Internal Tides Investigation by Means of Acoustic Tomography Experiment (INTIMATE) in 1998 at the Bay of Biscay shelf-break

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Abstract

INTIMATE 98 used acoustics to investigate internal waves in shallow water on the continental shelf of the Bay of Biscay in July 1998. For a period of four days intensive hydrological data gathering was made with in situ measurements of temperature, salinity, and current, together with SAR imagery. Coincidentally acoustic transmissions were made between a source and two vertical arrays. The hydrological analysis demonstrated the presence of a single dominant internal tide together with several packets of high frequency internal waves propagating from different points along the shelf-edge. The response of the acoustic signals to the barotropic and baroclinic tide is discussed.

1. Introduction

Understanding the physical mechanisms of internal tides is a major issue for oceanographers and operationals. The former want to understand the role of internal tides in energy transfer for the climate. The latter want to optimize the use of sonar systems. The aim of the INTIMATE experiment series is to study the effects of internal tides and solitons on low frequency acoustic propagation. The first experiment of the series, the INTIMATE96 sea trial, was conducted in 1996 on the Portuguese continental shelf. The experiment demonstrated the ability of broadband acoustics to infer both the medium [1, 2] and the instrumental geometry [3]. The next step of the INTIMATE project is to confirm these results in different environments. In particular, the Bay of Biscay is a very interesting area for internal tide studies. The shelfbreak is sharp and the barotropic forcing is strong. Combined together, these two characteristics induce strong internal waves propagation from each side of the shelf break [4, 6]. A previous experiment, called GASTOM90, had already revealed the influence of internal tides on long range acoustic propagation [7], although the experiment was devoted to mesoscale observation. The main objective of the INTIMATE'98 experiment was to study the effects on internal tides both in deep and shallow water, to check the feasibility of acoustic monitoring on internal tides, and to study the acoustical impact of the fluctuations of the superficial layer for operational purposes.

This paper presents some results of the internal wave analysis of data collected during INTIMATE98 and shows the major characteristics of the acoustical impact of internal tides and waves on low frequency acoustic propagation in shallow water. The experimental set up is given in section 2. The hydrological environment is described in section 3, in which the generation and propagation of solitary internal wave packet are outlined. Section 4 describes the acoustic propagation in the area and summarizes the effects of the surface tides and the internal tide. Conclusions and perspectives are drawn in section 5.

2. Experimental set up

The experiment was carried out in the period of 25 June - 30 July 1998 on the continental shelf in the Bay of Biscay (Figure 1a). The Gamma area, on which we focus in this paper, hosted the part of the experiment devoted to shallow water internal tides. Both acoustic and environmental measurements have been done during two days between July, 8^{th} and July 10^{th}.

2.1 Acoustic measurements

A total of 18 hours of acoustic transmissions were performed within the triangle G0-G1-G2. The acoustic source was kept in station in G0 at a mean depth of 74 meters, while the signals were collected on two 8-hydrophone vertical arrays in G1 and G2, located at around 10 km from G0. To assess signal propagation along and across the expected direction of propagation of the internal tide, one side of the triangle was parallel to the slope and another side was orthogonal. On each array, the hydrophones were regularly sampling the water column above and under the seasonal thermocline (respective depths were 34, 44, 54, 64, 74, 84, 94, and 104 meters).

The emitted signal was a Linear Frequency Modulation from 300 to 1000 Hz. Two elementary sequences of, respectively, 2 and 4 seconds chirps and separated by 2 seconds of silence were emitted every 12 seconds. A pulse compression was used to process the received signals. Each sequence was cross-correlated with the real 2 s emitted signal or with the 4 s emitted signal replica.

2.2 Environmental measurements

Environmental measurements were carried out during the acoustic phase. They have consisted in near-continuous CTD dips at M3. Two CTD stations were held respectively at M4 and G1.1. Stations with XBT launches were also done at G0 and G2, with a temporal sampling of half an hour.

A mooring, deployed at M2, recorded the temperature profile every minutes with 11 thermistors located at depth between 15 and 85 meters. Three S4 current meters were arranged on a mooring at depths of 10, 52 and 120 meters respectively. The S4-current meters mooring had also four additional temperature sensors to allow correlation of the thermocline structure and the internal currents. The temperature sensors were stand-alone and placed at 5 m, 10 m, 22 m, 37 m and 52 m. Finally, an extra mooring, which consisted of four temperature sensors placed at 15 m, 25 m, 35 m and 45 m depth, was designed on board and moored at M3.

