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Single receiver inversion in shallow water

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Low frequency propagation (0-200 Hz) in shallow water (10-400 m) is described by modal theory. When using a single receiver, one challenge is to extract information about the modes in order to localize an acoustic source and/or characterize the environment. Indeed, when source/receiver distance is about a few kilometers to a dozen of kilometers, modes are overlapped in time and in frequency. This article presents a method for extracting modal travel times using a single receiver without any a priori knowledge of the environment. Adaptive signal processing is applied to compensate for modal dispersion, using time and frequency warping transformations adapted to the physics of propagation. Warping allows to filter each modal contribution by overcoming inherent limitations of time-frequency representations. Once each modal component is filtered, high resolution estimation of modal travel times is performed using reallocated spectrogram. The extracted modal travel times are robust features of propagation, as they can straightforwardly be linked to modal group velocities. This article presents an inversion scheme based on these features. It is successfully applied on experimental data recorded in an ultrasonic tank.

1 Introduction

Underwater acoustics is commonly used for geoacoustical inversion and source localization. Classical at sea experiments use an array of receivers, which can be arranged vertically or horizontally. The use of an array of hydrophones increases the Signal to Noise Ratio (SNR) and the amount of available information thanks to distance aperture. However, deploying an array is expensive and time consuming in an operational context. Some studies using a sparse network of hydrophones have been proposed previously [1, 2, 3]. As the receivers are quite far away from each other in that kind of configuration, it might be problematic to record the same signal on every hydrophone [3, 4]. Other studies have been done using a single, fixed receiver. In term of operational context, the practical advantage of this configuration is obvious. However, it reduces the SNR and the quantity of available information. It is possible to overcome this by using broadband sources to gain frequency diversity [5, 6, 7].

In this paper, only broadband propagation in shallow water is considered. Although it is a classical configuration for underwater acoustics, it is still a challenging problem when coupled with single receiver. Indeed, for relatively low frequencies, the shallow water environment is dispersive: sound is distorted by the medium as each frequency travels at its own speed. The most suitable model to describe this propagation is the normal mode theory [8]. The pressure field can be decomposed into modes, and each mode is differently affected by dispersion. By characterizing the dispersion, it is possible to extract information about the environment or the source localization. While using a single receiver, extracting modal information is complicated and requires appropriate signal processing.

Because of dispersion, arrival times of a given mode differ for each frequency. These arrival times are used for localiza-

tion or inversion but they are often manually extracted [7, 9]. When several modes arrive simultaneously on the receiver, only few methods providing automatic extraction are available in the literature [10]. This paper proposes an automatic estimation of the modal arrival time requiring no a priori of the environment, and then use it as an input for an inversion algorithm.

First modal propagation is reviewed, and it is shown that modal information is embedded in time-frequency domain although not easily accessible. Secondly, The algorithm to extract modal arrival times is presented and a tomography method using these arrival times is proposed. Finally, the inversion algorithm is validated on experimental data recorded in an ultrasonic tank.

2 Modal propagation

As stated in the introduction, for shallow water and low frequencies, the most suitable propagation model is normal mode theory. In this case, in a range independent environment, the received signal $Y(f)$ after propagation between an impulsive source at depth z_s and a receiver at a depth z_r separated by a radial distance r is, in the frequency domain [8] :

$$Y(f) \approx Q \sum_{m=1}^N \Psi_m(f, z_s) \Psi_m(f, z_r) \frac{e^{jk_{rm}(f)r}}{\sqrt{k_{rm}(f)r}}, \quad (1)$$

where N is the number of modes, Ψ_m is the modal function of mode m , $k_{rm}(f)$ the radial wavenumber of mode m (which is supposed to be real as the evanescent modes are not taken in account), and $Q = \frac{e^{j\pi/4}}{\rho(z_s)}$ (with $\rho(z_s)$ the water density at the source depth).

