Passive Ocean Acoustic Tomography: Theory and Experiment

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Abstract

In this paper the Passive Ocean Acoustic Tomography (P-OAT) methodology is presented. This technique, avoiding the use of a dedicated active sound source, estimates the sea water temperature spatial distribution from the received noise emitted from ships of opportunity. The feasibility of the proposed methodology has been confirmed both by test-runs on semi-synthetic data and by the use of real acoustic and environmental data collected during INTIMATE00 experiment performed on October 2000 in the Atlantic Ocean off the Portuguese coasts.

1. Introduction

The objective of the Ocean Acoustic Tomography (OAT) [1] is to estimate ocean physical parameters (temperature distribution, currents variability, sediment structure) on wide areas using acoustic data analysis ([2], [3]). OAT basic principle relies on dependence of the acoustic propagation on the spatial distribution of the ocean parameters, in particular temperature.

Classical OAT uses a known sound source and in fixed location and, from the inversion of the acoustical pressure or of the travel time of the acoustic pulse received on an hydrophone array, estimates the sound speed field in the area between the source and the receivers; temperature and current field can be then deduced.

Even though OAT cannot be regarded as a routine monitoring technique, tomography experiments conducted so far have demonstrated that OAT can be successfully applied for long-term remote marine environment monitoring. Important oceanographic processes such as the evolution of seasonal thermocline [4], deep water formation [5], El Niño [6] and internal tides can be observed by means of acoustic methods.

To face most of the typical problems of active tomography, in this work an innovative approach – passive OAT (P-OAT) – developed in the frame of the TOMPACO project (TOmografia PAsssiva COstiera) is presented. In the passive tomography, differently from classical OAT, the unknown acoustic emission from ships of opportunity passing within the detection/classification range of the receiving array is the sound source [7]. This approach exhibits two main advantages: avoids the need of both economically and operationally expensive signal sources and allows the investigation of areas as wide as those swept by the moving ships.

After preliminary tests on semi-synthetic data, this methodology has been tested with real acoustic and environmental data collected in the framework of INTIMATE00 experiment; this paper reports the results achieved so far.

2. Passive OAT

In Fig. 1 a schematic representation of the link between a (point) source and the generic k^{th} hydrophone (k =1, …, N) of the receiving array is reported. The n^{th} received snapshot segment $y_k(t,t_n)$ of duration T is the convolution between the signal $s(t)$ emitted by the source (modelled as a member function of a random process in P-OAT), and the (supposed) deterministic channel impulse response $g_k(t;\ \mathbf{a})$, where $\mathbf{a}=[a_1;\ \dots\ ,\ a_N]^T$ is the ocean parameters vector (e.g. sound speed profile, bottom properties, absorption) on which the propagation depends.

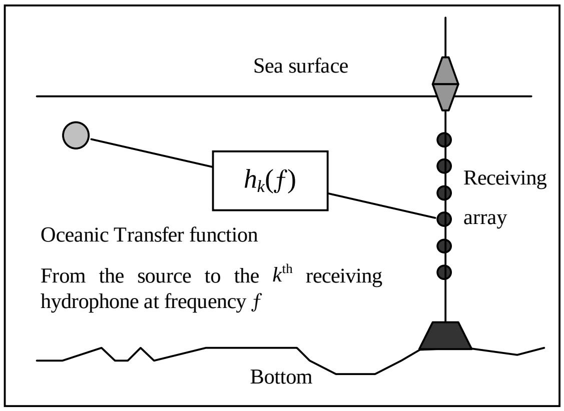

Fig. 1 – Representation of the acoustic link.

