Scaled Laboratory Experiments of Shallow Water Acoustic Propagation

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Laboratory experiments in underwater acoustics aim at the validation of theoretical acoustic propagation models in well controlled environments. Most of the experiments that have been conducted so far are related to local transmission-reflection phenomena which are encountered in problems of bottom reflectivity and bottom or material recognition. The experimental tank at the Laboratoire de Mecanique et d' Acoustique in Marseilles, provides an ideal environment for testing long range propagation codes. The tank is relatively long and the water depth is adjustable in order to simulate real propagation experiments in environments of variable depths. The purpose of this paper is to describe the experimental procedure for the realization of a long range propagation experiment in the tank using sources of appropriate frequency. The water bottom is simulated, using real sand with well known properties. The measured signals are processed to provide the acoustic field at various depths and ranges in the tank in dB units, and are compared with theoretical models based on normal-mode theory. The comparison in the cases studied, which corresponded to shallow water transmissions are encouraging. Technological problems and scaling factors are also discussed.

1 Introduction

Laboratory experiments for testing theoretical models of long-range ocean acoustic field predictions are not easy to be performed, in comparison with experiments aiming at the study of local reflectivity phenomena, due to the fact that the simulation of a long range environment in scale, should be done with great care to ensure that the geometry of the experiment corresponds to the theoretical considerations especially in what concerns boundary location and conditions as well as source and receiver location. Most of the models providing the sound field at long ranges in water are based on an axially symmetric environment. Thus, an experiment performed in a tank should ensure that no unwanted reflections from the walls are measured. To this end, wide and long tanks should be available. On the other hand, the structure simulating the bottom should be such that any assumptions adopted in the computer code should be well represented in the tank. Moreover, accurate calibration is needed as the experiments represent real-world experiments in scale. As the sound field in the sea is highly variable, even small errors in the geometry considered in the water tank or the operational parameters used in the computer code, may lead in high discrepancies between measured and estimated data, thus rendering validation of methods not possible.

Another difficulty in the performance of the tank experiments is the scaling factor relating tank to real experiment, which cannot be applied to all of the parameters of the tank experiment. Thus a one-to-one correspondence cannot be obtained. On the other hand, the validation of acoustic propagation models is still possible as the theoretical model can be applied in any case to the actual parameters of the tank experiment.

Tank experiments for underwater long-range propagation simulation have been performed successfully in the past [1]. The objective of the work performed here is to provide a follow-up of the experiments described in [1], using another tank facility of the same Laboratory and different source/receiver instrumentation taken from the “shelf”. Using conclusions derived from the present and previous tests, typical operational conditions and instructions for the performance of similar tests is expected to be defined in order to set-up the standards for the conduction of tank experiments aiming at the validation of long-range propagation codes.

2 Experimental Set-Up

2.1 Description of the experimental facility

The experiment was realized in the facilities of the Laboratoire de Mechanique et d’ Acoustique (LMA) in Marseille. The tank used is constructed by cement and it is 20 meters long, 3 meters wide and 1 m in depth (Figure 1). Water can be poured to a specified height to simulate the ocean water column. For the needs of the experiment the actual water column height was a little more than 5 cm. To simulate the ocean bottom, at the floor of the tank a layer of sand was deposited of a thickness of 60cm.

The tank is equipped with a system of mechanical beams moving on rails. Adjustable arms were attached on these beams, capable of carrying transducers and additional equipment. The whole system was computer controlled, thus giving great flexibility in changing the configuration of the experiments. Finally a rake was attached to the beams to ensure the flatness of the simulated water-bottom interface (Figure 2).

2.2 Instrumentation

Two small transducers with broad sensitivity in the few hundreds kHz range were used as both source and the receiver (Figure 3). Both were attached to the moving arms. Thus, the receiver could be moved independently from the source, both horizontally (in range) and vertically (in depth).

