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SIGNAL ANALYSIS APPROACH FOR PASSIVE TOMOGRAPHY : APPLICATIONS FOR DISPERSIVE CHANNELS AND MOVING CONFIGURATION

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Abstract: *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 take advantage of these sources, the concept of passive acoustic tomography has been introduced. According to this concept, the environment parameters could be extracted from the analysis of the received signals. While the signal's parameters are intimately related to physical parameters of the environment, their accurate extraction is crucial. That is, this task is complex while we work in completely passive context and when we deal with a large diversity of underwater signals. Generally, signals issued from underwater environment have complex time-frequency structures : non-linear time-frequency and multi-components. Two typical non-linearities are generated by the dispersive systems and the relative motion between transmitter and receiver. Despite the origin of these phenomena, the signal approach proposed in this paper will provide a unique framework for parameters extraction. This approach is based on the time-frequency-phase coherence of any natural non-linear time-frequency component. Taking advantage of this coherence, the non-linear structures can be efficiently extracted and used for physical parameters estimation. .*

Keywords: Time-frequency analysis, passive tomography, dispersive channels, motion effect

1. INTRODUCTION

One well known technique for underwater environment characterization consists in transmitting acoustic waves 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 tomography 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].

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.

In this paper, two applications contexts are considered. The first one consists of **dispersive environments** which concern the underwater systems operating at low frequencies (mainly, below 200 Hz). A dispersive channel modifies a transmitted signal in a complex way, bringing it deeply non-stationary. More precisely, a dispersive channel produces different delays of spectral components according to their frequencies : high frequencies are generally less delayed than the low ones [3]. The transformation of signal propagating in dispersive channel can be characterized by a non-linear change of the phase function of the signal : $\xi(t/t_r)$ where t_r is the reference time. For example, in shallow water environment, the phase changes according to $\xi(t/t_r) = \sqrt{(t/t_r)^2 - (\alpha/t_r)^2} (t > \alpha)$ [3]. This change is specific to each propagation path. In conclusion, a signal issued from a dispersive channel is composed by many versions of transmitted signal, each one having distinct time-frequency shape according to its propagation mode [1]. In addition, these versions are very close in time-frequency plane which bring difficult their separation.

The second application context concerns the characterization of the **motion effect** existing in the received signal. This characterization can either improve the performances of the existing systems either enable the use of some concepts. Namely, the motion effect impinging on a signal arising in a communication system could decrease the receiver performances [4]. If the motion is correctly estimated, its effect can be compensated increasing also the performances of the communication system. On the other hand, the motion constitutes a source of additional information since the successive positions of the source-receiver configuration allow the characterization of the underwater environment from different angles of “view” [4]. This property could be exploited in applications like sonar imagery or acoustic tomography. In all cases, the success of the operation is conditioned by the motion effect estimation.

In this paper we propose a common methodology to deal with the signal's structures specific to dispersive and moving configuration. Since no *a priori* on signals are authorized, the methodology exploits the coherence of fundamental parameters of any type of signals :

amplitude, frequency and phase. Specifically, the time-frequency structures of received signal will be separated by analyzing their continuity in terms of instantaneous amplitude, phase, frequency. Since these structures are closed (because of the multipath fading effect) the continuity criteria will be aimed to provide high-resolution capabilities. Furthermore, once the time-frequency structures estimated, they will be filtered by using the generalized time-frequency filters structures [5]. Finally, individually analysis of each structures and comparison between successive arrivals can provide information about phase changes due to the dispersivity or to the motion.

This methodology is analyzed in the context of underwater dispersive channel context and moving configurations. Realistic configurations will be used in order to illustrate the outperforming of the proposed approach. Although the outperforming is illustrated in the underwater configuration, the proposed approach is general since it exploits fundamental items related to any type of signals (amplitude, phase and frequency).

The paper is structures as follows. In the section 2 we define the concept of time-frequency-phase continuity and propose the signal processing methodology. The characterization of dispersive phenomena is illustrated in section 3. The motion effect analysis is illustrated in the section 4. We conclude in section 5.