An additional surface covering was obtained by an ERS-2 SAR image of the survey region on the 7th July at 11.13 UTC. At this time a total of three moorings together with 2 CTD, XBT stations were being made, giving a large potential for relating the SAR and *in situ* signatures.

3. Hydrological analysis

3.1 Mean environment

The mean sound speed profile is given in Figure 1b. The water depth is approximately 140 meters. The background sound-speed profile is characterized by three layers: the mixed layer, the thermocline and the bottom layer. The mixed layer is shallow (only a few meters), which was expected given the date of the experiment. The thermocline is reasonably sharp, extending from 10 meters to 50 meters. The sound speed gradient in the thermocline is about 0.35 s^{-1}. An important feature of this environment is that, owing to bottom friction, a bottom mixed layer exists between 50 meters and the bottom. As a consequence, a sound channel can be exploited under the thermocline.

3.2 Surface tide

The barotropic tidal velocity was inferred from the depth average of the timeseries of currents from the S4 mooring, gathered between neaps and springs. The semidiurnal constituents were found to dominate the tidal record with maximum current speeds of 0.4 ms^{-1}. The orientation of the semidiurnal velocity ellipses, (026° and 010° T from M2 and S2) suggests that the tides have a strongest component in the across slope direction (the general across-slope direction, neglecting canyons and ridges, is around 045° T, from Figure 2). This is the situation ideal for generating across-slope internal tides: however, the presence of canyons and ridges along the slope will cause along-slope variations in the internal tide as discussed next.

3.3 Internal tides and internal wave packets

Multiple packets of internal waves were seen in the ERS-2 SAR image of the 7^{th} July 1113 UTC taken during the experiment. Figure 2 shows a sketch of the leading wavefronts identified from the image, overlaid on the bathymetry. It is speculated that each lead wavefront with the same alphabetic character (e.g. A1, A2) represent tidal recurrence of the waves. The separation between the wavefronts from successive semi-diurnal tides suggests phase speeds in the range of 0.5 to 0.7 $m.s^{-1}$. The diamonds on Figure 2 indicate the position of internal wave source regions at ridges in the bathymetry identified by New [4]. The features 'C1', 'A1', and 'E1', whose short and undeveloped nature suggests they are close to the generation site, are located at the adjacent canyons to these ridges, suggesting that the canyons can also act as sources for internal tides.

The SAR image may be related to a 25-hour time series of temperature versus depth (Figure 3a) from the thermistor string mooring situated close to G0 (see Figure 2). The time of the SAR image is marked on Figure 3a. An oscillation of the thermocline of roughly semi-diurnal period can be identified in the data, with troughs of the internal tide around 37 hours and 49 hours. However the tidal oscillations are obscured by a number of wave packets labelled on Figure 3a. (Here the shorter period waves in these packets are referred to as internal waves as distinct from the longer internal tide.). The peak to trough amplitude of displacement of the internal tide is around 30 m, whilst the typical internal wave amplitude is 10-20 m (see Figure 3b). The largest measured internal wave during the experiment had an amplitude of 30 m.

The internal wave packets in Figure 3a have been related to the leading wavefronts shown in Figure 2 in [5]. For instance, the single solitary wave 'C2' was seen on the SAR image within 1 km of the G0 mooring and can be identified in Figure 3a as passing just after the SAR image was acquired. The other packets 'A2', 'D' and 'B1' (the latter shown in close up in Figure 4b consisting of six waves also seen in the SAR image) were also identified on the thermistor chain record, whilst the wave packet 'A' on Figure 3a, which occurs around 12.5 hours after 'A2' is tentatively identified with 'A1' on Figure 2.

The presence of multiple wave packets approaching from different sources in addition to a long wavelength internal tide at the experimental site points to the complexity of acoustic interpretation in the area.

4. Acoustical analysis

4.1 Mean propagation environment

The main characteristics of the propagation are given in Figure 4. As expected from the results of INTIMATE96, the received signals exhibits a multipath structure with two types of rays:

- Rays reflected at the bottom and at surface. They are the last arrivals and can be seen on every records. They are stable and generally well-resolved.
- Rays refracted in the thermocline. They can be also refracted in the bottom gradient (deep hydrophones) or they can reflect on the bottom (shallow hydrophones). In all cases, they constitute the main energetic part of the signal.

Intuitively, one can expect the first type of rays to be sensitive to the sea surface fluctuations (sea state and water depth) and to the bottom parameters. One can also expect the second type of rays to be sensitive to the displacement of the thermocline (position and gradient).