Equation (1) can be simply written as

$$Y(f) = \sum_{m=1}^N \widetilde{A}_m(f) e^{j\widetilde{\Phi}_m(f)}, \quad (2)$$

where

$$\widetilde{\Phi}_m(f) = k_{rm}(f)r \quad (3)$$

is the phase of mode m in frequency domain. It is an important quantity. We will show later that it gives the localisation of mode m in the time-frequency plane.

For each mode m , group speed v_{gm} can be defined as:

$$v_{gm}(f) = 2\pi \frac{\partial f}{\partial k_{rm}} \quad (4)$$

Group speed describes the propagation speed of energy. As it depends both on frequency f and mode index m , each frequency of each mode travels at its own speed. This is the definition of dispersive propagation. To extract information of the received signal, the modes have to be separated. If the distance between source and receiver is big enough (more than 15km in a classical shallow water waveguide), the modes are perfectly separated in time, and no further treatment is needed. However, if the distance is shorter, modes are overlapped in the received signal: for a given time, several modes coexist. As they also share a mutual frequency band, it is not possible to separate them, neither in time nor in frequency domain. To overcome this problem, the signal will be studied in the (joint) time-frequency domain.

In particular, we study the localization of the mode in the time-frequency plane. We define the modal arrival time $t_m(f)$ of mode m as the time at which frequency f arrives on the receiver. It is given using the definition of group velocity

$$t_m(f) = \frac{r}{v_{gm}(f)}. \quad (5)$$

Note that under stationary phase approximation, this definition is coherent with the signal processing definition of the group delay τ_m . As instantaneous frequency describes the time dependence of the dominant frequency in a signal, group delay is the dual quantity describing the frequency dependence of the dominant time in a signal [11] :

$$\tau_m(f) = -\frac{1}{2\pi} \frac{\partial \widetilde{\Phi}_m(f)}{\partial f}, \quad (6)$$

where $\widetilde{\Phi}_m(f)$ is the phase of the signal in the frequency domain as defined in equation (2). Recalling equations (3) and (4), we have

$$\tau_m(f) = -\frac{r}{v_{gm}(f)} = -t_m(f). \quad (7)$$

Figure 1 presents the theoretical arrival times in a classical shallow water Pekeris waveguide for a source/receiver distance $r = 5$ km. One can recognize that this pattern is linked to the classical group velocity pattern, although the

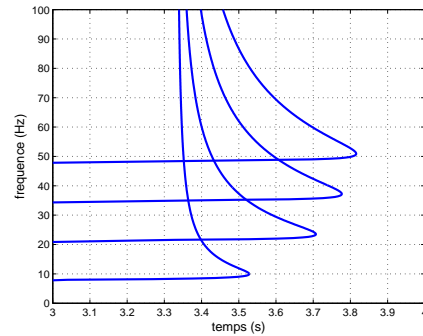


Figure 1: Theoretical modal arrival time in a Pekeris waveguide (water sound speed 1500 m/s, bottom sound speed 2000 m/s, depth 100 m)

arrival time pattern is range dependent. Modal arrival times carry information about the environment through group velocity. Moreover, they are also well defined in term of signal processing, and can therefore be extracted from the received signal. Thus, they are interesting features that we can use to build an inversion algorithm. The next section will present their estimation and utilization in an inversion scheme.

3 Inversion scheme

The inversion scheme follows two main steps:

1. modal arrival time extraction from the received signal,
2. inversion using the estimated arrival times.

3.1 Modal arrival time estimation

As shown in Figure 1, modal arrival times are non-linear and close from each other in the time-frequency plane. Because of time-frequency inherent limitations (time-frequency uncertainties and interferences), arrival time estimation is impossible without using adaptive signal processing. To overcome time-frequency limitation, we use dispersion based transformation, known as warping, to allow modal filtering on a single receiver.

