Acoustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Underwater channel characterization using opportunity sources : a time-frequency-phase approach

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Analyzing natural signals constitutes the main tool for characterization of physical phenomena. Underwater channel is an example of a *natural* environment potentially characterized by signals generated by various sources : underwater mammals, human activity noise, etc. In order to efficiently exploit the information from these signals two major problems should be addressed. **First**, since the signals are unknown or disturbed by unpredictable factors, we are deal with a blind processing context. That is, the lack of a priori hypothesis has to be considered. Generally, the signal has a complex shape characterized by multi-component non-linear time-frequency structures. The proposed solution consists in focusing our processing on *non-parametric time-frequency analysis* considering also fundamental signal items such as time-frequency energy and local phase analysis. The **second** problem is related to the complex connection between physical parameters of a phenomenon and parameters of signals characterizing this phenomenon. The proposed approach consists of combining the *physical model* with the information provided by a *parametric representation* of the signal. This framework helps to the definition of the concept of *underwater passive tomography* which provides the characterization of the underwater channel of interest by taking advantage of environmental signals : mammals vocalizations, motion sources, etc.

1 Introduction

Covering 70% of the planet, the ocean plays an essential role in the global eco-system. The oceanography is the science of ocean physical phenomena understanding, ocean modelling as well as the previsions of ocean evolution. In order to provide real data for ocean analysis *in situ* measurements are necessary, requiring a given number of sensors. This type of measure is often subject to spatial under sampling since a large number of sensors should be used for covering a given area of interest. Having in mind that this number could not be large enough (because of the complexity of managing a huge number of sensors) alternative techniques have been investigated in the past decade.

One well known technique consists in transmitting one acoustic wave and analyzing, at the receiver, the distortions induced by the environment. This technique, called *oceanic acoustic tomography* and introduced in 80s, allows monitoring ocean properties at variable spatial and time scales [1].

Once the feasibility of active acoustic tomography proved [2], starting in earlier 2000, new constraints are imposed by operational considerations:

- Fast deployment of tomographic system, knowing that the active tomography concepts use often complex sensors networks with high costs;
- Acoustic discretion knowing that the transmitted signals used for channel investigation could interfere with other signals existing in the environments.

These constraints were the main arguments behind the definition of passive acoustic tomography concept where the acoustical transmitted signals are replaced by signals transmitted by *natural opportunity sources* existing in the environment [2]. This concept has been developed during our participation to the advanced project “MODE” CA/2003/06/CMO from January 2004 to January 2007.

The difficulties in terms of signal processing are related to the lack of a priori information about signal's type as well as the complexity of underwater environment (in terms of noise, propagation effects, etc). In this context, the signal analysis methods are aimed to extract the parameters of received signals and to transform them in physical parameters related to the channel properties. The general concept proposed in our work is based on the combination between physical aspects and general signal's representation concepts which leads to an appropriate representation for the parameters extraction task.

The paper is structured as follows. In the section 2, we describe the problems of passive oceanic tomography. The aim is to point out on signal processing problems induced by the context of passive oceanic tomography. The section 3 is devoted to the definition of general signal processing framework. Its utilization, in the context of real configurations, is described in section 4. The section 5 points out on the concluding remarks and the future works in this field.

2 The concept of passive oceanic tomography

In order to respond to the *discretion* (required by military operations), *ecology* (for underwater fauna protection) and *estimation of underwater environment* constraints, the concept of passive oceanic tomography became an emergent field at the border of underwater acoustic and signal processing.

Conceptually, the passive oceanic tomography is defined by the set of analysis techniques of opportunity signals existing in the environment and the estimation of physical channel based on the parameters provided by signal analysis. The natural noise of the sea, the boat noise and the underwater mammal vocalizations are three examples of sources of opportunity signals. Since the results of inversion methods based on natural and boat noises are currently under investigation, a large number of studies have been conducted by considering signals transmitted by underwater mammals. We mention here the works of Thode et *all* [3] which proposed the use of one vertical linear antenna for sea bottom inversion using whale vocalizations. In the MODE project we have studied the problem of inversion techniques in blind configuration using time-frequency analysis tool. At the beginning of this project we were face to the difficulties of signal's analysis related mainly to the lack of hypothesis about transmitted signal and source position. The underwater noise and the propagation effects constitute additional difficulties addressed to signal's analysis methodology.

