A Computer Simulation of Underwater Sound Propagation Based on the Method of Parabolic Equations

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Abstract: - Due to high financial costs of test operations, computational acoustics has emerged as an important branch of underwater acoustics. A variety of numerical techniques have been introduced in this field, among which, only ray tracing, normal modes, fast field programming and parabolic equations methods have gained more enthusiasm from scientists and engineers. As PE method is suitable for low frequencies and shallow waters, and usually generates reliable results for all environments, we've employed this method in MATLAB routines to simulate acoustic wave propagation. Comparisons are made in figures 1-16 between simulation results and an ideal model.

Key-Words: - Acoustic wave propagation, MATLAB, PE method, Deep waters, Shallow waters

1 Introduction

Numerical Simulation is an important part of a research work, in which results are controlled for consistency, especially with computational acoustics, high operation costs are present (one should also keep in mind that even with these expensive tests, accuracy quite depends upon sampling and measurement resolution); Laboratory experiments therefore, achieve especial importance and underwater simulator packages enjoy significant role. Preparation of a complete software package for underwater wave propagation simulation depends upon many factors including:

- A Satisfactory knowledge of important medium features.
- A mathematical method encapsulating most of the physical features of the phenomenon under study.
- Identifying mathematical parameters and the way these should be embedded in simulation.
- Test of the results generated through the discretized model of problem.

The first and most important stage in a simulation is to identify the medium quantities, as this will serve as a means of building mathematical models for physical features. Many parameters can take part simultaneously in the mathematical modeling of a natural pattern, yet surely all can not be taken into consideration due to the limitations of present understandings. Thus different methods based on various degrees of freedom exist. However, only those models will be acceptable which can predict more physical parameters (simultaneously) and for which the results fits to natural patterns. On the other hand, models employed in computational acoustics have suitable model features and are applicable in their own special medium conditions. In all of these models, parameters of velocity, wave number, frequency depth and range, specification of acoustic source, the type of medium with respect to fluid mechanics measures such as condensability and incondensability of fluid, the existence of peripheral currents, range limited water environments, various medium noises such as ship noises, submarines, fishes, floating objects, wind, tide, tectonic features of sea bed such as ups and down, and finally medium properties such as deepness and shallowness may appear to be important. Yet, among parameters mentioned above, sea-bed, sea-level and type of the bed possess special importance [4]. In deep water model, with a source far away from sea-bed and surface, most of pre-mentioned parameters will loose their direct effects. As an example, reflection, refraction and bending of acoustic wave are implicitly canceled. Further complexity emerges in shallow waters due to small distance from bed to surface of medium. And all of these parameters do apply for the simulation. Thus, some of the techniques such as ray tracing based methods can not be employed anymore! In such circumstances, normal modes, fast fields and parabolic equations' methods are very suitable.

2 Materials and Methods

In the method of parabolic equations, the hyperbolic wave equation is first converted to a parabolic equation, which in turn is decomposed into two forward and backward terms and discretized through the method of finite differences [3]. Due to discretization complexities, only the following parameters are employed:

- Maximum depth of medium
- Maximum range of medium
- Source depth (location)
- Source frequency
- Receiver depth
- Water density

Through discretization, we are always encounter matrices which are updated according to the medium parameters, and we'll call them medium matrices. In some situations, these medium matrices become badly arranged, i.e. obtain high state norm. Bearing in mind the number and significance of employed parameters, one can expect that simulation results for shallow waters should have low accuracy, since in these waters, bed and surface boundaries as well as the quality of medium conditions quite affect the results.

In this work, the simulation of wave propagation has been carried out through C++ programming and MATLAB software. In fact, regarding the large numbers of range and depth discretization points, and resulting bulky medium matrices, MATLAB requires relatively more processing time compared to C++ codes which provide almost 10 times more processing speed. Yet MATLAB is employed merely because of its powerful graphic toolbox for producing figures and diagrams.

Next sections present the results of simulation program designed for both shallow and deep waters. All comparisons are made according to reference [1].

3 Results

3.1 Deep waters

Regarding deep water simulations, results are compared with reference [1] for three cases of convergence regions, deep acoustic channel (Munk model) and bed effect (Pekeris model).

3.1.1 Convergence regions

In the waters as deep as 1000 meters, temperature usually decreases as depth increases. For more depths, temperature remains constant at 4˚C, thus the velocity of sound increases because of overwhelming pressure. In some points of sound velocity variations curve, positive and negative gradients coincide with each other, and velocity of speed becomes negligible within these values [5].

