A COMPARISON BETWEEN EXPERIMENTS AND SIMULATION FOR SHALLOW WATER SHORT RANGE ACOUSTIC PROPAGATION

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Shallow waters acoustic propagation has been extensively studied in the last few years. Indeed, its understanding is of strong interest in a wide range of applications, from the impact on marine fauna to the modelling of harbour surveillance systems or sonar performance assessment. The issue is also a hot topic in standardization for the measurement of radiated sound levels from ships, at relatively short ranges. The study of shallow water environments is complex because of the interferences due to seafloor and sea surface reflections. On the one hand, different methods have already been developed to model the acoustic propagation, the most widespread being rays, normal modes, parabolic equations or wavenumber integration. These methods, based on different assumptions, can be applied to shallow water environments in some cases. On the other hand, an experimental campaign was done off the coasts of Brittany, in France, to measure the propagation between a source and a hydrophone placed at short distance in a shallow water environment. The transfer functions have been measured for a frequency range from 100 Hz to 10 kHz. The aim of this paper is to compare some of the numerical approaches to experimental data in the case of short range propagation. So far, such comparisons cannot easily be found in the literature. The comparison between the simulations and the experimental results shows good agreement in most of cases. A study to check the sensitivity of a range of input parameters such as water depth, water density or sound velocity in the sediment, is proposed using the Monte-Carlo method. Results for that case study show that shallow water acoustic propagation is more sensitive to geometrical parameters than material properties.

Keywords: underwater acoustics, shallow water, propagation.

1. Introduction

In the last decades, the anthropogenic activities in the oceans have dramatically increased, so that today underwater noise is a major concern. Indeed, noise can have an influence on marine fauna or on acoustic surveillance systems. That is why the investigation of the impact of man-made noise has become an active area of research. For instance, two European projects have recently assessed the influence of the marine traffic on the marine life in order to standardize the underwater noise measurement and give guidelines to reduce its impact [1].

This paper focuses more especially on shallow water acoustics, more adapted to model the coastal areas where human activities have also largely increased (growing traffic, number of offshore energy farms…). In shallow environments, acoustic propagation becomes more complex because of the multiple reflections on sea surface and sea bed, creating constructive or destructive interferences. This topic is largely addressed in a recent book by Katsnelson, Petnikov and Lynch [2]. In particular, the authors point out that it is difficult to know precisely the environmental parameters when modelling a problem. Heaney and Cox [3] used Monte-Carlo simulations to investigate the influence of several acoustic parameters on the acoustic field. More recently, Wang *et al.* [4] point out the variability of the results with regards to a number of input parameters. However, it is not possible through their study to evaluate which parameters have the biggest influence on the acoustic propagation in terms of uncertainties. In the present work, the authors focus on the short range acoustic propagation:

- The theoretical background on shallow water acoustics is briefly described in section 2, with an emphasis put on the assumptions of widespread underwater acoustic methods.
- Section 3 describes the experimental campaign.
- The experimental results are compared to the numerical predictions in section 4.
- In section 5, a sensitivity study is proposed with Monte-Carlo simulations to address the influence of the environment parameters on the acoustic propagation.
- Finally, conclusions are drawn in section 6.

2. Theoretical background on the calculation of shallow water acoustic propagation

The main goal when modelling underwater acoustic propagation is to predict the Transmission Loss (TL). Assuming that the acoustic propagative waves are plane waves, the TL can be defined from the far-field pressure p_0 artificially back-propagated at 1 m away from the source in a theoretical infinite and homogeneous environment, and from the pressure p at the calculation point, as defined in Eq. (1):

$$TL = 20 \log\left(\frac{p_0}{p}\right) \tag{1}$$

The main factors contributing to the TL are [5]:

- Geometrical divergence of the acoustical energy.
- Reflections on the bottom and on the surface. In a shallow environment, the reflections on the bottom and the surface create interferences that need to be taken into account when modelling the underwater acoustic propagation.
- Chemical absorption by the fluid, in particular at high frequencies. According to a model proposed by François and Garrison [5], the absorption coefficient is increasing with the frequency and is around 1 dB/km at 10 kHz. As only short range propagation is considered in the present study, this effect can be neglected.

