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DECONVOLUTION OF THE WAVEGUIDE IMPULSE RESPONSE FOR SOURCE LOCALIZATION AT LOW FREQUENCY

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ABSTRACT

In shallow water and at low frequency, acoustic propagation is generally described by normal mode theory, the acoustic pressure being a sum of propagating modes. Source localization is usually performed using matched-mode processing, based on an *a priori* knowledge of the environment. This work considers the use of horizontal linear arrays to perform source localization in the azimuth and range dimensions. The deconvolution of the waveguide impulse response from the array measurements is investigated to improve the localization accuracy. The deconvolution is performed using the Orthogonal Matching Pursuit algorithm, suitable when the number of sources is small compared to the number of HLA channels. Numerical simulations for Pekeris waveguide highlight good localization accuracy at various frequencies and some robustness to environmental mismatches. Results from measurement campaign, involving large HLA, low to ultra-low frequency and water depth up to 1500 m are investigated as well.

Keywords: array processing, underwater acoustics, low frequency, Pekeris waveguide

1. INTRODUCTION

Source localization is often considered using an array of hydrophones [1]. Beamforming techniques are generally applied to estimate the directions of arrival (DOA) of the sound waves from different sources. As the problem is ill-conditioned, high resolution methods were proposed to overcome some of the limitations of beamforming. Since the 2000s, deconvolution of the beampattern has been adapted from astrophysical imaging to airborn acoustics [2, 3] and underwater acoustics [4]. It designates a group of methods that iteratively suppress the contribution related to the array response to achieve better signal to noise ratio (SNR) and accuracy of the localization. The development of deconvolution was supported by a sparse hypothesis of the number of sources in regard with the number of sensors in the compressed sensing formalism [5].

In underwater acoustics, for low frequencies and shallow depth, acoustic propagation is computed by a sum of propagating modes [6, 7]. The source localization is then refereed to matched-mode processing (MMP) [8, 9]. In modal propagation, localization methods usually consider wideband to take advantage from the dispersive property of the propagation [7, 8, 10]. This paper introduces the deconvolution of horizontal line array (HLA) beampattern for a narrow band matched-mode processor. The deconvolution is performed using Orthogonal Matching Pursuit (OMP) [3, 11] to increase the localization accuracy.

The performance of the localization using MMP and OMP is estimated for simulations of a Pekeris waveguide and for a deep water campaign in the Channel of Mozambique.

2. LOW FREQUENCY ACOUSTIC PROPAGATION

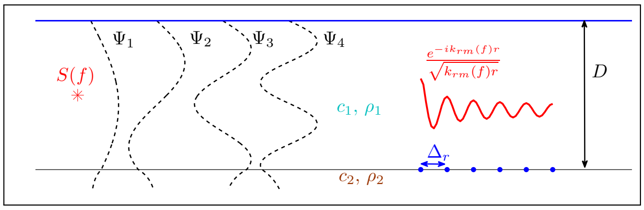

Figure 1: Propagation in a Pekeris waveguide

A Pekeris waveguide is defined by a homogeneous water layer {density ρ_1, sound speed c_1 and depth D} overlaying a semi-infinite seabed layer {density ρ_2 and sound speed c_2} as illustrated in Fig. 1.

The spectrum of a monochromatic source at a frequency f is $S(f)$. The source is located in $r_s = 0$ at the depth z_s, the acoustic pressure at the point r_p and depth z_p can be written as

$$y_p(f, r_p, z_p, z_s) = S(f) \sum_{m=1}^{M(f)} \alpha_m(f, z_p, z_s) \frac{e^{-ir_p k_{rm}(f)}}{\sqrt{r_p k_{rm}(f)}}, \quad (1)$$

where M is the number of propagating modes, α_m is an amplitude term (*i.e* $\alpha_m(f, z_p, z_s) = \Psi_m(z_s, f)\Psi_m(z_p, f)$, the product of modal function values at source and receiver depths) and $k_r m$ is the horizontal wavenumber [6]. The quantities α_m and k_{rm} are computed using the boundary conditions. The Pekeris waveguide is one of the simplest environment model, k_{rm} are computed by root finding.