Let consider that we have a received signal $x(t)$. The modal filtering algorithm is as following:

1. Compute $X(f)$, the Fourier Transform of $x(t)$, to go in the frequency domain.
2. Estimate the direct path arrival time $t_r = t_m(\infty)$ thanks to a recursive application of frequency warping [12]. This step realizes a dispersion based energy finder to detect the useful part of the signal.
3. Set causality with the estimated t_r and compute $x_{warp}(t)$, the time warped version of $x(t)$. Time warping is a

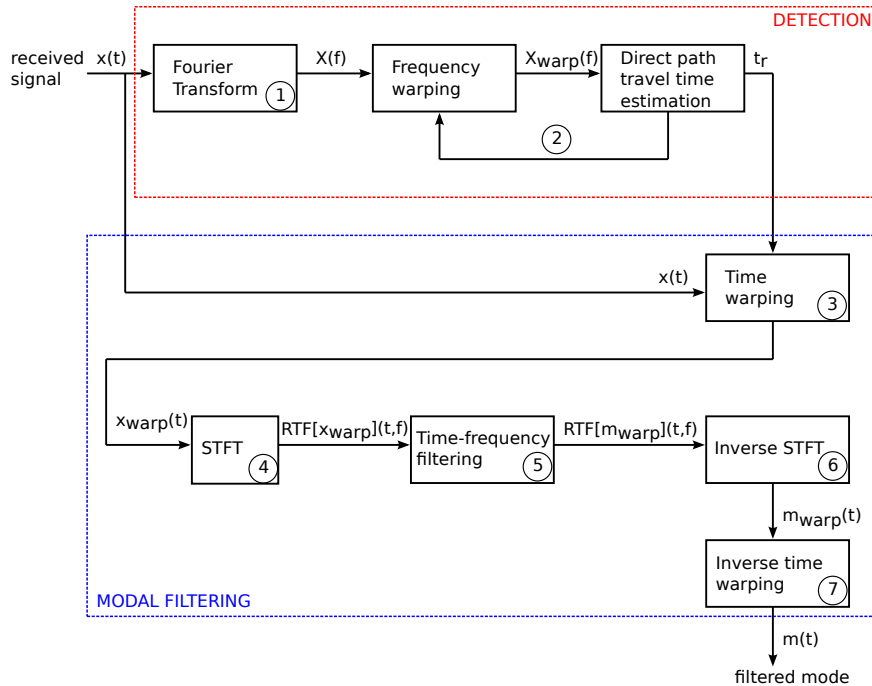


Figure 2: Modal filtering algorithm

dispersion based transformation allowing modal separation in the time frequency domain [13].

4. Compute Short Time Fourier Transform (STFT) of $x_{warp}(t)$ to get a time-frequency representation of the warped signal $RTF[x_{warp}](t, f)$.
5. As warped modal component are resolved in time-frequency domain, (warped) modal-filtering can now be done using a simple threshold filter in the time-frequency domain. This allows to isolate a warped mode in the time-frequency domain $RTF[m_{warp}](t, f)$
6. Go back to time domain thanks to inverse STFT. A warped mode $m_{warp}(t)$ is isolated.
7. Unwarped $m_{warp}(t)$ to get $m(t)$, the filtered mode in time domain.

This whole scheme is summarized in figure 2. Now that a single mode is isolated, modal arrival time estimation becomes trivial. It is a simple group delay estimation problem for a monocomponent signal. As the isolated mode can be noisy, we decided to do it in the time-frequency domain using reallocated spectrogram [14], which is a powerful signal processing tool allowing high resolution localization of monocomponent signal in the time-frequency domain.

3.2 The inversion itself

Note that the whole modal arrival time estimation process does not require any a priori knowledge on the environment nor on the source localization. For the inversion, we assume that the source/receiver range r is known. However, we do

not assume that source and receiver are synchronized. This is a realistic situation for a moored autonomous receiver which can loose time synchronization because of time drift during an experiment.

