Research Note

Underwater Channel Modelling-3D aspect in the Indian Ocean Region (IOR)

Gokul Karthiik, Dr. (Cdr) Arnab Das

EEE, BITS Pilani

Director, MRC

Background and Broad Introduction to Work

The science of production, transmission, reception, and utilization of sound in the sea is called ocean acoustics. Underwater propagation is predominantly done by acoustic waves. The attenuation and delay associated with the acoustic channel limits the range supported. It is essential in military and rescue operations and several commercial activities like exploration for minerals and oil, dredging, fisheries, and navigation.

The littoral zone or nearshore is the part of a sea, lake, or river that is close to the shore. In coastal environments, the littoral zone extends from the high water mark, which is rarely inundated, to shoreline areas that are permanently submerged [1].

The earliest attempts at modeling sound propagation in the sea were motivated by practical problems in predicting sonar performance in support of anti-submarine warfare (ASW) operations during World War II [2]. Earlier models used ray-tracing techniques which remained predominant during World War II. The ray-tracing method is a computationally heavy model. These paths could then be used to predict the corresponding sonar detection zones. This approach was a forerunner to the family of techniques now referred to as ray theoretical solutions. An alternative approach, referred to as wave-theoretical solutions, was first reported by Pekeris (1948), who used the normal-mode solution of the wave equation to explain the propagation of explosively generated sound in shallow water [3]. As modeling technology matured over the intervening decades, the attendant sophistication has complicated the simple categorization of ray versus wave models. The terminology is still useful in distinguishing those models based principally on ray-tracing techniques from those using some form of numerical integration of the wave equation [3]. Occasionally, a mixture of these two approaches is used to capitalize on the strengths and merits of each and to minimize weaknesses. Such combined techniques are referred to as hybrid approaches.

Specific Domain

Propagation of sound in the sea over long ranges is always by some form of ducted or guided propagation in which maximum energy is confined within the boundaries of the duct. These ducts are called sound channels, or waveguides in general. The deep sound channel, the surface duct, and the shallow water channel are the critical types of waveguides that exist in the oceans. The underwater channel can be characterized by the time dispersion phenomenon caused by the complex interaction of the source field with the sea surface and bottom. The radiated signal passes through a variable channel due to relative motion between the target vessel and the receiver vessel and the time-varying characteristic of the ocean medium itself.

Some properties of the ocean medium vary as a function of range (r) and azimuth (θ) from the receiver, in addition to depth (z) dependence. Based on this, models are further classified into the Range-Dependent model (3D) and the Range-Independent model (2D) [3]. The range dependent models consist of the parabolic equation model and the ray model. Range-dependent models are required to have a 3-dimensional aspect of the Transmission Loss.

The Parabolic Wave Equation (PE) is one of the most accurate and widely used modeling technique for modeling range dependencies in environments. It approximates the Helmholtz Equation (HE), assuming one-way propagation within an angular sector [4,5]. The PE method is based on assuming that outgoing energy dominates backscattered energy and factoring the operator in the frequency-domain wave equation to obtain an outgoing wave equation. Depending on the nature of approximation encountered in the elliptical wave equation, there exist infinite parabolic approximations and, therefore, infinite PE solutions. The split-step Fourier technique and various Finite Difference (FD) and Finite Element (FE) techniques have gained widespread use in the Underwater Acoustics community [5] for providing numerical solutions to the PE. The split-step Fourier algorithm is computationally efficient for long-range, narrow-angle propagation problems with negligible bottom interaction. For short-range, deepwater problems and shallow water problems in general, the propagation is wider angled, and bottom interacting paths become more important. This requires use of one of the wider angled PEs which can only be solved by the FD and FE techniques [6][7]. The PE method differs from the ray and FFP procedures in being a finite spatially evolutionary scheme. Consequently, it does not suffer from many of the errors inherent in these methods [8][9][10].

Tropical Littoral Waters- IOR

The IOR, owing to its tropical location, demonstrates complex fluctuations in the propagation characteristics due to random diurnal fluctuation in the surface parameters. The littoral waters in the extended Indian coastline further add to deteriorated sonar performance in the IOR [11]. Unlike the temperate region (North Pacific and North Atlantic oceans) where most of the advanced navies operate typically, the surface parameters of the tropical seas do fluctuate randomly and even the depth of sound axis is far less (of the order of 200 m in tropical waters compared to 1,500 m in temperate waters). Thus, a hypsometrically deep-water area behaves like an acoustically shallow region in the IOR [12].

Challenges and Opportunities

Doppler Effect

The receiver is assumed to be stationary, and the vessel is moving over the duration of observation, which causes the channel to be time-varying. In motion environments (such as platform motion of the moving sea surface and scattering), the slow propagation speed of sound introduces large Doppler spread or shifts, which causes severe interference among different frequency components of the signal [13]. On the outset, large Doppler spread results in an apparent increase in the rate of channel fluctuation.

