Acoustic Channel Frequency Response Estimation Using Sources of Opportunity

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***Abstract*—This work addresses the usage of ship radiated noise to estimate the ocean acoustic water propagation channel response between two vertical line arrays. We derive an expression for the frequency response channel estimate using a normal mode development based on cross-correlation methods, in a similar way as *Roux et al.* [1]. Its applicability and limitations in simulated and real conditions is discussed. Simulations are conducted using the normal mode model KRAKEN, based on the experimental setup and environmental parameters gathered during the RADAR'07 sea trial, off the west coast of Portugal, in July of 2007. In this sea trial two drifting vertical line arrays with 16 and 8 hydrophones were deployed in a range independent bathymetric area, at 300 m and 1.3 km distance from the Research Vessel NRP D. Carlos I, whose track then moved away from the arrays, radiating noise in the frequency band bellow 750 Hz. The wave fronts structure, obtained from actual acoustic data of the above referred sea trial, reveals agreement with the simulations obtained with the proposed approach. These results suggest the feasibility of the method for future application in a passive ocean acoustics tomography framework to the estimation of sound speed perturbations in the water column.**

***Keywords*—Frequency response, passive methods, cross-correlation, shipping noise.**

I. 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, as the underwater environment is naturally noisy, in recent years passive methods have been subject of growing interest (see [2, 3] and references herein). These methods use ambient noise, either natural or anthropogenic, instead of active sources, with the advantage of being non-invasive and non-damaging to marine life, including marine mammals. Therefore passive methods are considered low cost and environmentally friendly methods suitable for application during long periods of time. Predominant anthropogenic acoustic noise in the ocean, in the low frequency band (10 to 500 Hz), is due to commercial shipping [4], which is characterized by a few low discrete frequency tones superimposed on a diffuse background pedestal, traveling 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, well documented through the Automatic Information System (AIS) [5], where it would be simple to install receiver arrays, thereby enabling low cost spatial-temporal monitoring of oceanographic processes.

This work addresses the usage of ship radiated noise to estimate the ocean acoustic water propagation channel response between two vertical line arrays. The waveguide frequency response estimation is developed based on cross-correlation methods, using a normal mode approach [1, 6–8]. The RADAR'07 geometry and environmental parameters are used to perform simulations, where two vertical line arrays at 1 km distance are receiving the ship noise. The approach is analyzed and compared with real data processing.

II. MODEL DEVELOPMENT

The shallow-water ocean waveguide can be modeled as an horizontally stratified waveguide with an arbitrary sound-speed profile in the vertical plane. In such environment, long and medium range sound propagation can be properly described by the discrete normal-mode model. The solution of the wave equation for a narrow-band point source exciting an horizontal waveguide is often expressed as a linear combination of normal mode depth functions. Thus, assuming the medium reciprocity, the frequency response of the acoustic propagating field between two points can be expressed as:

$$H_{\omega_0}(R_{AB}, z_A, z_B) \propto \sum_n U_n(z_A) U_n(z_B) \frac{e^{jk_n R_{AB}} e^{-\alpha_n R_{AB}}}{\sqrt{k_n R_{AB}}} \tag{1}$$

where U_n is the n^{th} mode function sampled at depths z_A and z_B, k_n is the corresponding propagating horizontal wavenumber and R_{AB} is the horizontal range between points A and B. For clarity of notation the frequency response will be denoted as $H(A, B)$. In this work the source is assumed as a monotonic of frequency ω_0, characterized by strength (amplitude), $\mathcal{A}$, and a phase ϕ_0, 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 $H'_{SA}(\omega_0)e^{j\phi_{SA}(\omega_0)}$ and $H'_{SB}(\omega_0)e^{j\phi_{SB}(\omega_0)}$, where H'_{SX} is the amplitude and ϕ_{SX} is the phase, associated with a receiver at location X. Therefore, the received signal at location X can be written as

$$y_X(\omega_0, t) = \mathcal{A} e^{j(\omega_0 t + \phi_0)} H'_{SX}(\omega_0) e^{j\phi_{SX}(\omega_0)} + n_X(t) \tag{2}$$

where $n_X(t)$ is an uncorrelated additive zero mean noise component also uncorrelated with the signal.

