Are Ultra Low Frequency Waves Suitable For Detection ?

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***Abstract*- Seismic processing tools have been developed mainly by petroleum research. As underwater sources are now at low frequency (< 100 Hz), most of these methods can be adapted or directly used to underwater source detection in shallow water. In this paper, we will focus on detection using Ultra Low Frequency waves (ULF). The first step is to know how these waves propagate and which valuable information they can carry. A study of the propagation between an underwater source and sensors laid on the floor is proposed. Different transformations (velocity correction, frequency-wavenumber transformation) are used to estimate geoacoustical parameters on a real data set. Wave propagation simulation in a heterogeneous medium using finite-difference algorithm is made in a similar environment and to validate the methods, simulated geoacoustical parameters are estimated.**

I. INTRODUCTION

Ultra Low Frequency waves (1-100 Hz) are now widely used in underwater acoustic to get information on propagation parameters (acoustic and elastic). Because ULF waves are almost non-affected by absorption during their underwater propagation, they can be used to make long-range detection. At long distance, preponderant waves are guided waves, they must be taken into account during the horizontal transmission between an underwater source and receivers laid on the sea floor. To reach this information, 4-Components sensors are used. This sort of sensors, named Ocean Bottom Seismometers (OBS) provides the three components of the displacement and the variation of the pressure field. Using these sensors in a 2D acquisition, we obtain more information on the source, the propagation and the geoacoustical parameters.

Our objective is to show that using ULF waves and appropriate advanced signal processing tools, it is possible to extract information on the propagation media for a potential detection. We first study wave guides to know more about ULF propagation. Then, real seismic data, recorded by Ocean Bottom Seismometers, are used to recover geoacoustical parameters. In the last part, we simulate the previous data with a finite-difference algorithm for modeling P-SV wave propagation in heterogeneous media and simulated geoacoustical parameters are estimated to validate methods described in the first part.

II. DESCRIPTION OF THE MODES OF PROPAGATION

A. General context

Source detection based on wave theory is dependent on the model of propagation in the acoustic (sea) and elastic (sea floor) media. Let us consider an omnidirectional impulsive source located under the sea surface (Fig. 1). The cone of waves arriving under an incidence angle θ_1 inferior to the critical reflexion angle θ_c are partially transmitted in the sea floor. They do not contribute to long distance propagation (first approximation) whereas totally reflected wawes, guided between the sea surface and bottom, propagate further and create the wave guide.

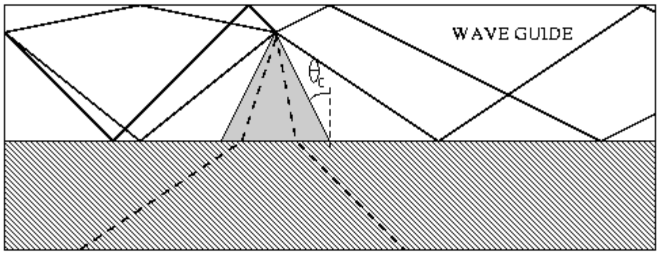

Fig. 1: Propagation approximation

B. Wave guide

After this brief introduction, a simple model of homogeneous wave-guide is presented (Fig. 2). We describe parameters necessary for studying the wave guide between source and sensors laid on the floor.

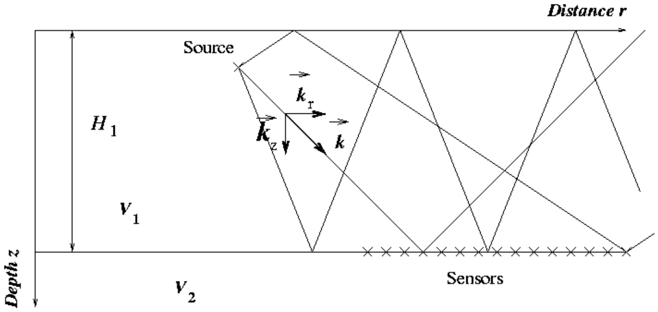

Fig. 2 : Wave guide parameters

$\vec{k}$ is the wavenumber and can be projected on distance and depth axis. V_1 is the wave velocity in the water layer and V_2 in the first sediment layer.

During the propagation path, interferences between different waves appear creating a wave guide [2]. Fig. 3 summarizes the interference principle in a homogeneous wave guide. k_u and k_d are the wavenumbers of up-going and down-going waves. R_1 and R_2 are respectively the reflexion coefficients at the air/water interface and at the water/sea-floor interface.