Over the last decades, several methods have been developed to calculate the TL. Some of these methods can be used for shallow water acoustics, depending on their assumptions:

- **Ray theory:** One of the most natural and intuitive way of describing the acoustic propagation in a domain is to determine the pressure along rays. According to the Snell-Descartes' law, the solution can be written as an amplitude function multiplied by a phase function, supposing that the amplitude varies much slower than the phase. This assumption is verified only if the speed of sound is not varying too much with space, and particularly with the immersion. In shallow waters, it can be considered that variation of speed of sound is usually small in comparison with the changes due to the interfaces. However, still according to the geometrical acoustics assumption, the ray theory is only valid if the channel depth is large in comparison with the wavelength. For example, for a channel depth of 30 m, this criterion implies that the ray theory should not be used for frequencies below 500 Hz.
- **Normal modes theory:** In a shallow water channel, the acoustic propagation is guided by the bottom and sea surface. Modes appear in the vertical direction and can lead to constructive or destructive interferences. In this situation, it is considered that all the energy is trapped in the stationary waves of the waveguide, and the acoustical field can be expressed as a sum of modes. The main limit of this approach is that the number of modes, and consequently the calculation cost, increase with the frequency and the channel depth [5]. The normal modes theory naturally takes into account the physical phenomena

that occur in a waveguide and is thus particularly well adapted to the study of sound propagation in shallow water environments.

- **Parabolic equations:** As the Helmholtz equation cannot be analytically solved in an environment whose properties vary with the distance, the parabolic equations technique consists in looking for a solution written as the product of two functions: a function that varies slowly with the distance, and a function that accounts for the propagation in a given direction. It supposes that the environment varies slowly with distance, and that the distance should be large compared to the wavelength (far-field approximation). One of the main limits of this approach is that it is limited to small angles because of the paraxial approximations. However, this limitation can be avoided by using more accurate approximations such as Padé's [6].
- **Wavenumber integration:** The wavenumber integration is a numerical technique that consists in considering the field as the sum of two terms: the first one due to the source in an unbounded domain and a second one solution of the homogeneous wave equation [7]. It is based on the calculation of depth-dependent Green's functions and their integration by using a fast field technique. This method has first been developed for stratified media and is therefore also adapted for modelling shallow water environments. Compared to normal modes theory, it accounts for all energy, whether trapped or not, and does not depend on the process of finding normal modes. However, this method has high computational costs and is then preferred only for low frequency and low range calculations.

Regarding the assumptions and the computational costs for each of the four propagation methods, the sketch in Figure 1 summarizes the range and frequency domains where the methods are preferred for channel depths up to several dozens of meters. The wavenumber integration and normal modes are particularly adapted to shallow water environments, but are preferred in the low frequency range because of their computational costs. The ray theory is preferred at high frequency because of its assumptions. The parabolic equation can be used at lower frequencies than the ray theory. Unlike the other methods, the parabolic equation can deal with range dependent problems, *i.e.* problems where environmental parameters vary with the distance to the source.

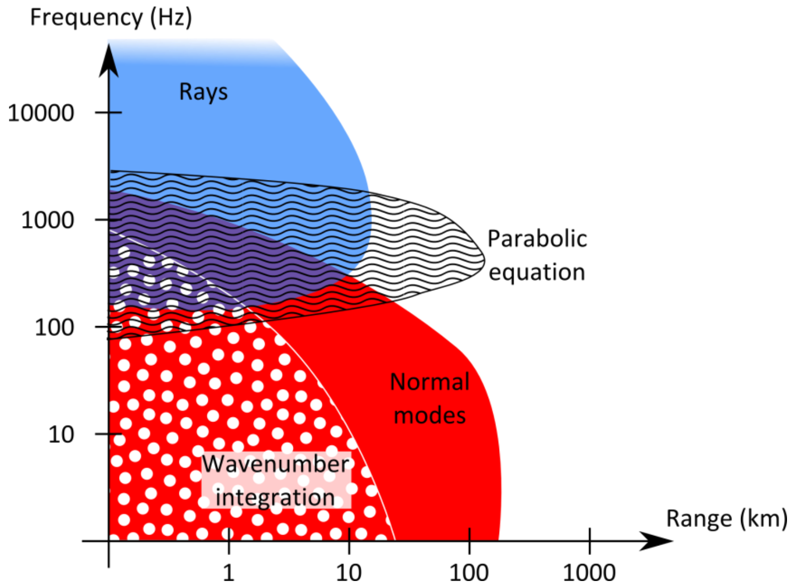


Figure 1: Sketch of the frequency and range domains for shallow water acoustic propagation models.