2. SIGNAL PROCESSING METHODOLOGY

The methodology proposed in this paper has the benefit to be general in the sense that it could be used for a large number to signal's types. For this purpose, the general model of analyzed signal is :

$$x(t) = \sum_{i=1}^N A_i e^{j\phi_i(t)} + n(t) \quad (1)$$

where: $x(t)$ is the received signal composed by N components, A_i is the amplitude of i^{th} component, $\phi_i(t)$ is the time-varying phase of i^{th} component and n is the noise. The general framework proposed in this section is aimed to provide an estimation of the phase law of each component.

Our strategy consists in performing an exhaustive search over a local but general model of the instantaneous phase. Hence, we firstly limit the observation range over a time window. This is illustrated in the figure 1 where the characterization of an arbitrary time-frequency component (solid line) is considered.

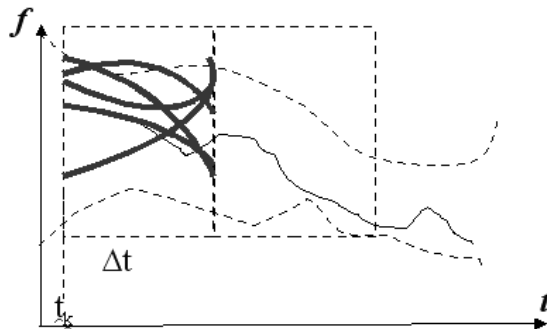


Fig. 1: Illustration of the exhaustive search procedure

As indicated by this figure, on each window, a set of time-frequency component of order 3 is constructed for different nodes over a grid parameter. For each component, the Log-

likelihood is estimated over the window and only a number of i components giving highest likelihood is selected. One such component over the window k are denoted M_i^k .

Next step consists in regrouping the detected components in each window. As each component M_i^k represents a local model of order three, the goal of the regrouping step is to find the chain $\{M_i^1, \dots, M_i^K\}$ that best represents the original component i with respect of maximum likelihood criterion. Hence, the strategy consists to associate two components if they verify some time-frequency-phase coherence criteria. Four different criteria are defined :

- **C^0 time-frequency continuity.** This criterion is given by $C^0(M_i^k, M_j^{k+1}) = |f_f(M_i^k) - f_i(M_j^{k+1})|$ where $f_i(M_i^k)$ is the initial frequency of component M_i^k and $f_f(M_j^{k+1})$ is the final frequency of component M_j^{k+1} . This criterion points on the frequency discontinuities between the component M_i^k and M_j^{k+1} (figure 2.a). More precisely, if $C^0(M_i^k, M_j^{k+1})$ has high value, the probability that M_i^k and M_j^{k+1} belong to the same time-frequency component is low;

- **C^1 time-frequency continuity.** The criteria is given by $C^1(M_i^k, M_j^{k+1}) = |\partial f_f(M_i^k) - \partial f_i(M_j^{k+1})|$ where $\partial f_i(M_i^k)$ and $\partial f_f(M_j^{k+1})$ respectively denote the initial and final instantaneous frequency rates of the components M_i^k and M_j^{k+1} . As indicated by figure 2.b this criterion rules the connection of M_i^k and M_j^{k+1} in the following way if the rates of IFLs are almost the same the time-frequency content variation is smooth being subject to a single component (figure 2.b). In this case M_i^k and M_j^{k+1} are merged. If the rates are too different the both components do not belong to the same structure;

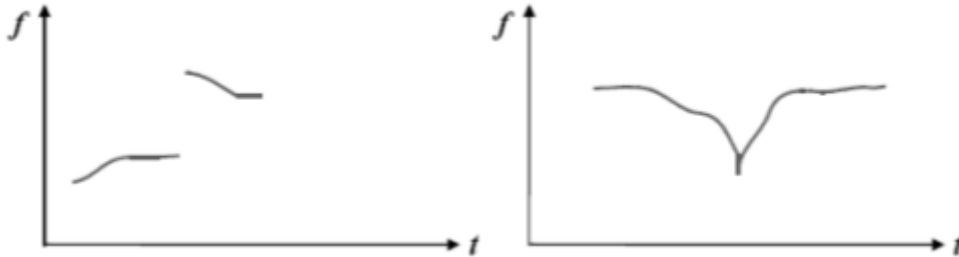


Fig. 2 : C^0 et C^1 time-frequency continuity

- **Amplitude continuity.** The criteria is given by $d(A(M_i^k, M_j^{k+1})) = |A(M_i^k) - A(M_j^{k+1})|$ where $A(M_i^k)$ denote amplitude of M_i^k estimated. This criterion materializes the general observation that the energy of a time-frequency component varies slowly;