From operational point of view, we have proposed three concepts of passive tomography whose definitions are dependent to the type of source:

- Discrete tomography which is based on an active system transmitting signals similar to the ambient noise. The similarity of time-frequency content of transmitted signal with respect of the noise one ensures the secret of this operation. In term of signal processing, an efficient analysis of ambient signals is required, leading to the identification of signal's structures, appropriate for inversion [5];

– Assisted tomography which takes advantage of the opportunity signals transmitted by a cooperating entity whose position is known. The only unknown element is the transmitted signal that has to be estimated;

– Autonomous tomography is the most complex concept since the configuration is totally unknown. Except the estimation of transmitted waveform, the motion parameters should be also taken into consideration [2].

In terms of signal processing we propose a unitary analysis framework based on the physical model integration during the parametric characterization of instantaneous phase of received signal. The next paragraph describes this framework as well as its particularization for the three tomography concepts defined above.

In order to develop these concepts, several measurement campaigns, aimed to provide realistic scenarios for signal processing and inversion, are necessary. One of these campaigns, called PASSTIME 2005, has been developed in October 2005 in Bay of Biscay [4] by French Office of Naval Research (SHOM).

As transmitted signals, several "classical" waveforms have been used : sinusoids, linear and cubic chirps as well as signals imitating some underwater mammal vocalizations. The knowledge of transmitted waveform allows us estimating, by matching filtering, the channel impulse response. This one has been used as reference data and compared with the impulse responses (IRs) estimated in blind contexts.

The receiving configurations have been defined with respect of the concepts mentioned before. Hence, in the case of discrete tomography, 320 vocalizations have been used for defining the synthesized vocalizations necessary for inversion [5]. Concerning the assisted tomography, the aim is to find the impulse response using only passive configurations. The comparisons with active inversion have been done for 2000 recordings. Finally, the autonomous tomography has been materialized by using realist motion scenarios.

3 Signal analysis framework

While the time-frequency content of natural opportunity signals is generally non-linear, we focussed our research on the polynomial phase modelling of received signals [3]. We assume that the signal received by the passive tomography system, x, is composed by the attenuated and delayed versions of the transmitted signal, s

$$x(t)=\sum_k \alpha_k s(t-\tau_k)+n(t) \qquad (1)$$

where n denotes the perturbations (noises, interfering signals, etc). As the signal s is unknown, the proposed processing consists of parametric analysis of instantaneous phase of received signal, in the context of the convolutive mixture (1). Thanks to its general character, we chose the polynomial model as parametric model.

$$s(t)=\exp\left[j2\pi\phi(t)\right];\phi(t)=\sum_{i=1}^{N} a_i t^i \qquad (2)$$

The concept of the polynomial phase modelling has been developed around the high order ambiguity function (HAF) introduced by Peleg and Porrat in 1991. Its main property is that for a signal defined by (2), the N^{th} order HAF is peaky at a frequency location ω_N expressed as :

$$\omega_N = N!\tau^{N-1}a_N \qquad (3)$$

where τ is the lag (delay) used for HAF evaluation. Consequently, an attractive way to estimate the polynomial coefficients is to evaluate the peak location of the associated HAFs. Unfortunately, as illustrated in [6], the classical phase modeling procedures are unable to deal with noised multi-component PPS's (which is always the case in underwater signals context). One potential solution is then to combine many HAFs, evaluated for different set of lags. However, the way of combining the HAF evaluated for many set of lags (multi-lag HAF - mlHAF) is a very challenging problem in polynomial phase modeling field. In [6], we proposed to linearize the relation between ω and τ given by (3). This operation involves the definition of a new lag set, provided by a warping operator [6] defined as :

