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TRACEO3D Ray Tracing Model for Underwater Noise Predictions

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Abstract. Shipping noise is the main source of underwater noise raising concern among environmental protection organizations and the scientific community. Monitoring of noise generated by shipping traffic is a difficult challenge within the context of smart systems and solutions based on acoustic modeling are being progressively adopted to overcome it. A module of sound propagation stands as a key point for the development of a smart monitoring system since it can be used for the calculation of acoustic pressure, which can be combined with estimates of the source pressure level to produce noise predictions. This paper addresses the usage of the TRACEO3D model for application in such systems; the model validity is addressed through comparisons with results from an analytical solution and from a scale tank experiment. The comparisons show that the model is able to predict accurately the reference data, while a full-field model (normal mode-based, but adiabatic) is only accurate till a certain degree. The results show that TRACEO3D is robust enough to be used efficiently for predictions of sound propagation, to be included as a part of a smart system for underwater noise predictions.

Keywords: Shipping noise, monitoring, Underwater acoustic, Ray tracing, Smart systems

1 Introduction

Shipping noise is the main source of underwater noise raising concern among environmental protection organizations and the scientific community. Shipping noise can propagate at long distances (like tens or hundreds of kilometers), thus having the potential to mask and/or disturb biological relevant sounds, such as those vocalized by marine animals for mating, orientation or detection of prays and predators. Monitoring of shipping noise is a difficult challenge due to many factors like, for instance, lack of equipment standardization and the large extensions to be covered (as a reference, the Portuguese EEZ itself has an area of about 1,7 million km2). Recently, the Marine Strategy Framework Directive [1] proposed the adoption of shipping noise modeling to overcome such difficulties. Generally speaking, realistic estimates of noise require transmissions loss (TL) predictions in coastal zones with a complex bathymetry and/or a complex sound speed distribution. To ease the computation load of the predictions they can be based on the adiabatic coupling of modes and/or the so-called N × 2D modeling, in which the three-dimensional field is constructed using N slices of predictions on a vertical plane, produced with a two-dimensional model. A shipping noise prediction tool based on this approximation, combined with data from an Automatic Identification System (AIS), is discussed in [2] and shows that the system is able to produce relevant estimates of shipping coastal traffic. However, it is well known that even in the simplest case a three-dimensional bathymetry, either by itself or combined with a sound speed field, can induce propagation not confined to a given slice, an effect known as out-of-plane propagation. Modeling of acoustic fields in three-dimensional waveguides, accounting for out-of-plane propagation, had been an active field of research for many years [3,4,5]. In this context the wedge problem has been an important reference given the availability of an analytical solution [6,7,8]. Despite the apparent simplicity of the wedge problem the corresponding analytical solution has revealed many interesting features of three-dimensional propagation, such as horizontal refraction, mode coupling and rays propagating up-slope before connecting a source to a receiver. Recent evidence from tank scale experiments fully supports the analytical predictions [9].

Of interest for the topics discussed here is the TRACEO3D ray tracing model, which is able to predict fields of acoustic pressure and particle velocity in environments with elaborate boundaries; the model is under current development at the Signal Processing Laboratory (SiPLAB) of the University of Algarve. This paper looks forward for a robust module of sound propagation for noise predictions, through the comparisons of TRACEO3D predictions with results from an analytical solution of the wedge problem, and with results from a scale tank experiment [5]; both cases are considered to provide a robust reference to test the model's accuracy. The comparisons show that the model is able to predict accurately the reference data, while adiabatic coupling is only valid for a small wedge.

The remainder of this paper is organized as follows: Section 2 identifies the relationship of this work to the issue of Technological Innovation for Smart Systems; Section 3 compactly describes the TRACEO3D model; Section 4 provides a brief description of the analytical solution for the wedge problem, and of the scale tank experiment; Section 5 discusses the comparisons; Section 6 presents the conclusions and future work.

2 Relationship to Smart Systems

Generally speaking, Smart Systems are technologies able to combine data processing with sensing, data exploration and communication, and capable to analyze complex situations in order to take autonomous decisions. Although the availability of sensors is increasing in terms of accuracy and specificity (thus providing a better adaptation to the system objectives) the capability to develop predictions simultaneously with the acquisition of data improves the ability of a given Smart System to deal with real word (mostly unpredictable) situations. Of particular importance for the system is to rely on environmental knowledge to compensate for a given lack of information, or to proceed to a given task given a certain type of previous information. For the specific conditions of underwater acoustics a fundamental component of the Smart System should be a module for predictions of sound propagation, which can be further processed in order for the Smart System to proceed accordingly. Particular examples of such modules can be found in the literature for the case of underwater noise monitoring [2], underwater communications [10] and source tracking [11].