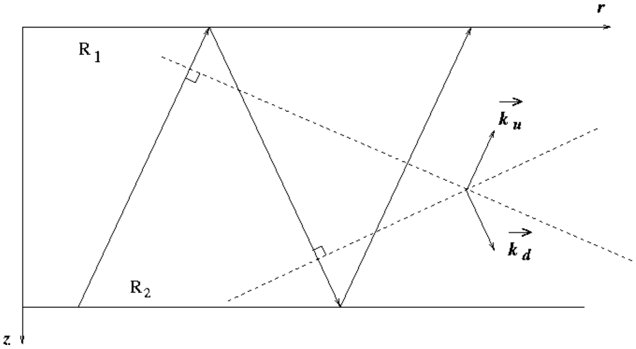

Fig. 3 : Creation of a wave-guide

In order to interfere constructively, the two waves fronts (which differ from two reflections at the sea surface and at the sea floor) must present a phase shift multiple of $2\pi m$. This condition, known as resonance condition, can be written as:

$$R_1R_2e^{4\pi jk_{zm}H_1}=e^{2\pi jm} \tag{2.1}$$

where m is the number of the mode and $4\pi jk_{zm}H_1$ represents the phase shift due to the vertical propagation difference between the two wave fronts.

Depending on the coefficients R_1R_2, two cases are described [1]:

- If $|R_1R_2|=1$, the wave-guide is perfect; all the energy stays in the water layer.
- If $|R_1R_2|<1$, which is more realistic, a part of the energy disappears during the reflection by transmission to the layer below (leaky guide).

In the second case [7], a classical expression of R_2 is $R_2=e^{-j\theta_2}$. The vertical wavenumbers of the modes, given by (2.1), are the discrete solution of :

$$k_{zm}+\frac{\theta_2}{4\pi H_1}=\frac{2m-1}{4H_1} \tag{2.2}$$

Besides, the radial propagation is given by the propagation law in the sea :

$$k_{rm}^2+k_{zm}^2=f^2/V_1^2 \tag{2.3}$$

with f the frequency. Waves propagate at long distance only if ${k_{rm}}^2>0$, this hyperbol equation shows that, in this case, the cutoff frequency is $f_{cm}={V_1}^2{k_{zm}}^2$. Taking into account (2.4), the cutoff frequency around the critical angle is :

$$f_{cm}=\frac{(2m-1)V_1}{4H_1\sqrt{1-(V_1/V_2)^2}} \tag{2.4}$$

C. Characterization of the modes in the f-k domain

The pressure field, in space (*r,z*) and frequency (*f*) can be expressed with a sum of modes [5]:

$$p(r,z,f)=S(f)\sum_m A_m\Psi_m(z)X_m(r) \tag{2.5}$$

with A_m : Excitation function of the mode *m*.

$\Psi_m(z)$: Energy repartition on the depth axis *z*.

$X_m(r)=\frac{1}{\sqrt{r}}e^{-2\pi jk_{rm}(f)r}$: Radial propagation.

In order to characterize the modes of propagation, we introduce the “frequency-wavenumber” representation, which is the square modulus of the double Fourier transform of a section $p(r,z,t)$ in time and radial distance [4]. This representation, named $f-k$ representation, is :

$$P(k_r,z,f)=\iint p(r,z,t)e^{-2\pi j(ft-k_rr)}dtdr \tag{2.6}$$

At a depth z_0 , the pressure field becomes :

$$p(k_r,z_0,f)=S(f)\sum_m A_m\Psi_m(z_0)\delta\left[k_r-k_{rm}\right] \tag{2.7}$$

This expression shows that pressure only depends on the source spectrum. As a result, all the treatments made in the frequency-wavenumber domain ($f-k$) will still be efficient when the explosive source will be replaced by a boat source in detection problems (as long as this source has a broadband spectrum).

The *f-k* representation permits the separation of the different modes (Fig. 4) [6][4].

