INFERRING OCEAN TEMPERATURE VARIATIONS FROM SHIPPING NOISE

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Abstract: *Acoustic passive methods to infer properties of the oceanic medium have been subject of progressive emphasis in order to obtain low cost, environmental friendly, long time characterization of the ocean. To this end a first step consists in the estimation of the frequency response of the medium or its time domain counterpart, the impulse response. In this work we consider distant ship noise as an opportunity source characterized by a few low frequency discrete tones. Therefore, the frequency response of a shallow water acoustic channel is estimated at these discrete frequencies, between two vertical line arrays (VLA's). The influence on the estimates of several factors of uncertainty such as range, depth and tilt variations in the VLA's is investigated. For validation purposes, a phase conjugation method is considered. In a preliminary approach towards passive ocean acoustic tomography implementation the estimates obtained by the proposed method are applied in a matched field framework to track sound speed profile variations. Simulations are conducted based on experimental setup and environmental parameters gathered during the MREA07 sea trial that took place in the Tyrrhenian Sea, near Elba Island in May 2007. The results show that, although shadowed, the obtained frequency response estimates allows to obtain a permanent focus and enables the tracking of sound speed profile variations in the water column.*

Keywords: *Passive inverse methods, coherent noise processing, ocean acoustic passive tomography*

1. INTRODUCTION

In underwater acoustic applications (acoustic communications, source localization, environmental monitoring) noise is usually considered a nuisance factor, therefore, several methods have been developed to minimize its impact. However, the underwater environment is naturally noisy and in last years passive methods have been subject of growing interest (see [1] and references herein). These methods use ambient noise, either natural or anthropogenic, instead of active sources. Therefore they are considered to be low cost and environmentally friendly methods and are able to be applied for long periods of time. Predominant acoustic noise in the ocean is due to shipping, which is characterized by a few low discrete frequency tones superimposed on a diffuse background pedestal, travelling over long distances and carrying water column structure information. Nowadays there is a vast number of near shore maritime routes with high levels of traffic, where it would be simple to install receiver arrays, thereby enabling low cost spatial-temporal monitoring of oceanographic processes.

In this work we consider long range ship noise as opportunity sources for tracking sound speed/temperature perturbations. The waveguide frequency response estimation is developed based on cross-correlation methods, using a normal mode approach [2, 3]. The MREA07 geometry is used to perform simulations, where two VLAs at 4 km distance are receiving the ship noise. The method is validated with a phase conjugation procedure and it is shown that the inclusion of uncertainty factors in the VLAs position can still be accounted for. Finally it is shown that the tracking of sound speed/temperature variations is possible.

2. MODEL DEVELOPMENT

We consider the ship noise as a monotonic source of fixed frequency ω_0 characterized by strength (amplitude) $\mathcal{A}$ and a phase φ, wide-sense stationary and ergodic stochastic processes. The ship is at location S, two receivers are at locations A and B and the propagation channels are considered as linear systems. Assuming that the frequency response at frequency ω_0, between the source and the receivers are respectively $H_{SA}(\omega_0)e^{j\varphi_{SA}(\omega_0)}$ and $H_{BA}(\omega_0)e^{j\varphi_{SB}(\omega_0)}$, where H_{SX} is the module and φ_{SX} is the phase, considering the receiver at location X. Therefore, the received signal at points A and B can be written as

$$y_A(\omega_0, t) = \mathcal{A}(t)e^{j(\omega_0 t+\varphi(t))}H_{SA}(\omega_0)e^{j\varphi_{SA}(\omega_0)} + n_A(t). \quad (1)$$

$$y_B(\omega_0, t) = \mathcal{A}(t)e^{j(\omega_0 t+\varphi(t))}H_{SB}(\omega_0)e^{j\varphi_{SB}(\omega_0)} + n_B(t), \quad (2)$$

where $n_A(t)$ and $n_B(t)$ are uncorrelated additive zero mean noise components, uncorrelated with the signal. One can write the cross-correlation function at 0 lag (i.e. cross power) between the receiver A and receiver B as

$$r_{AB} = E[y_A(\omega_0, t)y_B^*(\omega_0, t)], \quad (3)$$

where $E[.]$ represents the expectation operator. Assuming a deterministic behavior of the frequency responses this cross-correlation function between two receivers can be written as

$$r_{AB} = E[\mathcal{A}^2(t)]H_{SA}(\omega_0)H_{SB}(\omega_0)e^{j(\varphi_{SA}-\varphi_{SB})} + E[n_A(t)n_B^*(t)], \quad (4)$$

where $E[\mathcal{A}^2(t)]$ represents the variance of $\mathcal{A}(t)$ and is assumed constant. As it can be observed, the cross-power does not depend on the initial phase φ. The term $E[n_A(t)n_B^*(t)]$ represents the cross-power of the noise and under the assumptions made it will vanish.

