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Observation of Acoustical Signal Fluctuations by Time-Frequency Analysis Methods

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Summary
In this paper, acoustic data collected in shallow water during INTIMATE00 sea trials are analysed with the aim to detect fluctuations in acoustical signals under the effect of a time-varying environment. Some time-frequency analysis methods, i.e., Gabor Expansion and Wigner-Ville Distribution, have resulted to be adequate to find out fluctuations in the received signals, in particular, such analyses reported different time-frequency behaviour in relation with different tidal conditions. The variations observed in the received acoustic data have been compared with the temperature data collected during the sea trials and the related sound-speed profiles: it has been reported that major fluctuations over time in the acoustic signal occur in correspondence of the sound-speed profile changes linked to environmental variability.

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1. Introduction

The propagation of sound in shallow water strongly depends upon many different variables that make the sea an inhomogeneous dynamic medium. Some examples of inhomogeneities in the sea are the rough sea surface, the bottom, and temperature. In particular, the temperature mainly influences the sound speed: the continuous variation of its structure induces different recombinations in the sound propagation modes that result in fluctuations in the received acoustic signals. Recently, sound propagation in shallow water under the effect of time varying environment has been studied and experimentally tested. In [1] Nielsen and Siderius present two experiments conducted in the Mediterranean Sea in shallow water conditions with the aim to assess fluctuations in acoustical signals acquired by a linear array. The authors have noticed that the time variability of the water-column sound speed can have a significant impact on the stability of arrival time and received energy levels. In [2] Apel *et al.* have shown that internal waves activity, strongly dependent upon time, affects the sound velocity structure along the acoustic path inducing fluctuations in the received signals in terms of travel-time and acoustic energy. The effects of internal waves on acoustic propagation have been also studied during INTIMATE96 experiment [3].

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In this paper, data collected during INTIMATE00 sea trials in shallow water are analysed with the aim to detect fluctuations in acoustical signals. Some time-frequency analysis methods have been applied and compared to reveal possible fluctuations of the received acoustic signals over the observed period. The short time Fourier transform, having a limited time-frequency resolution, was not suitable for this task. Instead, other time-frequency analyses, i.e., Gabor Expansion and Wigner-Ville Distribution, have resulted to be adequate to find out variations in the received signals, in particular, such analyses reported different time-frequency behaviour (mainly in the higher frequencies region) in relation with different tidal conditions. Finally, in order to correlate these changes with the variability of oceanographic features, we have monitored the sound velocity profile evolution, and we have observed the occurrence of major signals fluctuations over time in correspondence of the sound speed vertical structure changes.

2. The Experiment

The INTIMATE00 sea trial was carried out on October 2000 in the Atlantic Ocean, off the town of Setubal, Portugal. During the five-days experiment an acoustic source, deployed at 60 m depth from the oceanographic vessel of the Portuguese Hydrographic Institute, transmitted a linear frequency modulated sweep, 2 s long, from 170 to 600 Hz, over three different 5-km fixed paths. The acoustic receiver was a 16-hydrophone 4-m spacing vertical light array also equipped with thermistors and pressure gauges, suspended from the sea surface between 30 and 90 m. The three paths were chosen according to the bottom topography in order to have a range independent (flat bottom), a smoothed increasing, and a strong varying bottom case. The selected area, due to its topographic and oceanographic conditions, displays a great spatial and temporal variability, thus permitting experimental tests on different environmental scenarios even in a limited area and during a short period experiment. Data here analysed regard the range-independent case over a period longer than 24 hours. Oceanographic measurements were performed during the experiment by the use of thermistors, currentmeters and pressure gauges from fix moorings to control the temporal evolution of environmental conditions. The choice of this area also guaranteed to perform the work at sea in stable weather conditions.

3. Time-Frequency Analysis

Our aim was to analyse the signals received by a linear array over time in order to detect variations in the informative content of such signals and, if possible, to find out correspondence between these fluctuations and the changes of some oceanographic features (sound speed, currents, tides, internal waves). To this end, the signals received on the hydrophones during the day have been examined through time-frequency analysis methods, able to show with a good resolution in what way the signal spectrum evolves while the signal is received. For each of the two tidal conditions, several 2-seconds snapshots have been quality checked and selected for the analysis.