4.2 Acoustical impact of tides and solitons

The time series of the acoustic records are given in Figure 5. In a general way, the same features as those observed on INTIMATE96 [1] signals can be noticed. The general structure of impulse response is very stable with time, but interesting fluctuations can be seen in the energy of the first spike and the time of propagation of the last rays. We have carried out exhaustive simulations to quantify the influence of different geometrical and environmental parameters [8]. A summary is presented in Table 1. The fluctuations of the sound speed profile are represented by Empirical Orthogonal Functions (EOF), which is convenient in our case since two EOFs capture about 90 % of the variability (Figure 6). The effects of internal tides and solitons are, first, to modify the position of the thermocline (first EOF) and, second, to modify the gradient (EOF2). It must be emphasized that broadband signals are relevant to the study of the tidal effects because of their stability with respect to undesired fluctuations of geometrical parameters. In addition, the effects of different environmental parameters are separated on the impulse response, so that a simple dedicated inversion scheme [1] can be applied.

Environmental		First spike		Late arrivals	
Parameters		Time	Amplitude	Time	Amplitude
Surface tide		No	5 %	20 ms*	No
Internal tide	EOF 1	No	40 %*	9 ms	No*
	EOF2	No	50 %*	1 ms	No*

Table 1: Summary of the effects of the environment on the waveguide impulse response. The star symbol denotes the cases illustrated on Figures 7 and 8. The surface tide ahs an influence on the travel times of late arrivals and a small influence on the amplitude of the first spike. The thermocline displacement (EOF1) and gradient (EOF2) have a drastic influence on the amplitude of the first spike. The vertical displacement of the thermocline is also influent on the arrival time of late arrivals.

4.2.1 Effect of the surface tide

An example of the influence of the sea surface elevation is given in Figure 7. The barotropic tide induces a sea surface elevation which results in modifications of the surface-bottom ray paths. As a consequence, both absolute and relative travel time (referred to the first arrival) are fluctuating, and an M2 cycle can be seen in the late arrivals when the whole record is lined up on the leading edge. The amplitude of the fluctuations can reach 15 ms. Concerning the energy of the first spike, it is almost unaffected by the sea surface elevation except for shallowest hydrophones, on which simulations show that fluctuations of 30% can occur. This was expectable since the rays in the first spike do not interact with the surface.

4.2.2 Effects of the internal tide

The internal tide has two main effects:

- the fluctuations of the position of the thermocline tends to periodically increase and decrease the mean sound speed over the water column. As a consequence, the travel times of the bouncing rays similarly increase or decrease, which results in a signature of the M2 cycle in the temporal series. It must be noted that even if they are of the same order, the fluctuations due to internal tides are smaller than the fluctuations due to the surface tide (Table 1). This suggests that, for inversion purposes, the effect of the surface tide will have to be filtered out.
- Both position and gradient of the thermocline can affect the amount of energy contained in the first spike (Figure 8). The fluctuations are of several tens of percentage with respect to the energy of the first spike in the impulse response computed with the background profile. This is a major result since it suggests that, as it was the case for INTIMATE96, a matched field processing on the first spike could be efficient to retrieve EOF coefficients.

5. Conclusion

This paper has given a preview of the oceanographic and acoustic analysis of INTIMATE98 data. This analysis is in accordance with what was expected. From the oceanographic point of view, a dominant M2 internal tide cycle has been observed, together with the presence of solitary waves packets. From the acoustic point of view, the data analysis has shown that the observation made during INTIMATE96 were confirmed in a different environment. In particular, the temporal series of impulse response of the wave guide exhibits a stable multipath structure, with separate effects of the barotropic and baroclinic tides.

At the time of the paper was written, no inversion results were available; However, the effects of internal tides on acoustics tend to confirm that simple inversion schemes (such as those used for INTIMATE96) could efficiently retrieve the main features of internal tides (amplitude, direction, wavelength). In addition, a detailed analysis of the effects of solitons will be carried out.