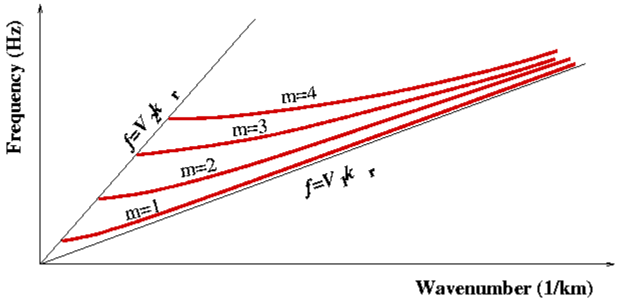

Fig. 4: Modes representation in the $f-k$ domain

A mode m is characterized by (2.3). Moreover $k_{zm}=f_{cm}/V_1$ implies ${k_{rm}}^2=\frac{f^2-{f_{cm}}^2}{{V_1}^2}$. This hyperbole represents the mode m without taking into account the angle of propagation. Indeed, at long range, modes are non-damped out only if $\theta_1>\theta_c$. In this case, $k_{rm}=(f/V_1)\sin\theta_1$ must satisfy $k_{rm}>f/V_2$ and modes exist only above this asymptote. As a result, the representation of a mode in the $f-k$ domain is a part of a hyperbol (Fig. 4).

IV. GEOACOUSTICAL PARAMETER ESTIMATIONS

Signal processing tools are now used to estimate some of the geoacoustical parameters [3][4][6]: water layer velocity V_1, first sedimentary layer velocity V_2, water depth H_1.

A. Estimation of the water layer velocity V_1

From the initial section in the time-distance domain [*r,t*], we apply a time correction along the distance axis *r*. The record of each sensor is time shifted so that the direct wave impinges on all sensors at the same time. This time correction gives an estimation of the water layer velocity (Fig. 5).

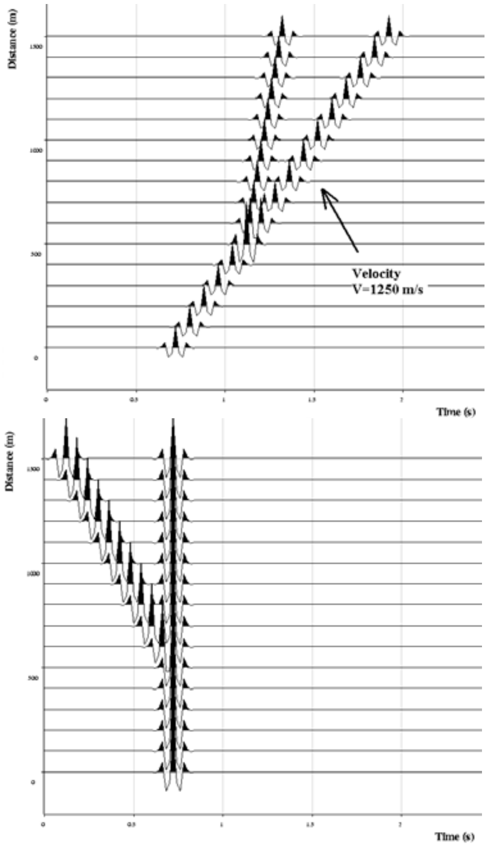

Fig 5. : Synthetic time-distance section before and after velocity V correction.

B. Estimation of the velocity V_2 in the first sediment layer

To estimate V_2, classical techniques [4] are based on the identification of the refracted wave velocity. This estimation is possible on the $f-k$ representation. After the correction of the water layer velocity (V_1), the refracted wave velocity (V_2) is given by

$$V_2=\left[\frac{1}{V_{\text{app2}}}+\frac{1}{V_1}\right]^{-1} \tag{3.1}$$

where V_{app2} is the apparent refracted wave velocity measured on the $f-k$ representation. This estimation is possible only if sensors are quite closed to the source: with far sensors, refracted waves can’t be seen because of their large attenuation at long distance. We prefer using $f-k$ representation on the entire section, which shows different modes of propagation and allows us to use properties established in the first part.

After the V_1 velocity correction, the asymptote $f=V_2k_r$ is shifted in $f=V_{\text{app2}}k_r$ (with V_{app2} defined above). As a result, we can find V_2 by estimating the slope of this asymptote after the V_1 velocity correction. This asymptot is a straight-line throught all the mode cutoff frequencies.

C. Estimation of the water depth H_1

Depth water is measured directly on the $f-k$ plot. All cutoff frequencies are extracted in term of temporal frequency coordinate. Equation (2.4) allows us to recover the water depth H_1.

IV. APPLICATIONS ON REAL AND SIMULATED DATA

Our objective is to extract geoacoustical parameters on a real data set. We first apply methods described below on this data set. Then to validate the methods, a simulation in a similar environment is realised and simulated geoacoustical parameters are estimated.

A. Application on real data

Techniques described above are now used on real data to recover geoacoustical parameters. The field data set has been recorded on a synthetic antenna of 240 Ocean Bottom Seismometers (OBS) laid on the North Sea floor. The hydrophone is mainly used but vertical geophone gives identical results for our objective. Spatial sampling and time sampling are respectively 25 m and 4 ms [3].