A standard algorithm for joint time-frequency analysis is the Short Time Fourier Transform, but, because of its limited time-frequency resolution, it has been found inadequate for our application, as it is not able to reveal differences in the received signals over time. An instrument very helpful to fulfil our objective has been the Gabor Expansion (see Figure 1) that provides for expanding a signal $s(t)$ into a set of functions concentrated in both time and frequency domains [4]. The resulting representation is the following:

$$s(t) = \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} C_{m,n} h_{m,n}(t),$$

where $C_{m,n}$ are called the Gabor coefficients and the set of elementary functions $\{h_{m,n}(t)\}$ consists of a time- and frequency-shifted function $h(t)$. By choosing adequately the set of elementary functions it is possible to find out the right balance between time and frequency resolutions obtaining results with a good stability.

In Figure 1 two beam signals over time and the relative Gabor coefficients in low and high tide condition are shown, but while the signal in time allows only to observe differences in the signal envelope, the time-frequency Distribution makes possible to appreciate differences in the joint time-frequency domain. Figure 1a shows a typical example of Gabor Expansion applied to an acoustic signal acquired during a low tide period. The distribution presents an impulse that linearly moves in an almost continue way over frequency and time. Besides, we can notice an evident central red peak at about 400 Hz. In Figure 1b we present the Gabor coefficients of a high tide signal. Note that the impulse doesn't move anymore in a continuous way: the time-frequency representation presents fringes, 'sobs', mainly at higher frequencies (greater than 500 Hz). A further difference concerns the doubling of the central red peak at about 400 Hz. The multitude of acoustic data acquired over a long period of time has allowed us to conclude that the fluctuations observed in the time-frequency behaviour are not occasional, but connected to the tidal conditions. To better appreciate these fluctuations we can show the results obtained by the Wigner-Ville Distribution (WVD) (see Figure 2). The WVD of a signal $s(t)$, $W(t,f)$, is defined as follows:

$$W(t,f) = \int_{-\infty}^{+\infty} s(t+\tau/2)s^*(t-\tau/2)\mathrm{e}^{-\mathrm{j}2\pi ft}\mathrm{d}\tau,$$

where the term $s(t+\tau/2)s^*(t-\tau/2)$ is the instantaneous correlation of the signal $s(t)$. Compared to STFT and Gabor Expansion, WVD can better characterize a sig-

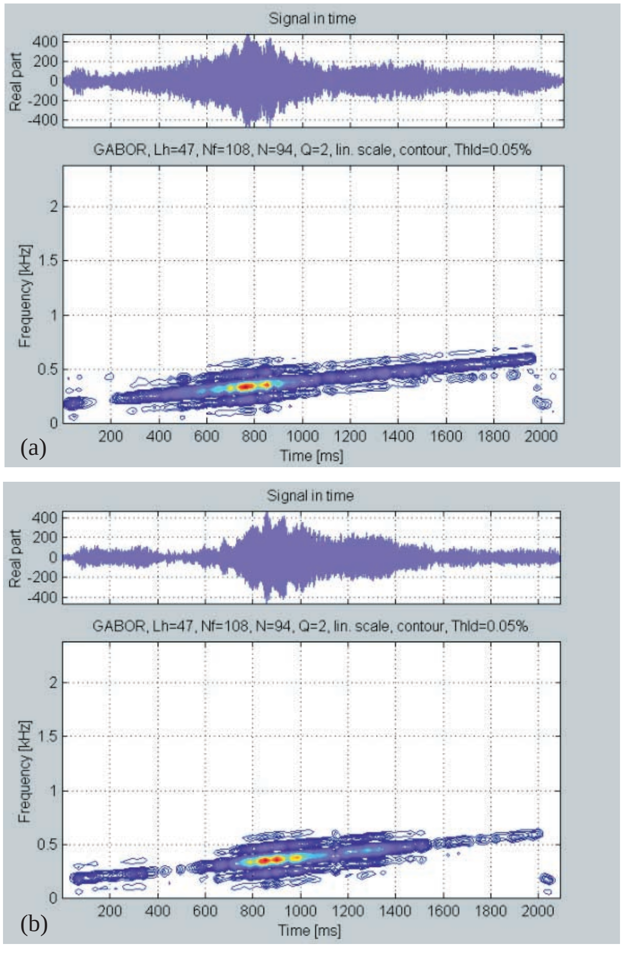

Figure 1. In both figures the beam signal over time (up) and the relative Gabor coefficients (down) are shown. (a) Signal acquired during low tide; (b) signal acquired during high tide.