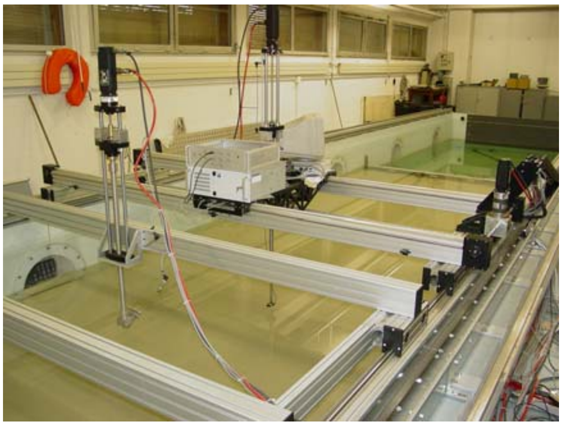


Figure 1: The experimental tank of the LMA.

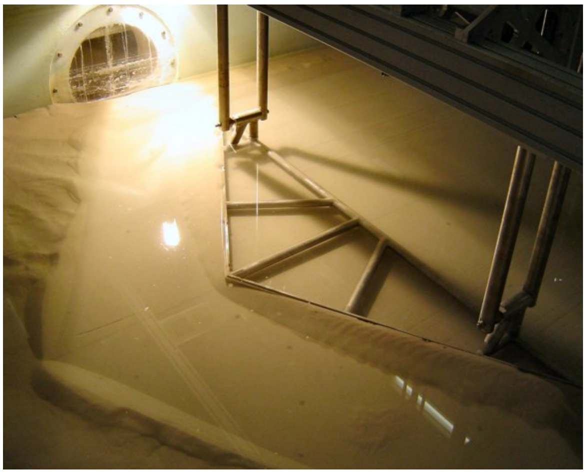


Figure 2: The rake of the tank

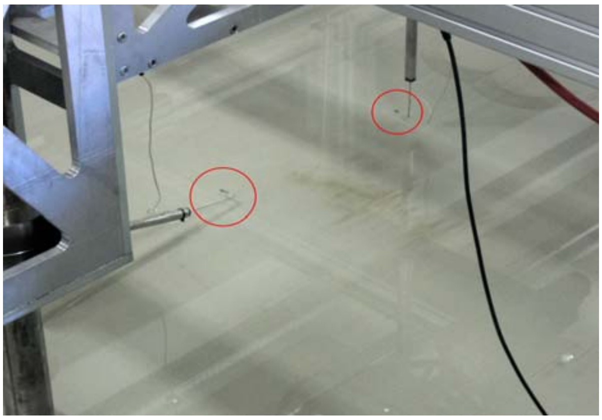


Figure 3: The source and receiver transducers. They are indicated by red circles.

A continuous sine wave at 124 kHz was produced by a wave generator device and the received signal was recorded by a data acquisition card at the computer. The emission and reception procedure were continuously monitored by means of an oscilloscope.

2.3 Experimental configuration

The design of the experiment was such that a 1:1000 scale factor was anticipated. Taking into account that the frequency of the signal was 124 kHz, the corresponding real experiment was associated with a source of 124 Hz. Note that the frequency of 124 kHz is considered "low" for tank experiments due to the fact that it is very difficult to manufacture very small transducers working at lower frequencies. The frequency of the simulated experiment is also considered "low". In order to simulate a shallow water experiment, the depth of the water column in the tank was decided to be of the order of 5 cm so that a real water depth around 50 m is considered. It was finally measured to 5.52 cm corresponding to an actual water depth of 55.2 m. The maximum range used in the tank was 5 m to simulate a real range of 5000 m.

2.4 Calibration

Initial measurements were carried out in order to specify the geometrical and physical parameters of the experiment. In particular the following parameters were measured:

- *The flatness of the sea floor*. The rake was used to level the sand in the tank in order to ensure a horizontal floor.
- *The depth of the water*. Using a high frequency transducer placed in the water

column at an arbitrary position, the depth of the water column was measured using travel time measurements of a signal transmitted vertically. Reflections from both the bottom and the surface were used. The time was measured in μsec with an accuracy of one decimal point. The sound speed used for the conversion of the time to distance was calculated on the basis of the water temperature which was continuously measured. Throughout the experiment the temperature was 16.27 ±0.01 ºC corresponding to a sound speed of 1470.3 ± 0.05 m/sec The calculated water depth was 5.52 cm with an error margin of ±0.1 mm