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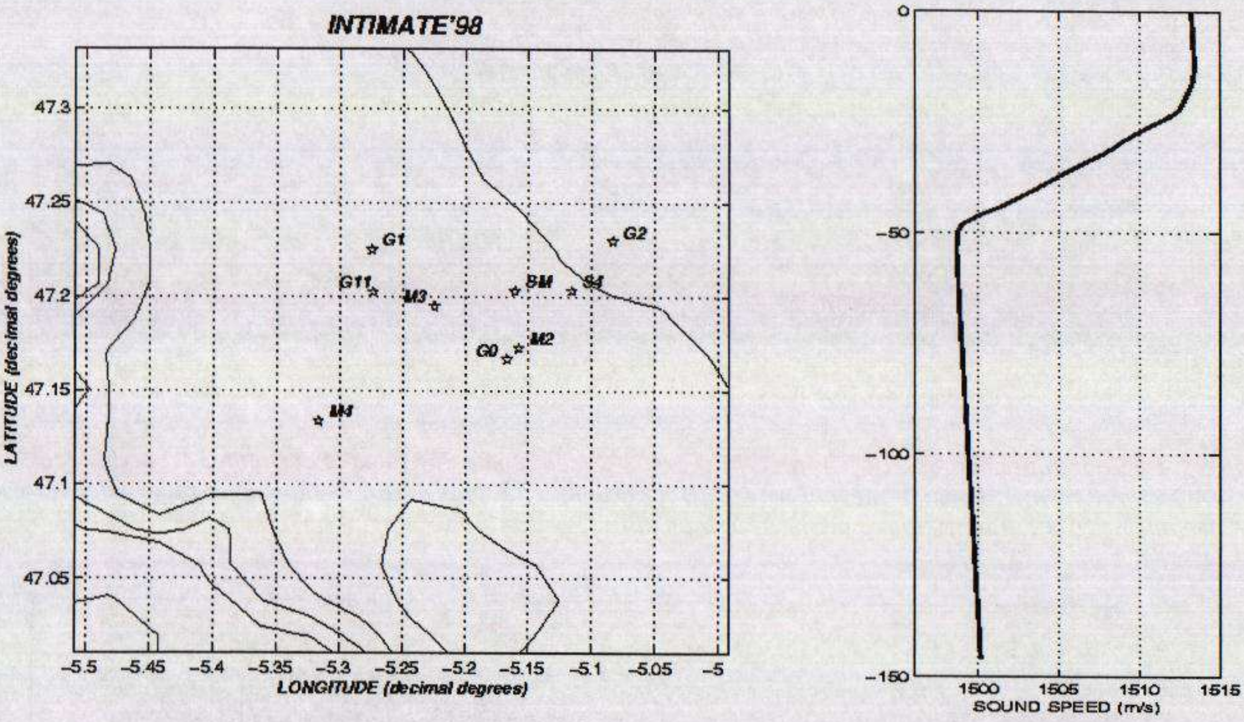


(a) (b)

Figure 1. Site and background sound-speed profile for INTIMATE98. Two vertical arrays are deployed in G1 and G2. The source is dipped in G0. The bottom mixed layer is 100 m thick due to bottom friction. This induces a sound channel.