Backscattering due to Polymetallic nodules

The parabolic equation model approximates the backscattering amounting to zero. However, this is not a practical scenario. Polymetallic nodules (PMN) are found in large quantities in the deep-sea regions of the major oceans of the world. This PMN consists of metals of high commercial value such as manganese, nickel, cobalt, and copper. The occurrence of PMN across these oceans has been well-studied [14]. Studies have reported that the distribution of PMN on the deep-sea floor is not uniform [15][16][17]. The soundwaves are backscattered due to the abundance of PMNs present in the Indian Ocean Region and pose a challenge to the usage of the parabolic equation model.

Bathymetric Datasets

Bathymetry refers to the study of underwater depth of ocean floors or lake floors. The shallow-water bathymetric data are usually collected and managed by regional organizations for regional interests [18]. Hence, the shallow-water bathymetric datasets are often not as co-ordinated internationally and not as standardized as Deepwater datasets. This leads to the use of different sources of bathymetry data by ocean modelers.

The absence of a common dataset for shallow regions leads to bathymetry becoming a variable in model simulations. Hence, there is a need for a common dataset for shallow waters in the Indian Ocean. Tsunami simulations are critically dependent on the bathymetry used, as are the source-region estimates based on backward ray tracing [19][20]. Therefore, there is a need to generate reliable bathymetry on the continental shelf of the Indian Ocean to eliminate a potential source of differences among various model studies.

South-East Indian Ocean – Case Study

The Navel Ocean Centre, California, has used the parabolic equation model to study acoustic propagation over a wide variety of typical ocean environments. Bathymetric conditions encountered were continental slopes, ocean basins, underwater ridges, and seamounts [21]. Also, the oceanographic conditions have varied from those typical of subtropical waters in the north (South-East Indian Ocean) to Antarctic waters south of the Polar Front. These conditions have presented a severe test of the capabilities of current acoustic modeling techniques. Despite difficulties both in initializing and in running the parabolic equation model on the continental slope, the general level of agreement between measurement and prediction is encouraging [22]. The Navel Ocean Centre has successfully used the parabolic equation model to simulate the same [23]. The same could be tried for the northern Indian Ocean Region as well.

Broad Areas of Research

Implementation of Sensor Networks

Applications of sensor networks vary from the oil industry to aquaculture and include instrument monitoring, pollution control, climate recording, prediction of natural disturbances, search and survey missions, and study of marine life. Sensor networks that measure low-frequency seismic activity from remote locations can provide tsunami warnings to coastal areas [24] or study the effects of submarine earthquakes(seaquakes). Sensors can be used to identify hazards on the seabed, locate dangerous rocks or shoals in shallow waters, mooring positions, submerged wrecks, and to perform bathymetry profiling. As discussed earlier, the bathymetry profile of shallow water regions are of immense importance.

Application of ML/AI Techniques

Artificial intelligence (AI), particularly machine learning (ML), is widely studied to enable a system to learn of intelligence, predict and make an assessment instead of the needs of humans [25]. Switching the traditional channel modeling to machine learning channel modeling still in its early stage. One of the main issues in the current method is to accurately predict the channel parameters, whereas using machine learning techniques could enhance the prediction and reduce the complexity. Machine Learning can be used to predict and estimate the wireless channel parameters and examine large and small-scale fading, including parameters such as path loss, delay path loss exponent, carrier phase shifts, Doppler spread and random variable that explains the largescale fading [26].

REFERENCES

[1] Littoral Zone. (2007). Littoral Zone. Retrieved 14 June 2020, from https://en.wikipedia.org/wiki/Littoral_zone.

[2] A. Quazi and W. Konrad, "Underwater acoustic communications," Communications Magazine, IEEE, vol. 20, no. 2, pp. 24 –30, march 1982.

[3] P.C. Etter, Underwater Acoustic Modeling and Simulation, 4th ed., CRC Press, New York, 2013.

[4] F. D. Tappert, "The parabolic approximation method," in Wave Propagation and Underwater Acoustics, edited by Keller and Papadakis, Lecture Notes in Physics, vol.70, Springer, New York, 1977.

[5] Hardin and F. D. Tappert, "Applications of the split step Fourier method to the numerical solution of nonlinear and variable coefficient wave equations," SIAM Review, vol. 15, p. 423, 1973.

[6] F.B. Jensen, W.A. Kuperman, M.B. Porter and H Schmidt, Computational Ocean Acoustics, Springer-Verlag, New York 2000.

[7] Technical Report, CARE/SP/TD/2010/1, titled "Synthetic Data Generation for Radiated Noise of Marine Vessels," Apr 2010.