$$\tau_w = \tau^{\frac{1}{k-1}} \qquad (4)$$

After this step, the evaluated mlHAF for this lag set is peaky at an angular frequency α_w depending *linearly* of τ. The effect of the warping function (4) in the frequency-lag plane consists of disposing the mlHAFs peaks on parallel lines with the lag axis. We can define also the Warped HAF as in [6] :

$$WHAF_k[s;\omega]=\sum mlHAF_k\left[s;\omega,\tau_w\right] \qquad (5)$$

Next example illustrates the capability of the WHAF approach to deal with noisy multi-component signals. Considering a mixture of two cubic frequency modulations corrupted by white Gaussian noise (SNR=8 dB).

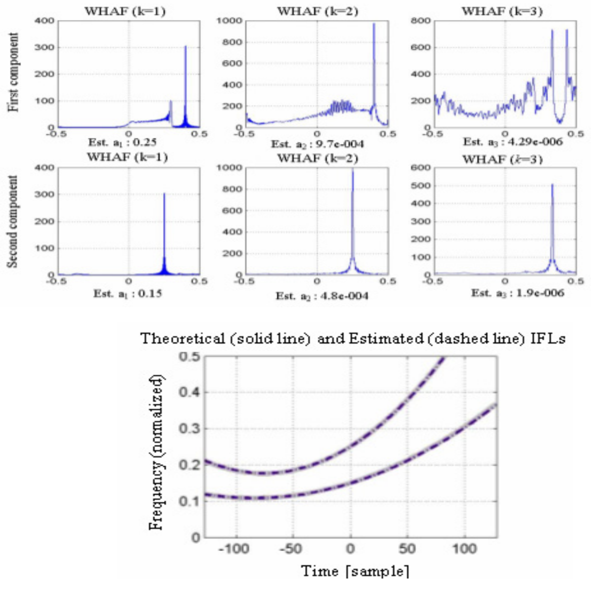

Fig. 1 WHAF-based polynomial phase modeling

We can notice that the polynomial coefficients, obtained via (3) form frequency locations corresponding to spectral peaks, are correctly estimated. This is reflected by a correct IFL (Instantaneous Frequency Law) estimation.

The polynomial phase characterization provided by this method allows designing the most appropriate signal's representation space for the extraction of the channel parameters. This space is defined by stationarising the mixture (1) via a time-frequency warping operator defined from the model (2). This principle is illustrated by the following example. . The warped space is given by the turned time-frequency axis where the arrival components are stationary. Furthermore, a conventional spectral analysis technique provides the frequencies of these components which are, via the convolutive mixture model assumption, directly related to the physical parameters – time delay and attenuations.

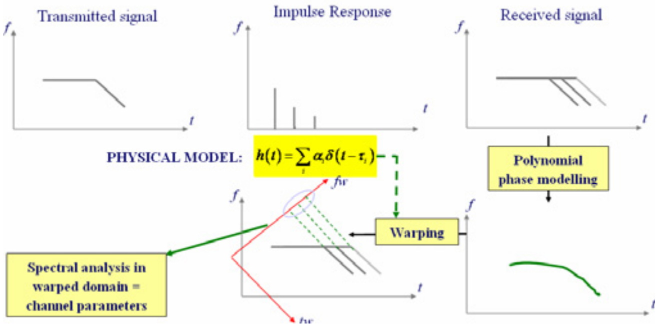

Fig. 2 Physical modeling based on signal analysis

In this example, we notice the symbiosis which characterizes the proposed architecture. Thanks to the polynomial analysis of the phase (required by the lack of a priori information on the transmitted signal) and the description of the physical context of the problem, we can connect the parameters of the signal to those of the environment. This principle has been employed, as a signal analysis-physical model estimation methodology, in the three passive tomography concepts defined in the previous section.

In the case of the discrete tomography we notice (Fig 3) that only the polynomial phase modelling is necessary to provide the parameters for the signal's synthesis. That is, the polynomial coefficients characterizing the received signal's phase are used to design a synthesized waveform, similar from acoustic perception point of view to the real environmental data. This waveform is used in an active tomography system as indicated in the figure 3.