3. Description of the experimental campaign

A few years ago, a short-range underwater acoustics propagation experimental campaign was conducted in a shallow water environment off the coasts of Brittany, France [8]. Two hydrophones were placed in water: one just next to an acoustic source (considered collocated) and another at some distance, as shown on Figure 2. One peculiarity here is that we focus on short range propagation (about 40 m to compare with 30 m sea floor depth).

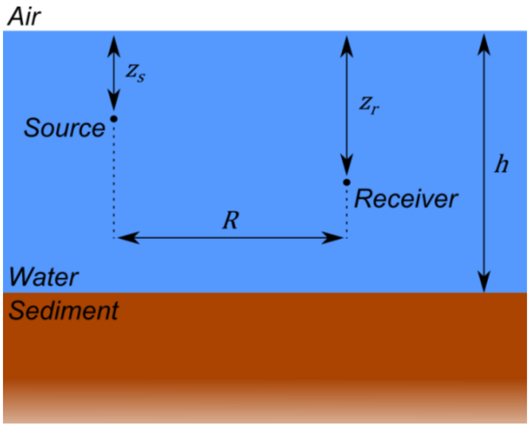


Figure 2: Sketch of the measurement configuration.

Three frequency bands have been measured separately:

1. low frequencies (LF): between 100 and 1500 Hz with a step of 5 Hz,
2. mid frequencies (MF): between 1500 and 4500 Hz with a step of 10 Hz,
3. high frequencies (HF): between 4500 Hz and 10000 Hz with a step of 20 Hz.

These three frequency bands have been investigated separately so that different acquisition systems, and more particularly different hydrophones, can be used in line with the frequency range. Along with the tidal variations, this explains why the geometrical parameters of the experimental setup slightly differ in the three configurations, as shown in Table 1.

Table 1: Geometrical parameters for the three configurations.

Parameter	Notation	Case		
		LF	MF	HF
Channel depth (m)	h	29	27	27
Source immersion (m)	z_s	14.6	13.85	12.2
Receiver immersion (m)	z_r	10.1	8.35	8.1
Range (m)	R	42.4	38.12	37.92

Because the channel is shallow, it is considered that the water density and the speed of sound in water are homogeneous in the channel [5]. The bottom is flat and assumed to be a semi-infinite space made of sediment. In the simulations, the sediment is often modelled as an equivalent fluid. The values presented in Table 2 are arbitrarily chosen, in accordance to usual values for water and sand.

Table 2: Water and sediment parameters.

Parameter	Notation	Value
Speed of sound in water	c_0	1500 m/s
Water density	ρ_0	1024 kg/m^3
Speed of sound in sediment	c_s	1749 m/s
Sediment density	ρ_s	1941 kg/m^3