Initial data are time corrected with a velocity $V_1=1520$ m/s as it was explained on the synthetic data in III-A. Results in the time-distance domain and in the temporal frequency-spatial frequency domain are presented on Fig. 6 and 7.

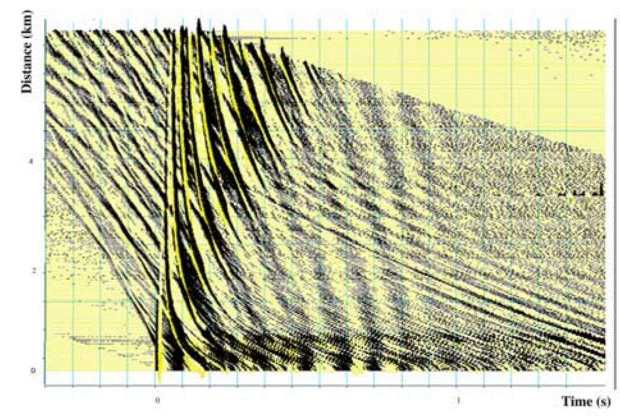

Fig 6: Time-distance section after V_1 velocity correction

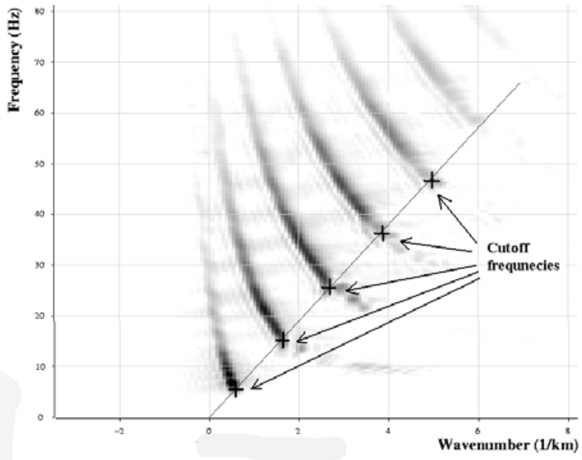

Fig. 7: $f-k$ transform of the real data section Fig. 6

We first use a small part of the entire section (Fig. 8) to determine V_2 thanks to the refracted wave velocity. A $f-k$ transform of the extracted section is made, we find using (3.1) V_2=1906 m/s.

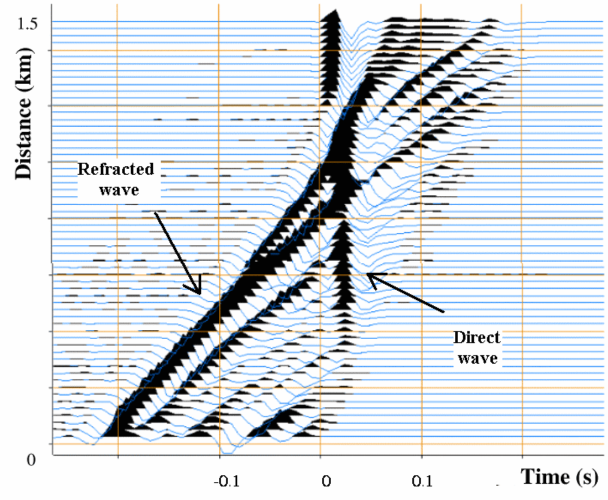

Fig 8: Direct and refracted waves

The other possibility to estimate V_2 is also used, Fig. 7 allows to find the asymptote slope and so to determine V_2=1876 m/s. Results are closed : estimations only differ from 1.6 % from one method to the other.

Then H_1 is estimated with (2.4). Cutoff frequencies of the different modes give several values for H_1.

Modes	1	2	3	4	5
Freq(Hz)	6.9	14.7	25.0	35.4	45.0
Depth (m)	94.1	132.4	129.8	128.3	129.8

We remove the first estimation of H_1 because estimation of f_{c1} is known with an uncertainty of 1 Hz which represents 20 % as f_{c1} is around 5 Hz. The estimated value of H_1 is then H_1=130.1 m

B. Application on simulated data

To validate methods presented in III., geoacoustical parameters are estimated on simulated data. The simulation algorithm uses a finite-difference method for modeling P-SV wave propagation in heterogeneous media. This time-distance algorithm, computed by Virieux [8], gives stable results for step velocity discontinuities, which is the case for a water layer above an elastic media. As a result, it is possible to simulate the real data presented in IV-A. The model used the previous estimated geoacoustical parameters V_{1_0}=1520 m/s, V_{2_0}=1825 m/s, H_{1_0}=140 m.