Assuming the deterministic behavior of the frequency response, the cross-correlation function at 0 lag (i.e. cross power) between the receivers A and B can be written as

$$r_{AB} = E(\mathcal{A}^2)H'_{SA}(\omega_0)H'_{SB}(\omega_0)e^{j(\phi_{SA}(\omega_0)-\phi_{SB}(\omega_0))}+ \\ + E(n_A(t)n_B^*(t)) \quad (3)$$

where $E(.)$ represents the expectation operator. As it can be observed, the cross-power does not depend on the initial phase. The term $E(n_A(t)n_B^*(t))$ represents the cross-power of the noise and under the assumptions made it will vanish. Considering the normal mode approach [1, 6], the cross-correlation between two vertical line arrays on the same vertical plane, probed with radiated noise ship, can be written as

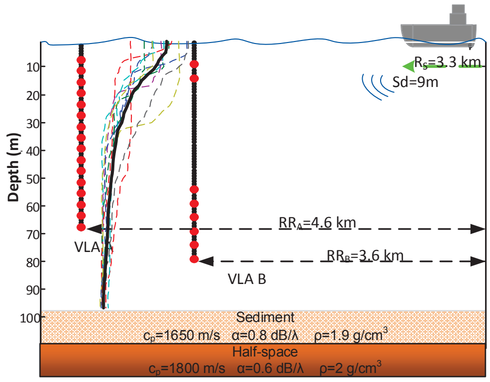
$$\tilde{H}(A,B) \propto \sum_n \frac{U_n^2(S)}{k_n} U_n(A)U_n(B)\times \\ \times \exp(-jk_n r_{AB}) \times \exp(2\alpha_n r_{med}) \quad (4)$$

where r_{med} stands for the average complementary range from the ship's location to its closest vertical line array, $2\alpha_n$ is an attenuating factor, and $U_n^2(S)$, the square of the n^{th} mode function sampled at the source depth position. The latter factor arises naturally from the cross-correlation operation between the two frequency responses. The other two factors account for the median range traversed by the ship and the attenuation due to distance between the ship and the VLA. This estimated frequency response, $\tilde{H}(A,B)$, can be seen as proportional to the term $H'_{SA}(\omega_0)H'_{SB}(\omega_0)e^{j(\phi_{SA}(\omega_0)-\phi_{SB}(\omega_0))}$ in Eq. 3. In the next section the previous expression will be analyzed and compared with experimental data processing.

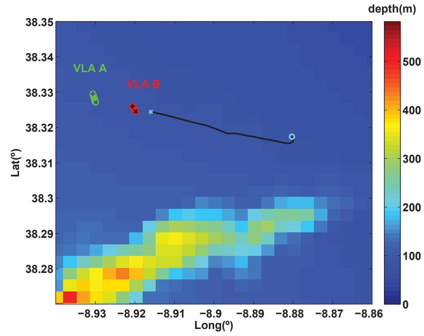
III. Analysis of the RADAR'07 Data Set

The RADAR'07 experiment/sea trial took place from 9 to 15 July, 2007, in the continental platform, off the west coast of Portugal near the town of Setúbal, approximately 50 km south from Lisbon and involved the oceanographic ship NRP D. Carlos I, from the Portuguese Navy. The data collected included active acoustic data covering a wide band from 500 Hz up to 15 kHz, received on the three vertical arrays and used for network tomography as well as for high-frequency tomography and underwater acoustic communications [9]. In this section it will be considered a period of one hour of Julian Day 194 (13 th of July). The geometry for that specific period is depicted in Fig. 1 (a). The environment is range independent with a 98m depth water column, a 10 m depth sediment layer above a sediment half-space. The geometry setup reflects the positioning of two VLAs used in the sea trial. The distance between the VLAs is 1 km, VLA B distance to the ship is initially 300 m and and goes to 3.6 km. The VLA A has 16 hydrophones, equally spaced from 6 to 66 m depth. VLA B has 8 hydrophones, two at 9 and 14 m, and the other six are equally spaced from 54 to 79 m depth. Fig. 1 (b) depicts the estimated GPS track of the R/V NRP D. Carlos I, during a period of one hour of Julian Day 194 as well as the GPS estimated drift of both VLAs. Fig. 1 (c) presentes the GPS estimated angle between VLA A, the ship and VLA B, which shows the change in the relative positioning between the moving vessel and the drifting VLAs.