- *The operating depth of both the source and the receiver*. The position in depth of both transducers was determined electronically by means of the control device of the tank beams moving system, after prediction of the 0 depth which was done using the following procedure: The transducer was put at certain depth and then it was slowly raised until the transducer was exactly at the surface. This position corresponds to the actual 0 of the depth position. The touch of the surface was difficult to be observed with naked eye or any other direct observation method, so a zoomed picture of the instrument from a digital camera was used as in Figure 4. This procedure ensures that relative positions of source and receiver are determined by a very good accuracy, however it is evident that a more elaborate procedure is needed in order to obtain the absolute position of source and receiver with the maximum possible accuracy.
- *The parameters of the bottom*. The bottom was made by sand deposited a few days before the experiment to ensure that good consolidation is obtained. Density and sound speed in the bottom was determined by laboratory measurements and was set to 1977 kg/m^3 and 1710 m/sec correspondingly. No shear speed was considered, thus the bottom was treated as fluid medium. The attenuation was adjusted later and was based on a best fit between measurements and theoretical calculations. The value of 0.5 dB/λ was observed to give good match.

Figure 4. Optical observation for the calibration of the zero level in the measurement of the depth.

3 Propagation Model

For the comparison of the measured acoustic field with theoretical predictions, the programme MODE4 [2] based on a Normal Mode representation of the acoustic field in range-dependent axially symmetric environments has been used, using the expression

$$p(r,z)=\sum_{n=1}^{N} A_n H_0^{(1)}(\kappa_n r)u_n(z)u_n(z_0) \qquad (1)$$

where,

$p(r,z)$ is the acoustic pressure

$u_n(z)$ is the eigenfunction of order n

κ_n is the associated eigenvalue

z_0 is the source depth and

A_n is the normalization constant.

In our case, we have used an environment consisting of a single water layer of constant speed over a fluid half-space. For this case we know that the spectrum of the eigenvalues consists of a discrete plus a continuous spectrum [3] and we have kept only the discrete one, thus keeping in the sum the propagating modes only. This is known to be a very good approximation for long range propagation cases.

The programme provides the Transmission Loss (TL) as a function of range end depth for a specified number of frequencies.

$$TL=-20\log\frac{|p(r,z)|}{|p_{ref}|} \qquad (2)$$

where p_{ref} is a reference pressure. The TL calculated by the programme is referred to a distance of one meter from the sound source.

It should be noted that attenuation in the bottom for a signal of high frequency as the one used in the experiment is very high, thus ensuring that no reflections from the actual tank bottom is expected. Therefore the treatment of the sea-bed in the model as a semi-infinite medium is well justified.

4 Results

4.1 Signal Processing

A CW signal was continuously transmitted, but it was recorded for a short time after the receiver was reached its specified range and/or depth. Range steps every 1 cm or depth steps every 1 mm were considered as described in section 4.2. The measured signals contained several periods of the CW signal (Figure 5). The recorded signals were Fourier Transformed to obtain their spectrum in the frequency domain. Taking the magnitude of the transformed version of the signal at the frequency of 124 kHz, we get at each range and depth the field corresponding to $|p(r,z)|$ of equation (2).

4.2 Computer simulation

Following the geometrical characteristics of the tank, and the operational properties of the experiment, the MODE4 code has used the following data in its input.