[8] West, M. & Sack, R. A., New correction procedures for the fast field program which extend its range. Proceedings of the 4th International Symposium on Long Range Sound Propagation. NASA Conference Publication 3101, NASA, Langley, VA, 1990, pp. 201-9.

[9] West, M., Sack, R. A. & Walkden, E, The fast field program (FFP). A second tutorial: Application to long range sound propagation ~ the atmosphere. Applied Acoustics, 33 (1991) 1-30.

[10] West, Martin & Gilbert, Kenneth & Sack, R.A.. (1992). A tutorial on the Parabolic Equation (PE) Model used for long range sound propagation in the atmosphere. Applied Acoustics - APPL ACOUST. 37. 31-49. 10.1016/0003-682X(92)90009-H.

[11] Das, Arnab, 'Naval Operations Analysis in the Indian Ocean Region—A Review', Journal of Defence Studies, Vol. 7, No. 1, January 2013, pp. 49–78; 'Effective Underwater Weapon Systems and the Indian Ocean Region', Journal of Defence Studies, Vol. 7, No. 3, July 2013, pp. 159–68.

[12] Etter, Underwater Acoustic Modelling and Simulation, n. 4; See Das, 'Naval Operations Analysis in the Indian Ocean Region' and 'Effective Underwater Weapon Systems and the Indian Ocean Region', n. 15.

[13] Misra, A., & Gupta, D. (2013). Challenges being faced by underwater wireless sensor networks and its countermeasures, International Journal Of Advance Research In Science And Engineering IJARSE , 2 (9).

[14] U. Von Stackelberg and H. Beiersdorf, "The formation of manganese nodules between the clarion and clipperton fracture zones southeast of hawaii," Marine Geology, vol. 98, Issue 2, pp. 411–423, 1991.

[15] International Seabed Authority, "A geological model of polymetallic nodule deposits in the clarion clipperton fracture zone," Tech. Rep. 6, 2010.

[16] H. S. Jung, Y. T. Ko, S. B. Chi, and J. W. Moon, "Characteristics of seafloor morphology and ferromanganese nodule occurrence in the Korea Deep-Sea Environmental Study (KODES) area, NE equatorial Pacific." Marine Georesources And Geotechnology, vol. 19, no. 3, pp. 167–180, 2001.

[17] L. J. Wong et al., "Acoustic Backscattering Properties of Polymetallic Nodules from the Indian Ocean Basin: Results from a Laboratory Measurement," 2019 IEEE Underwater Technology (UT), Kaohsiung, Taiwan, 2019, pp. 1-6, doi: 10.1109/UT.2019.8734442.

[18] Sindhu, B., Suresh, I., Unnikrishnan, AS, Bhatkar, N. V., Neetu, S., & Michael, G. S. (2007). Improved bathymetric datasets for the shallow water regions in the Indian Ocean. Journal of Earth System Science, 3 (116), 261–274.

[19] Lay T, Kanamori H, Ammon C J, Nettles M, Ward S N, Aster R C, Beck S L, Bilek S L, Brudzinski M R, Butler R, DeShon H R, Ekstr¨om G, Satake K and Sipkin S 2005a The Great Sumatra–Andaman Earthquake of 26 December 2004; Science 308 1127.

[20] Neetu S, Suresh I, Shankar R, Shankar D, Shenoi S S C, Shetye S R, Sundar D and Nagarajan B 2005 Comments on “The Great Sumatra–Andaman Earthquake of 26 December 2004”; Science 310 1431a.

[21] R.W. Bannister et a!., “Project Tasman Two: low frequency propagation measurements in the South Tasman Sea,” J. Acoust. Soc. Amer., Vol 58, 1975, S85.

[22] F.D. Tappert , “Parabolic equation method in underwater acoustics ,” J. Acoust. Soc. Amer., Vol.55, 1974, S34.

[23] K.M. Guthrie, D.F. Gordon, “Parabolic equation predictions compared with acoustic propagation measurements from project Tasman two”, Navel Oceans System Centre Technical Report, 133, 1977.

[24] N.N. Soreide, C.E. Woody, S.M. Holt, Overview of ocean based buoys and drifters: Present applications and future needs, in: 16th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, January 2004.

[25] Aldossari, Saud & Chen, Kwang-Cheng. (2019). Machine Learning for Wireless Communication Channel Modeling: An Overview. Wireless Personal Communications. 106. 10.1007/s11277-019-06275-4.

[26] Z. Qin, H. Ye, G. Y. Li and B. F. Juang, "Deep Learning in Physical Layer Communications," in IEEE Wireless Communications, vol. 26, no. 2, pp. 93-99, April 2019, doi: 10.1109/MWC.2019.1800601.