Our objective is to recover these simulated geoacoustical parameters using previous methods on the simulated data set and to compare results. Fig 9 and 10 present the time-distance and $f-k$ plots of the simulated data set.

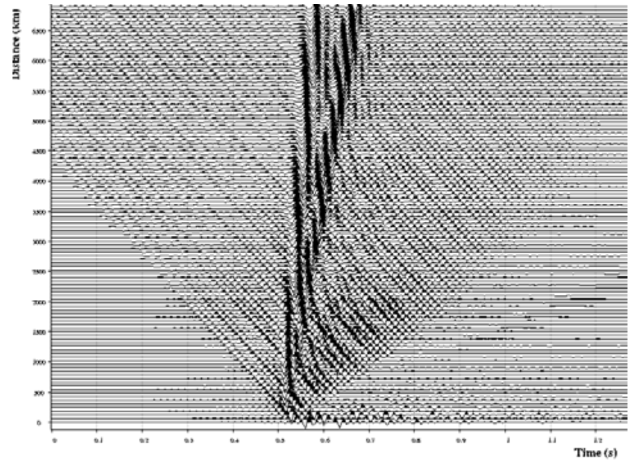

Fig. 9: Time-distance section after V_1 velocity correction

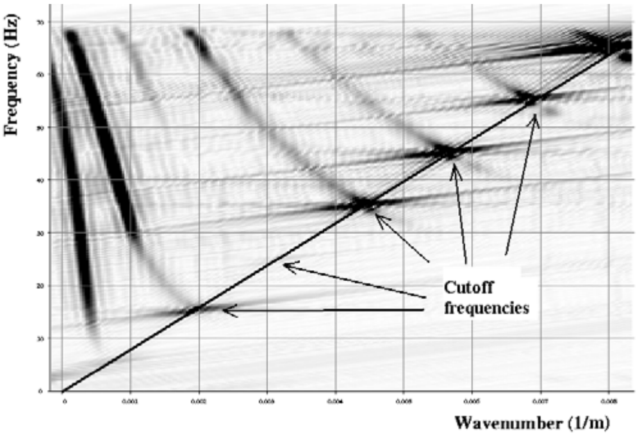

Fig. 10: $f-k$ transform of the simulated section Fig. 9

After processing, estimation of V_1 is measured at 1520 m/s. The second parameter to recover is the velocity of the second layer. This layer is often a water saturated sedimentary layer. Two methods (refracted and f-k asymptote characterization) are used to determine V_2.

- Refracted waves velocity: V_2=1884 m/s
- Asymptote in the f-k domain: V_2=1880 m/s

We observe that these two velocities are closed. In practise, second method is more realistic and easier than the first one. Finally, cutoff frequencies given by studying the $f-k$ representation allow an estimation of H_1 as it was done on real data.

Modes	1	2	3	4	5
Freq.(Hz)	5.5	15.3	25.3	35.6	45.1
Depth (m)	118.0	127.2	128.3	127.6	129.5

As it was done on real data, an average water depth is calculated: $H_1 = 128.1$ m. We can compare estimated values to values used to simulate.

$$V_1 = V_{1_0} + 0\%$$

$$V_2 = V_{2_0} + 0.5\%$$

$$H_1 = H_{1_0} + 1.4\%$$

To conclude, methods proposed in III., seem to be efficient to estimate geoacoustical parameters. The next step would be to try these methods on data with a boat source in order to detect and localize this source.

V. CONCLUSION

As underwater sources produce more and more low frequency signals (<100 Hz), underwater wave propagation is dependant of the substrata. In this frequency domain and in shallow water configuration, wave propagation is mainly described by guided waves. As this type of propagation is well studied in seismic, we illustrated that some specific methods can be adapted to underwater source detection based on Ultra Low Frequency waves.

Guided wave propagation has been briefly presented to explain propagation and information carried by these waves. We have shown that 4C-components sensors laid on the floor are valuable sensors : different transformations (frequency–wave number transformation, velocity correction) have been applied to estimate geoacoustical parameters on a real data set. To validate our result, a comparison between real data and simulated data (obtained by a finite-difference algorithm for modeling wave propagation in heterogeneous media) has been made. To extend this work and to prove definitively that ULF waves are suitable for detection, it will necessary to use real underwater sources (submarines, boats).

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