The frequency response between the source and the receiver using the normal mode long range approximation can be written as [2, 3]

$$H_{\omega_0}(R_{SA}, z_S, z_A) \propto \sum_{n=1}^{N} U_n(z_S)U_n(z_A)\frac{e^{ik_nR_{SA}}}{\sqrt{k_nR_{SA}}}, \quad (5)$$

where R_{SA} is the range between S and A, S is the source and A is a receiver, z_X represents de depth associated with X, N is the number of modal functions U_n and k_n is the corresponding horizontal wavenumber. For a matter of simplicity we will indicate the frequency response as $H(S, A)$. Using a similar approach as in [2] and assuming the reciprocity of the medium, an estimate $\widetilde{H}(S, X_k)$ for the frequency response between the source S and the receiver array **X**, where X_k is the k-th receiver of array **X**, **X** being **A** or **B**, were obtained as

$$\widetilde{H}_I(S, \mathbf{A}), \text{ where } \quad \widetilde{H}_I(S, A_k) = \sum_i H(B_i, A_k)H(B_i, S). \quad (6)$$

$$\widetilde{H}_O(S, \mathbf{B}), \text{ where } \quad \widetilde{H}_O(S, B_k) = \sum_i H(A_i, S)H^*(A_i, B_k), \quad (7)$$

the subscript *I* means that Eq. (6) was obtained using the receivers of the inner array **B**, while the subscript *O* means that Eq. (7) was obtained using the receivers of the outer array **A**. Assuming the normal mode approximation the cross-correlation between the receivers in arrays **A** and **B** can be written in a matrix form as

$$H^s(\mathbf{A}, \mathbf{B}), \text{ with } {H^s}_{k,l} \propto \sum_n \frac{U_n^2(S)}{\sqrt{k_n}}\widetilde{H}(A_k, B_l), \quad (8)$$

where ${H^s}_{k,l}$ can be seen as proportional to the term $H_{SA}(\omega_0)H_{SB}(\omega_0)e^{j(\varphi_{SA}-\varphi_{SB})}$ in Eq. (4).

2.1. Model validation

In this section we consider two approaches for validation purposes of the estimates obtained above. The first is a phase conjugation procedure for source localization; the second is a matched field based method for sound speed estimation.

2.1.1. Phase Conjugation

Phase conjugation, or its time domain counterpart time reversal, is a well known method of sound refocusing that had been spread in time and space by propagation through the ocean. In this work we compare a reference field, given by a normal mode propagation model and the focused field obtained with the estimates developed above according to

$$PC(z, \omega) = \sum_{A_i} H^*(A_i, B_0)\, H(A_i, z). \quad (9)$$

$$\widehat{PC}(z, \omega) = \sum_{A_i} H^{s*}(A_i, B_0)\, H(A_i, z), \quad (10)$$

where PC indicates the reference focused field obtained with the frequency responses given by the propagation model; $\widehat{PC}$ is the estimated focused field, obtained via the estimated frequency response H^s and z represents the depth at, or near to, the focal point.

2.1.2. Matched field

Matched field processing methods have been used for tomography purposes [4]. In this work we apply this technique to estimate perturbations in the sound speed profile, which occur usually due to the variations of day cycle. One of the most robust methods in matched field processing is the Bartlett processor that can be written as

$$P_{Bart}(\phi) = \frac{1}{N_{\mathbf{B}} \cdot N_\omega} \sum_\omega \sum_i \left| \left(H_0^s(\mathbf{A}, B_i, \omega, \phi) \right)^H \left(H_0(\mathbf{A}, B_i, \omega, \phi_0) \right) \right|^2, \tag{11}$$

where P_{Bart} is the Bartlett power, ϕ represents the sound speed profile and ϕ_0 is the mean sound speed profile, $N_{\mathbf{B}}$ is the number of receivers in VLA **B**, N_f is the number of frequencies, the subscript 0 stands for norm_2 normalization of H^s and H_0, B_i is the i^{th} receiver of VLA **B**, ω is the frequency and the superscript H stands for conjugate transpose operation. P_{Bart} is a broadband processor incoherent in both frequency and space.

