BROADBAND MATCHED-FIELD PROCESSING OF TRANSIENT SIGNALS IN SHALLOW WATER

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SUMMARY

This paper presents a full-wavefield narrowband high-resolution technique that uses the spectral decomposition of the sample covariance matrix to resolve the vertical arrival structure of the harmonic acoustic field. The broadband processor is obtained by weighted averaging of the narrowband range-depth ambiguity estimates within the source signal frequency band. Results obtained with this processor on short transient pulses collected in the North Elba I. area in 1989 with a 62m aperture vertical array, showed stable and accurate localizations over long time intervals. These results also demonstrate that the sound field, received over a given frequency band, is relatively stable over time and is in agreement with the predictions given by a standard normal-mode propagation model.

1. INTRODUCTION

Matched-field processing of vertical arrays is now a well known technique for range and depth localization of sound sources in the ocean. Following the pioneering work of Hinich[1] and Bucker[2] a large number of theoretical studies have been published that were aimed at comparing various matched-field processors and testing their robustness to erroneous and/or incomplete knowledge of environmental or system parameters[3-6]. Despite this large effort, reports of successful experimental results have been rare. References [4-6] include some studies of experimental matched-field localization with vertical arrays in shallow water. In the above referenced literature, there is no evidence of stable source localization results and, in general, only an occasional agreement was found between the measured and the predicted sound field; in most cases only a few (and sometimes only one) range-depth surfaces were shown for each data set.

This paper shows, using experimental data, that stable and accurate range-depth localization of a sound source in shallow water is possible by matched-field processing of a vertical array. This was achieved by extending the well known narrowband plane-wave MUSIC algorithm to full-wavefield broadband range-depth estimation. It is shown, with both synthetic and experimental data, that the proposed broadband processor provides higher source localization stability than the narrowband processor in the same conditions. The application of this technique to the localization of short transient pulses transmitted in a (modelled) range-independent waveguide of 120 m depth and received on a 62 m aperture vertical array showed that precise and stable results could be obtained during long time intervals.

2. THEORETICAL BACKGROUND

The data model: The received signal is modelled as the solution of the wave equation at the receiver location for a narrowband point source exciting a horizontally stratified, parallel waveguide. The normalized spatial dependence of the acoustic pressure field measured at sensor depth z_l due to a unit power harmonic source at location $\theta_T^t = (z_T, r_T)$ is commonly expressed as a linear combination of the waveguide normal-mode depth functions[7], i.e.,

$$p_l(\theta_T, \omega_k) = \sum_{m=1}^{M_k} \frac{a_m(z_l, \omega_k) a_m(z_T, \omega_k)}{\sqrt{k_m(\omega_k)}} e^{-\alpha_m(\omega_k) r_T} e^{i k_m(\omega_k) r_T}, \qquad (1)$$

where M_k is the number of modes supported by the waveguide at frequency ω_k, $\alpha_m(\omega_k)$ is the mth mode attenuation coefficient and the two sets $\{a_m(z, \omega_k); m = 1, \ldots, M_k;\ 0 < z < H\}$ and $\{k_m(\omega_k); m = 1, \ldots, M_k\}$ are the mode depth functions and the corresponding mode horizontal wavenumbers characterizing the propagation channel of depth H at frequency ω_k. Note that equation (1) has been obtained by normalizing the range dependence, a phase shift and an arbitrary constant. The measured acoustic pressure is represented by the L-dimensional array $\mathbf{y}(\theta_T, \omega_k)$ defined by

$$\mathbf{y}_n(\theta_T, \omega_k) = b_n(\omega_k)\mathbf{p}(\theta_T, \omega_k) + \epsilon_n(\omega_k), \qquad n = 1, \ldots, N; k = 1, \ldots, K, \qquad (2)$$

assumed to be, for a given k, an N sample draw of a multivariate, complex, normally distributed random variable Y, $\mathrm{N}(0, \mathbf{R}_y)$ where the signal in Eq. (1) is assumed to be corrupted by additive, uncorrelated and zero-mean complex Gaussian noise ϵ_n and where $b_n(\omega_k)$ is a complex random variable that represents the source amplitude at frequency ω_k and time snapshot n.

Conventional matched-field processing: The conventional range-depth source localization technique consists of passing the received acoustic pressure (2) through a bank of narrowband matched filters based on the model replica prediction for each range-depth location θ, i.e.,

$$\mathrm{RD}_{\mathrm{CMF}}(\theta, \omega_k) = \mathbf{p}(\theta, \omega_k)^H \hat{\mathbf{R}}_y(\omega_k) \mathbf{p}(\theta, \omega_k), \qquad \theta \in \Theta \qquad (3)$$

where Θ is the two dimensional range-depth parameter search space and $\hat{\mathbf{R}}_y(\omega_k)$ is the sample cross-covariance matrix of the received signal, commonly estimated as the N sample-mean of the received data outer product. The source location estimate $\hat{\theta}_T$ is obtained as the coordinates of the absolute maximum of the ambiguity surface given by (3).