For a time-invariant channel and a stationary emitted signal, the link between the source and the k^{th} receiver is thus formally given by the relation:

$$Y_k(f;t_n) = G_k(f;\mathbf{a})\,S(f;t_n) \tag{1}$$

where the uppercase symbols are the finite time Fourier transforms (i.e. FFT) of the corresponding lowercase symbols and where the dependence from the environmental parameters set $\mathbf{a}$ has been explicitly indicated only in $G_k(f;\ \mathbf{a})$ for sake of simplicity. In vector notation we have

$$\mathbf{y}(f,t_n) = S(f,t_n)\,\mathbf{g}(f;\mathbf{a}) \tag{2}$$

where $\mathbf{y}(f,t_n) = [Y_1(f,t_n), \dots ,Y_N(f,t_n)]^T$ and $\mathbf{g}(f;\mathbf{a}) = [G_1(f;\ \mathbf{a}), \dots , G_N(f;\ \mathbf{a})]^T$

The (incoherent) P-OAT approach can be formally faced using the NxN cross spectral matrix $\mathbf{C}(f;\ \mathbf{a}) = E[\mathbf{y}(f,\ t_n)\ \mathbf{y}^H(f,\ t_n)]$ of the received signal (superscript H is the transpose conjugate) which, from (2), can be expressed as

$$\begin{aligned}\mathbf{C}(f;\mathbf{a}) &= E[\mathbf{y}(f,t_n)\mathbf{y}^H(f,t_n)] \\ &= \sigma_S^2(f)\,\mathbf{W}(f,\mathbf{a})\end{aligned} \tag{3}$$

where the NxN matrix $\mathbf{W}(f;\ \mathbf{a}) = \mathbf{g}(f;\ \mathbf{a})\ \mathbf{g}^H(f;\ \mathbf{a})$ can be viewed as the cross spectral matrix of a unitary impulsive source and $\sigma_S^2(f) = E[|S(f,t_n)|^2]$ is the unknown source power spectral density.

Nearly all the OAT processors rely on (3), as the estimation of the unknown environmental parameters $\mathbf{a}$ can be performed in the usual following steps:

- compute a finite-time estimate $\hat{\mathbf{C}}(f;\ \mathbf{a})$ of the unknown received cross spectral matrix $\mathbf{C}(f,\ \mathbf{a})$ from the received signals;
- guess an arbitrary environmental parameter vector $\mathbf{b}$ and compute the estimate of the propagation matrix $\hat{\mathbf{W}}(f;\ \mathbf{b}) = \hat{\mathbf{g}}(f;\ \mathbf{b})\hat{\mathbf{g}}^H(f;\ \mathbf{b})$ using an acoustic propagation model well suited to the measurement area;
- introduce a metric for the distance between $\hat{\mathbf{C}}(f;\mathbf{a})$ and $\hat{\mathbf{W}}(f;\mathbf{b})$ and let the guessed environmental parameter set $\mathbf{b}$ span its physically meaningful ensemble.

A possible simple metric $D(\mathbf{a},\mathbf{b})$ of the "distance" between real (unknown) and estimated environmental parameter sets $\mathbf{a}$ and $\mathbf{b}$ may be

$$D(\mathbf{a},\mathbf{b}) = \frac{\hat{\mathbf{g}}^H(f;\mathbf{b})\hat{\mathbf{C}}(f;\mathbf{a})\hat{\mathbf{g}}(f;\mathbf{b})}{\hat{\mathbf{g}}^H(f;\mathbf{b})\hat{\mathbf{g}}(f;\mathbf{b})} \tag{4}$$

If the propagation model used to estimate the transfer functions vector exactly reproduces the true propagation in the medium, then $D(\mathbf{a},\mathbf{b})$ defined by (4), known as Ambiguity Function, attains one maximum value when the $\mathbf{b}=\mathbf{a}$, i.e. when the estimated parameters match with the real ones.

Of course, the basic relation used in the present paper is particularly focussed toward the P-OAT, where the source signal is unknown and no absolute signal phase is available; in different contexts (i.e. active OAT) other approaches may be better suited.

2.1 The passive pre-processing block

As the source power spectral density is unknown, before the Ambiguity Function evaluation, the passive OAT has first to select the frequency bins belonging to the propagating signal, rejecting from the subsequent processing the noise bins. In this work, the extraction of the source main sound components relies on the decomposition properties of the received signal cross spectral matrix, whose structure is closely related to the useful signal spectral distribution.