- **Instantaneous phase continuity.** The criteria is given by $d\phi(M_i^k, M_j^{k+1}) = |\angle \cos(\phi_f(M_i^k) - \phi_i(M_j^{k+1})) + i \sin(\phi_f(M_i^k) - \phi_i(M_j^{k+1}))|$ where $\phi_i(M_i^k)$ and $\phi_f(M_j^{k+1})$ respectively denote initial and final instantaneous phase M_i^k . This criterion merges two candidate components if the phase is continuous.

With these criteria, we define the penalty function of two components belonging to two consecutive windows by

$$p(M_i^k, M_j^{k+1}) = \alpha C^0(M_i^k, M_j^{k+1}) + \beta d(A(M_i^k, M_j^{k+1})) + \gamma C^1(M_i^k, M_j^{k+1}) + \delta d\phi(M_i^k, M_j^{k+1}) \quad (2)$$

where the coefficients $\alpha, \beta, \gamma, \delta$ allow to define the weight of each criteria. Based on these criteria, the regrouping strategy consists to search over all the possible chains $\{M_i^1, \dots, M_i^K\}$ the one that minimizes the penalty function

$$p_{opti} = \arg \min \sum_k p(M_i^k, M_i^{k+1}) \quad (3)$$

The minimization of this penalty function leads to each individual time-frequency structure. This procedure is illustrated in the figure 3.

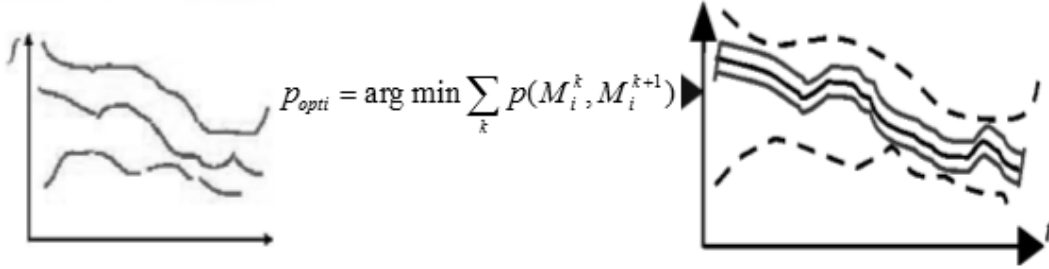


Fig. 3 : Fusion of local 3rd order components

After the optimisation procedure (3) we merge the local 3rd order components in order to get the time-frequency trajectory of the most energetic component. Furthermore, this trajectory is used to design the time-frequency filter (figure 3, right part) and to extract the samples corresponding to this component. While generally the time-frequency trajectory is non-linear, a time-frequency filter with non-linear time-frequency shape has to be designed. The solution, proposed in [5], consists of time-warping the component in order to get a stationary signal. Thus, a band-pass filter is used to isolate the stationnarized component from the mixture. An inverse warping will bring the extracted component in time domain.

This methodology, based on local 3rd order component matching, structures fusion and time-frequency filtering, is iterated until all signal's component are extracted. Its using in the context of dispersive channels and moving configuration is addressed in the next sections.

3. ANALYSING SIGNALS FROM DISPERSIVE ENVIRONMENTS

In this section we illustrate how the methodology previously defined performs in the case of signals issued from dispersive environments. Such a signal is illustrated in the figure 4 where we consider an isovelocity channel with $h=16 m$, a transmitter and receiver located at $4 m$ depth. The range transmitter-receiver is $2000m$. The spectrogram of the first four modes is indicated in the figure 4.

