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# TIME-FREQUENCY-PHASE TRACKING APPROACH : APPLICATION TO UNDERWATER SIGNALS IN A PASSIVE CONTEXT

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## ABSTRACT

One of the most challenging applications of time-frequency representations deals with the analysis of the signal issued from natural environment. Recently, the interest for passive underwater context increased, basically due to the richness of the information carried out by the natural signals. Taken into account the non-linear multi-component time-frequency behavior of such signals, their analysis is a complex problem. In this paper we introduce a new time-frequency analysis concept that aims to extract the non-linear time-frequency components. The main feature of this technique is the joint use of time-amplitude, time-frequency and time-phase information. This is materialized by a short-time polynomial phase modeling and the fusion of local information according to the best locally matches of local cubic frequency modulations. Tests provided on real data illustrate the benefits of the proposed approach.

**Index Terms** — *Time-frequency analysis, Time-varying filters, Signal Representations*

## 1. INTRODUCTION

While the human activities in coastal zones significantly increased in last decade, studying the impact of these activities on the underwater fauna became a very important topic. The main purpose is to ensure the protection of species as well as to avoid collision which could have dramatic effects [1], [2]. On the other hand, the increased number of military operations in coastal zones requires a deep analysis of the impact of sonar's signals to the underwater mammals. Namely, the signals transmitted by the sonar systems are characterized by high transmitted power and by spectral bands similar to the mammal's sounds. Therefore, analyzing underwater mammal's vocalizations provides rich information concerning the impact of military activities on the behaviour of marine species. In addition,

when the coastal activities are considered, the swallow water propagation must be considered, implying, at very low frequencies, the study of dispersion phenomena [3].

These two types of applications, analysis of underwater mammal vocalizations and operation in dispersive environments, require efficient signal analysis methodologies. The difficulties in terms of signal processing are related to the lack of *a priori* information about signal's type (*passive context*) as well as the complexity of underwater environment (in terms of noise, propagation effects, etc). In addition, the signals corresponding to underwater mammal vocalizations and to dispersion contain generally multiple non-linear time-frequency (TF) structures. In this paper we propose a common methodology to deal with the signal's structures specific to dispersive and to mammal's vocalizations. Since no *a priori* on signals are authorized, the methodology exploits the coherence of fundamental parameters of any type of signals: instantaneous amplitude, frequency and phase. Specifically, the time-frequency structures of the received signal will be separated by analyzing their continuity in terms of instantaneous amplitude, phase and frequency. Furthermore, once the time-frequency structures estimated, they will be filtered by using the generalized time-frequency filters structures. Realistic configurations will be used in order to illustrate the outperforming of the proposed approach.

The paper is structured as follows. In the section 2 we define the concept of time-frequency-phase continuity and propose the signal analysis methodology. Results for both mammal's vocalizations and dispersion will be discussed in the section 3. We conclude in the section 5.

## 2. TIME-FREQUENCY-PHASE TRACKING STRATEGY

Generally, underwater mammal vocalizations as well as the signals received from dispersive channels are

characterized by several time-frequency components having non-linear instantaneous frequency laws (IFLs). In addition, the amplitudes of these components could be time-varying due to the propagation phenomena, for example. Such a signal is synthesized in the figure 1.a and it is used to illustrate the time-frequency-phase strategy defined in this section. This signal is composed by three time-frequency components as expressed by Eq. 1 :

$$s(t) = s_1(t) + s_2(t) + s_3(t); t=0, \dots, 1023 \quad (1.a)$$

$$s_1(t) = A_1(t) \cdot \exp[j2\pi(0.2t + 4.77 \sin(2\pi 0.001t))] \quad (1.b)$$

$$A_1(t) = 2.2 - 4.88 \cdot 10^{-4}t$$

$$s_2(t) = A_2(t) \cdot \exp[j2\pi(0.19t - 1.4 \cdot 10^8 \cdot (t - 512)^2)] \quad (1.c)$$

$$A_2(t) = 2 - 7.6 \cdot 10^{-8}(t - 512)^2$$

$$s_3(t) = A_3(t) \cdot \exp[j2\pi(0.18t - 15 \cdot e^{3.8 \cdot 10^{-6}(t-512)^2})] \quad (1.d)$$

$$A_3(t) = 1.8 - 1.9 \cdot 10^{-4}t$$

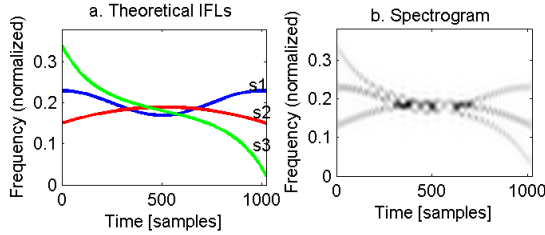


Fig. 1. Signal with three non-linear T-F components

As illustrated in figure 1, the signal (1) has a complex time-frequency structure characterized by non-linear crossing component. The figure 1.b shows the spectrogram's limits : when the T-F components are close (around 512<sup>th</sup> sample) it is not possible to clearly visualize the three component. This is a consequence of the trade off between time and frequency resolutions and it could affect any time-frequency tracking method based on short time Fourier analysis (see [4] for one example).