From (3), introducing noise, the (j, k) element of the cross-spectral matrix $\mathbf{C}(f;\mathbf{a})$ can be expressed as

$$C_{j,k}(f;\mathbf{a}) = \sigma_X^2(f) W_{j,k}(f;\mathbf{a}) + \sigma_N^2(f)\delta_{j,k} \quad (5)$$

where $\sigma_N^2(f)$ is the noise power spectral density at frequency f, supposed independent on hydrophone index. Performing now the singular value decomposition (SVD) of the received cross-spectral matrix $\mathbf{C}(f;\mathbf{a})$ we have the relation:

$$C(f;\mathbf{a}) = \mathbf{V}(f;\mathbf{a})\mathbf{\Lambda}(f;\mathbf{a})\mathbf{U}^H(f;\mathbf{a}) \qquad (6)$$

where $\mathbf{V}(f;\mathbf{a})$, $\mathbf{U}(f;\mathbf{a})$ and $\mathbf{\Lambda}(f;\mathbf{a})$ respectively are the left and right eigenvectors matrices and the singular values diagonal matrix of rank R. From (5) and (6), only when the frequency f really belongs to a signal component propagating trough the medium, there is one dominant eigenvalue and $\mathbf{V}(f;\mathbf{a})$ and $\mathbf{U}(f;\mathbf{a})$ are ill conditioned (rank~1). Thus, whether the source signal or the noise component dominates at given frequency might be assessed by analysing the dominant eigenvalues distribution of the SVD decomposition of the cross spectral matrix $\mathbf{C}(f;\mathbf{a})$.

This eigen-decompostion approach reveals more powerful then classical FFT analysis to select the frequencies where the signal can be extracted from noise. FFT approach only analyses the power spectral levels, discarding the spatial coherence information. However, care must be taken in the lower frequency band, if the wavelength appreciably exceeds the hydrophone spacing. In such a case a suitable normalization factor has been inserted in $\mathbf{\Lambda}(f;\mathbf{a})$ analysis to account for the spatially correlated noise effect.

The proposed method has been also applied to the experimental passive data collected during the INTIMATE00 sea trial. In Fig. 2 the estimated cross spectral matrix magnitude has been reported for signal and noise frequency bins (vessel moving at 2 Km from the array); in the two cases, the diagonal and off diagonal structure of $\mathbf{C}(f;\mathbf{a})$ allows an unambiguous classification and selection of the frequency bins to be subsequently processed by the P-OAT.

A further analysis has been carried out on the experimental data to confirm that the amplitude and relative phase time variability of the $\mathbf{C}(f;\mathbf{a})$ is practically negligible during the time window (i.e. 2 sec.) chosen for P-OAT, thus allowing reliable estimates.

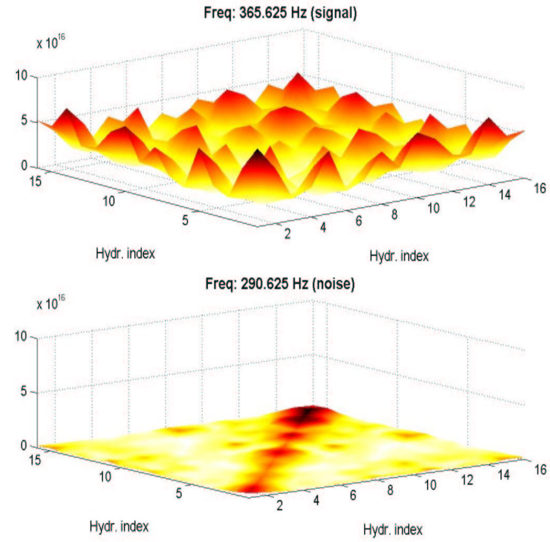

Fig. 2 – Cross spectral matrix magnitude on signal and noise bins.

3. INTIMATE00 sea trial campaign

The data used to test the tomographic processor were collected in the framework of INTIMATE00 (INternal TIdes Measurements with Acoustic Tomography) experiment, carried out from 15 to 22 October 2000 in the Atlantic Ocean, in front of the Portugal coasts off Setubal.

Acoustic data were collected by a 16 hydrophones Ultra Light Vertical Array (ULVA) also equipped with thermistors, pressure and tilt gauges. The array, floating around a fix position located at 8° 56' W - 38° 18' N at a sea depth of ~110 m, ensured an acoustic aperture between 30 and 90 m. Environmental condition in the area of the experiment (from 8° 50’W to 9°03’ W and from 38°13’ N to 38° 22’ N) were monitored during the whole period by means of three fixed mooring with currentmeters, temperature and salinity sensors, two thermistor chains, which operated for shorter periods and by XBT profiles taken from the oceanographic vessel. A short description of the main oceanographic characteristics during the experiment can be found in [8] and some preliminary results in [9].