If all the sensors are at the same depth, for a typical HLA configuration, only the propagation over range can be considered. Thus, the knowledge on the horizontal wavenumbers k_{rm} allows describing the propagation. Several studies have been dedicated to estimate the wavenumbers (see [7] for instance) and thus to infer the source and/or environment properties. In the following, we illustrate how this information is used in the MMP.

3. DECONVOLUTION FOR MODAL PROPAGATION

Considering an array of P hydrophones, the direct problem can be put under a matrix product

$$\mathbf{y}(f) = \mathbf{A}(f)\mathbf{x}(f) \quad (2)$$

where $\mathbf{y}$ is the vector of the P measurements $y_p(f, r_p)$ of the array, $\mathbf{A}$ is a $P \times N_s$ dictionary of propagation and $\mathbf{x}$ is the vectors containing the amplitude of the N_s sources distributed over space. The source positions and amplitudes is then given using a pseudo-inverse scheme

$$\hat{\mathbf{x}} = \mathbf{A}^H(\mathbf{A}\mathbf{A}^H)^{-1}\mathbf{y}. \quad (3)$$

In the case of beamforming, $\mathbf{A}$ describes the angles of arrivals to estimate. In the case of MMP, $\mathbf{A}$ describes the replica of the modal propagation. Its elementary component is then simplified to:

$$A_{np}(f) = \sum_{m=1}^{M(f)} e^{-ir_{np}k_{rm}(f)}. \quad (4)$$

Compared to Eq. (1), the amplitude terms are dropped: α_m depend only on the source and sensor depths; the range dependant losses, *i.e.* the cylindrical losses, may only contribute significantly at shorter ranges and mainly to estimate the source level.

Eq. (3) is ill-conditioned because of the discrete spatial sampling and additive noise. As we assumed the number of sources with non-zero amplitude to be small compared to the number of hydrophones, the inversion is regularized as

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} |\mathbf{x}|_{\ell 1} \text{ subject to } \mathbf{y} = \mathbf{A}\mathbf{x}. \quad (5)$$

where $||_{\ell 1}$ is the absolute value operator.

The second part of eq (5) is similar to the Eq (3). Eq. (5) can be solved by numerous methods. We propose to apply the OMP which belongs to the group of greedy algorithms [11]. It aims to suppress iteratively the contributions of sources through the array impulse response until a stop criterion is reached. OMP is known for its robust convergence according to the resolution of the search grid [3].

4. SIMULATIONS

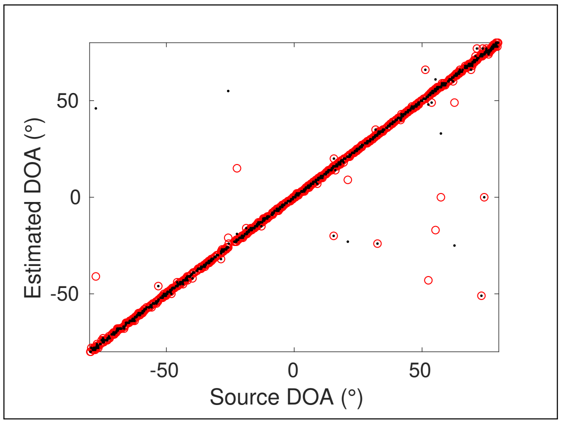

Figure 2: DOA estimates for MMP (red circle) and OMP (black dots) at 10 Hz (1 mode)

Acoustic propagation in a Pekeris waveguide is simulated. The depth is 100 m, the seabed density 2 kg.m^{-3} is and the seabed sound speed is 1700 m.s^{-1}, in order to simulate a sandy bottom. The array is composed of 100 hydrophones spaced of 5 m, at a depth of 10 m. The source position is randomly drawn: the range is drawn between 1 and 5 km and its DOA is drawn between -80 and

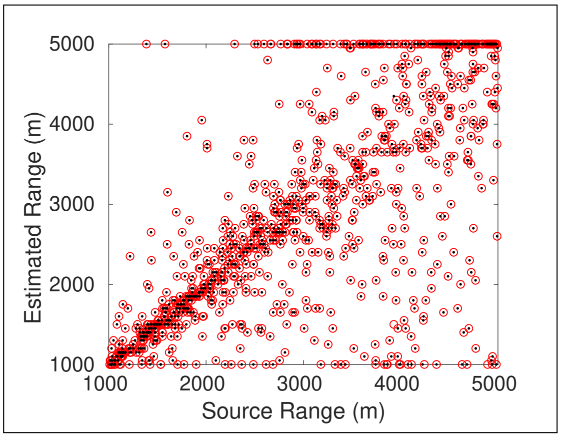

Figure 3: Range estimates for MMP (red circle) and OMP (black dots) at 10 Hz (1 mode)

