Incoherent versus Coherent Matched Mode Processing for shallow water source localization using a single hydrophone.

B. Nicolas[1], G. Le Touzé[1], C. Soares[2], S. Jesus[2], J.I. Mars[1]
[1]GIPSA-LAB, Dep Image Signal, 961, Rue de la Houille Blanche, BP 46, 38402 St Martin d´Heres Cedex, France
barbara.nicolas@gipsa-lab.inpg.fr
[2]SIPLAB, FCT-Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

Abstract- *The aim of this paper is to propose a method of source localization using a single hydrophone in shallow water. To perform this localization, modes are first filtered in the time-frequency plane and then used in two different Matched Mode Processors: Incoherent and Coherent broadband processors. Results on simulated data are presented.*

Keywords: source localization , shallow water, modal filtering, Matched Mode Processing.

I. INTRODUCTION:

Source localization using a single hydrophone is a challenging task. The first method has been proposed by Frazer et al.[1] but was very sensitive to the environment knowledge. Then, Kuperman et al. [2] proposed a localization method based on spectrogram in deep water environments. More recently, Jesus et al. [3] developed a method based on ray theory in the low frequency domain (300-800 Hz).

As we focus on low frequency waves (1-100 Hz) in shallow water environments, none of these methods can be used. In our case, propagation is modeled by mode theory and this propagation has to be taken into account to localize the source. Consequently we propose in this paper two Matched Mode Processing methods based on modal filtering in the time-frequency plane to localize an Ultra Low Frequency source in depth and range using a single hydrophone.

After a short presentation of propagation and modal filtering, we present the two processors that we developed: Incoherent and Coherent broadband Matched Mode Processors (MMP) on a single hydrophone. The processors are applied on simulated data.

II. MODAL FILTERING AND MATCHED MODE PROCESSING

A) Modal Propagation

Considering a Ultra Low Frequency source (1-100 Hz) in a shallow water environment allows the use of normal mode theory to model the propagation. In this case, for a broadband source S located at (R_s, Z_s) in a classical Pekeris waveguide (made of two isovelocity layers), the received acoustic field on the hydrophone $M(0, Z_h)$ is expressed, in the frequency domain, by:

$$Y_{real}(R_s, Z_s, \nu, Z_h) = \sum_{m=1}^{M} X_{real}(R_s, Z_s, \nu, Z_h, m)$$

where $X_{real}(R_s, Z_s, \nu, Z_h, m)$ is the mode m recorded at frequency ν on the hydrophone (at depth Z_h). It can be expressed by:

$$X_{real}(R_s, Z_s, \nu, Z_h, m) = B\,S(\nu)\,\psi_m(Z_s, \nu)\,\psi_m(Z_h, \nu)\, e^{ik_{rm}(\nu)R_s} \Big/ \sqrt{k_{rm}(\nu)R_s}$$

with B a constant and $S(\nu)$ the source spectrum at the frequency ν. $\psi_m(Z_s, \nu)$ and $\psi_m(Z_h, \nu)$ are respectively the mode amplitudes at the source and receiver depths and $k_{rm}(\nu)$ is the horizontal wavenumber. By looking at this expression of X_{real} , we can note that the source location (range and depth) is contained is the mode m. As a result, these modes will be used to localize the source.

B) Modal Filtering

The first step of the method consists in filtering the modes X_{real} that will be used in the Matched Mode Processing (MMP). This step is done using a time-frequency representation (t-f) adapted to guided propagation in underwater acoustics which is invertible [3]. We must note that the t-f transform can be used to filter modes only if the time length of the source is short compared to the differences between mode arrival times. After this step, one can access the different modes separately.

C) Matched Mode Processing (MMP)

Once modes have been filtered, they are used in the processors. We adapt works from Matched Field Processing to Matched Mode Processing using a single hydrophone: a signal recorded on a hydrophone is replaced by a mode.