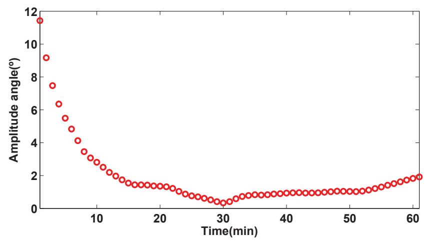
Fig. 2 depicts an illustrative example of the received signal and filtered noise at hydrophone 3 of VLA B. Fig. 2(a) shows an example of the received signal at one hydrophone of one VLA, where it is clearly observable the band of the active



(a)



(b)



(c)

Fig. 1. Baseline environment considered for simulations: experiment geometry and sound speed profiles, measured (dashed) and mean sound speed profile (solid) (a) ; Research Vessel NRP D. Carlos I GPS estimated track, on Julian Day 194 of RADAR'07 sea trial and GPS estimated position of the two VLA's, imposed on a bathymetric map of the region (b); GPS estimated angle between VLA A, the ship and VLA B (c).

signals, as well as the noise band bellow 500 Hz. Fig. 2(b) depicts the filtered acoustic noise in the 30 - 460 Hz band, where the discrete tones emanating from the NRP D. Carlos are clearly visible [10]. Fig. 2(c) presents a temporal representation of the acoustic filtered noise, which reveals the presence of spikes. For ship noise processing acoustic data sets acquired at both VLA receivers were selected, from 10 h 50 m to 11 h 50 m of Julian Day 194 of the referred sea trial RADAR'07. Since all active signals were transmitted above 500 Hz, the acoustic data sets were bandpass filtered in the 30 - 460 Hz band. After inspection of the spectrograms of the filtered data set and due to the frequent presence of discrete tones, the frequency homogenization of the noise was accomplished by means of absolute whitening [8]. The pairwise cross-correlation of hydrophones belonging to the two VLAs was performed using a 15 s length window, with 14 s overlap. The results of this

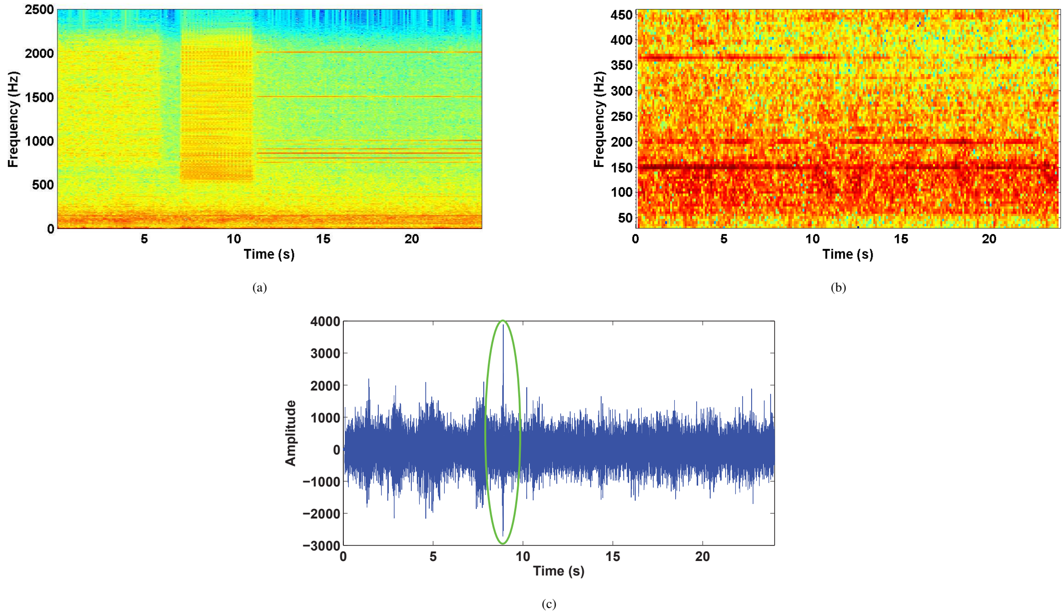


Fig. 2. Spectrogram of the received signal at one hydrophone (a); Noise spectrogram (b); A temporal series of the noise with a strong spike (green circle)(c).