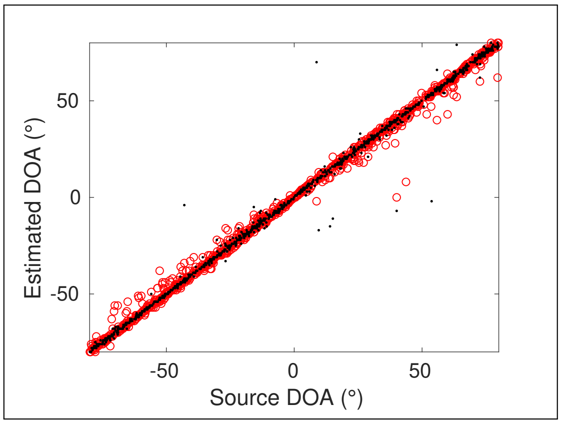

Figure 4: DOA estimates for MMP (red circle) and OMP (black dots) at 50 Hz (7 modes)

80 ° (0 ° is the broadside of the array). 1000 positions are drawn uniformly. The research space is defined for angles between -80 and 80 °, with an accuracy of 1 °, and for ranges between 1 and 5 km, with an accuracy of 50 m. The source emits at two frequencies: 10 Hz and 50 Hz, 1 and 7 modes propagate respectively. Gaussian noise is added on the receiver, Eq. (1), in order to have an averaged SNR of 0 dB in the bandwidth of f over the $[1\ 5]$ km range. OMP stop criterion is adapted to the SNR. The MMP result is given by the greatest value of $\hat{\mathbf{x}}$.

The computational time using OMP is approximately 20 % longer than MMP. Results of range and DOA estimates are compared to the true values for MMP (red circles) and OMP (black dots) in Fig. 2 and Fig. 3 at 10 Hz and in Fig. 4 and Fig. 5 at 50 Hz.

At 10 Hz, 1 mode propagates. The average errors on DOA are 0.45 ° and 0.22 ° for MMP and OMP respectively, Fig. 2. The average errors on range are 115 m and 104 m for MMP and OMP respectively, Fig. 3. It seems the error on the range increases with the distance, it can be related to an increase of the SNR with range as the source signal is more attenuated. MMP and OMP results are close to the true values as only 1 mode propagates and there is no interference pattern. However, MMP has a larger lobe of the ambiguity function while OMP provides a sparse solution.

At 50 Hz, 7 modes propagate. The average errors on DOA are 0.058 ° and 0.045 ° for MMP and OMP respectively, Fig. 4. The average errors on range are 413 m and 47 m for MMP and OMP respectively, Fig. 5. Results of MMP are impacted by the modal interference pattern: for the DOA, angles are estimated larger than the true values for negative DOAs and smaller than the true values for positive DOAs; for the range, results show strong sensitivity to local maxima. In particular, around 1500, 3000 and 4500 m, MMP is unable to localize the sources. Deconvolution performed by OMP allows retrieving results closer to the true values. As the frequency is higher, the main lobe of the ambiguity function is smaller for MMP than at 10 Hz but OMP achieves a smaller resolution thanks to the sparse approximation.

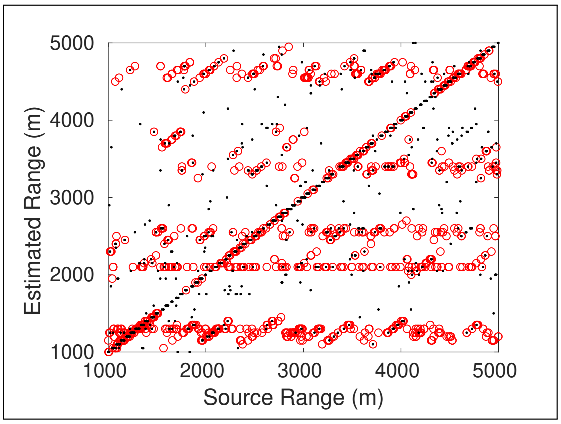

Figure 5: Range estimates for MMP (red circle) and OMP (black dots) at 50 Hz (7 modes)

5. APPLICATION TO SOUSACOU CAMPAIGN

Shom operated the SOUSACOU campaign in the Mozambic Channelin February 2021. A seismic array of 480 sensors over 3 km was used. The depth is about 2300 m. Seabed is mainly gravity flow sedimentation. Narrow band signal was detected around 5 Hz where 15 modes propagate.