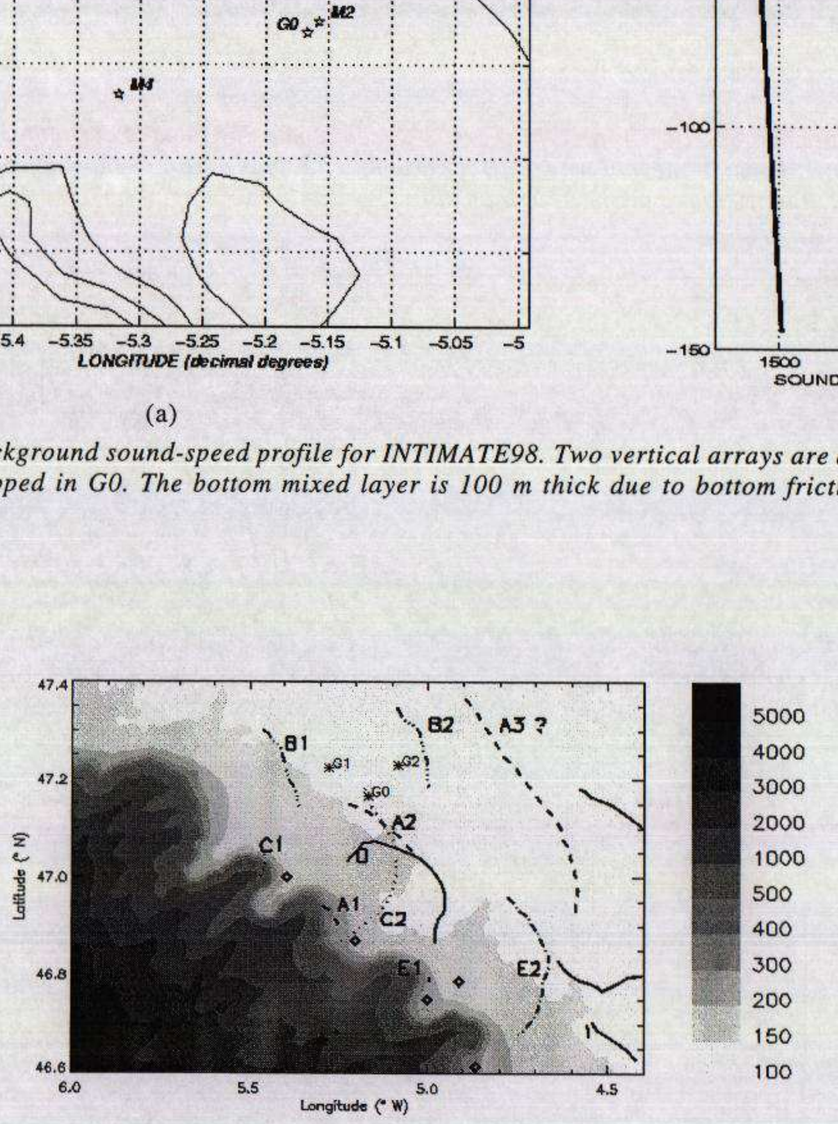


Figure 2. Bathymetry of the Bay of Biscay shelf edge, from the EPSHOM 1 nautical mile database (depth in metres). Overplotted as lines are traces of internal wavefronts from the ERS-2 SAR image of 7th July 1998, 1113 UTC. (A1...A3, marked as dashed lines, B1, B2 marked as lines of dash-and 3 dots, C1, C2, shown as dotted line, D as a solid line and E1, E2 as chained lines). The acoustic positions G0, G1 and G2 are labelled with asterisks.

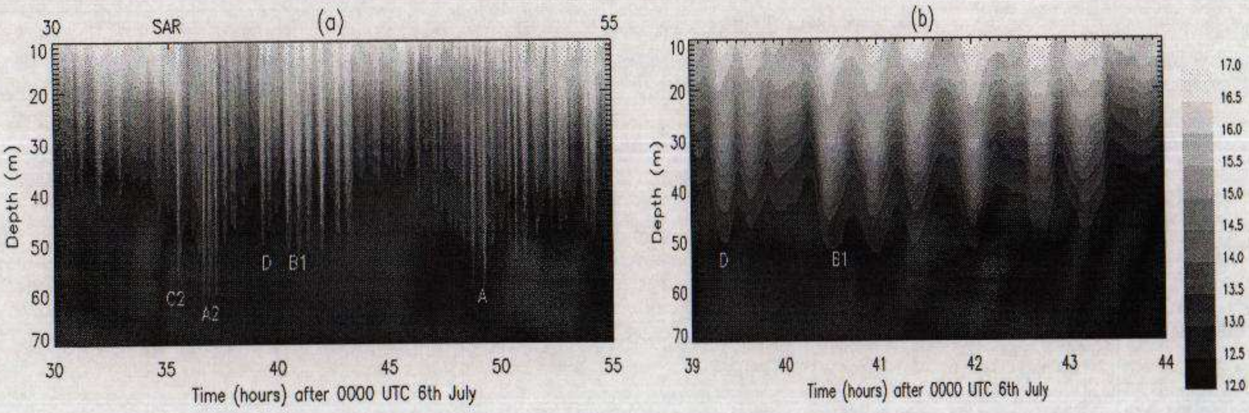


Figure 3. Contours of temperature (°C) from the thermistor chain mooring located close to G0 (see Figures 1 and 2). a) A 25 hour record showing internal waves. b) A close up of 5 hour duration showing typical internal waves with periods of 20-30 minutes and peak to trough amplitudes of 0-20 m.