3 The TRACEO3D Ray Tracing Model

The TRACEO3D model is a recent three-dimensional extension of the TRACEO ray model [12,13]. Generally speaking, TRACEO3D produces a prediction of the acoustic field in two steps: first, the Eikonal equation is solved in order to provide ray trajectories; second, ray trajectories are considered as the central axes of Gaussian beams, and the acoustic field is calculated as the coherent superposition of beam influences. The model can take into account the environmental variability in range, depth and azimuth.

4 The Wedge Problem

The general geometry of the wedge problem is shown in Fig. 1, with the wedge apex aligned along the Y axis; in the given geometry α stands for the wedge angle, and the source is located at the position (0, 0, zS). Propagation along the positive/negative X axis is known as downslope/upslope propagation, respectively, while propagation along the Y axis is known as cross-slope propagation. Two-dimensional acoustic models can be used to predict accurately upslope and downslope propagation and the models accuracy had been properly confirmed through comparisons with experimental data. Cross-slope propagation on the other side leads to out-of-plane effects and requires a three-dimensional model.

4.1 The Analytical Solution

A detailed description of the analytical solution can be found in [6,7,8]. Overall, the solution is based on the method of images, where the contribution of each image can be represented in terms of a Bessel function expansion inside an improper integral; numerical implementation of the solution is generally intensive because the convergence of the series is slow, and worsens when small α are considered; in this case the image solution can be replaced with the much faster adiabatic-mode solution. The limits of validity of the adiabatic solution still remain a topic of intense discussion.

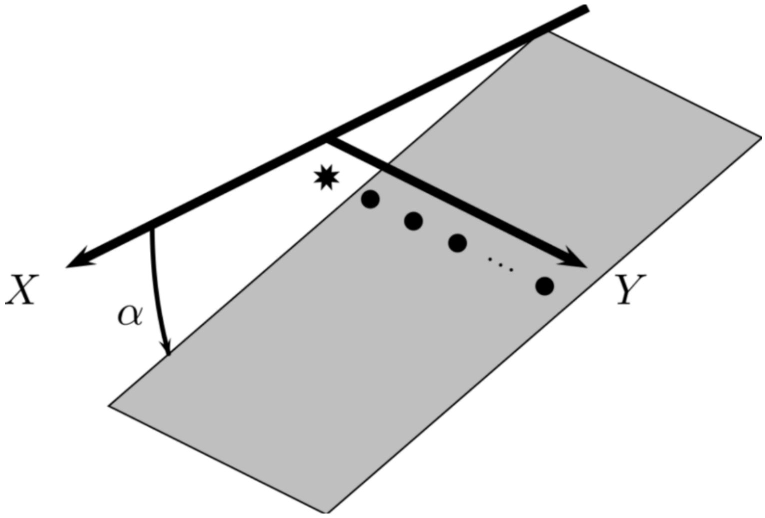


Fig. 1. Geometry of the wedge problem; the star indicates the source position; the dots indicate an array in the cross-slope direction.

4.2 The Scale Tank Experiment

The experimental data was obtained from an indoor shallow-water tank of the LMA-CNRS laboratory in Marseille. The tank experiment is described in detail in [5,14], therefore a compact description is presented in this section. The inner tank dimensions were 10 m long, 3 m wide and 1 m depth. The source and the receiver were both aligned along the across-slope direction, as shown in Fig. 2. The bottom was filled with sand and a rake was used to produce a slope angle $\alpha \approx 4.5°$; sound speed in the water was considered constant and corresponded to 1488.2 m/s. The bottom parameters corresponded to $c_P = 1655$ m/s, $\rho = 1.99$ g/cm^3 and $\alpha_p = 0.5$ dB/λ. The source was located at 8.3 mm depth and bottom depth at the source position corresponded to 44.4 mm. The ASP-H (for horizontal measurements of across-slope propagation) data set was composed of time signals recorded at a fixed receiver depth and at several source/receiver distances starting from r = 0.1 m until r = 5 m in increments of 0.005 m, providing a sufficiently fine representation of the acoustic field in range. Three different receiver depths were considered, namely 10 mm, 19 mm and 26.9 mm, corresponding to data subsets referenced as ASP-H1, ASP-H2 and ASP-H3, respectively. Acoustic transmissions were performed for a wide range of frequencies; however, comparisons are presented only for data from the ASP-H1 subset with the highest frequency (180.05 kHz); this is due to the fact that the higher the frequency the better the ray prediction. It is important to remark that a scale factor of 1000:1 is required to properly modify the frequencies and lengths of the experimental configuration; that implies that the following conversion of units is adopted: experimental frequencies in kHz become model frequencies in Hz, and experimental lengths in mm become model lengths in m; for instance, an experimental frequency of 180.05 kHz becomes a model frequency of 180.05 Hz, and an experimental distance of 10 mm becomes a model distance of 10 m. Sound speed remains unchanged, as well as compressional and shear attenuations.