Incoherent Matched Mode Processing: We first build the data vectors $\underline{X_{real}}(R_s, Z_s, \nu)$ and the replica vectors $\underline{P_{simu}}(r, z, \nu)$ (which are column vectors), at each frequency, in the following way:

$$\underline{X_{real}}(R_s, Z_s, \nu) = \begin{bmatrix} X_{real}(R_s, Z_s, \nu, Z_h, m_1) \\ .... \\ X_{real}(R_s, Z_s, \nu, Z_h, m_M) \end{bmatrix}$$

$$\underline{P_{simu}}(r, z, \nu) = \begin{bmatrix} P_{simu}(r, z, \nu, Z_h, m_1) \\ .... \\ P_{simu}(r, z, \nu, Z_h, m_M) \end{bmatrix}$$

where r and z denotes the possible locations of the source for the replica vectors. Each vector contains all the modes recorded on the single hydrophone at a given frequency ν. Then, the classical Bartlett processor, for a given frequency ν, is built:

$$B_{Incoherent}(r, z, \nu) = \frac{\underline{P_{simu}}^H(r, z, \nu)\,\underline{X_{real}}(R_S, Z_S, \nu)\,\underline{X_{real}}^H(R_S, Z_S, \nu)\,\underline{P_{simu}}(r, z, \nu)}{\left\|\underline{P_{simu}}(r, z, \nu)\right\|^2 \left\|\underline{X_{real}}(R_S, Z_S, \nu)\right\|^2}$$

where H is the conjugate transpose operator.

As the source is broadband, it is possible to combine the information given by each frequency to improve the source localization. This combination is made here by summing the contribution of each frequency to obtain an incoherent processor. This incoherence is due to the fact that the processor does not cross the frequencies and consequently that the mode phases disappear in the processor. Mathematically, localization is performed by maximizing the following function :

$$(\hat{R}_s, \hat{Z}_s) = Arg \max_{(r,z)} \sum_{\nu=\nu_1}^{\nu_F} B_{Incoherent}(r, z, \nu)$$

Coherent Matched Mode Processing: The aim of this processor is to process frequencies coherently [4]. To do so, as proposed in [5], a normalized super-vector is built for the real data and for each simulation. For the real data (resp. the simulation data), we first build the normalized vectors $\underline{X_{N\,real}}(R_s, Z_s, \nu)$ (resp. $\underline{P_{N\,simu}}(r, z, \nu)$) for each frequency ν and then concatenate them. As an example, for the real data, the column super-vector (SV) is:

$$\underline{X_{SV\,N\,real}}(R_s, Z_s) = \begin{bmatrix} \underline{X_{N\,real}}(R_s, Z_s, \nu_1) \\ .... \\ \underline{X_{N\,real}}(R_s, Z_s, \nu_F) \end{bmatrix}$$

If this super-vector is used in the localization processor, the results will not be satisfactory due to the source phase. To avoid this problem, the real data are scaled at each frequency so that they have zero phase on the most energetic mode. This scaling will be indicated using the subscript PC for Phase Compensated.

To do so, we first choose, for each frequency, the reference mode. Then, each vector $\underline{X_{N\,real}}(R_s, Z_s, \nu)$ is multiplied by an exponential function containing the opposite of the reference mode phase and these vectors are concatenated leading to the vector $\underline{X_{SV\,N\,PC\,real}}(R_s, Z_s)$. This multiplication is also performed on the simulated data (with the reference mode taken from the real data) so that the processor compares equivalent quantities (in the real and replica data).

This phase compensation, adapted from the proposition of Michalopoulou [5], is a crucial step of the processing. It allows the localization of a source without having information on its spectrum: on the real data, the phase of the source spectrum, which is the same for all the modes at a given frequency disappears thanks to the multiplication by the exponential function. Then, the correlator is:

$$B_{Coherent}(r, z) = \underline{P_{SV\,N\,PC\,simu}}^H(r, z)\,\underline{X_{SV\,N\,PC\,real}}(R_s, Z_s) \\ * \underline{X_{SV\,N\,PC\,real}}^H(R_s, Z_s)\,\underline{P_{SV\,N\,PC\,simu}}(r, z)$$

And the source location is estimated by maximizing the previous correlator:

$$(\hat{R}_s, \hat{Z}_s) = Arg \max_{(r,z)} B_{Coherent}(r, z)$$

Contrary to the Incoherent processor, this Coherent processor crosses the frequencies and uses the mode phases (without the influence of the source phase) to localize the source.