3. SIMULATIONS

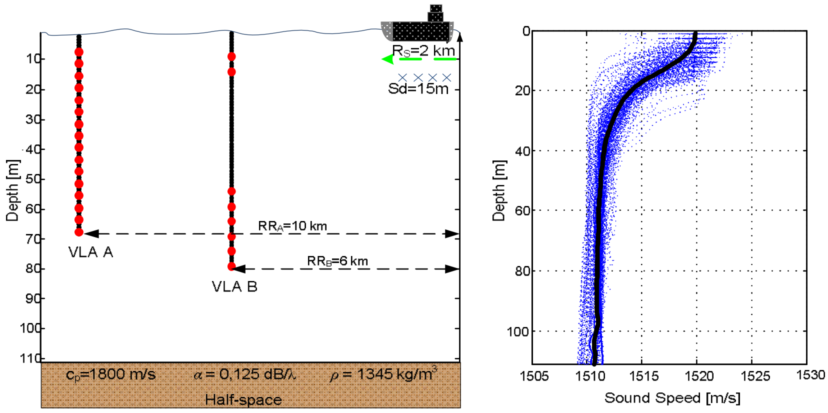

Fig. 1: Baseline environment considered for simulations: experiment geometry (left) and sound speed profiles, measured (dashed) and mean sound speed profile (solid) (right).

In this section a simulation scenario is considered, based on the MREA07 sea trial experiment [5] that took place near the Elba Island, in the Tyrrhenian Sea. The geometry is depicted in Fig. 1 (left). The environment is range independent with a 112m depth water column above a sediment half-space. Fig. 1 shows on the right hand side the sound speed profiles collected during the MREA07 sea trial (dashed) and the mean profile (solid). The geometry setup reflects the positioning of the two VLAs used in the sea trial. The distance between the VLAs is 4 km, the VLA **B** distance to the ship is initially 6 km and then slowly decreasing to 4 km. The VLA **A** has 16 hydrophones, equally spaced from 6 to 66 m depth. The VLA **B** has 8 hydrophones, two at 9 and 14m, and the other six are equally spaced from 55 to 79 m depth. The numerical simulations were obtained with the normal mode model KRAKEN [6]. The estimated frequency response in the 100-300 Hz band, between the two VLAs obtained in Eq. (8) is assessed by means of the phase conjugation method described in the previous section. Fig. 2 shows the space-time ambiguity surface of the focused field at the 2nd hydrophone of the VLA **B** where one compares the reference focused field (a), obtained via Eq. (9), with the noise cross-correlation estimated focused field using Eq. (10) (b), revealing a good agreement in ambiguity surfaces. It is clear in both plots that the peak is at true depth (14m). Temporally the focus is also well compressed at zero lag, although as it would be expected, with higher levels of ambiguity in the noise cross-correlation estimated focused field.

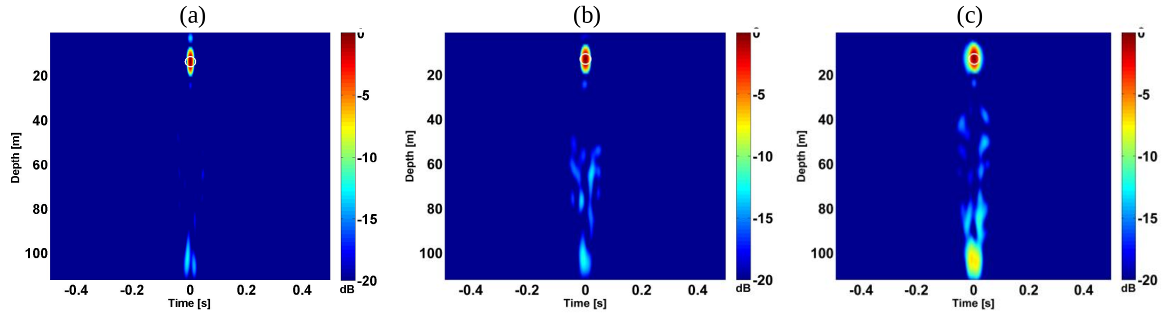

*Fig. 2: Comparison of the spatial-temporal representation of the focused fields on the 2nd hydrophone of VLA **B**: (a) - focused field, using Eq. (9); (b) – noise cross-correlation estimated focused field using Eq.(10); (c) – mean noise cross-correlation estimated focused field affected by random array tilt perturbation.*