Both acoustic and non-acoustic data collected by the ULVA were transmitted onboard through a radio link, thus allowing a constant quality control, although limiting the distance between the vessel and the ULVA position up to few kilometres.

For the passive OAT test, the oceanographic vessel steamed at a speed of 10 kn following a radial trajectory between the NW and the NE transects, respectively at 1, 2 and 3 km from ULVA position (Fig. 3). The selected ship track insured a quite uniform flat and a mid-range variant bottom. The vessel (acoustic source) position and its relative sea bottom depth were directly recorded onboard. The test lasted about 1 hour and was performed with a good whether condition. The experimental area was free from other vessels.

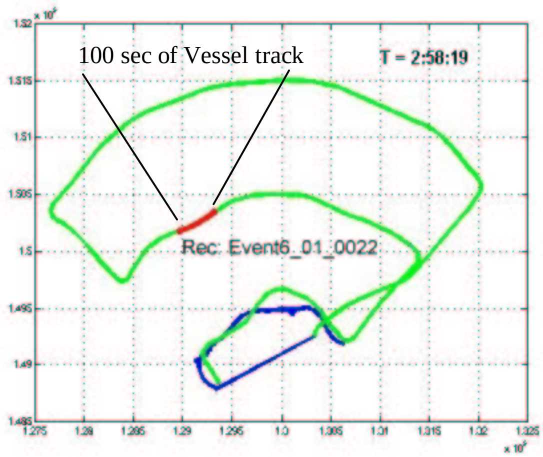

Fig. 3 – Ship (acoustic source) track for P-OAT experiment from GPS data.

4. Passive OAT results

To reduce the parameter space to be inverted, a routine technique in OAT is the SSP decomposition with the Empirical Orthogonal Functions (EOF) [10] which relies on the availability of an SSP historical database in the investigated area. Unfortunately, apart few tens of XBT deployed during the sea trial, the absence of an historical database in the Setubal area led us either to use the limited XBT samples to estimate an EOF base or to steer toward an alternative approach, based on the Hydrostatic Normal Modes (HNM) for which a single mean SSP profile is needed [11]. In the processing carried out so far we addressed to the latter technique: using either the thermistors chains or XBT data a single mean temperature profile $s_0(z)$ has been estimated; solving the Navier-Stokes equation in the hydrostatic approximation, the HNMs to be used in the P-OAT inversion have been estimated [12]. In Fig. 4 a thermistors chain temperature has been reported vs. Julian day. In Fig. 5 the first four HNF estimated from thermistors data have been reported.

Relying on the HNFs expansion functions $H_k(z)$, z being the depth, we explicitly assume that each unknown SSP $s(z)$ (to be estimated by the P-OAT) may be approximated by the expansion

$$s(z) = s_0(z) + \sum_{k=1}^{M} \alpha_k H_k(z) \qquad (7)$$

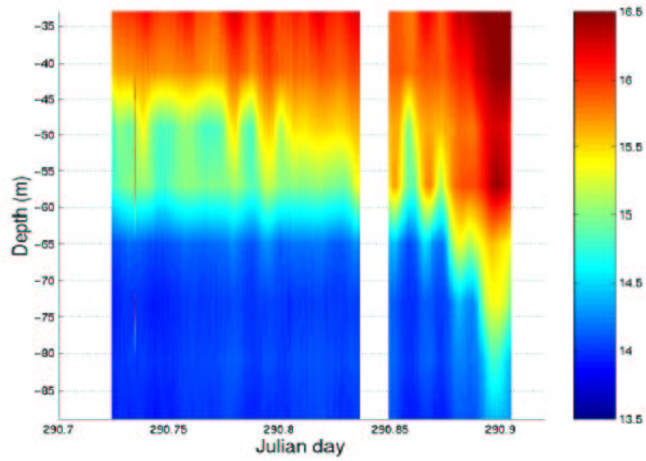

Fig. 4 – A thermistors chain measured temperature vs. time.