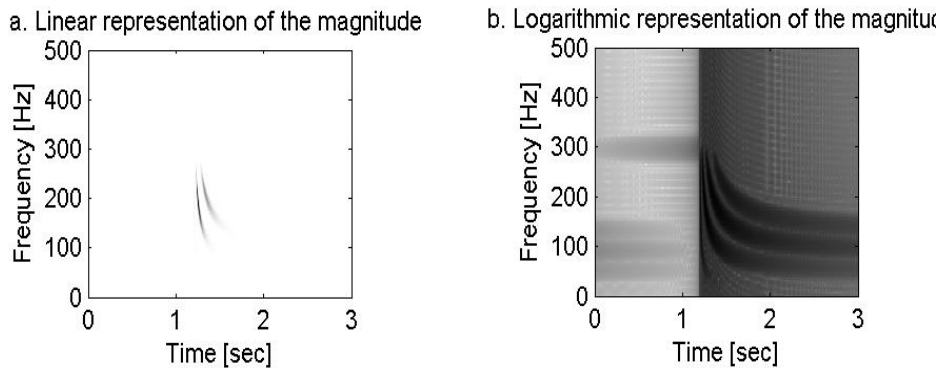


Fig. 4 : Spectrogram of four modes characterizing a dispersive channel

As shown by this figure, identifying the four components is not a simple task. The linear representation (figure 4.a.) shows only two modes the other two being invisible because of their much smaller energies with respect of strongest ones. One can use a logarithmic representation (figure 4.b) the price to pay being the poorer resolution. For these reasons the

extraction of each individual mode could be a complex problem for a classical time-frequency technique.

Using the proposed methodology, at the first iteration (figure 5), the fusion of the local most matched cubic FMs provides a time-frequency shape corresponding to the third order modal arrival (figure 5.a). This shape allows us defining a time-frequency filter (figure 5.a) which extracts the corresponding signal (figure 5.b). The spectrogram of residual signal is illustrated in the figure 5.c. We remark that the time-frequency-phase criteria provide an accurate estimation of time-frequency structures of the signal. The time-frequency filters designed from this estimation (figure 5.a, d, g) allow accurately extracting the modal arrivals (figure 5.b, e, h et i). After second iteration, we remark also that the filtering-based extraction highlights less energetic components. It is a consequence of filtering out the first two most energetic components. This property of the proposed methodology proves its interest for signals composed by several arrivals with large differences of magnitude.