Next we consider the influence on the estimated frequency response of uncertainty factors in the VLAs position: distance between the arrays, depth and tilt, individually taken into account. These uncertainties were modeled using Gaussian random perturbations to simulate GPS uncertainty and surface waves and Uniform random perturbations to simulate ocean current effects. Standard deviations of 5 m, 50 cm and variance of 3 deg, were used for array range, sensor depth and array tilt respectively. For each uncertainty factor a set of 200 realizations was performed where for each realization the noise cross-correlation estimated field was obtained. Afterwards the mean noise cross-correlation estimated field was used with the phase conjugation method to assess the influence of the parameters perturbation. Fig. 2 (c) shows the influence of tilt perturbations which revealed overall the same behavior as when the perturbations were not considered. This behavior was also noticed for the other uncertainty factors. The model used to study the uncertainty factors in the VLAs position will be further investigated in future work.

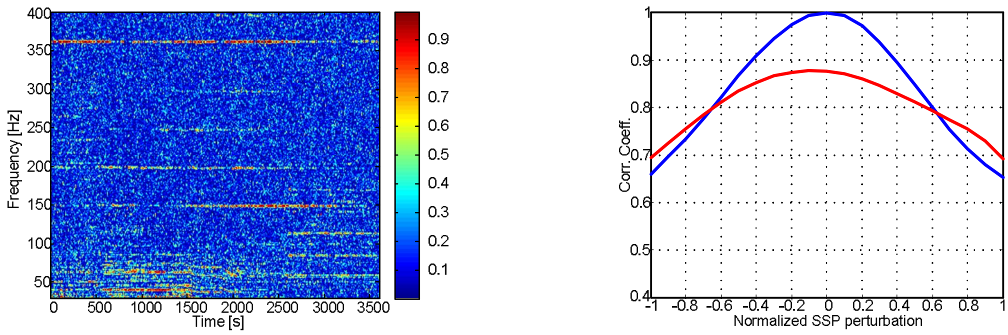

Fig. 3: Left–spectrogram of a radiated ship noise up to 400 Hz band; Right–Bartlett processor in frequency responses comparison of Model/Model (blue) and Estimates/Model (red).

According to the matched field based approach we investigated the ability of the estimated frequency responses between the VLAs, Eq. (8), to track sound speed profiles variation. For this purpose, the collected sound speed profiles in the MREA07 sea trial represented in Fig. 1 on the right (dashed) were used. Fig. 3 on the left presents the spectrogram of the radiated noise of a research vessel, where a set of few low frequency tones is clearly observable up to 400 Hz. Therefore, in the simulations, a set of 11 equally spaced discrete frequencies were considered in the 100-300 Hz band. Fig. 3 (right) depicts the behavior of the Bartlett processor, obtained with Eq. (11), using only the frequency responses given by the propagation model (blue) and using the noise cross-correlation estimates (red). The x-axis represents the normalized sound speed perturbation index α, $-1 \leq \alpha \leq 1$. The used sound speed $\phi(z) = \phi_0(z) + \alpha|\phi_{min}(z) - \phi_0(z)|$, for negative α, and $\phi(z) = \phi_0(z) + \alpha|\phi_{max}(z) - \phi_0(z)|$, for positive α, where ϕ_0 is the mean sound speed profile represented in Fig. 1 (solid), ϕ_{min} and ϕ_{max} are respectively the minimum and maximum collected values of sound speed profiles. The trend of the processor reveals that the estimated frequency responses are able to track variations in the sound speed profiles, although the peak is lower and broader.

4. CONCLUSIONS

In this paper we consider a passive method for the estimation of the underwater acoustic channel frequency response, using a normal mode approximation, where the opportunity source is the ship noise at long range. It is shown that it is possible to characterize the acoustic channel between two arrays at discrete frequencies, typically produced by distant ships in a realistic coastal shallow water scenario. Moreover, it was demonstrated through simulations that the frequency response estimates of the acoustic channel can be used in a matched field inversion procedure to track sound speed/temperature perturbations between the two arrays. This work is a contribution for the usage of noise cross-correlation methods to estimate the sound speed perturbations in shallow coastal water.

5. ACKNOWLEDGEMENTS

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