Similarly, the model adjustment in a frequency band - taken as the mean of the Bartlett peak powers at each frequency in the band - is poorer with the NB model than with the BB model. Strict interpretation of those numbers would indicate that model adjustment is always better in the frequency band on which the environmental parameters were estimated. However, model adjustment is not all in the MFP process since, as it will be seen in the next section, the localization of the moving source gave similar results in narrow and broadband while much stable in the later.

Another way to illustrate the model adjustement dependency on frequency is shown in figure 2. That figure represents the mean square error (mse) between the predicted and measured acoustic fields along the receiving array for each frequency within the considered band. It can be seen that in the neighborhood of the central frequency of 170 Hz the mse is lower for the narrowband model than for the broadband model. When moving away from the central frequency the mse of the narrowband model increases while the mse of the broadband model decreases. The reason for this is that in the narrowband case a good match is forced only for one frequency, while in the broadband case the field has to be matched for the whole band of frequencies.

When comparing the results shown in table 1 with those of [1], substantial differences can be noticed, specially for the source location: those obtained here are in all cases

Model parameter	NB	BB
Geometric		
source range (m)	5602	5593
source depth (m)	76.0	76.3
receiver depth (m)	112.6	113.4
water depth (m)	129.4	129.4
Sediment		
comp. speed upper (m/s)	1486	1477
comp. speed lower (m/s)	1534	1538
density (g/cm^3)	2.3	2.3
attenuation (dB/λ)	0.08	0.09
thickness (m)	3.3	3.7
Bottom		
comp. speed (m/s)	1572	1571
density (g/cm^3)	1.87	1.82
attenuation (dB/λ)	0.11	0.11
NB Bartlett Power (dB)	-0.23	-0.26
BB Bartlett Power (dB)	-0.40	-0.35

Table 1: Estimation results for the narrowband and broadband processors

closer to the expected values. One reason for that is the number of iterations and the population size chosen by Gingras, that seem to be too low for the optimum of the surface to be attained. In reality the number of forward iterations used here is of the order of 1.5 10^6 while in [1] it was 2 10^5 which represents less than a factor 10 increase and irrelevant when compared to the search space size of 10^{24}.

III- **Moving source tracking**

Assuming that the environment is stationary, the parameters estimated above are used for estimating the source position during the set of data in which the source is moving away from the receiver. Again, both the single-frequency and multi-frequency cases were considered. The procedure for estimating the cross-spectral matrices was identical as for the fixed source part. In the GA optimization procedure both the population size and the number of iterations were considerably reduced to 40 and 20, respectively. The crossover probability was ajusted to 0.7 and the mutation probability to 0.041. Figure 3 shows the results obtained for the source range and depth in the single frequency case. For comparison purposes the true source range/depth position and the results obtained by [1] are shown in the same figure. It can be easily noticed that the approximately constant 400 m bias in range obtained by Gingras was considerably reduced to 100 m - which is within the GPS accuracy used for the true range curve [4]. Source depth estimation during has also been improved with an error of approximately 3 m against 5 or 6 m for Gingras *et al.* For the broadband case the source range estimation results, Fig. 4, are very similar to those obtained in the single frequency case with, however, considerably less

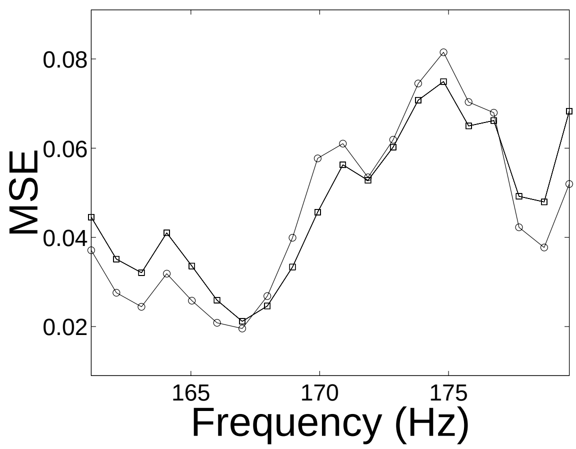

Figure 2: Error between the measured acoustic field and predicted field using: the narrowband environmental estimates (squares) and the broadband environmental estimates (circles).

Time	NB	BB
1	88	85
2	97	123
3	106	100
4	94	100
5	82	88
6	111	100
7	173	120
8	82	103
9	85	117
mean	102	104
std	29	14

Table 2: Estimated source speed in m/minute during source tracking for the narrowband (NB) and the broadband (BB) cases ; bottom lines are mean speed and standard deviation

oscillations. In order to quantify those oscillations, table 2 shows the estimated source speed, *i.e.* the slope of the curve range vs. time, in m/minute for the narrowband and the broadband cases. That source speed should be relatively constant and as close as possible to the surface ship speed of 108 m/minute. Both the narrowband and the broadband processors provided a mean speed close to the expected surface ship speed with, however, a much smaller standard deviation of 14 m/minute in the broadband case than the 29 m/minute in the narrowband case.

Finally, a comparison of the normalized Bartlett peak power for the narrowband and the broadband MF processors is shown in Fig. 5 together with equivalent results obtained by Gingras [1]. Assuming that the Bartlett peak power is an indicator of model adjustment, it can be noticed that the model estimated in this paper offers, in general, and specially for the broadband case, a much better fit than that provided by the model estimated by Gingras.