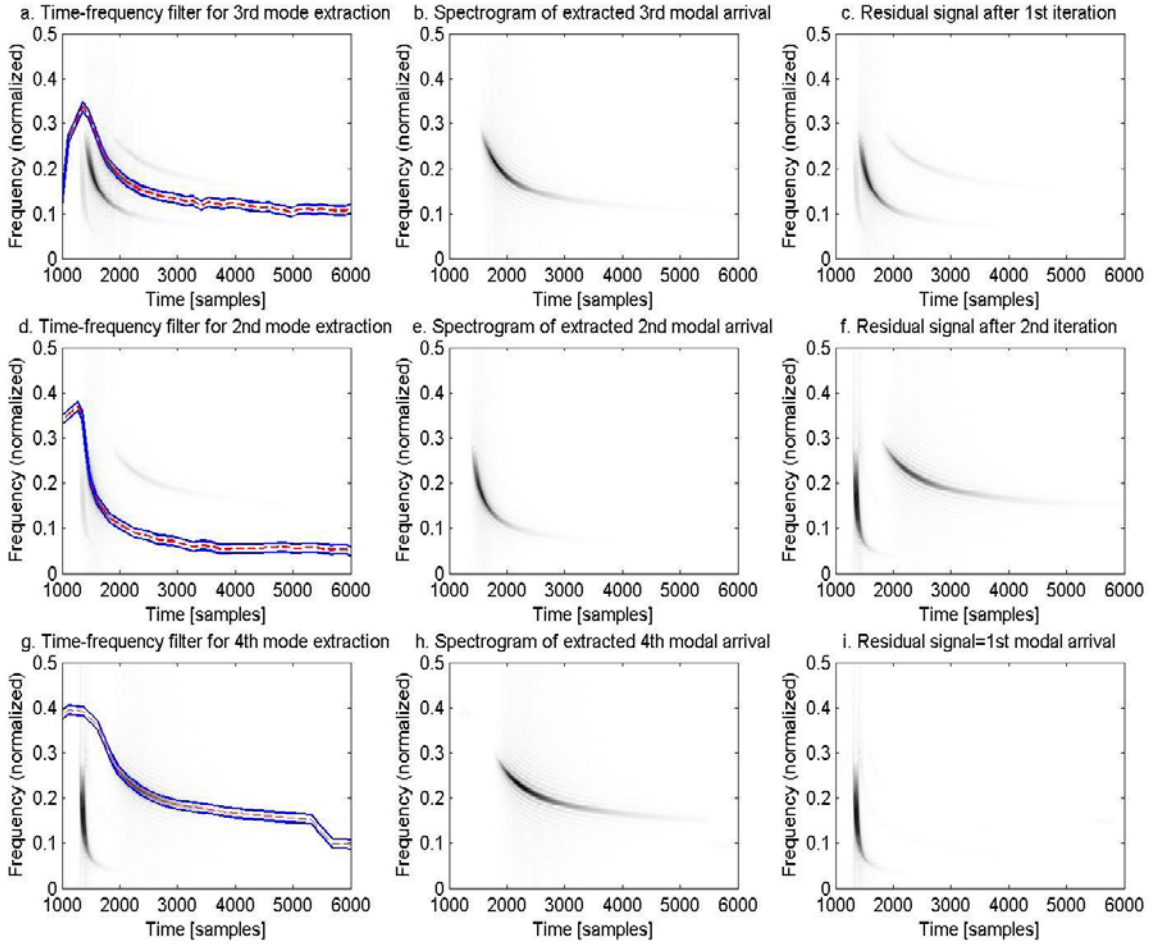


Fig. 5: Extraction of the third order mode from the signal defined in the figure 4

The time-frequency-phase criteria provide the time-frequency shape of the most energetic component of the signal. Furthermore, this shape produces the time-frequency filter which physically extracts the component. This is actually the novelty of the proposed methodology with respect of Matching Pursuit-based approaches which performs the component extraction via a subtraction. While this operation requires the estimation of component's magnitude (which is not always an easy task) the method proposed in our paper performs component's extraction via a time-frequency filtering procedure. In this way, the extraction is independent of component's amplitude which is of great benefit in the study of dispersive phenomena.

4. ANALYSING SIGNAL ISSUED FROM MOVING CONFIGURATION

In this section we focus on the motion effect analysis using the methodology proposed in section 3. For this purpose, we consider the scenario defined in figure 6 : the transmitter, located at a depth of 5 m , moves as indicated in figure 6, with 5 m/s . Two sensors, located at 40 m and at a relative range of 100 m , are used as receiving structure. The transmitter emits a pure 12 kHz sinusoid. The spectrogram of the signal received by the sensor 2 is plotted in the bottom of figure 6. This figure shows intuitively the non-linear time-frequency Doppler modulation due to the source moving. Nevertheless, the exact time-frequency modulation is difficultly estimated by exploiting spectrogram while the multi-path propagation produced destructive interferences which create gaps in the time-frequency distribution.