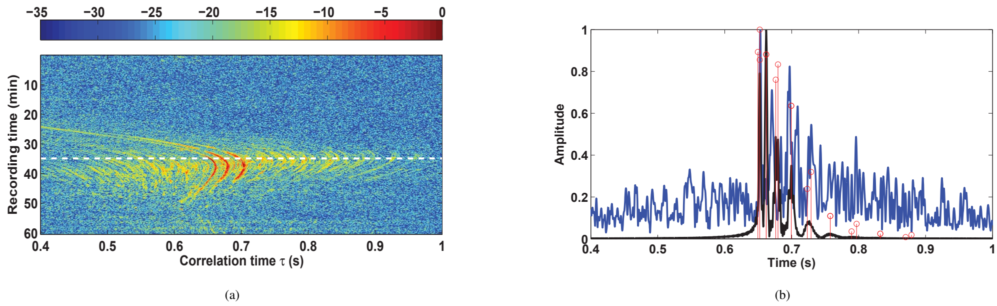


Fig. 3. Representation of the temporal evolution of the time-domain cross-correlation function between the 13-3 pair of hydrophones from VLA A and B, respectively, during one hour of recorded data. The cross-correlation function is plotted in a dB scale and normalized by its maximum (a) ; Average of 15 samples of the previous time series (in blue) corresponding to the period of time represented by the white dashed line in (a), superimposed with the simulated frequency response (in black) and the corresponding delays and amplitudes from a ray tracing model perspective (in red) (b).

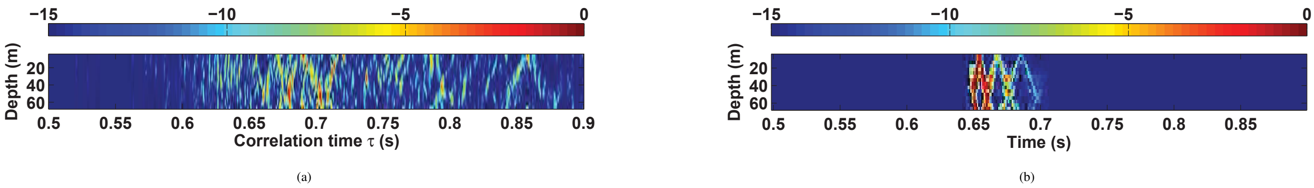


Fig. 4. Wave front obtained form a period of 11 min of data, 11 h 22 min to 11h 33min (a); Simulated wave front, obtained with Eq. 4 (b). The color scale is in dB.

operation for the hydrophone pair 13-3, of VLA A and VLA B respectively, are shown in Fig. 3 (a). The signature of the ship track can be observed, and additionally the wave fronts structure, which corresponds to the period of nearly 10 min when the ship is almost aligned with the two VLAs. This is in accordance with Fig. 1(c), where GPS estimated angle $A\hat{S}B \approx 1^{\circ}$, with A, B standing for VLA A position and VLA B position, respectively.

Fig. 3 (b) shows the average of 15 samples of the previous time series corresponding to the period of time represented by the white dashed line in Fig. 3 (a), superimposed with the simulated frequency response and the corresponding delays and amplitudes from a geometric acoustics perspective, obtained with the ray tracing model TRACEO [11]. The behavior of the estimated frequency response agrees with the amplitudes and delays obtained with the ray tracing model, and the trend of the real data plotted is in also fair agreement. With the present data set, the ship is aligned with both VLAs only for a short period, what could explain the high levels of the sidelobes depicted. This is a constraint of present results, which would overcome with an optimized processing/estimating method to be developed.

Fig. 4 (a) presents a composite of successive time series from one minute to eleven minutes of averaged cross-correlated data between hydrophone 3 of VLA B and all hydrophones of VLA A, using one minute correlation window with 59 s overlap. Fig. 4 (b) shows the cross-correlation for the same hydrophones, however, obtained with Eq. 4. In Fig. 4 (a) one can observe the structure of the traveling wave fronts as if they where emanating from hydrophone 3 of VLA B to hydrophones of VLA A. In Fig. 4 (b) it is visible a similar pattern as in Fig. 4 (a) but only appear the first traveling wave fronts. Nonetheless, the behavior agrees with the real data. However, a possible explanation for this difference is that environmental parameters considered to model the bottom layers are not well adjusted to the drifting position of the VLAs, suggesting that the bottom layer sediment should be considered more rigid sediment than the one modeled.

IV. Conclusion

In this work the usage of ship radiated noise to estimate the ocean acoustic water propagation channel response between two vertical line arrays was addressed. The developed waveguide frequency response estimate was analyzed and compared with real data processing, providing some preliminary results that suggest the feasibility of the method for future application in a passive ocean acoustics tomography framework to the estimation of sound speed perturbations in the water column.

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