Thanks to the detection step presented in the last section, time synchronization can be artificially recovered. Frequency warping allows to point the sample corresponding to t_r in the received signal. This sample is chosen as the new time origin. This defines relative arrival times which are directly measured on the signal

$$t_m^{rel}(f) = t_m(f) - t_r. \quad (8)$$

The inversion

$$\hat{\mathbf{A}} = \min_{\mathbf{A}} \left\{ \sum_{m,n=1}^{M,N} \left[\widehat{t_m^{rel}}(f_n) - t_m^{rel}(f_n, \mathbf{A}) \right]^2 \right\}, \quad (9)$$

is carried out over a set of M modal components and N frequency components for a set of parameters represented by vector \mathbf{A} . The quantity $\widehat{t_m^{rel}}(f_n)$ represents estimated relative arrival time at frequency component n .

4 Application on experimental data

The inversion scheme is benchmarked on experimental data recorded in an ultrasonic tank. Ultrasonic tanks allow to do small scale experiments at high frequency in a perfectly controlled environment. Indeed, if distances (source/receiver distance and depth) are reduced by a factor N , frequency has to be multiplied by the same factor N (the wavelength is then divided by N) so that the scale remains the same and the physics of propagation does not change.

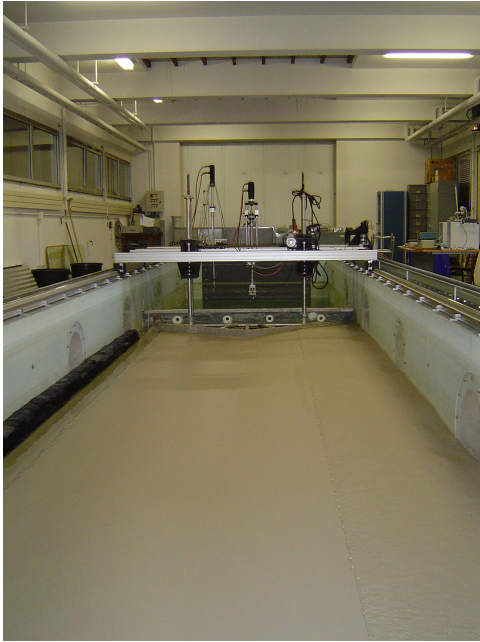


Figure 3: The ultrasonic tank in Laboratoire de Mecanique et d'Acoustique (Marseille, France)

4.1 Presentation of the dataset

The tank belongs to Laboratoire de Mecanique et d'Acoustique (LMA) in Marseille, France. It is presented on figure 3. This tank is 3 m wide and 10 m long, and possesses relatively low frequency emission/reception system. The tank bottom is covered with a thick layer of fine sand. This sand layer is deep enough so that the waveguide can be considered as a Pekeris waveguide with parameters :

- water column : sound speed : $c_1 = 1480 \text{ m.s}^{-1}$, density : $\rho_1 = 1000 \text{ kg.m}^{-3}$, depth : $D = 8 \text{ cm}$;
- bottom : sound speed $c_2 = 1700 \text{ m.s}^{-1}$, density : $\rho_2 = 2000 \text{ kg.m}^{-3}$;
- source central frequency around $f_c = 150 \text{ kHz}$ and bandwidth around 250 Hz,
- source/receiver separation $r = 11,2 \text{ m}$,
- source and receiver depth was not measured.

This experimental protocol corresponds to a classical very low frequency underwater acoustic experiment, with a scaling factor $N = 1000$. The experimental parameters in oceanic scales are then : $D = 80 \text{ m}$, $r = 11.2 \text{ km}$, $f_c = 150 \text{ Hz}$. All figures given in the following section are presented in the oceanic scale.