Throughout thermo-cline layer having the same property, sound begins propagating nearly in parallel with surface having small inclination. As sound wave enter deeper water, it hits and is diffracted by different layers, and velocity gradient starts playing a quite reverse role and bends the wave upward. As a result of this bending, wave returns back to the water surface. The process up to this point has created a convergence region of about 50km. Beyond this convergence region, silence region is present. Then, wave bends downwards again and the process repeats.

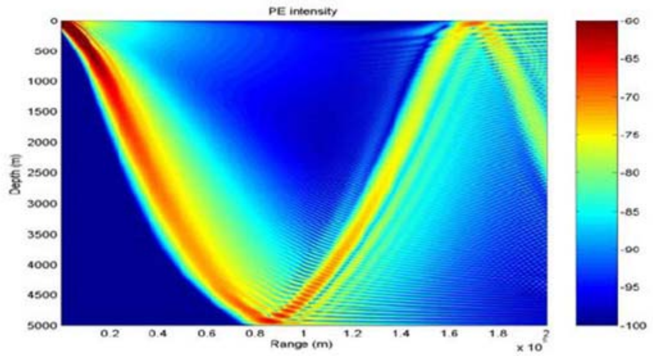

Fig.1 Convergence region for a source placed in the depth of 20 (m) and frequency of 50 (Hz)

The wave propagation pattern shown in Fig.1 is one of the most interesting propagation aspects in deep waters. The pattern is called convergence pattern that is sound wave generated by a sea-born source and sent downwards, goes under diffraction in deep waters and returns back to the surface to construct regions of high energy density and can be received in distances of several kilometers away.

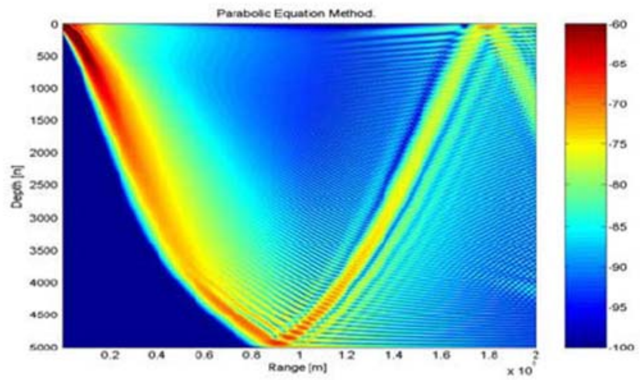

Fig.2 Convergence result from our software for a source placed in the depth of 20 (m) and frequency of 50 (Hz)

Comparisons between results from our designed software and those of reference [1] are made in Figures 1 and 2. As seen from these figures, due to lack of attenuation from bed, propagation pattern is quite similar to that of [1]. Fig.3 illustrates the profile of two-channel velocity in the north east of Atlantic Ocean, which is a result of mixing waters from Atlantic Ocean and Mediterranean Sea at Gibraltar canal. This pattern is

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obtained for a source placed 20(m) bellow surface with output angles of $\pm 10°$.