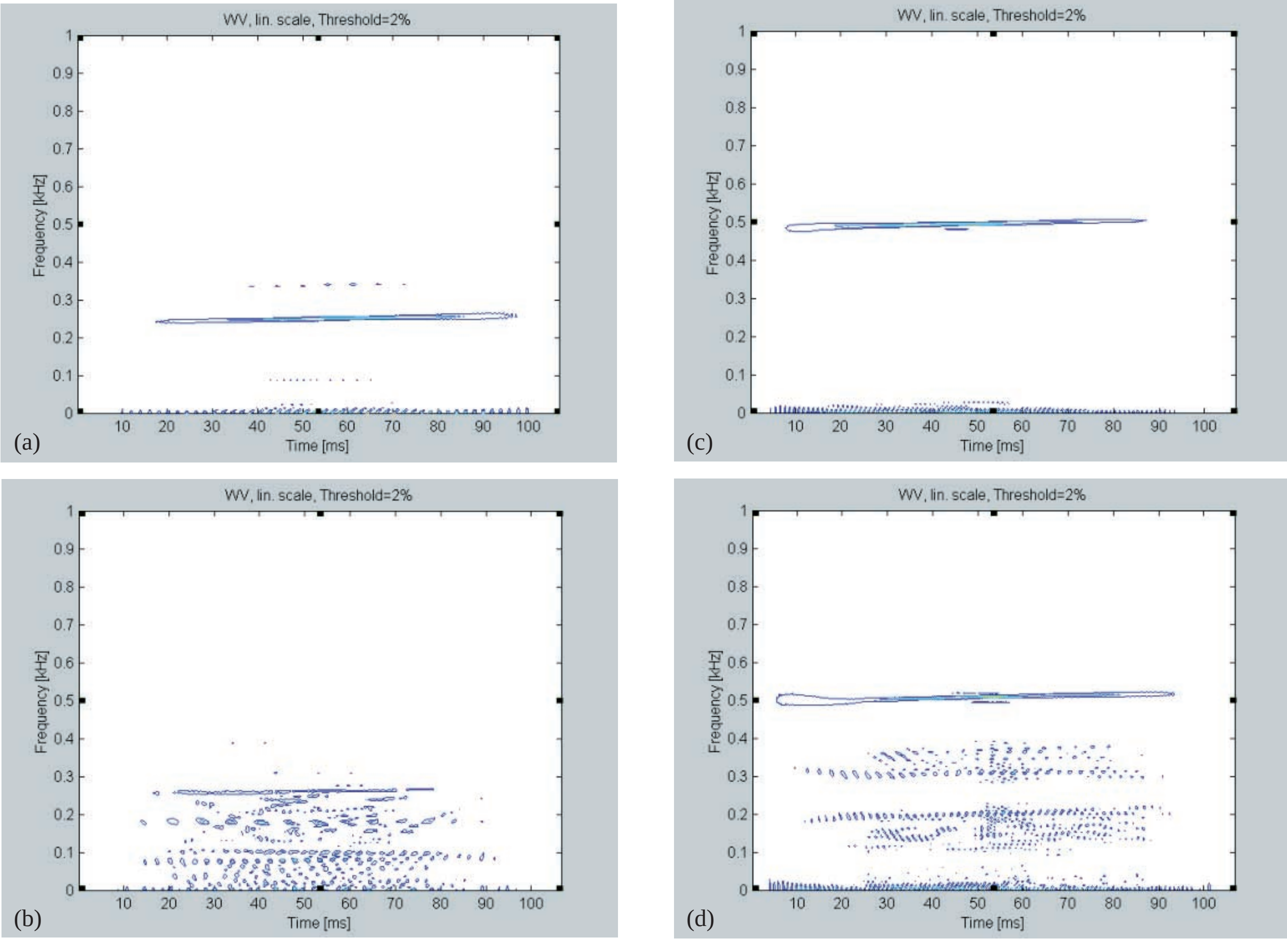

Figure 2. Wigner-Ville Distribution of specific signal portions. (a and c) Low tide and (b and d) high tide conditions.