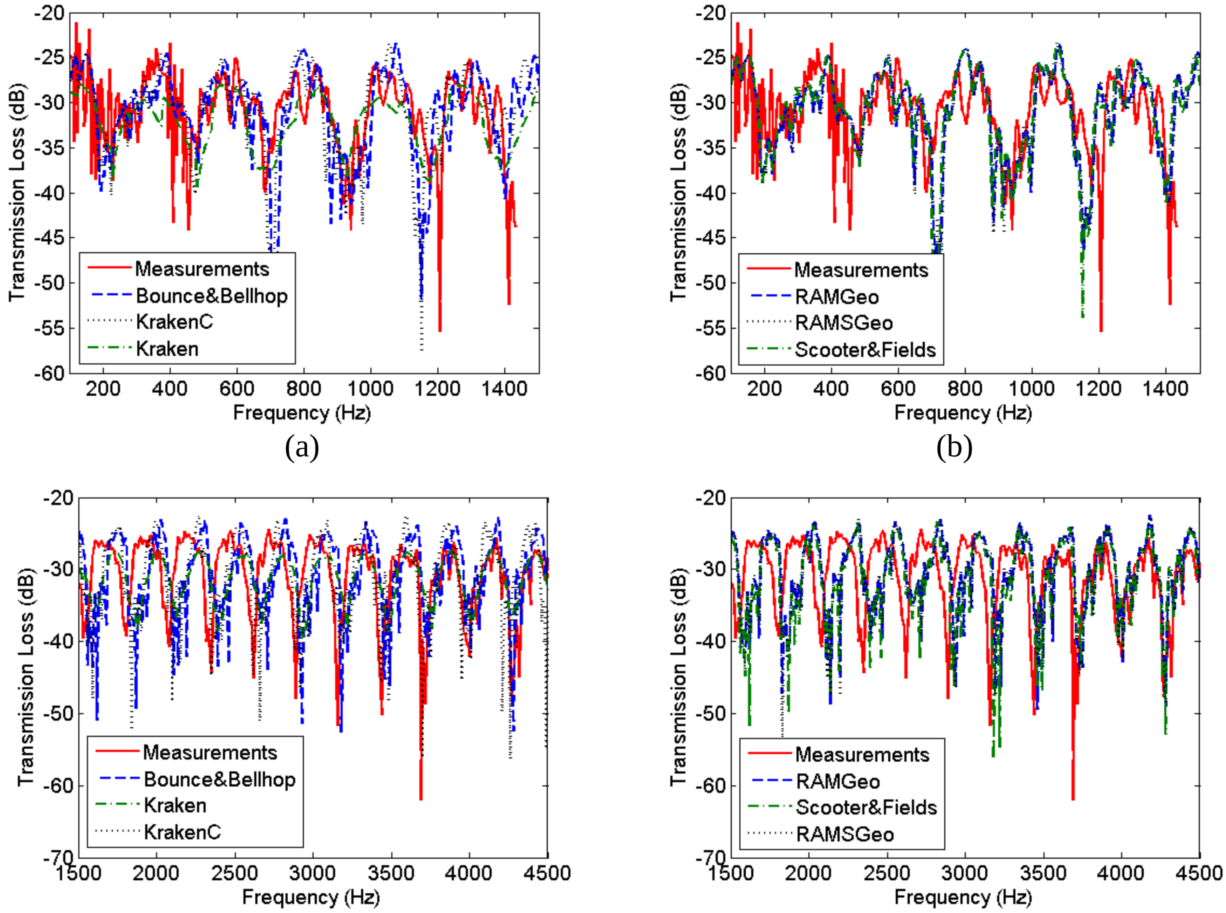
4. Results comparison

Underwater acoustic propagation loss is calculated for each configuration with AcTUP. AcTUP is an open-source Matlab toolbox developed by Duncan *et al.* [9], based on a variety of propagation codes freely available in the Ocean Acoustics Library [10]. Several propagation codes based on the methods described in section 2 are selected for the TL calculations, as seen in Table 3.

Table 3: Propagation codes used for shallow water acoustics simulation.

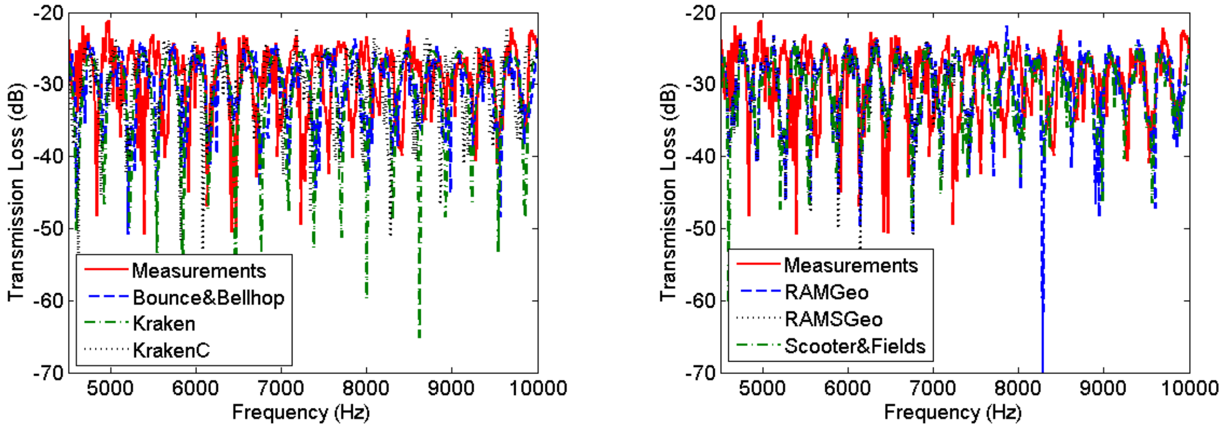
Name of the propagation code	Theoretical model
Bounce & Bellhop	Ray theory
Kraken	Normal modes theory
KrakenC	
RAMGeo	Parabolic equations
RAMSGeo	
Scooter & Fields	Wavenumber integration