Localization results using OMP is presented in the ambiguity function in Fig. 6. To improve the readability, sparse detections are circled in red. The main source is identified at 9300 m and 32 °. It shows consistency with a preliminary AIS but additional work is required. Secondary sources are located at the end-fire position (90 °) around 2 km. The localization corresponds to the radiated noise from the operating ship *Pourquoi Pas ?*.

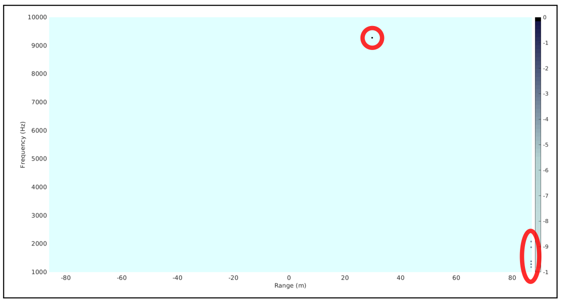

Figure 6: Sources localized by OMP during SOUSACOU campaign.

6. PRELIMINARY CONCLUSION

The study shows that taking into account the modal propagation physics into the deconvolution can improve the localization performance. It emphasises that array processing should rely on appropriate physical knowledge of the propagation.

Application to real measurements show encouraging results. Contamination by radiated noise of the operating vessel can be critical to define the sparity level and will be investigated deeper for the presentation.

The examples are focused on narrowband signals, but methodology could be extended to wideband or multi frequency analysis.

7. REFERENCES

[1] H. Mermoz, "Imagerie, corrélation et modèles," in *Annales des télécommunications*, vol. 31, pp. 17–36, Springer, 1976.

[2] T. F. Brooks and W. M. Humphreys, "A deconvolution approach for the mapping of acoustic sources (damas) determined from phased microphone arrays," *Journal of sound and vibration*, vol. 294, no. 4-5, pp. 856–879, 2006.

[3] T. Padois and A. Berry, "Orthogonal matching pursuit applied to the deconvolution approach for the mapping of acoustic sources inverse problem," *The Journal of the Acoustical Society of America*, vol. 138, no. 6, pp. 3678–3685, 2015.

[4] B. Oudompheng, B. Nicolas, and L. Lamotte, "Localization and contribution of underwater acoustical sources of a moving surface ship," *IEEE Journal of Oceanic Engineering*, vol. 43, no. 2, pp. 536–546, 2017.

[5] E. J. Candes, "The restricted isometry property and its implications for compressed sensing," *Comptes rendus mathematique*, vol. 346, no. 9-10, pp. 589–592, 2008.

[6] F. B. Jensen, W. A. Kuperman, M. B. Porter, H. Schmidt, and A. Tolstoy, *Computational ocean acoustics*, vol. 2011. Springer, 2011.

[7] F. Le Courtois and J. Bonnel, "Compressed sensing for wideband wavenumber tracking in dispersive shallow water," *The Journal of the Acoustical Society of America*, vol. 138, no. 2, pp. 575–583, 2015.

[8] Y. Le Gall, F.-X. Socheleau, and J. Bonnel, "Performance analysis of single-receiver matched-mode localization," *IEEE Journal of Oceanic Engineering*, vol. 44, no. 1, pp. 193–206, 2017.

[9] S. Lee and N. C. Makris, "The array invariant," *The Journal of the Acoustical Society of America*, vol. 119, no. 1, pp. 336–351, 2006.

[10] T. Yang, "Beam intensity striations and applications," *The Journal of the Acoustical Society of America*, vol. 113, no. 3, pp. 1342–1352, 2003.

[11] Y. C. Pati, R. Rezaiifar, and P. S. Krishnaprasad, "Orthogonal matching pursuit: Recursive function approximation with applications to wavelet decomposition," in *Proceedings of 27th Asilomar conference on signals, systems and computers*, pp. 40–44, IEEE, 1993.