The mode subspace approach: The mode subspace approach is a full-wavefield generalization of the MUSIC algorithm commonly used in spatial array processing for directions-of-arrival (DOA) estimation[8]. Assuming $L > M_k$, the subspace spanned by the eigenvectors of the sample cross-covariance matrix $\hat{\mathbf{R}}_y(\omega_k)$ associated with the largest M_k eigenvalues is the maximum likelihood estimate of the required mode subspace[8]. Thus, the source location estimate $\hat{\theta}_T$ is given by the coordinates of the maximum of the multi-dimensional surface obtained by plotting the functional

$$\mathrm{RD}_{\mathrm{MS}}(\theta, \omega_k) = |\hat{\mathbf{E}}_{L-M_k}(\omega_k) \hat{\mathbf{E}}_{L-M_k}^H(\omega_k) \mathbf{p}(\theta, \omega_k)|^2, \qquad \theta \in \Theta \qquad (4)$$

where $\hat{\mathbf{E}}_{L-M_k}(\omega_k)$ is an estimate of the orthogonal complement of the mode subspace span obtained by eigen decomposition of matrix $\hat{\mathbf{R}}_y(\omega_k)$.

The broadband matched-field processor: The broadband matched-field processor is obtained by a weighted average of the range-depth ambiguity surfaces calculated for each narrowband cell over the source signal bandwidth. Thus, if the source signal bandwidth is $[\omega_{k_1}, \omega_{k_2}]$,

$$\mathrm{RD}_{[\cdot]}(\theta) = \frac{1}{k_2 - k_1 + 1} \sum_{k=k_1}^{k_2} \beta_k \mathrm{RD}_{[\cdot]}(\theta, \omega_k), \qquad \theta \in \Theta \tag{5}$$

where $\{\beta_k; k = k_1, \ldots, k_2\}$ is a weighting function.

3. RESULTS AND CONCLUSIONS

The system/environment scenario shown in figure 1 was that of the SACLANTCEN North Elba'89 experiment that took place at north of Elba Island (Italy) in Nov/Dec 1989. The environmental parameters were established in[9]. The SACLANTCEN normal-mode code (SNAP) was used to generate the normal-mode functions and to compute the modal attenuation coefficients. The vertical array spans the water column from 40 to 102m depth with 64 nested hydrophones. The transient signals transmitted from the source were a series of exponentially damped sinusoids with the same center frequency f_c=250 Hz and 100 ms duration at 10 s interval. The signal bandwidth of 15 Hz gave rise to approximatelly 10 frequency bins with a sampling frequency of 3000 Hz and a FFT block size of 2048 samples.

Narrowband results: In order to be able to access the relative performance of the broadband versus narrowband processing, a single frequency (250 Hz) line has been extracted from the broadband data and processed. The results obtained with the MS processor are shown in Figure 2 and indicate that although at some moments a high detection ratio is obtained (Figure 2a) it does not correspond to any accurate and stable source location estimate (Figure 2b). The running of the CMF processor in the same example gave similar results in terms of source localization instability with, however, a much lower detection ratio.

Broadband results: Figure 3 shows the results obtained with the broadband mode-subspace processor over the band 245-256 Hz with source power spectrum weighting. From Figure 3 it can be noticed that the localization is stable and relatively accurate throughout the 7-min run which is the major accomplishement when comparing with the narrowband case.

Conclusions: The processing of experimental broadband transient signals, obtained in a shallow water area showed that the broadband mode subspace method could achieve very stable source location estimates with sidelobe rejections up to 2 dB, during long periods of time. Using the broadband conventional matched-field processor on the same data set gave poor results: no localization could be obtained during the analysis of the whole data set. The observation of the time sequence of range-depth ambiguity surfaces shows that the broadband signal field used by the mode subspace approach is relatively stable in time and highly correlated with the predictions given by a standard normal-mode model. This is, probably, the most important result obtained from this study and leaves great hope for the use of this technique on other environments and with other array arrangements.

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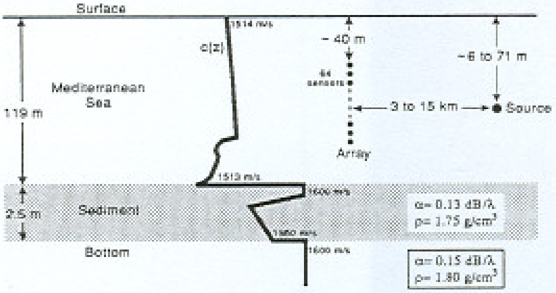

Fig. 1: The experimental shallow water environment.

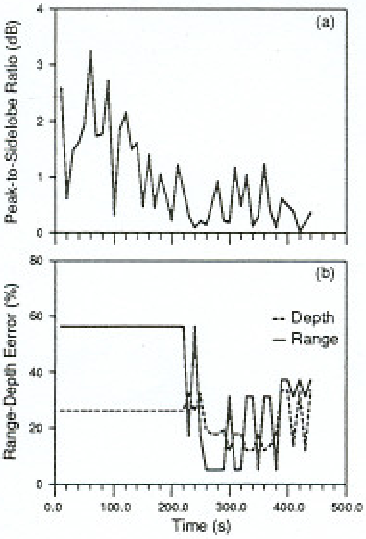

Fig. 2: Narrowband MS processor at 250 Hz

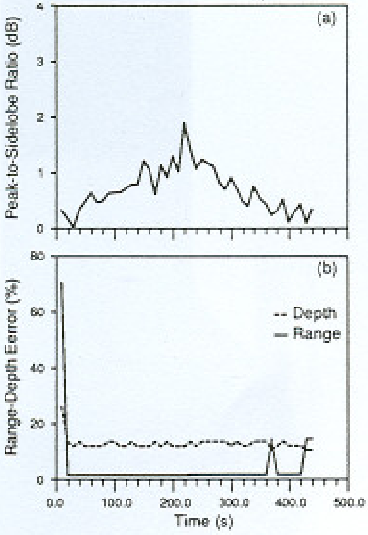

Fig. 3: Broadband MS processor at 244-256 Hz.