The results are presented in Figure 3. The results for the low frequencies are presented in the top row, the middle frequencies in the middle row and the high frequencies at the bottom. For each configuration, the propagation codes are presented on two separated plots, to help the reader to see the different curves. The red solid lines are the results from the measurements. Generally, it can be said that all the propagation codes fit the experimental results quite well. It seems that Kraken performs a little bit worse than the other codes. This can be explained by the fact that Kraken uses only real modes, and cannot account for the energy that is not trapped in these waveguide modes. The effect of leaky modes is taken into account through the complex modes in KrakenC [11]. In general, the differences can also be due to uncertainties in the environmental parameters. A sensitivity study is proposed in the next section to evaluate their impact.



(a) (b)

(c) (d)



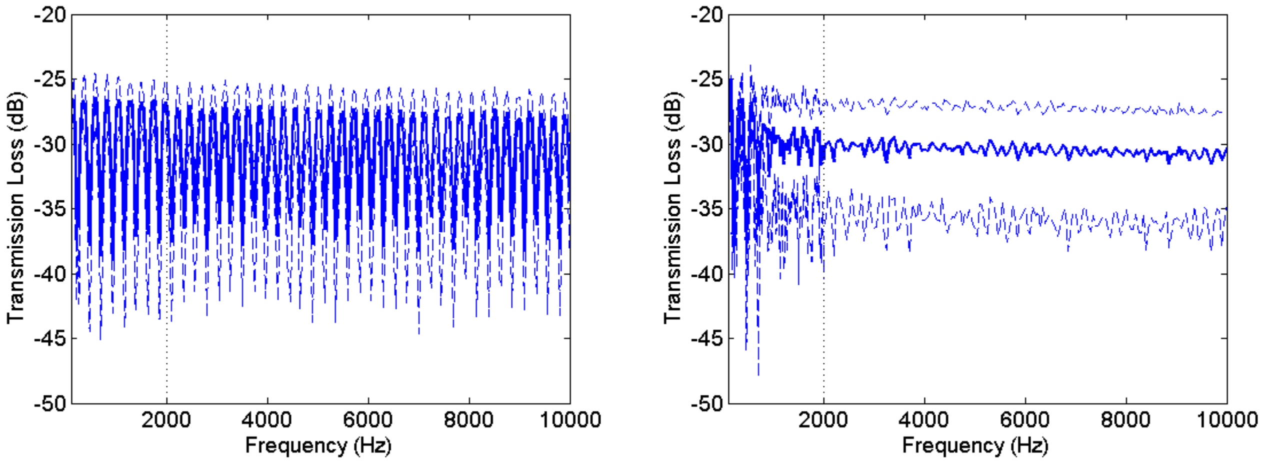
(e) (f)

Figure 3: Comparison between the Transmission Loss measured and predicted by underwater acoustics propagation tools. (a) and (b): LF. (c) and (d): MF. (e) and (f): HF.

5. Sensitivity to input parameters

For experimental campaigns at sea, it is almost impossible to know exactly all the environmental parameters required to model the acoustic propagation. In this section, we propose to look at the influence of each parameter separately. The 4 geometrical parameters for the low frequency case described in Table 1 and the 4 material parameters of Table 2 are taken as initial parameters. We run Monte Carlo simulations to vary these 8 parameters, according to a uniform distribution law within plus or minus 10% from the initial value. On each of the Monte Carlo simulations, only one of the 8 parameters varies. To achieve good statistical estimate within a reasonable time scale, 200 simulations are made for each case. According to Figure 1 and the results in section 4, KrakenC (complex modes theory) is used in the low frequency range (from 100 to 2000 Hz, with a step of 10 Hz) while Bounce&Bellhop (ray theory) is used in the higher frequency range (from 2 to 10 kHz with a step of 20 Hz).