III. APPLICATION ON SIMULATED DATA

This section will show the results obtained on simulated data. We first give the results obtained for a single realization of the noise, for different Signal to Noise Ratio (SNR), and then present the method performances with a statistical study of the localization.

We simulate a Pekeris waveguide of 130 m depth with a water velocity of 1520 m/s and and bottom velocity of

1875 m/s. The source is an unknown impulsive source (frequency band: 1-70 Hz) located at R_s=5000 m. The source depth is Z_s=40 m in the first part and is Z_s=20 m for the statistical study.

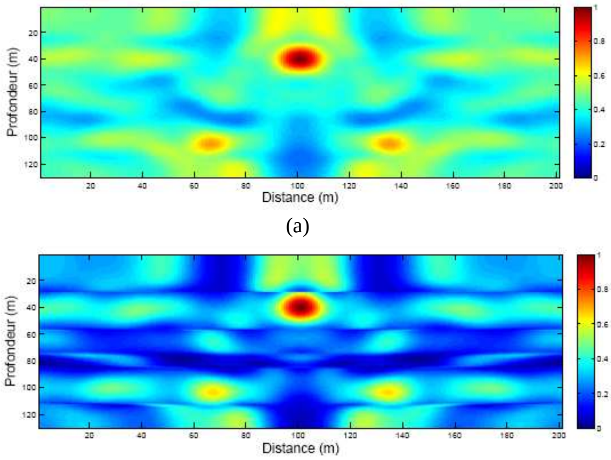
Modes are filtered using the time frequency representation adapted to guided waves. We use the 7 first modes to perform the localization. The spatial sampling of the source location to build the replica fields is 10 m in range and 1 m in depth.

To estimate the processor performances, we define two criteria: the width of the main lobe of the ambiguïty surface (at 75%) and the ratio between the main ML and secondary SL lobes (defined by 10 log10 (ML/SL). This last criterion is equal to infinity in the best case and to 0 in the worst (when the main and secondary lobes have the same amplitude).

We can also note that all the ambiguity planes are normalized to have their maximum equal to 1 and are plotted with a scale between 0 and 1 (so that the colorbar does not depend of the size of the ambiguity plane). This normalization allows us to compare the ambiguity planes.

A) Results on a particular case

We first show the results without noise. Ambiguïty planes for Incoherent and Coherent processors are presented on figure 1 and criteria are summarized in Table 1. We can see that in both cases the localization is achieved but that localization using Coherent MMP is more accurate (smaller width, higher ratio ML-SL).



(a)

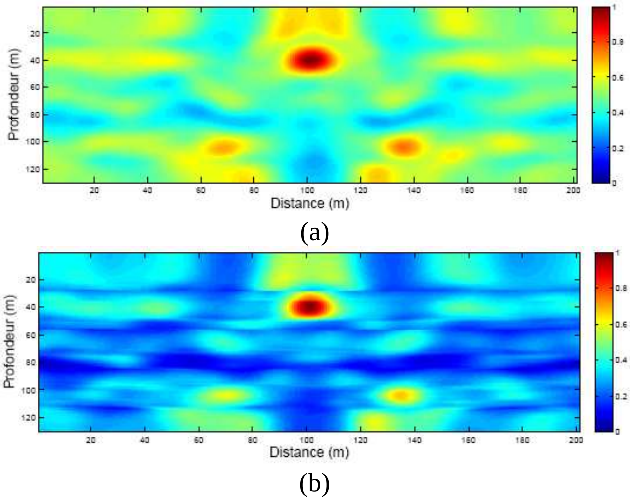
(b)