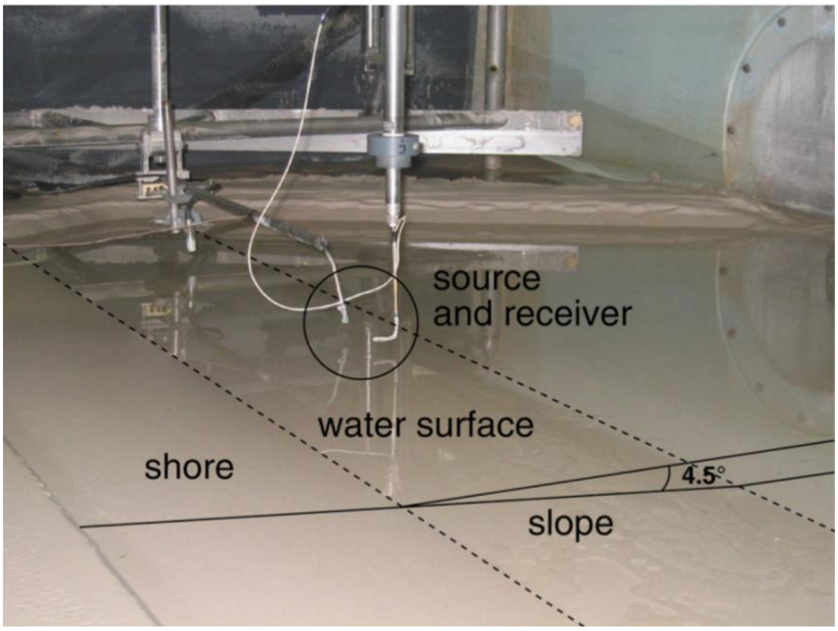


Fig. 2. Indoor shallow-water tank of the LMA-CNRS laboratory of Marseille (from[5]).

5 Comparisons

The TRACEO3D and KRAKEN models were used to perform TL predictions, which were compared with results from the analytical wedge solution and with measurements from the scale tank experiment. The KRAKEN model is based on normal mode theory [15]; as in the case of TRACEO3D, KRAKEN 3D calculations can be done in two steps: first, modes can be calculated on a two-dimensional grid; second, modes can be coupled along different directions over the grid to produce a 3D prediction. For smooth bathymetries one-to-one exchange of modal energy (i.e. adiabatic coupling) can provide accurate and computationally efficient 3D predictions.