The transmission loss modulus is plotted as a function of the frequency for each varying parameter in Figure 4. The solid thick line is the mean value over the 200 simulations and the dashed lines are the mean values plus or minus the standard deviation. The vertical dotted line shows the frequency limit between the range calculated with the normal modes and the range calculated with the ray theory. It can be seen that the two calculations meet correctly at 2000 Hz.



(a) (b)

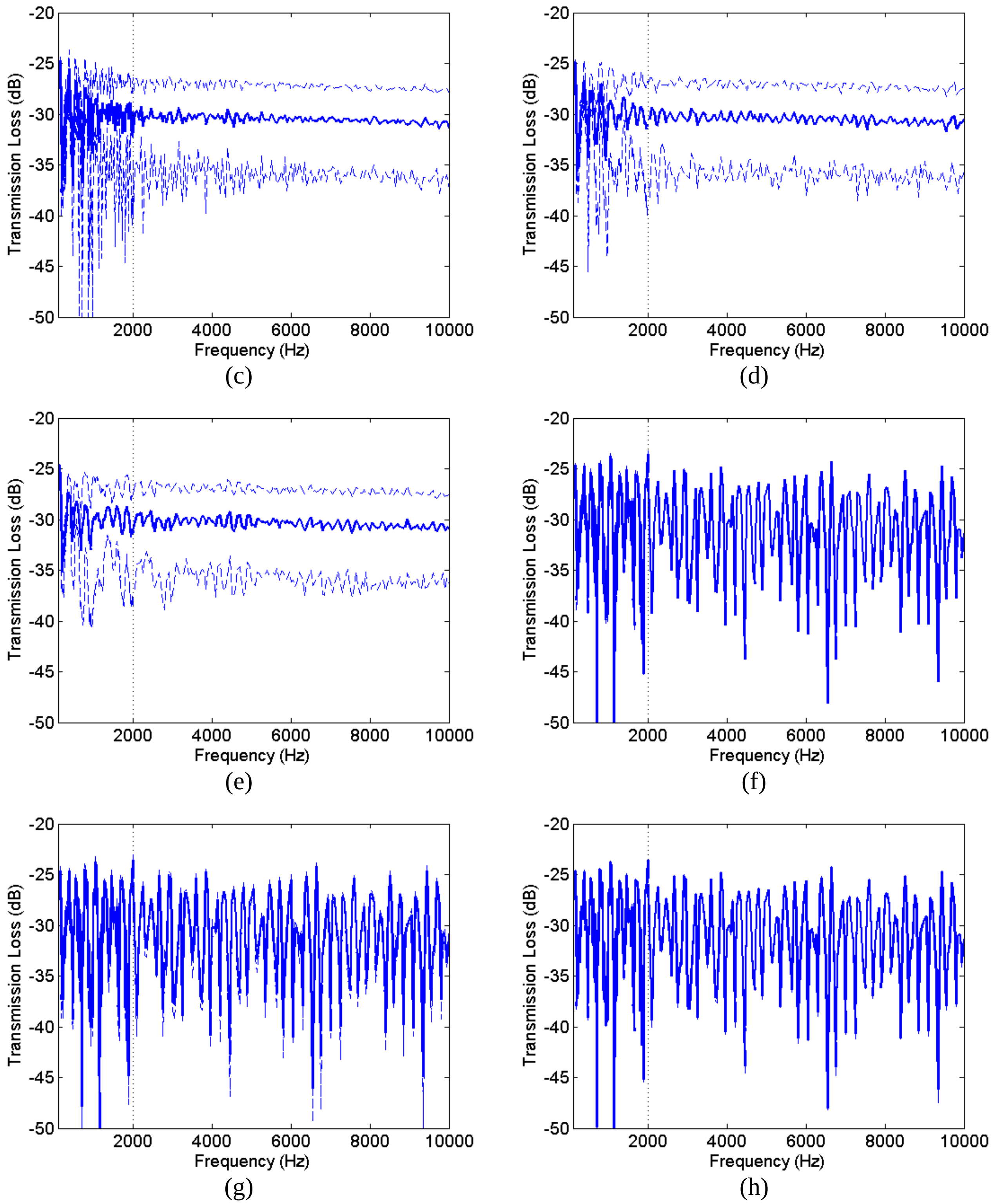


Figure 4: Senitivity of the TL with regards to the input parameter: (a) Channel depth, (b) Source immersion, (c) Receiver immersion, (d) Range, (e) Speed of sound in water, (f) Water density, (g) Speed of sound in sediment, (h) Sediment density.

From the plots in Figure 4 it can be said that the geometrical parameters, in particular the source immersion, the receiver immersion and the range between the source and the receiver have a big influence on the TL results, with standard deviation of about 5 dB. It can be seen that the uncertainties on the speed of sound in water have also a big impact on the results. However, the speed of sound in water can today be determined precisely, with uncertainties usually lower than 0.1 m/s, which is less than 0.01 % of the reference value. A variation of 10% on the water density, the speed of sound in sediment and the sediment density has a weak influence on the results. The parameters for mud or rocks being within the 10% range around the sand parameters, it can thus be said that it is not necessary to determine precisely the seabed characteristics in this case. To sum up, this sensitivity study shows that it is important for a shallow water and short range configuration to have a good knowledge of the geometrical parameters.

6. Conclusions

Underwater acoustic propagation has been studied for shallow water environments in the particular case of short range, which is a problem of interest for assessing the impact of sound on marine life in local protected areas, or for the measurement of radiated noise from silent underwater vehicles in shallow waters. For the purpose of the study, some open-source propagation codes have been used, and the numerical results were compared to experimental results for