nal's properties in the joint time-frequency domain, as it achieves a higher time-frequency resolution and it does not suffer from the so-called window effect [5]. To perform a zoom on some selected regions of the time-frequency diagram we have chosen signal portions that were significant in the preliminary analysis. Comparing the results obtained for two signals, received in low and high tidal condition respectively, it's possible to note what follows: (1) The Wigner-Ville Distribution does not present particular differences for signal portions containing central frequencies at about 350 Hz; (2) The Wigner-Ville Distribution evidences remarkable changes between high and low tide conditions for signal portions containing low frequencies (at about 250 Hz), see Figures 2a, 2b and high frequencies (at about 500 Hz), see Figures 2c, 2d. In the high tide condition, the distributions show not only a peak that linearly moves over frequency and time, but also other spurious terms at lower frequencies. All the panels shown in Figure 2 have been obtained with the same threshold level, manually tuned to highlight the above mentioned differences. To obtain good results, we have experienced that it is convenient to reduce signals that impinge on the array coming from the surface and seafloor regions close to the array itself. To do this, a pre-processing stage by broadside beamforming [6] has shown to be very efficient and has allowed us to obtain results with a greater stability for all the time-frequency analyses.

4. Oceanographic Conditions and Sound Speed Profile

The area of the experiment is characterised by a coastal shelf of about 100 m depth and 200 km wide, interrupted by a deep and narrow canyon. Due to the presence of this canyon internal tidal waves develop, with associated important vertical displacements leading to a strong modification of the vertical ocean structure. Data obtained from a fix mooring (T2) located between the acoustic source and the array and equipped with currentmeters, temperature and salinity sensors have permitted to monitor the environmental conditions during the experiment and are here reported. Additional information were obtained by thermistors located in the vertical hydrophones array and by XBT measurements in the area. Temperature time series (Figure 3a) at six different depths (12 m, 17 m, 22 m, 32 m, 52 m, 82 m) well evidence intense oscillations up to 2 °C in the layer between 32 m and 82 m which are responsible for the modification of the vertical structure of sound speed profile. The upper layer is well mixed as observed also in currentmeters time series and does not seem af-

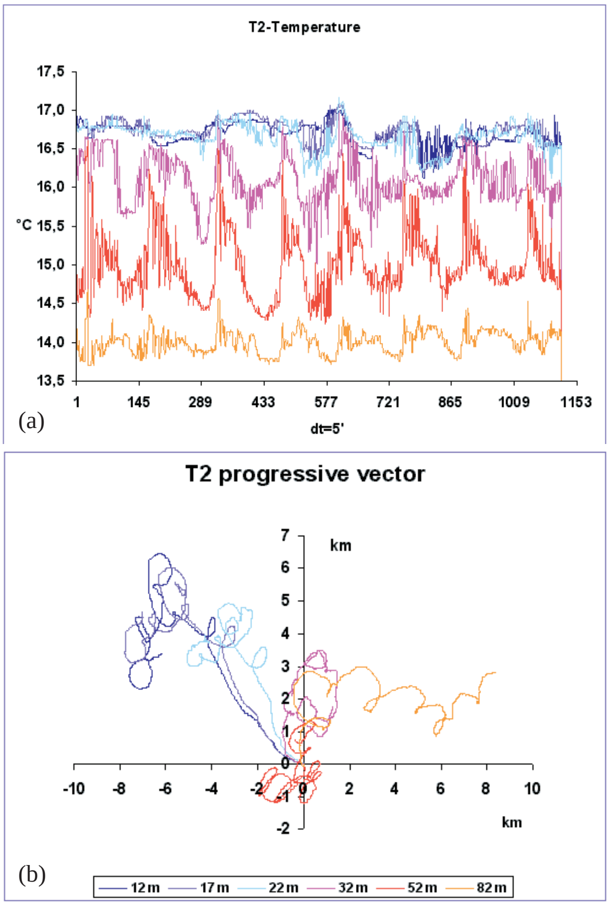

Figure 3. (a) Temporal series of temperature at six levels form mooring T2. (b) Progressive vector of currents at six levels.