Water depth: 5.52 cm

Sound speed in water: 1470.3 m/sec

Sound velocity in the bottom: 1710 m/sec

Density of the bottom: 1977 kg/m^3

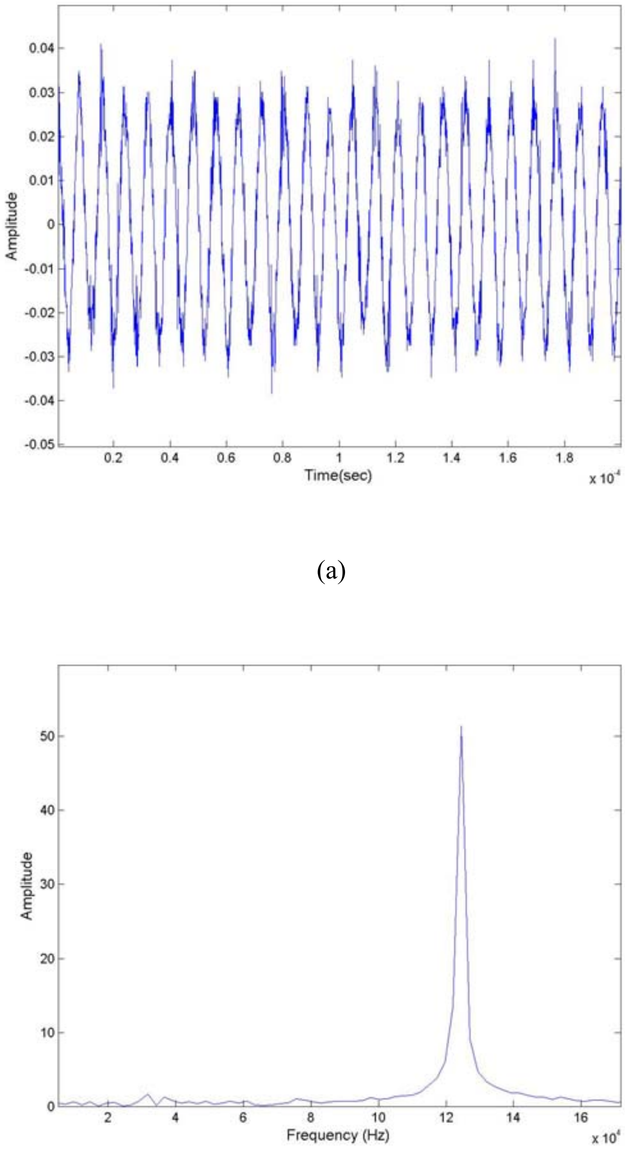
Attenuation in the bottom: 0.5 dB/λ

The sound source has been placed at various depths in the water.

Two sets of measurements have been carried out. First set corresponds to measurements made every 1 mm in depth for the ranges of 4 and 5 m. for each source position. A separate measurement was made for source and receiver depths both at 2.5 cm at range steps of 1 cm.

The TL calculated using the MODE4 code is to be comparable with results obtained by signal processing. According to theory, the TL given in MODE4 corresponds to a reference field in the range of 1 m. In order to be as close as possible to the situation to be encountered in the full scale of the simulated tank experiments, it was decided that the reference range in the calculations should be 1 cm. Due to the spherical propagation considered for the reference field, a correction factor of 40 dB has been applied in the results of MODE4.

As measurement of the reference field in the real experiment (distance 1 cm from the source) was not possible the TL of the measured field was calculated



(a)

(b)

Figure 5 An example of the measured signal (a) and its spectrum (b).

by adjusting the levels of $\log\left|p(r,z)\right|$ to get the best fit at a single experiment. It was easily observed that the adjustment was the same in all the experiments performed, thus confirming the reliability of the method suggested.

4.3 Comparison

We present here figures illustrating the comparison of measured vs. simulated TL for some characteristic sets of experiments. Figure 6 corresponds to measurements of the field as a function of depth at the range of 4 m from the source. Source depth was 2.5 cm. Note that we have not included measurements made at the water surface. Figure 7 corresponds to measurements made in range for source and receiver positions set at 2.5 cm depth. They are both typical examples of the data vs. calculations curves obtained for the various configurations considered.

For the frequency of 124 kHz, 5 propagating modes are present in the waveguide. Therefore a multi-mode structure of the sound speed is expected and actually illustrated by simulations.

It is easily seen that a relatively good comparison between measured and simulated results does exist in all cases, thus confirming that the specific multi-mode structure is well represented. Of course calculated and predicted sound fields do not exactly coincide. This observation led to an attempt of adjusting the parameters of the environment considered in the simulation and which were difficult to be directly controlled or determined (bottom density, bottom sound speed and attenuation). However there was no substantial improvement of the calculated results, which confirmed that the discrepancies were not due to the input data.

After some additional consideration it was concluded that the discrepancies might be due to the fact that at the frequency of 124 kHz, the response of the hydrophone is not ideal, thus introducing electronic noise in the measurements. This observation is very useful in the design of a future experiment, as the conditions of emission and reception should be ideal in order that the measured data could be used as the source of benchmark results for the validation of theoretical models.