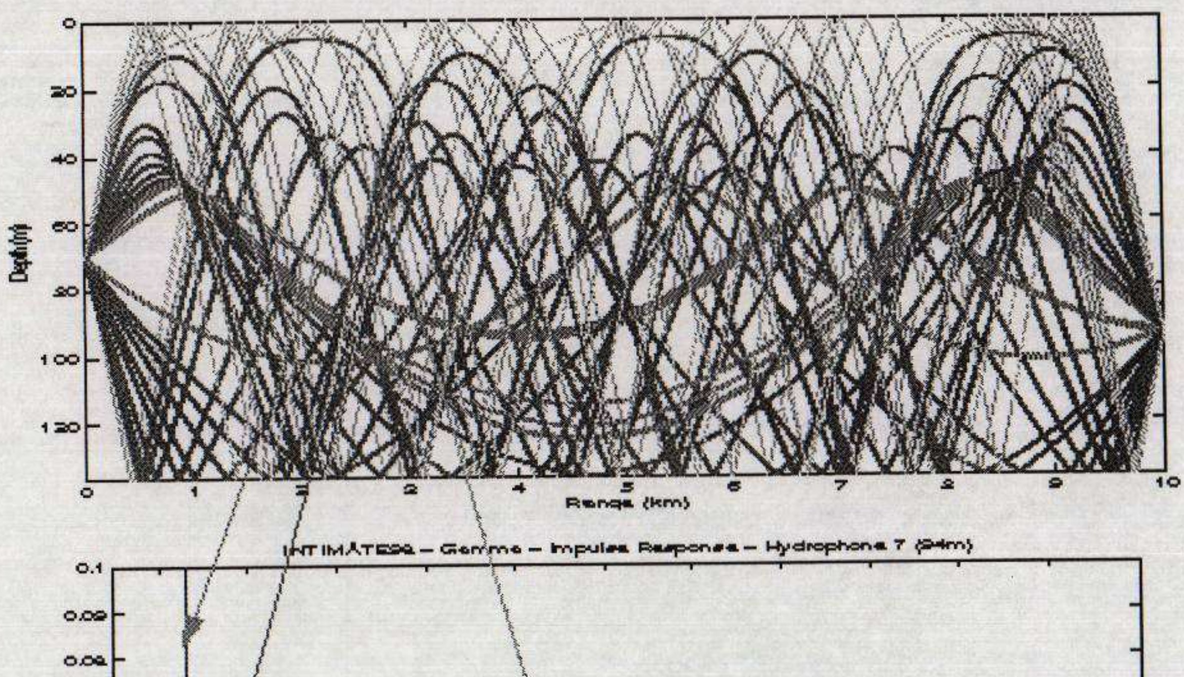


Figure 4. Ray tracing and impulse response for the propagation at G1 for hydrophone 7 (94 meters). The early arrivals correspond to rays guided in the channel. Such rays only exist for deep hydrophone. The second arrivals are rays refracted in the thermocline and reflected on the bottom. The late arrivals are rays reflected at the surface and on the bottom.