An alternative to this type of methods is the local analysis of time, frequency and phase coherence and to use this information to merge local components in order to get the global T-F structures characterizing the signal. The first step of this methodology is the **short time polynomial phase modeling of order 3**. As the signal is characterized by non-linear heterogeneous T-F components (see Fig 1.a for an example), its short-time analysis is a natural way to represent *efficiently* the T-F content of signal. Approximating the local T-F content by Gabor atoms or by linear chirps has been analyzed in the previous works (see [5] for a synthesis). In our approach, we propose to use the cubic FM (frequency modulations) in order to better approximate the non-linear parts of the signal's IFLs. In addition, using cubic FM for short-time signal's phase modeling, the window size is less important than in the case of linear chirps.

In our context, the short time polynomial phase modeling of order 3 is given by Product High Order Ambiguity Function (PHAF) [6]. This analysis is done in adjacent windows, half-overlapped, as illustrated in the figure 2.

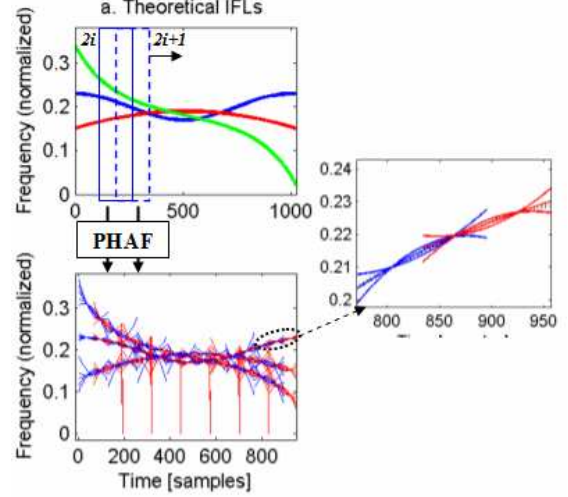


Fig. 2. 1<sup>st</sup> step : Short time PHAF in half over-lapped windows

For each window position, the WHAF of order 3 is applied providing the 3<sup>rd</sup> order phase modelling of the components. The IFLs estimations obtained for two (overlapped) neighbour windows,  $2i$  and  $2i+1$ , are plotted in the figure 2 (for two windows of 128 samples, covering the time interval 832-1024 samples). We can remark that the IFLs are well fitted to the modelled components. Indeed, in real situation, this modelling is affected by noise and/or by close components. For this reason, PHAF provides, for each window, several estimations of the same component. Let consider  $N_c$  estimates for each window. Let us denote the set of phase functions obtained from PHAF-based phase modelling applied in  $i^{th}$  window as :

$$D^{(i)} = \{\psi_k^{(i)}\}_{k=1, \dots, N_c} \quad (2)$$

where  $\psi_k^{(i)}$  is the  $k^{th}$  phase function of order 3 defined as :

$$\psi_{kt}^{(i)}(t) = \sum_{l=1}^3 a_{kl} t^l; t \in [iT; (i+3/2)T] \quad (3)$$

where  $T$  is the window size.

As indicated in the figure 8, the phase functions are just an approximation of the real time-frequency content of the signal. For this reason, they are used for regrouping procedure provided by the second step of the methodology – **fusion of local time-frequency-phase information**. The phase functions (2) are used to build local filter functions which extract the signal's samples corresponding to the time-frequency regions defined in the neighbourhood of the local functions [7]. The design of these filters is illustrated in the figure 3 for the region corresponding to the interval 832-1024 samples.