Fig. 1. Ambiguity planes for source localization without noise using Incoherent (a) and Coherent (b) Matched Mode Processing

Method	Ratio ML-SL	Vertical width	Horizontal width
Incoherent MMP	1.42 dB	16 m	140 m
Coherent MMP	1.86 dB	15 m	120m

Table 1. Ratio ML-SL and lobe width for the Incoherent and Coherent MMP without noise

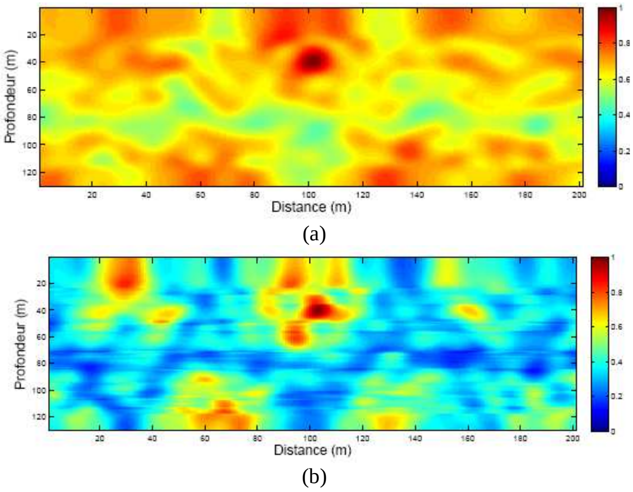
Then a Gaussian white noise is added on the data and localization is performed. Figure 2 and 3 show the results respectively for a SNR of 0 dB and -7.5 dB. In both cases the localization is achieved and results are better using the Coherent MMP than using the Incoherent MMP (smaller width, higher ratio ML-SL).



(a)

(b)

Fig. 2. Ambiguity planes for source localization for a SNR of 0 dB using Incoherent (a) and Coherent (b) Matched Mode Processing



(a)

(b)

Fig. 3. Ambiguity planes for source localization for SNR of -7.5 dB using Incoherent (a) and Coherent (b) Matched Mode Processing

SNR	Method	Ratio ML-SL	Vertical width	Horizontal width
0 dB	Incoherent MMP	1.31 dB	18 m	150 m
	Coherent MMP	2.03 dB	15 m	110 m
-7.5 dB	Incoherent MMP	0.83 dB	23 m	170 m
	Coherent MMP	0.88 dB	18 m	130m

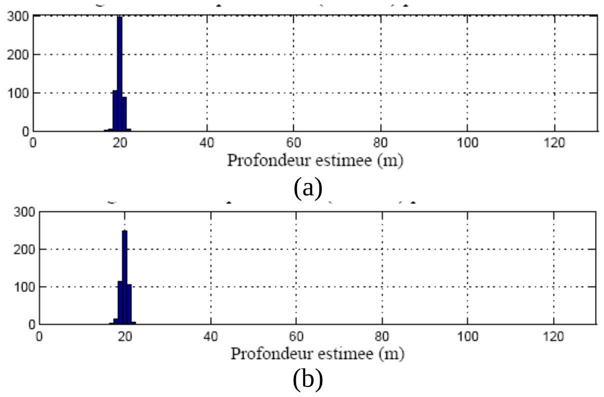
Table 2. Ratio ML-SL and lobe width for the Incoherent and Coherent MMP for a SNR of 0 dB and -7.5 dB.

B) Statistical results

To study the possible superiority of one of the method on the other we make a statistical study of the localization results. 500 realizations of the noise are used and localization results are studied.

As we have seen before, without noise, the localization is perfectly achieved. Consequently, we show the results for the two previous SNR: 0 dB and -7.5 dB.