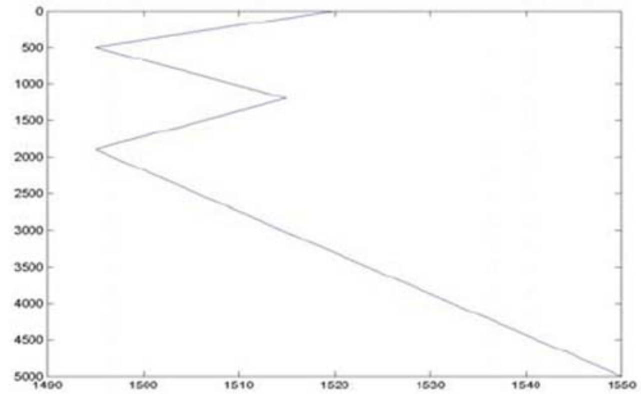

Fig.3 Two-Channel velocity profile

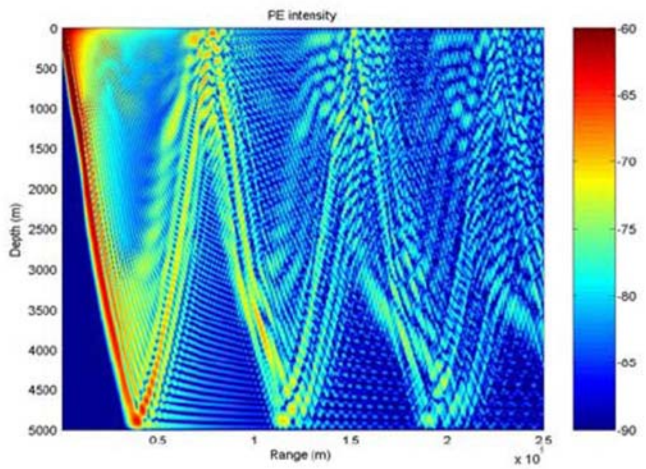

Fig.4 Wave propagation pattern as well as convergence regions of about 70(km)

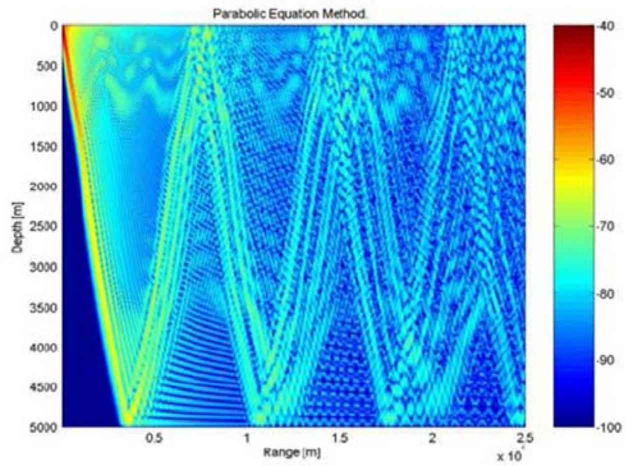

Fig.5 Software output for wave propagation pattern as well as convergence regions which are about 70(km)

In Fig.4, wave propagation pattern from PE method is depicted. Fig.5 is also the same pattern resulting from designed software package.

3.1.2 Deep channel sound propagation (Munk model)

Thanks to the diffraction of sound waves in upper and lower regions of the acoustic channel, propagation occurs completely. The axis of acoustic channel coincides with the surface, and in the medium geographical latitudes can rest up to 1000 meters beneath the surface. The profile of Munk velocity is considered an ideal profile for ocean, which can be used to view most of the oceanic propagation landscapes. This profile is generally shown as in Fig.6.

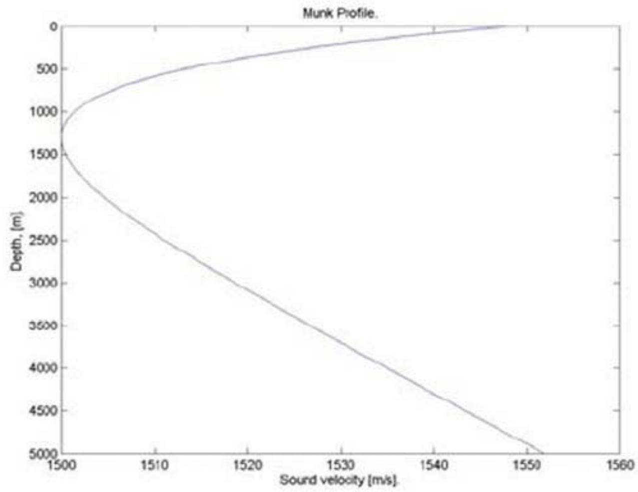

Fig.6 Munk velocity profile

Munk velocity is given as:

$$c(z) = 1500.0\left[1.0 + \varepsilon\left(\tilde{z} - 1 + e^{-\tilde{z}}\right)\right] \qquad (1)$$

Where, the quantity of ε is given as:

$\varepsilon = 0.00737$

And the scaled depth parameter is defined as:

$$\tilde{z} = \frac{2(z - 1300)}{1300}$$

We assume that, the medium has a homogenous bed with the density of 1000 (kg/m^3), sound velocity of 1600(m/s) and source frequency is 50(Hz). With these assumptions, and according to [1], propagation pattern will be as shown in Fig.7. As well, the output from our software can be seen in Fig.8. As seen from these figures, acoustic wave power from a single source, is trapped in deep-water acoustic channel, thus propagation will continue for long distances as there is no attenuation due to reflections from bed or surface. Power transmitted through deep acoustic channel is directly proportional to the angular width of transmission from acoustic source.