short range propagation, showing good agreement. A sensitivity study was conducted using the complex normal modes at low frequency and the ray theory at high frequency. High sensitivity to geometric parameters can be seen, while the results vary less with the sediment and water properties. This result is of importance for measurements campaign, knowing that attention should be paid on the determination of the geometrical parameters (source and receiver positions), whereas a rough estimation of the sediment parameters and the water density are sufficient to obtain satisfying results.

REFERENCES

1 AQUO-SONIC, *Guidelines for regulation on UW noise from commercial shipping*, 30 November 2015

2 B. Katsnelson, V. Petnikov, and J. Lynch. Fundamentals of shallow water acoustics. Springer Science & Business Media, 2012

3 K. D. Heaney and H. Cox. A tactical approach to environmental uncertainty and sensitivity. IEEE Journal of Oceanic Engineering 31(2):356-367, 2006.

4 L. Wang, S. Robinson and P. Theobald. Calculation of ship source level in shallow water by propagation modelling. *Proceedings of Inter-Noise 2016*, Hamburg, Germany, 2016

5 X. Lurton, *An Introduction to Underwater Acoustics: Principles and Applications*, *Chapter 2*, Spring-Verlag Berlin Heidelberg, 2010.

6 M. D. Collins, A split-step Padé Solution for the parabolic equation method. *The Journal of the Acoustical Society of America*, 93(4):1736-1742, 1993.

7 H. Schmidt and F. B. Jensen, A full wave solution for propagation in multi-layered viscoelastic media with application to Gaussian beam reflection at fluid-solid interfaces, *The Journal of the Acoustical Society of America*, 77(3):813-825, 1985.

8 C. Alzir and P. Marin-Curtoud, Determination of a correction factor for radiated noise measurement in shallow waters, *Proceedings of Undersea Defence Technology*, Hamburg, Germany, 27-29 June 2006.

9 A. J. Duncan and A. L. Maggi, A consistent, user friendly interface for unning a variety of underwater acoustic propagation codes, *Proceedings of Acoustics 2006*, Christchurch, New Zealand, 2006.

10 http://oalib.hlsresearch.com/

11 A. L. Maggi and A. J. Duncan, *AcTUP v2.2lα, Installation & User Guide*, Centre for Marine Science & Technology, Curtin University of Technology, Australia.