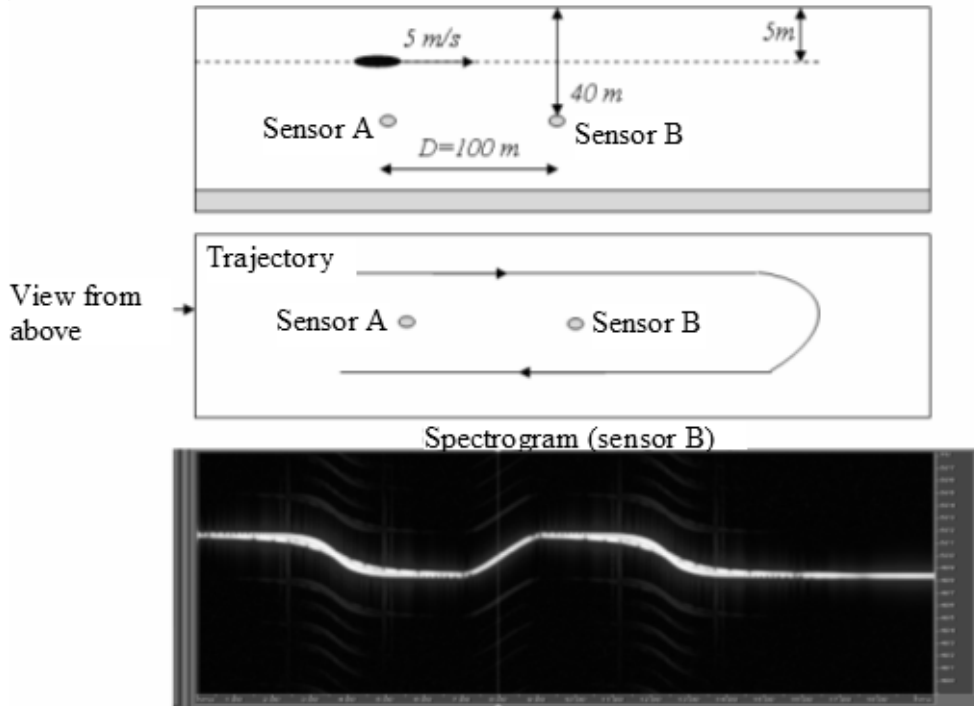


Fig. 6 : Moving configuration scenario

Applying the time-frequency-phase coherence we can extract exactly the time-frequency modulation as indicated in the figure 7. The time-frequency trajectories extracted from the signals received to the two sensors correspond well to the moving scenario.

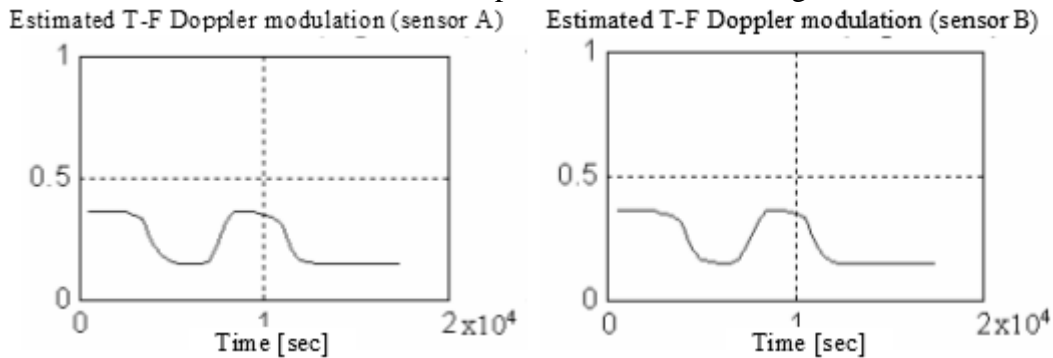


Fig. 7 : Extracted time-frequency modulations generated by the transmitter motion

This result is explained by the robustness of the time-frequency-phase concept in the presence of coherent perturbation as the multi-path interferences.

5. CONCLUSION

In this paper we presented a general methodology for multi-component signal analysis in the passive tomography context. The signal's model is general while it is composed by multiple components having arbitrary non-linear time-frequency behaviours. In addition, no hypothesis about the noise is considered. In these conditions, the proposed methodology attempts to extract all components which could be very helpful in the context of passive tomography. Each individual component contains information about the propagation path and/or about the trajectory of the source/receiver. The main idea is to exploit the time-frequency-phase coherence of each component. More precisely, while the time-frequency

content of each component is typical to the physical phenomenon of interest, the instantaneous phase and/or its derivatives of the component are continuous. This general property of (almost) all physical phenomena is the central item of the proposed methodology.

The first step of the methodology is to project the short time signals (obtained by windowing the full signal) on a dictionary of 3rd order components (or cubic frequency modulation). The best locally matched components of each window are retained. In the second step, the 3rd order components of close window are merged according to the minimisation of continuity criteria. The combination of the components minimizing the penalty function constitutes the time-frequency trajectory of one of the signal's components. This trajectory serves to filter out this component. The procedure is iterated until all components are estimated.

Thanks to the universality of this property, this methodology could be successfully applied in different area of applications arising from passive tomography domain. Two cases have been considered in this paper : characterization of underwater dispersive phenomena and monitoring of motion effect of an underwater sources.

The further works will be concentrated to more complex scenarios in order to improve the operational aspects related to this methodology. One of the work directions will be focused on the automatic selection of the continuity parameters.

6. ACKNOWLEDGEMENTS

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