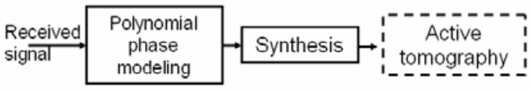

Fig. 3. Processing diagram for discrete tomography

The signal analysis principle becomes more complicated in the context of assisted tomography. While the transmitting is not authorized, only the received signals will be used according to the principle illustrated in the figure 4.

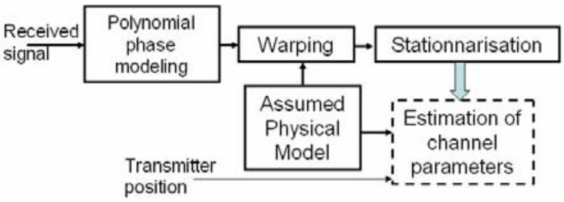

Fig. 4. Processing diagram for assisted tomography

The received signal will be analyzed in order to find the polynomial phase coefficients, in a multi-components context. These parameters as well as the assumptions concerning the physical design of the channel allow designing the corresponding representation space for the extraction of the channel parameters. These will be geometrically connected thanks to the known position of the transmitter (fig. 4).

Since this information is not anymore available in the case of the autonomous tomography, we note in the figure 5 that the analysis of the source motion is essential, implying a multi-sensors processing.

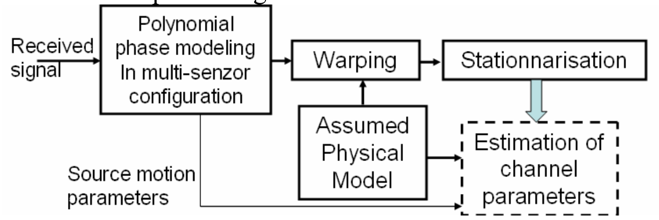

Fig. 5. Processing diagram for autonmous tomography

More precisely, taking into account the "traditional" approximation of a motion vector by a polynomial law, the polynomial phase modelling constitutes an effective tool for the analysis of the source motion [6]. However, the main difficulty consists in separating the time-frequency contents of the transmitted signal and of the modulation introduced by the Doppler effect. As a solution, we showed that the polynomial phase modelling could offer an effective solution [8]. More precisely, considering a tone (with frequency f_0) as transmitted waveform and an uniform source motion (with speed v), we have analytically shown in [8] that the received signal can be modelled as :

$$s_1(t)\propto \exp\left\{j2\pi\sum_{i=0}^{3}a_i t^i\right\} \tag{6}$$

with

$$a_0=\frac{r_0\sin\theta_0}{c};a_1=f_0-f_0\frac{(r_0\Omega\cos\theta_0+v\sin\theta_0)}{c}$$
$$a_2=-\frac{f_0(-0.5r_0\xi\sin\theta_0+v\Omega\cos\theta_0)}{c};a_3=\frac{0.5\xi f_0 v\sin\theta_0}{c} \tag{7}$$

where r_0 is the initial range between transmitter and receiver, θ_0 is the angle between the vertical and transmitter-receiver line of sight, c the speed of sound and (Ω,ξ) are the parameters of angular motion associated to the relative source-receiver position changes (figure 6).

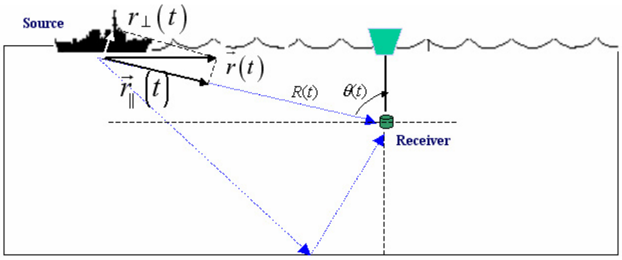

Fig. 6 Dynamic transmitter-receiver configuration

This result shows the interest behind polynomial phase modelling in the context of Doppler effect estimation. On the other hand, it points on the significance of the motion in low frequency bands : even if the motion is uniform and the transmitted signal simple (here, a tone), the modulation induced by motion is of order 3. The separation between signal's parameters and the motion ones could be also solved by the polynomial phase modelling and the physical considerations related to motion effect. The problem is much more complex when the multi-path configuration is considered and this is currently part of our research activities.