Still, the comparison between measured and calculated fields is considered satisfactory for analytical studies of the multi-mode propagation in a shallow water environment.

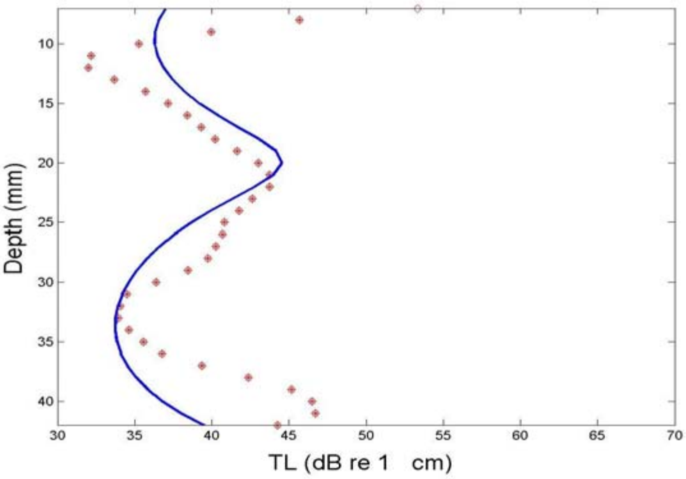


Figure 6: Comparison of calculated (line) and measured (stars) TL of the acoustic field in the tank at the range of 4 m. Source depth 2.5 cm

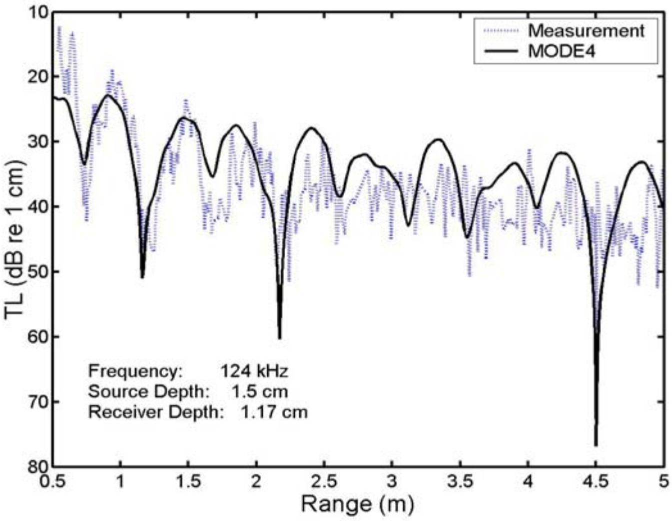


Figure 7: Comparison of calculated (solid line) and measured (dotted line) TL of the acoustic field in the tank for source depth 1.5 and receiver depth 1.17 cm.

5 Summary

Scaled tank experiments were performed to study the conditions under which the corresponding measurements can be used for the validation of the theoretical acoustic propagation models. Careful calibration of the geometrical operational parameters of the experiment was done, while off the shelf equipment was used. The modal specific character of the acoustic field was easily observed and verified, as variations in range and depth of the measured acoustic field fit very well with associated variations of the calculated field. The lack of perfect match can be attributed to the fact that the transducers were not specifically designed for the sought experiment. Indeed, as the transducers used in the experiment were not made to work at such "low frequencies" (124 kHz), there is a bad signal/noise ratio and the results are strongly corrupted by noise.

Moreover, the water depth is a very sensitive parameter. We need to know it with a high accuracy (better than 1/10 mm) which has to be taken into account in a future tank experiment. Also, procedures for the accurate determination of the source and receiver position should always be applied in order to get maximum accuracy in range and depth.

The tests to be performed in the future will focus on wave propagation over elastic media and range dependent environments by using appropriate material to simulate the bottom. Careful selection of the transducers and the corresponding signals to be operationally consistent is expected to enhance the correspondence between measured and calculated fields, thus creating the necessary conditions for the creation of a data base of benchmark exercises for the validation of the theoretical models.

Acknowledgments

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