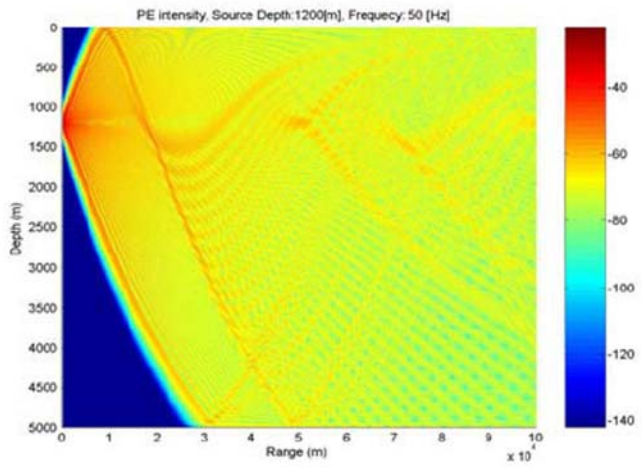

Fig.7 Wave propagation pattern using Munk velocity profile for source frequency and depth of 50(Hz) and 1200(m) respectively

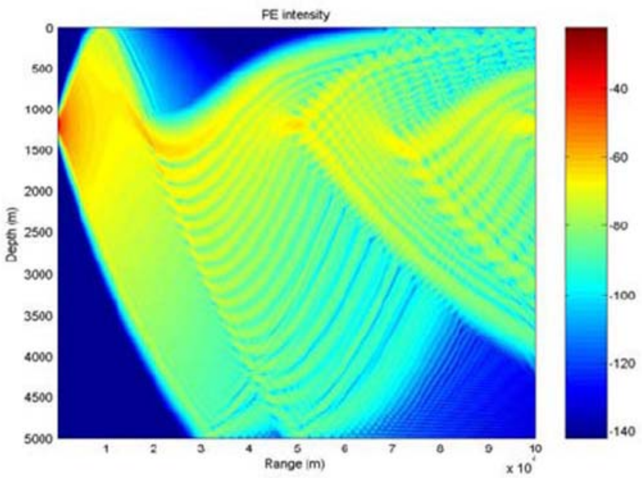

Fig.8 Software output for Wave propagation pattern using Munk velocity profile for source frequency and depth of 50(Hz) and 1200(m) respectively

In the following section, we are going to deal with this problem with same velocity profile, for a 20(Hz) source placed in three different depths.

3.1.3 Wave propagation, considering sea-bed effect (Pekeris model)

The diagram of Pekeris model is illustrated in Fig.9, which includes homogeneous fluid layer and bed attenuation [2]. Considering bed effect on the propagation of underwater acoustic waves, as well as the parameters employed in Pekeris model, transmission attenuation diagram of Fig.11 is generated by our software. The output from Pekeris model [2] is also presented in Fig.10. As seen from these figures, a maximum difference of -40dB exists for the distance of 220km, between results from our simulation and those of reference [2]. The main reason for this difference is due to not employing some of the parameters in the simulation.

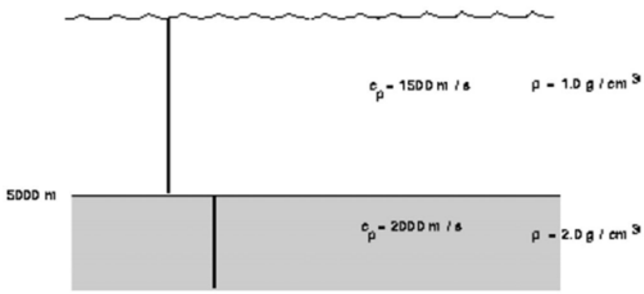

Fig.9 Pekeris propagation model

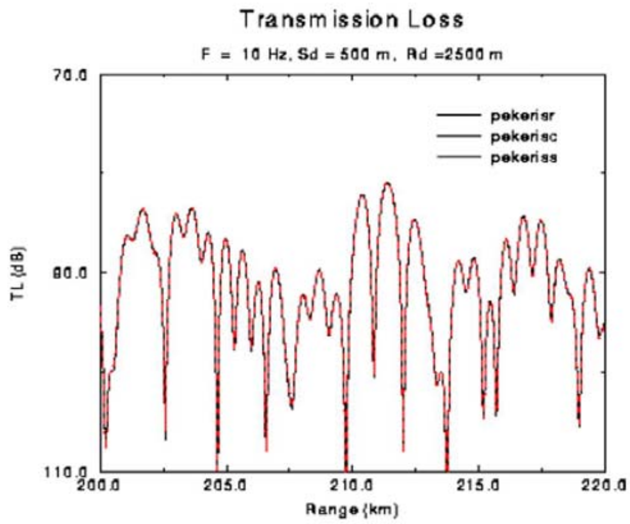

Fig.10 Transmission loss for source frequency and depth of 10(Hz) and 500(m), and a receiver placed at 2500(m) beneath surface