The proposed analysis architecture proposed in this paragraph has been tested through many real configurations. The following paragraph illustrates only the principal results obtained in the context of the passive tomography.

4 Results

The effectiveness of the architecture previously presented was studied using real data obtained in the measurement campaign, PASSTIME, organized in October, 2005 in the Bay of Biscaya by the Military Center for Oceanography Brest [4].

Concerning the discrete tomography, the following example shows the capacity of the proposed analysis framework to analytically characterize the instantaneous phase of real signals. We note that, in spite of the multi-components behaviour of the received signal, its two time-frequency structures are well estimated.

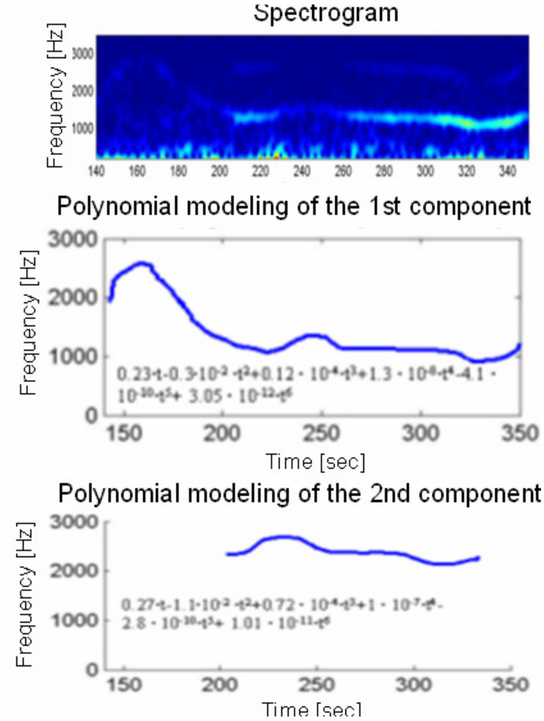

Fig. 7 Polynomial phase modelling of an underwater mammal vocalization

The polynomial expressions of the instantaneous phases of time-frequency components of underwater mammal vocalizations constitute a sparse representation of these natural signals. Their analytical description in term of polynomials yields to an efficient way for synthesising waveform acoustically similar to vocalisations existing tin the channel. The analysis done for all set of real signals issued from PASSTIME campaign proved the feasibility of the discrete tomography concept [5].

Concerning the assisted tomography concept, the purpose was to estimate the real channel impulse response using the signal received from a cooperative entity. An example of such processing is illustrated in the figure 8.

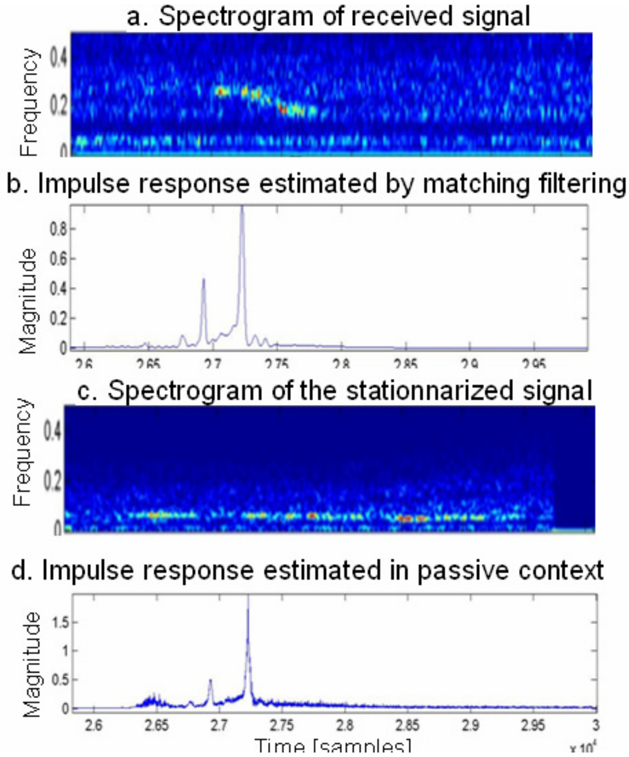

Fig. 8 Example of the estimation of the channel parameters by the concept of the passive acoustic tomography