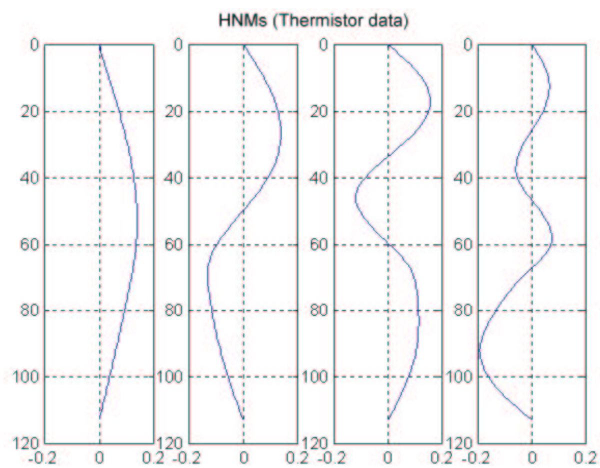

Fig. 5 – First 4 HNMs estimated for the experimental area up to 120 m depth.

From experimental XBT data, it has been confirmed that, using (7), every experimental SSP collected during the campaign is actually well approximated with only the first 2 or 3 HNM

The processed time segment for P-OAT corresponds to 2 sec. data window (start of the 100 sec. track segment indicated in Fig. 3) with a 10 kn ship track at 2000 m nearly constant distance from the ULVA and a nearly flat sea bottom (~103 m) from the ship to the ULVA.

Although the singular value analysis used for the signal bins selection indicated a very high signal component at 366 Hz; a mid-energy signal bin at

665 Hz has been selected for the P-OAT subsequent processing. The choice of selecting a less favourable frequency component comes from the need to test the P-OAT feasibility on the more dense spectral components rather then on a unique best-case bin, which is not necessary present in every ship sound spectra.

For the P-OAT processing the assumed environmental model is reported in Fig. 6, with sound source (vessel) distance and depth, array geometry and bottom physical properties (density ρ, absorption α and sound speed c). The SSP reported in Fig. 6 is the one measured by the closest, both in time and space, XBT deployment and it will be used to benchmark the SSP estimated after the P-OAT inversion. For the estimation of $\hat{\mathbf{g}}(f;\, \mathbf{b})$ in (4) the PROSIM broadband adiabatic normal mode propagation model [13] has been adopted.

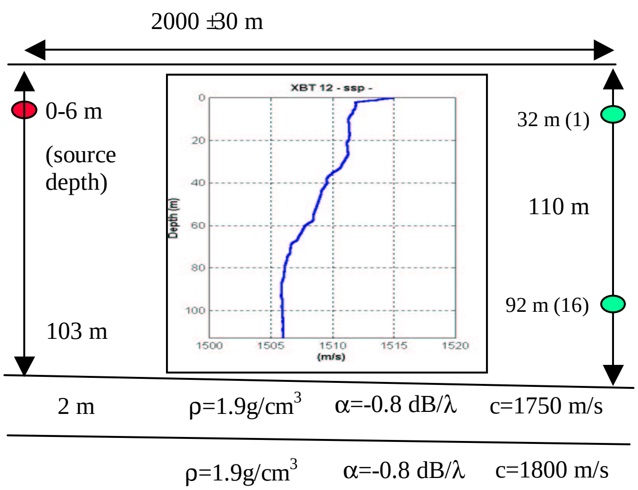

Fig. 6 – Environmental model used for the inversion processing with experimental SSP.

P-OAT inversion has been used to jointly estimate, in an unique process, four environmental parameters: the cooperative ship depth, range and the HNM $\alpha_{1,2}$ expansion coefficients (assuming M=2). The resulting four-dimensional Ambiguity Function has been separately projected for ship sound source location in Fig. 7 and for the two HNM coefficients in Fig. 8. The estimated source location complies with what expected from the vessel used as sound source (~2020 m distance and 0-3 m depth). The presence of an unique maximum in Fig. 8 leads to an unambiguous estimate of the Sound Speed Profile, which has been reported in Fig. 9, together with an SSP actually measured in a nearby position. The agreement between the SSP estimated by P-OAT and the experimental one is satisfactory, also taking into consideration that the measured SSP location doesn't match with the ship-ULVA propagation line.