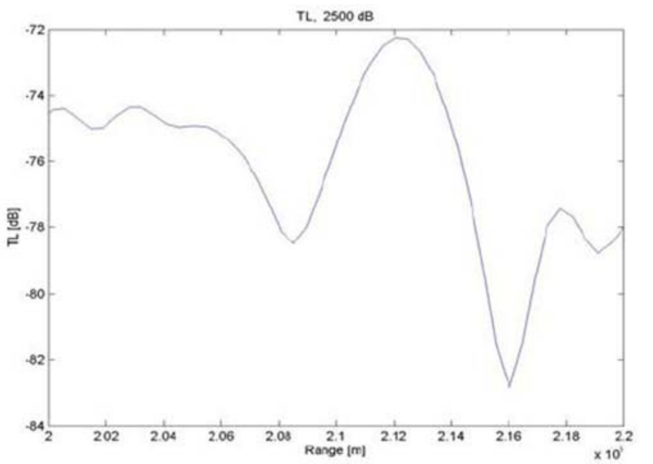

Fig.11 Transmission loss output from our software for source frequency and depth of 10(Hz) and 500(m), and a receiver placed at 2500(m) beneath surface

3.2 Shallow waters

The main characteristic of acoustic propagation in shallow waters is that sound velocity profile is nearly constant or goes under a downward diffraction. Therefore long distance acoustic wave propagation will take place with periodic incidences to the bed. Thus the most significant paths of wave will be those of reflections from bed and surface.

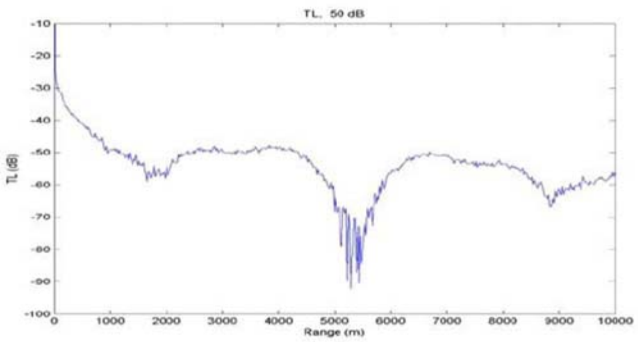

Fig.12 Transmission loss output from our software for a 20(Hz) source placed 100(m) beneath surface

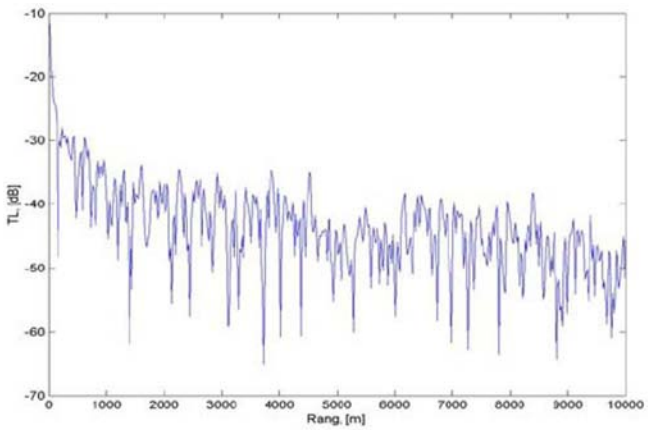

Fig.13 Transmission loss for a 20(Hz) source placed 100(m) beneath surface

Regarding shallow waters, water surface and volume and bed characteristics are all important and time/space-varying parameters. Therefore, studying the quality of acoustic wave propagation in shallow waters in long distances is a valuable and interesting issue.