The results of channel parameters estimation obtained in a passive configuration were compared with the results provided by matching filtering – widely used in the active tomography context. Figure 8 presents a result obtained for one of the 2000 recordings of PASSTIME campaign. We notice the good concordance between the results obtained in passive configuration (figure 8.d.) and those provided by matching filtering (figure 8.b). This accurate estimation was possible thanks to the efficient stationnarization of the received signal which, as indicated in the figure 8.c., has been appropriately done.

Finally, the autonomous tomography has been studied by considering the signals transmitted by motion sources. In this context, we have firstly proved the correlation between the polynomial coefficients estimated from signals received by two sensors (figure 9).

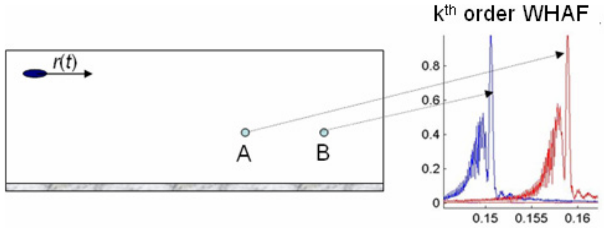

Fig. 9 Spatial correlation between polynomial coefficients in the case of signals received by two sensors

As indicated in this figure the WHAFs at a given order are *almost* similar the differences being related to the relative motion *seen* by this sensors. Hence, it is theoretically possible to separate the motion parameters from the signals+channel's ones. This property of the WHAFs evaluated in multi-sensors configuration, currently under investigation, allows us estimating the local impulse responses as shown in the example given by figure 10.

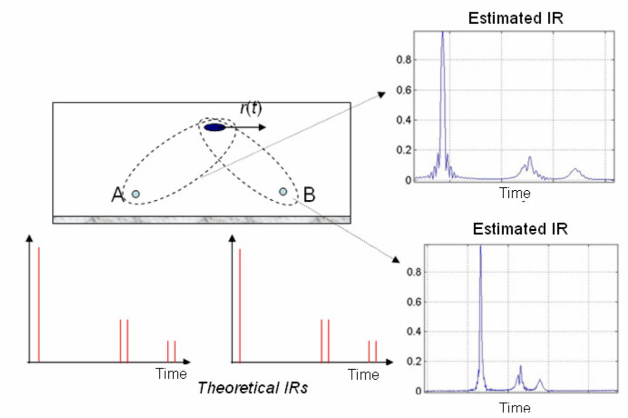

Fig. 10 Estimation of IRs in a moving configuration

5 Conclusions

The passive oceanic tomography is a new characterisation concept of the underwater environment presenting a growing interest in the current operational context. In this paper we synthesised our work in this field in the form of a general signal analysis framework in a "blind" context - the main difficulty in term of signal representation. This architecture is designed around the polynomial modelling of the instantaneous phase of the received signal and the transformation of this one in a suitable representation space for physical channel parameters estimation. This transformation is based on the joint use of the warping techniques and the physical model of the channel.

The significant number of the tests allowed us to objectively compare several analysis methods and to prove the operational feasibility of the concept of the passive acoustic tomography.

In future works, we will concentrate our work on taking into account more complex configurations by taking care of the various phenomena like dispersion and the generalized motion.

Acknowledgments

The authors are very thankful to the Military Center for Oceanography, Brest for the financial support of this work, under research contract CA/2003/06/CMO, as well as for the very rich scientific exchanges.

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