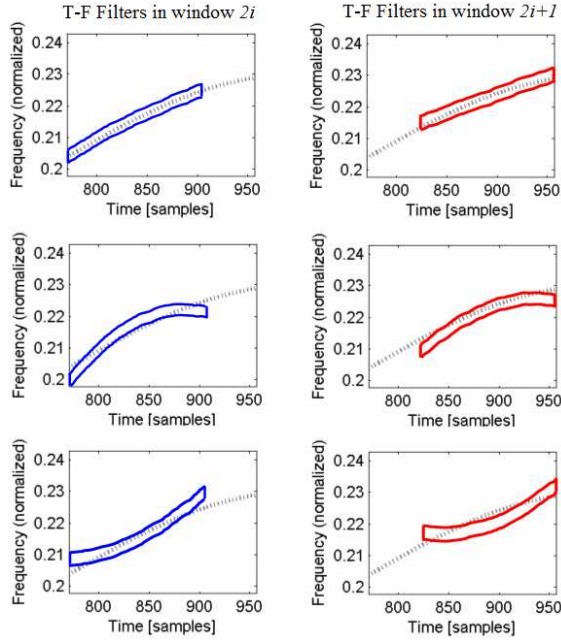


Fig. 3. Local T-F filters defined for two adjacent windows

Let consider the analyzed signal  $x$  and  $2i$  and  $2i+1$  two analyzing windows (as illustrated in the figure 2). Let consider  $D^{(2i)} = \{\psi_k^{(2i)}\}_{k=1, \dots, N_c}$  and  $D^{(2i+1)} = \{\psi_k^{(2i+1)}\}_{k=1, \dots, N_c}$  - sets of phase functions provided by the PHAF for  $2i^{th}$  and  $(2i+1)^{th}$  windows, respectively. Using these phase functions, we build, as indicated in figure 3, the sets of T-F filters  $\{W_k^{(2i)}\}_{k=1, \dots, N_c}$  et  $\{W_k^{(2i+1)}\}_{k=1, \dots, N_c}$ . With help of these filters, we extract, from the analyzed signal  $x$ , the corresponding signal's samples denoted by :

$$\begin{aligned} \{s_k^{(2i)}\} &= \{(W_k^{(2i)} x)(t)\}_{k=1, \dots, N_{comp}} \\ \{s_k^{(2i+1)}\} &= \{(W_k^{(2i+1)} x)(t)\}_{k=1, \dots, N_{comp}} \end{aligned} \quad (4)$$

Using these samples, we decide that two phase functions,  $\psi_m^{(2i)}$  and  $\psi_n^{(2i+1)}$ , are regrouped (ie, they belong to the same T-F component) if the correlation of corresponding samples,  $\{s_m^{(2i)}\}$  and  $\{s_n^{(2i+1)}\}$ ;  $m, n = 1, \dots, N_c$  is maximal for all pairs  $(m, n)$  :

$$\begin{aligned} (\hat{m}, \hat{n}) &= \max_{\substack{m \in [1, N_c] \\ n \in [1, N_c]}} \left| \langle s_m^{(i)}(t), s_n^{(i+1)}(t) \rangle \right| \Rightarrow \\ &\Rightarrow \psi_{\hat{m}}^{(i)} \circ \psi_{\hat{n}}^{(i+1)} \subset \text{Trajectory} \\ \text{T-F } \phi_j &[ (i-1)T : (i+1)T ] \text{ of signal } x \end{aligned} \quad (5)$$

where «  $\circ$  » symbolizes the fusion of two phase functions belonging to the same trajectory defined in the time interval  $(i-1)T : (i+1)T$  of the  $j^{th}$  component of the signal. After

studying all segments of the signal, we define the time-frequency trajectory corresponding to the  $j^{th}$  component of the signal as the fusion of phase functions following (5) :

$$\phi_j(t) = \psi_{k_1}^{(1)} \circ \psi_{k_2}^{(2)} \circ \dots \circ \psi_{k_i}^{(i)} \circ \dots \circ \psi_{k_N}^{(N)} \quad (6)$$

where  $N$  is the number of analyzing windows and  $k_i$  is the index of the phase function obtained from the  $i^{th}$  window.

The T-F trajectory  $\phi_j(t)$  is used to design the time-frequency filter that will extract the  $j^{th}$  component of the signal. This constitutes the third step of the methodology *global time-frequency filtering*. For the signal (1), the first estimated trajectory, obtained for a SNR=5.1 dB, corresponds to the signal  $s_1$  (Fig. 4.a). Around this trajectory, we build the time-frequency filter [7] that will extract the samples of the corresponding component. We remark that the residual signal contains the component  $s_2$  and  $s_3$  proving the accuracy of filtering procedure (Fig 4.b). At the next iteration, the residual signal (Fig 4.b) is processed in the same way until all trajectories are estimated (Fig 4.c).