4.2 Inversion of the experimental data

Figure 4 presents the signal recorded in the tank, in time domain. It is impossible to discern the modes as they are

overlaped in time. Figure 5 presents the spectrogram of the recorded signal and the corresponding estimated arrival times (in white). As stated in section 3.1, time axis was shifted between the two figures. The modes are really close from each other in the time-frequency plane, so arrival time estimation is difficult. One can see that first two modes are not really well estimated: the arrival time curves are not regular. These first modes are the ones with the most horizontal propagation, so we can assume that our scheme might not be accurate for the water sound speed inversion

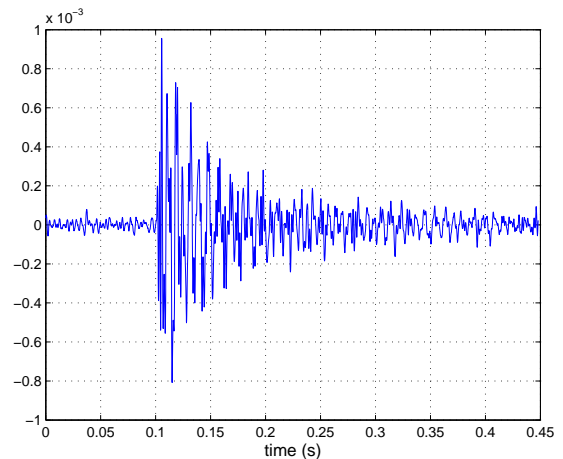


Figure 4: Signal recorded in the tank

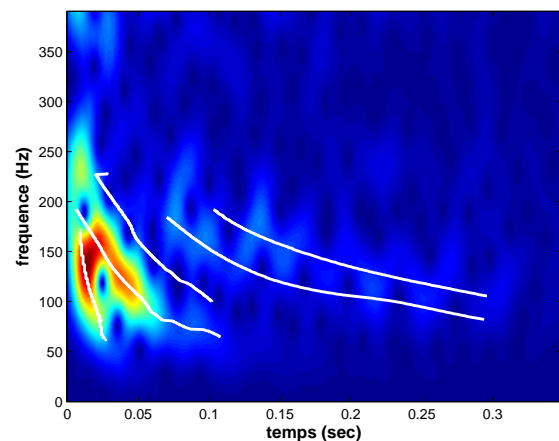


Figure 5: Spectrogram of the recorded signal in the tank, and corresponding estimated arrival time

After arrival time estimation, the last thing to do is to choose a propagation model to compute the replica. Here, we choose the Pekeris waveguide model to match the tank environment. In this case, the replica calculated using equation 8, depend on five parameters: depth D , water sound speed c_1 , bottom sound speed c_2 , and the densities of the water and the sediment, ρ_1 and ρ_2 . Because the dependence of group velocity -and thus of modal arrive time- on density is weak (compared to that of the water depth and sound speeds) these parameters are constrained to the values, $\rho_w = 1000 \text{ kg/m}^3$

and $\rho_b = 2000 \text{ kg/m}^3$. Thus the minimization vector is formed by three parameters, $\mathbf{A} = [D, c_w, c_b]$.

Inversion algorithm is applied on estimated arrival time. The parameter research space is :

- $c_1 \in [1450, 1545] \text{ m.s}^{-1}$ with a 5 m.s^{-1} step,
- $c_2 \in [1550, 1850] \text{ m.s}^{-1}$ with a 20 m.s^{-1} step,
- $D \in [60, 99] \text{ m}$ with a 3 m step.

This parameter space is small enough so that an exhaustive research can be done. However, it is big enough so that it does not require an important a priori knowledge on the environment. The inversion result is $\hat{c}_1 = 1545 \text{ m/s}$, $\hat{c}_2 = 1710 \text{ m/s}$ et $\hat{D} = 81 \text{ m}$. This result is quite good as water depth and sediment sound speed are really well estimated (our a priori about the environment was $c_2 = 1700 \text{ m/s}$ and $D = 80 \text{ m}$). However, as predicted by a quick analysis of the estimated arrival times, the estimated water sound speed is not relevant. It corresponds to a boundary of our research space.

5 Conclusion

In conclusion, this paper presents an inversion algorithm based on a single source/receiver pair configuration. By using frequency diversity, it compensates for the lack of distance aperture. Warping processing allows to extract modal information from the signal recorded on the receiver. This information can be used as an input for an inversion algorithm. The proposed algorithm is successfully applied on an experimental small scale dataset, and it provides an accurate estimation of the bottom properties.

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