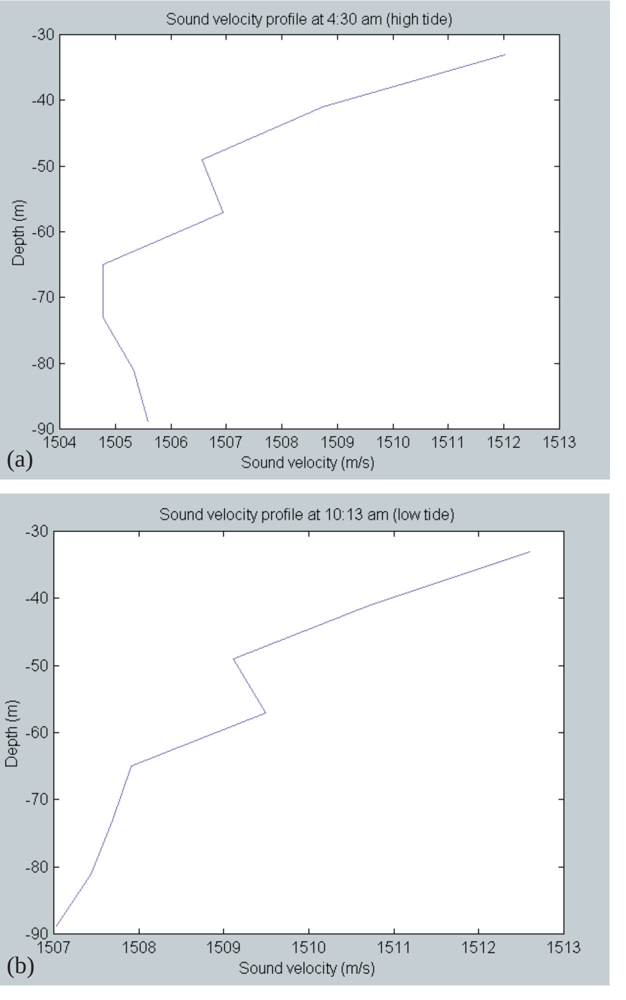

Figure 4. Sound velocity profile at two different hours of the day. (a) High tide period; (b) low tide period.

fected by internal waves movements. Main oscillation has the period in the band of semi-diurnal tide; spectral analysis evidenced secondary peaks of energy also in the inertial band (which at this latitude is 18.3 h), and at higher frequencies (a neat peak appears around 6 h period), but the amplitude associated to these oscillations is not relevant for this kind of study.

Currents are strongly baroclinic, with both tidal and inertial movements as shown in the clockwise meanders reported by the progressive vectors at the six depths (Figure 3b). Mean velocity is about 6 cm/s at all depths with peaks up to 20 cm/s. They are mainly directed northwest along the coast in the upper layer, while in the layer affected by internal waves rotations are prevailing and the net horizontal transport is reduced. Near bottom currents seem to reverse. Such currents are not able to directly influence sound propagation, but are responsible of observed horizontal displacements of the hydrophones array up to about 25 m, which could modify the acoustic path geometry. Such data have allowed to monitor the sound velocity profile over time making possible to correlate the fluctuations observed in the acoustic signals behaviour with changes in the sound speed structure. In particular, it has been possible to find a relation between such variations and the tidal conditions: different sound velocity profile in terms of shape and value range have been observed in low and high tide. The velocity profiles shown in Figure 4, obtained from temperature data acquired from thermistors located on the hydrophones array between 30 and 90 m, are representative respectively of high tide (a) and low tide (b). Relevant differences both in the sound speed structure and intensity (up to 3 m/s at the same level) can be observed. In addition we have noticed that the high tide profiles present all the same shape: there is always a velocity minimum at depth of about 70 meters; in low tide profile such minimum does not appear: the velocity decreases in a monotonic way with increasing depth after 60 meters.

5. Conclusions

The analyses of oceanographic and acoustic measurements performed in an area interested by intense internal waves forced by semidiurnal tides, have allowed to observe remarkable changes over the day both in the sound speed profiles and in the received acoustic signals. The changes in the environmental conditions seem able to modify the sound propagation in the area between the source and the receiving array, and to induce fluctuations in the received acoustic signals. To which degree these fluctuations are due to the modification in the sound speed profile or to the different waveguide effect produced by the geometrical change of the vertical and horizontal displacement during low and high tide phase will be better investigated. In any case, the joint time-frequency analysis here described has allowed to evidence such fluctuations with a good precision, thus confirming that direct acoustic methods can be exploited for the remote monitoring of environmental parameters. To this aim we have observed that the more conventional analyses, like Short Time Fourier Transform, have not a sufficient resolution to conduct the desired investigation, while other time-frequency analysis methods, e.g., Gabor Expansion and Wigner-Ville Distribution, have obtained full success, highlighting some fringes in the signal band connected to the tidal condition.

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