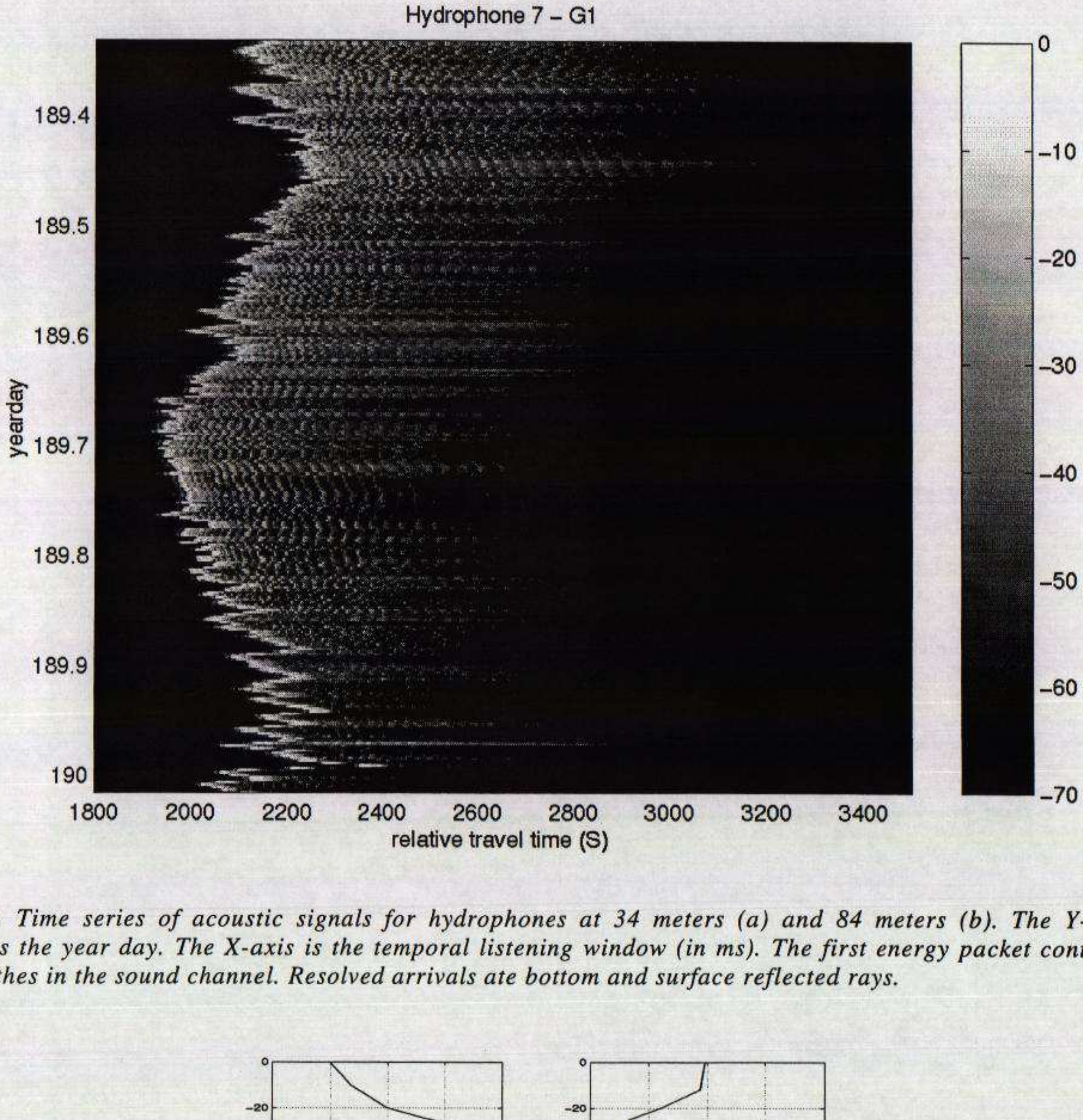


Figure 5. Time series of acoustic signals for hydrophones at 34 meters (a) and 84 meters (b). The Y-axis represents the year day. The X-axis is the temporal listening window (in ms). The first energy packet contains direct pathes in the sound channel. Resolved arrivals ate bottom and surface reflected rays.

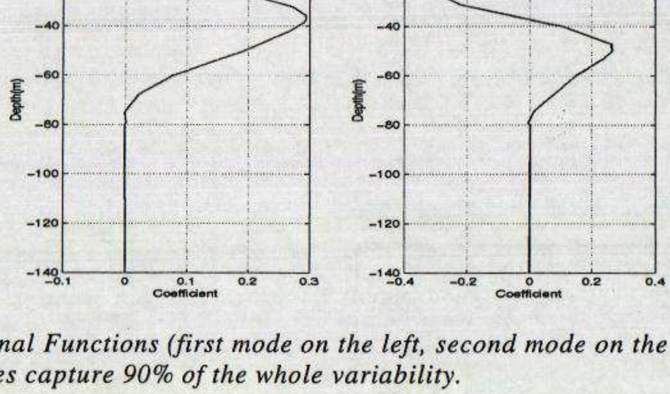
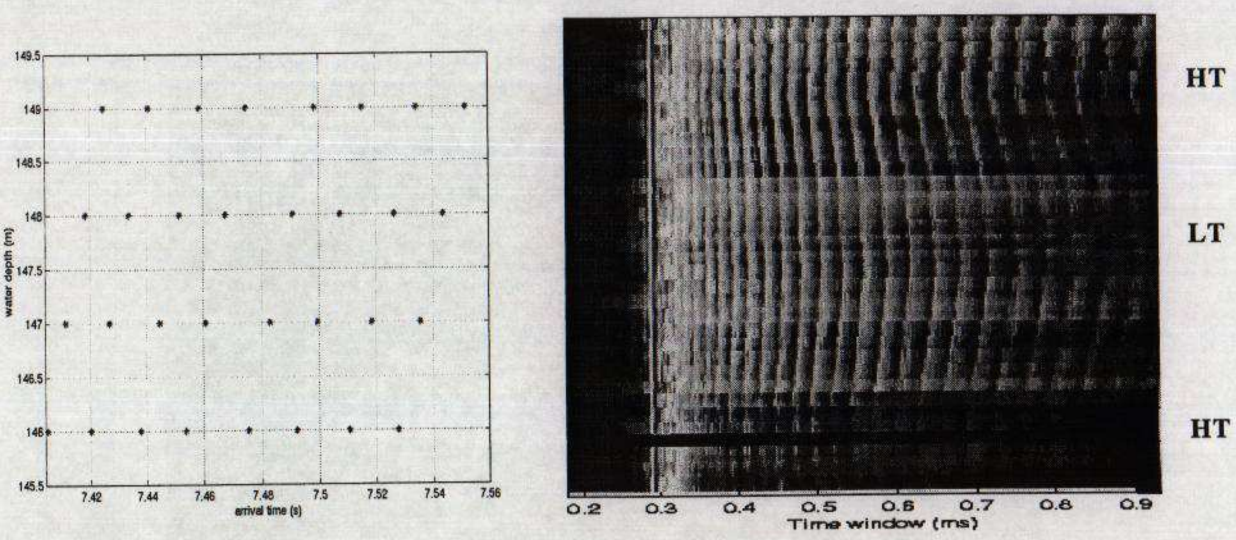


Figure 6. Empirical Orthogonal Functions (first mode on the left, second mode on the right) for the hydrological environment. These two modes capture 90% of the whole variability.