To make a comparison between our simulation results and findings of reference [1], we assume a medium with the maximum depth of 200 meters, and source frequencies of 100(Hz) and 20(Hz). Acoustic velocity in water column is 1500(m/s). Also, velocity, density and attenuation coefficient of bed are 1700(m/s), 1.5(gr/cm^3) and 1(dB/km) respectively. Fig.12 depicts a sample software output for the range of 10(km). Fig.13 is also obtained from reference [1]. It's obvious that, differences between these two runs exist. This is due to not employing some parameters such as bed attenuation in our software, which in turn translates to incomplete comparison for shallow waters. As two other important missing parameters, power and dimensions play no role in our simulation. However, as we know change in power has a significant effect on the propagation process owing to overwhelming importance of medium noises in this situation.

Most of the existing simulations of uneven beds' attenuation are carried out assuming parameters such as density, velocity and cutting and pressing attenuation. Therefore, as mentioned above, discrepancies in simulation results are natural.

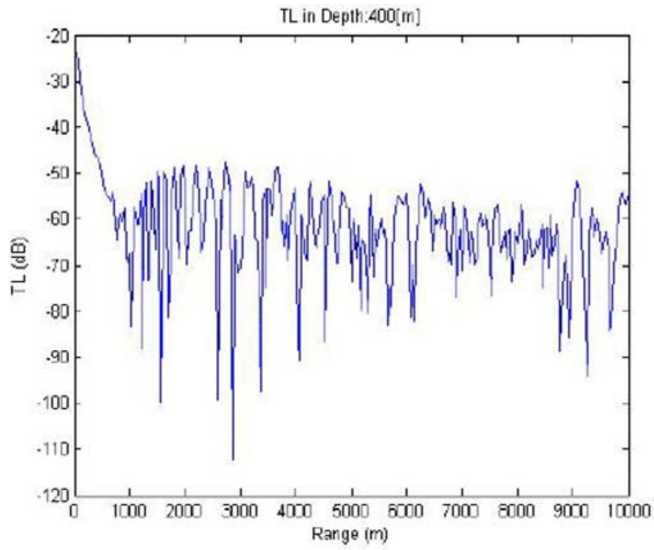

Fig.14 Comparison between software output and spherical transmission loss

As the next step, we first assume that the medium has a maximum depth of 100(m) and then consider a 50(Hz) source located in a depth of 20(m).velocity of sound in water column is 1500(m/s). Also velocity, density and bed attenuation coefficient are 1700(m), 1.5(gr/m^3) and 1(dB/km) respectively. Sample simulation output for the 10(km) range is depicted in Fig14. We've made comparison of this section with the spherical wave propagation, for the same range: As another situation, we assume that water column has a velocity profile gradient constant of around 0.0610 and the bed to be homogeneous. In this condition, sound velocity of 1500(m/s) at source point will increase up to 1506.4(m/s) at bed side. Results of utilizing this situation are illustrated in Fig.15 and Fig.16.

4 Conclusions

As mentioned earlier, and according to sample simulation outputs and comparisons made with Reference [1] we anticipate that diagrams presented by reference [1] and the output from our software(Fig.2) are quite similar. This is due to neglecting bed attenuation effect. If we evaluate the error in this situation, it will appear to be 5(dB) per 200(km), and stems from not taking source power into account. Convergence distance in wave propagation pattern for north-eastern Atlantic Ocean waters according to [1] is 70(km) (Fig.4). Result from our simulation for the same pattern is also 70(km) (Fig.5), which indicates a close agreement between our simulation and reference [1].

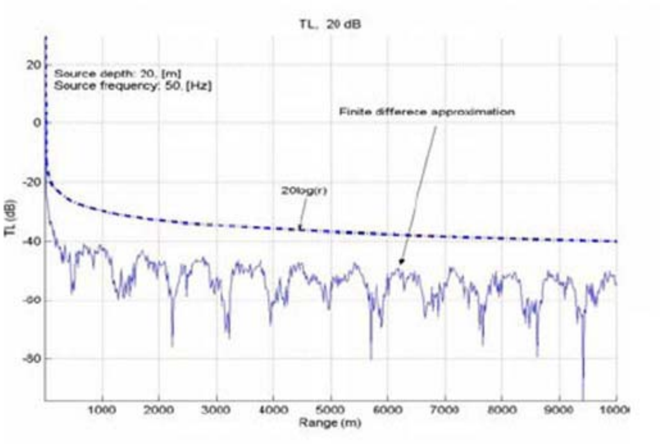

Fig.15 Software output for wave propagation from a 100(Hz) source placed 400(m) beneath surface