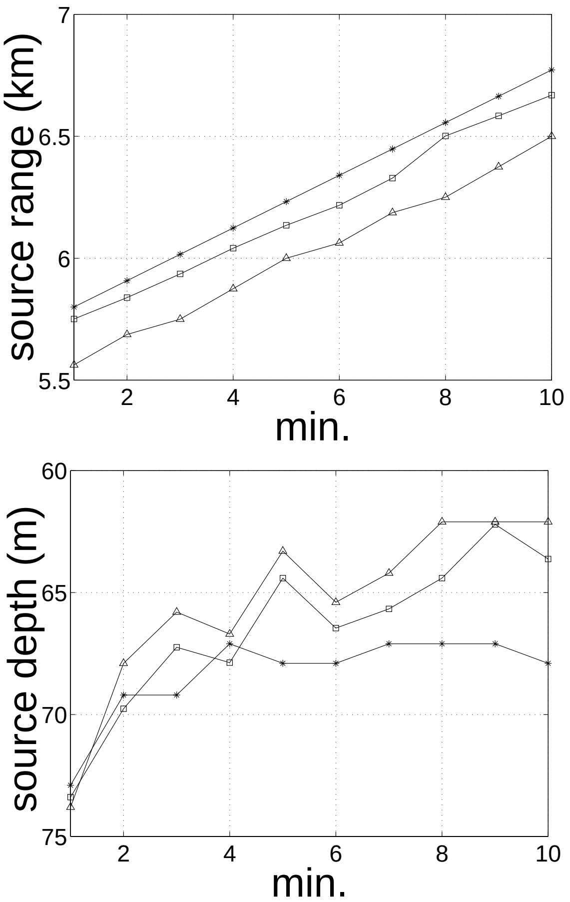

Figure 3: Comparison of source tracking results in the single frequency case: source range (a) and source depth (b); GPS estimated location (asterisks), narrowband tracking (squares),tracking in [1] (triangles)

One more interesting point is that, considering the bandwidth in this example, the computation of a broadband model is not significantly more expensive than that of a single frequency. On an DEC4100 AlphaServer (1 processor), CSNAP needs 86 ms to compute a model for the single frequency and the 126 ms for the 20 Hz band, which is only a 50% increase in computation time.

IV- **Conclusion**

MFP was applied to the North Elba data for locating a moving sound source. First the acoustic channel environmental parameters were estimated using an intensive genetic algorithm based search procedure in a portion of the data where the source was stationary. Then, holding the environmental parameters fixed, the moving source part of the data set was processed to test the source tracking capabilities of the algorithm. Both the environmental parameter estimation and the source tracking were performed at a single frequency of 170 Hz - in order to facilitate comparison with previous results - and in a band of 20 Hz around that single frequency. The results have not only shown

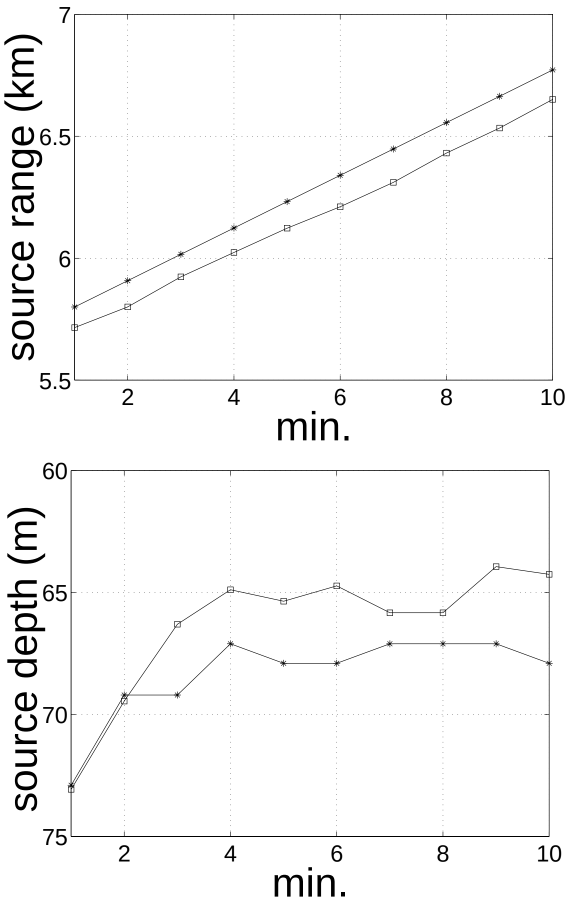

Figure 4: Broadband tracking results: source range (a) and source depth (b); GPS estimated location (asterisks), broadband tracking (circles)

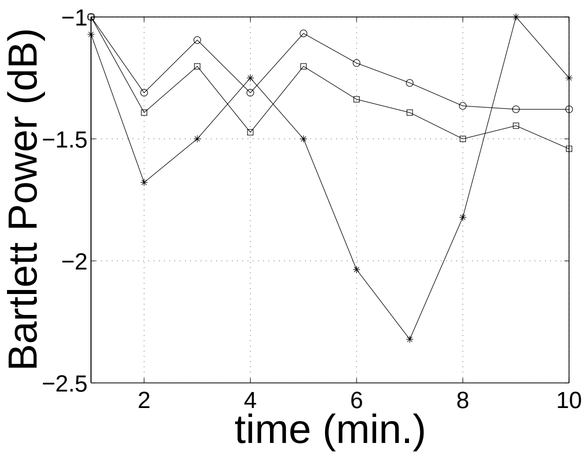

Figure 5: Normalized Bartlett peak power during source tracking in the narrowband case (squares), broadband case (circles), and form [1] (triangles)

that the environment stationarity assumption is valid, but also that broadband algorithm can give a real improvement to the source tracking. This result has been obtained due to a more intensive optimization search during the environmental inversion than that in previous studies. This shows that joint estimation of the environment and source location along time – generaly known as focusing [5] – can be advantageously replaced by a computationally more expensive inversion of the environment on part of the data followed by a much less intensive algorithm for source location estimation.

V- **References**

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