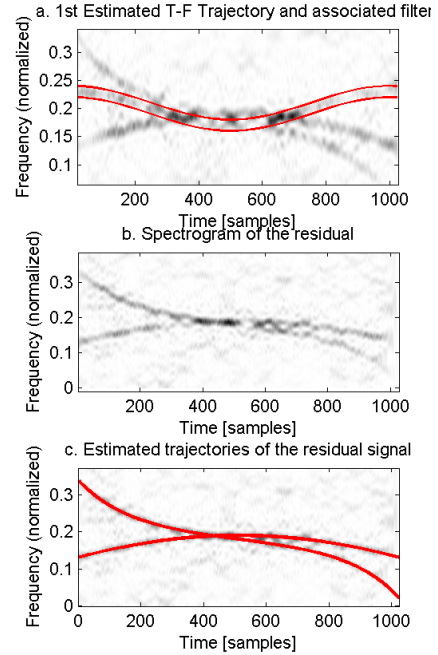


Fig 4. Global T-F filtering

Consequently, the iterative application of the three steps of the time-frequency-phase methodology allows extracting individual components of the analyzed signal.

### 3. RESULTS

First, we consider the analysis of a real dolphin vocalizations recorded in Bay of Brest, France. The spectrogram (Fig 5.a) shows that this signal is composed by three successive whistles but the precise time-frequency variations are not easily “visible” (especially, in the case of the second harmonics).

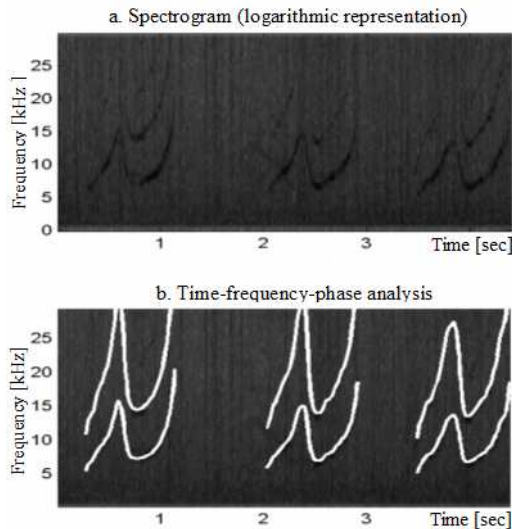


Fig.5. Dolphin vocalization analysis (sampling frequency, 96 kHz)

The time-frequency-phase analysis highlights the T-F variations of the whistles (white curves in Fig 5.b) in spite of the interferences with clicks and other components. This characterization could be very helpful in various applications such as localization, classification, etc.

The second example concerns one signal simulating two modal arrivals from a dispersive channel characterized by depth of 80 m, range source-transmitter of 4800 m and both the source and the transmitter are at depths of 10 m.

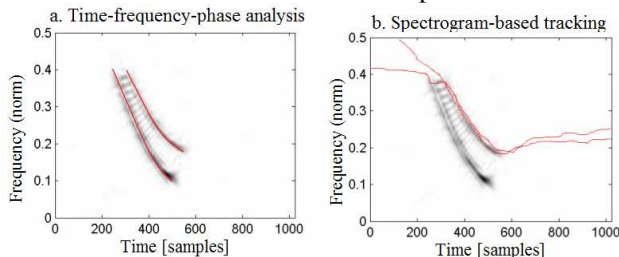


Fig.6. Modeling signal from dispersive channel

As illustrated in Fig 6.a, the proposed approach succeeds to follow accurately the two modes even if they are very close and their amplitudes are different. In comparison, the result provided by the technique defined in [4] fails : while the interferences are stronger than the amplitudes of the components, the tracking method will switch from the 1<sup>st</sup> to the 2<sup>nd</sup> component as illustrated in the figure 6.b. This example shows the interest for tracking the time-frequency-phase continuity, this technique being independent to the amplitudes of components.

#### 4. CONCLUSIONS

In this paper we defined a new methodology for time-frequency tracking of complex signals characterized by non-linear time-frequency components. The main concept is the

time-frequency-phase coherence which is locally exploited by polynomial phase modelling of order 3.

The results, provided for synthetic and real data, proved the efficiency of the proposed methodology. Looking simultaneously on the time-frequency and phase information (by local polynomial phase modelling of order 3), allows us following all time-frequency variations, in spite of crossing or noise interferences. The time-frequency-phase information acts as a continuity criterion preserving the time-frequency structure of any component. Second, after tracking one component, its extraction via a global time-frequency filtering is done. In this way, the extraction is independent of component's amplitude.

Although the outperforming is illustrated in the underwater configurations, the proposed approach is general since it exploits fundamental items related to any type of signals (amplitude, phase and frequency).

In further works, we will concentrate both on theoretical and applicative aspects. Concerning theoretical works, the purpose is to introduce other phase analysis operator, more robust and general. The further versions of this methodology will be studied in some real applications such as underwater signal classification and localisation.

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