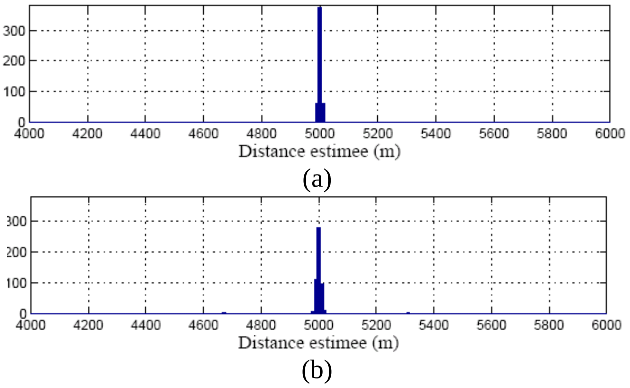
For a SNR of 0 dB, figure 4 shows the histogram of the depth localization for the two processors (Incoherent and Coherent MMP) and figure 5 shows the histogram of the range localization for the two processors. Figure 6 and 7 show the same results than figures 4 and 5 for a SNR of -7.5 dB.



(a)

(b)

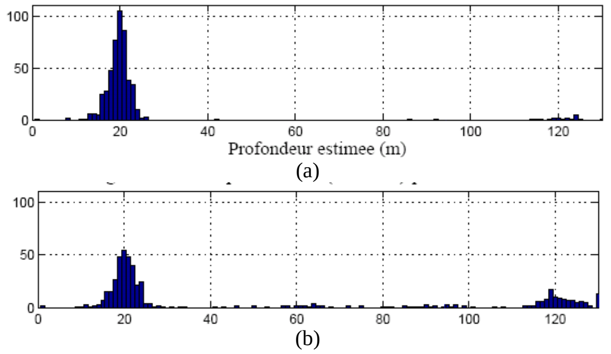
Fig. 4. Histogram of the depth localization for a SNR of 0 dB using Incoherent (a) and Coherent (b) Matched Mode Processing



(a)

(b)

Fig. 5. Histogram of the range localization for a SNR of 0 dB using Incoherent (a) and Coherent (b) Matched Mode Processing

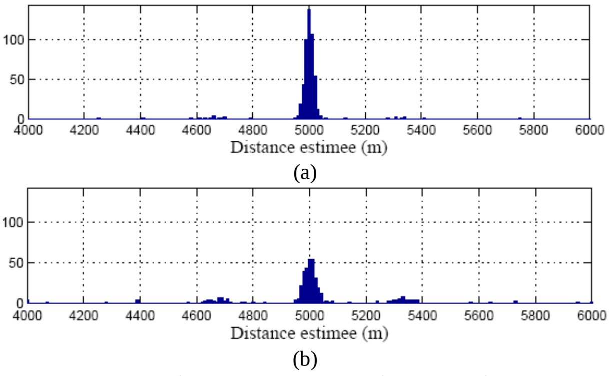


(a)

(b)

Fig. 6. Histogram of the depth localization for a SNR of -7.5 dB using Incoherent (a) and Coherent (b) Matched Mode Processing

Contrary to expectations from the previous study (section III.A.), the results using Coherent MMP are less satisfactory than the ones using Incoherent MMP (Z_s is equal to 20 m and R_s to 5000 m). Indeed, even if the widths with Coherent MMP are smaller and the ratio ML-SL higher, the localization itself shows more errors. As a result, Coherent MMP should only be used for data with a high SNR whereas Incoherent MMP can be used even if the SNR is low. Looking at the width of the main lobe with Coherent MMP we can note that this MMP maybe be useful to separate sources in a given medium. Studies have to be done to show the feasibility of this multiple localization.



(a)

(b)

Fig. 7. Histogram of the range localization for a SNR of 7.5 dB using Incoherent (a) and Coherent (b) Matched Mode Processing

IV. CONCLUSIONS

We propose two Matched Mode Processors to localize a source in shallow water environments using a single hydrophone. We show that the Coherent Processor allows a more accurate localization as well as a reduction of the side lodes in the case of a high SNR. When the SNR decreases, the Incoherent Processor shows better results and is able to localize the source with less error.

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