5. Conclusions

The first results achieved for passive acoustic tomography performed in the framework of TOMPACO and INTIMATE00 projects have been described. The Sound Speed Profile estimation has been satisfactory achieved by processing the acoustic data of a unknown passive source (vessel) with no a priori information about its distance and depth.

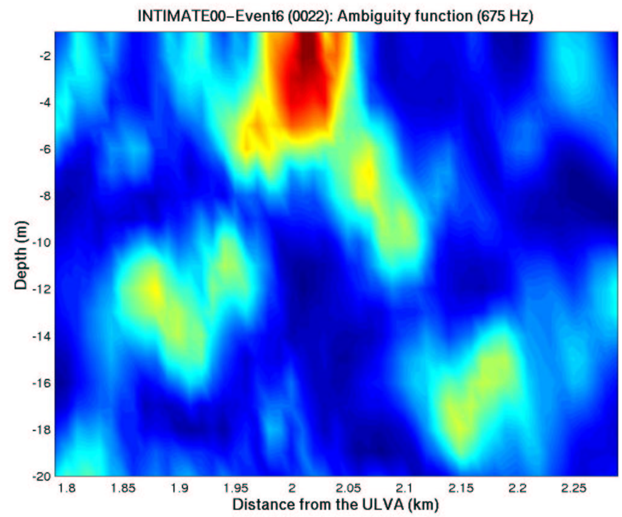

Fig. 7 – P-OAT Ambiguity Function for source range and depth estimation.

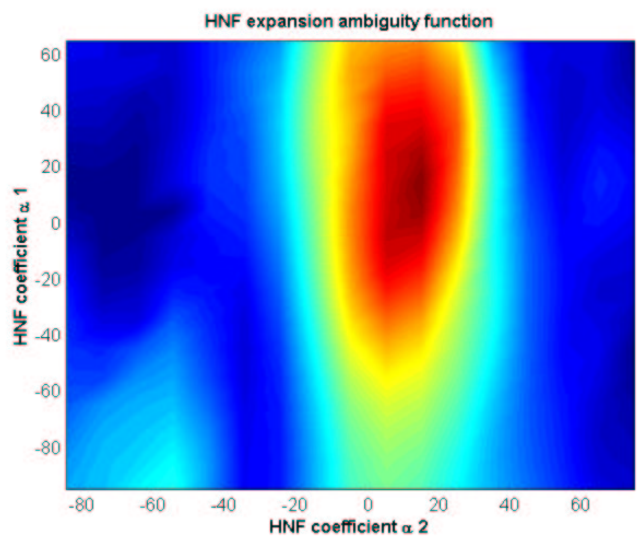

Fig. 8 – P-OAT Ambiguity Function for HNM expansion coefficients.

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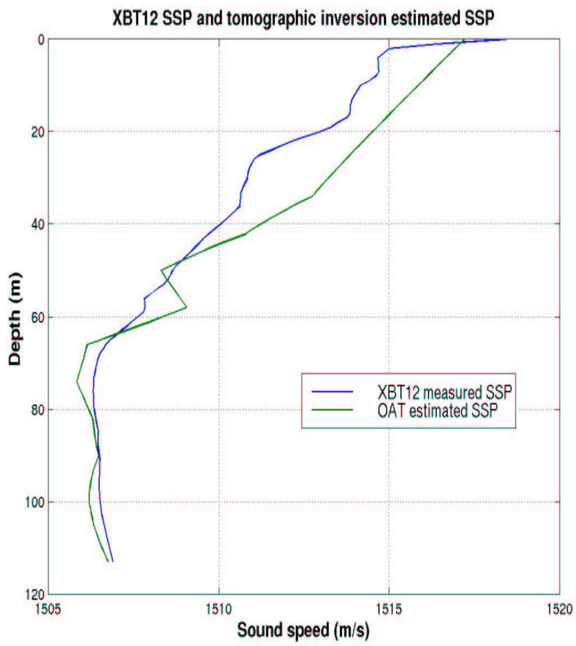

Fig. 9 – P-OAT estimated SSP and measured SSP in a nearby position.

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