(a) (b)

Figure 7. Influence of the surface tide on acoustic record for hydrophone 4. In (a) arrival time of the last rays versus the water depth. The times are changing in a quasi-linear way (20 ms for a 4 m tidal amplitude). In (b), lined-up real sequences over 18 hours. Note the fluctuations of the late arrivals, following a M2 cycle (HT = High Tide, LT = Low Tide). Fluctuations can reach 30 ms owing to internal and external tides.

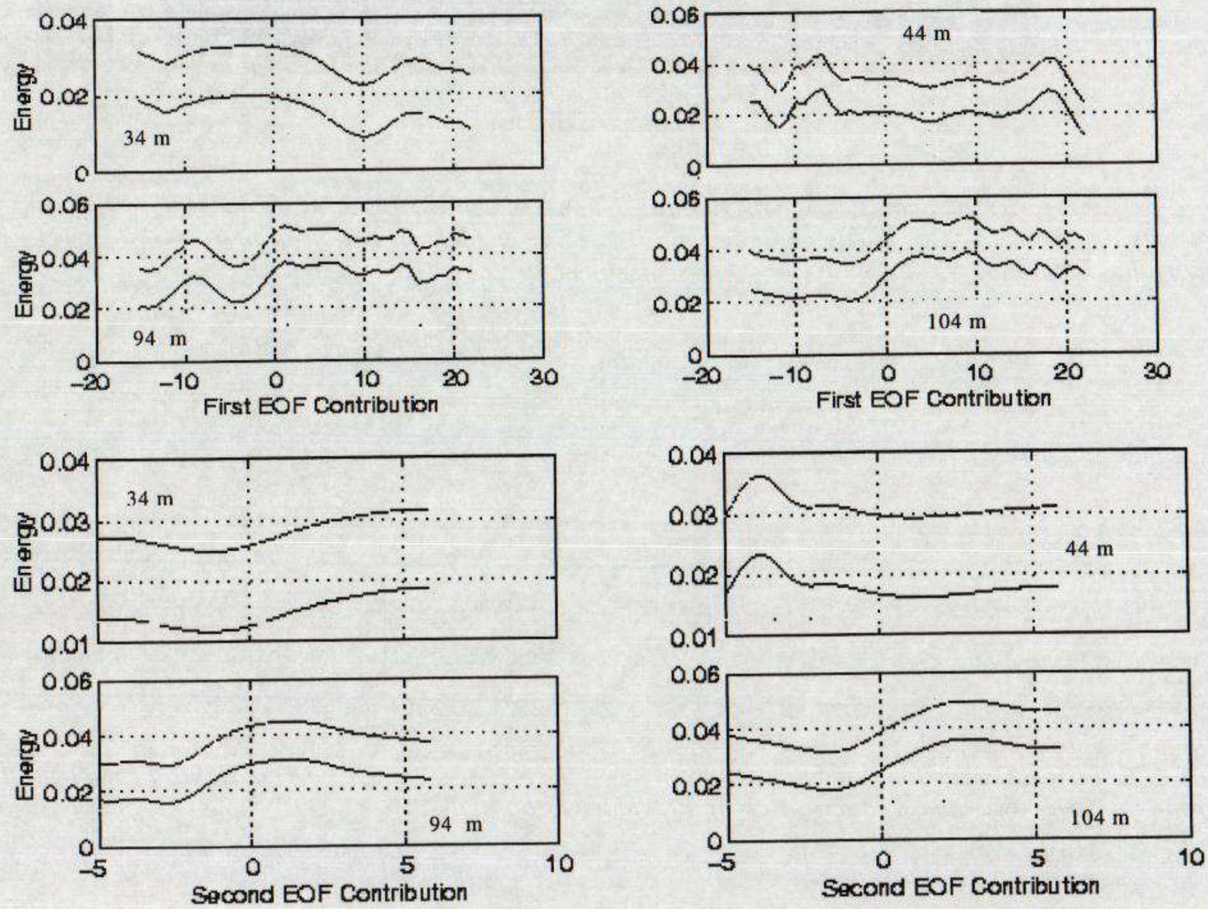


Figure 8. Influence of internal tides (two modes) on the acoustic propagation: Fluctuations of the energy of the first spike (lower curve) and of the whole signal (upper curve) on four different hydrophones.