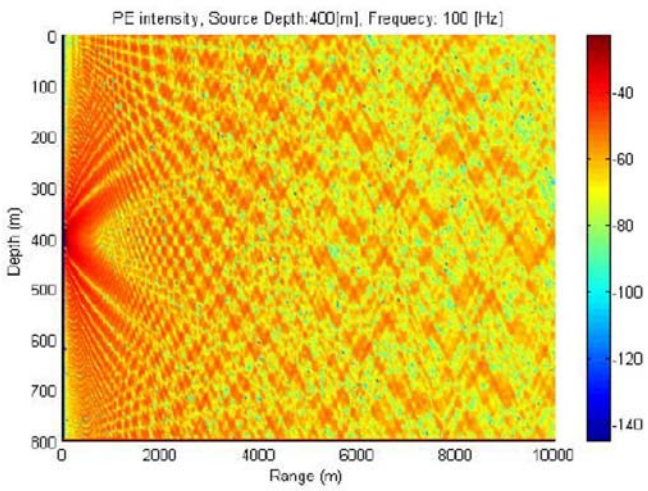

Fig.16 Software output for transmission loss; 20(Hz) source placed 400(m) beneath surface

The wave propagation pattern according to reference [1] and employing Munk velocity profile, a 50(Hz) source placed 1200(m) bellow surface and a medium with the density of 1000(kg/m^3) and sound velocity of 1600(m/s) is depicted in Fig.7. The output from our software is also presented in Fig.8 for comparison. Error value is minimum in the depth of 1200(m), since the transmitted acoustic power from generating source is confined in deep acoustic channel. Therefore, wave can continue to propagate for long distances due to reflections from bed and surface. Bed attenuation exists in Pekeris model for which simulation is carried out for a range of 220(km) (Result from reference [1] is depicted in Fig.1). Our simulation result is also presented in Fig.11 for comparison. From these figures, it is obvious that a maximum of 40(dB) difference exists between results in this range, which is due to not considering the parameters of bed attenuation and reflection coefficient of liquid-solid surface. Also volume scattering phenomenon is neglected in the software output. For shallow water situation with the maximum depth of 200(m), source frequency and depth are chosen as 20(Hz) and 100(m) respectively. The velocity of water column is assumed 1500(m/s), and velocity, density and attenuation of bed are considered to be 1700(m/s), 1.5(gr/cm^3) and 1(dB/km) correspondingly. According to Fig.12 which is the result of our simulation for a range of 10(km), and Fig.13 from reference [1], it's apparent that the error value for the range of 9(km) is 5%:

$$\text{error value} = \frac{|\text{actual value - measured value}|}{\text{actual value}} * 100$$

$$\text{error value} = \frac{|58 - 16|}{58} * 100 = 5$$

However, for the range of 5200(m), we have:

$$\text{error value} = \frac{|60 - 92|}{60} * 100 = 54$$

This error is due to not employing bed attenuation parameters as well as giving no role to the important source parameters such as source power and dimensions in our simulation software. According to Fig.13, and comparing simulation result with spherical propagation dissipation in a medium with a maximum depth of 100(m), source frequency and depth of 5(Hz) and 20(m), sound velocity in water column of 1500(m/s), and bed velocity, density and attenuation constant of 1700(m/s), 1.5(gr/cm^3) and 1(dB/km) respectively, transmission dissipation value is 18.4%:

$$\text{error value} = \frac{|38 - 55|}{38} * 100 = 18.4$$

The calculated error is used to compare simulation output with an ideal mathematical model. Also it's remarkable that, here we've neglected bed attenuation coefficient.

References:

[1] Jensen F.B., Kuperman W.A., Porter M.B. and Schmidt H., *Computational Ocean Acoustics*, AIP series in modern acoustics and signal processing, 1993

[2] Pekeris C.L., Theory of propagation of explosive sound in shallow water, *Geol.Am. Mem.*, Vol. 27, 1948. Soc.

[3] Etter P. C., *Acoustical oceanography and simulation*, Spon press, Taylor and Francis, group, 2003

[4] Brooke G.H. and Thomson D.J., Non-local boundary conditions for high-order parabolic equation algorithms, *Wave Motion*, Vol. 31, PP. 117–129, 2000

[5] Collins M. D., Kuperman W. A., McDonald B. E. and Siegmann W. L., Parabolic equation modeling of azimuthally adverted gravity waves, *Wave Motion*, Vol. 31, pp. 131-138, 2000.