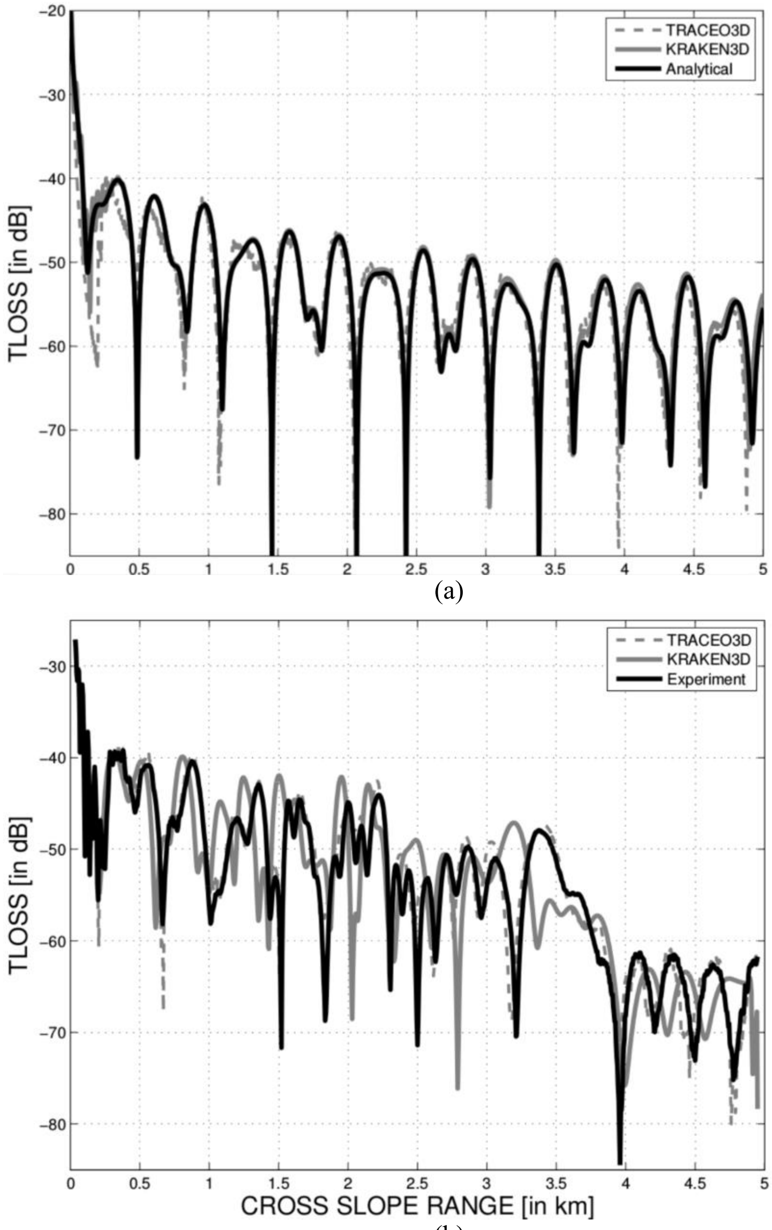
Waveguide parameters for the analytical solution and for the experimental data are shown in Table 1; it is important to remark the difference in frequencies: for the analytical case the frequency is much lower than for the experimental data; such low value of frequency is important to test whether the ray approximation can be still valid for the parameters of the analytical solution. Comparisons for the analytical solution and for the experimental data are shown in Fig. 3. In Fig. 3(a) one case see clearly that the two models produce accurate predictions, although KRAKEN's prediction is smoother, a fact that can be attributed to the low value of frequency. On the other hand, in Fig. 3(b) KRAKEN's prediction is only accurate at the initial ranges, and quickly starts to diverge due to the failure of the adiabatic prediction to account for the exchange of energy between modes of different orders. TRACEO3D on the other side is able to produce an accurate prediction in both amplitude and phase along the entire cross-slope range, thus showing the capability of the model to deal with an arbitrary wedge slope.

Table 1. Parameters for the wedge problem.

Parameters	Units	Analytical solution	Scale tank experiment
α	°	0.5	4.5
Frequency	Hz	50	180.05
Sound speed	m/s	1500	1488.7
Source depth	m	10	8.3
Depth at source position	m	90	44.4
Bottom compressional speed	m/s	2000	1700
Bottom compressional density	kg/m^3	2	1.99
Bottom compressional attenuation	dB/λ	0.5	0.5

6 Conclusions

The discussion presented in the previous sections demonstrated the feasibility of using TRACEO3D as a module of sound propagation for noise predictions, through the comparisons with results from an analytical solution of the wedge problem and measurements from a scale tank experiment. The comparisons show that the model is able to predict the reference data, while adiabatic coupling is only valid for a small wedge. Despite the low frequency limitation, typical of ray theory, TRACEO3D was able to provide an accurate prediction for the analytical (low-frequency) case. The results also indicate that TRACEO3D can be able to deal with arbitrary bathymetries, a feature of fundamental importance for the development of a Smart System for the monitoring of shipping noise. Future work will be dedicated to optimize the current version through parallel computing, allowing decreasing the computational time, and enabling the model to provide fast predictions in an environment with a fine grid. Further improvements will also look for efficient solutions of 3D eigenrays search and fast 3D calculations of particle velocity.



(a)

(b)

Fig. 3. Comparisons for the (a) analytical solution and (b) experimental results.

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