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Review Article

# A Review on Methods and Approaches in Underwater Acoustics

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**Keywords**

Underwater Acoustics, Wave Propagation, Ambient Noise, Underwater Acoustic Communication.

**Abstract**

The field of underwater acoustics has been extensively developed over the past four decades in response to practical needs originating within both the naval sonar and the marine seismology communities. In contrast to electromagnetic waves, which are highly attenuated in water, acoustic waves can propagate long distances in underwater environments. For this reason, sound waves are used in water in much the same way that electromagnetic waves are used in the atmosphere to sense the environment and communicate. Hence, there is SONAR (Sound Navigation and Ranging) instead of radar, acoustic communication instead of radio, and acoustic imaging and tomography instead of microwave or optical imaging or x ray tomography. Underwater acoustics is the science of sound in water (most commonly in the ocean) and encompasses not only the study of sound propagation, but also the masking of sound signal by interfering phenomenon and the signal processing for extracting these signals from interference. This paper reviews the latest advances on underwater acoustics, specifically underwater acoustic communication and wave propagation.

## 1. Introduction

The word acoustics means "science relative to sound" and comes from the Greek akoustikos. The history of Underwater Acoustics starts with Greek philosopher Aristotle (384 322 BC) who mentioned that sound could be heard in water as well as in air .At the end of the 15th century, Leonardo da Vinci wrote: "If you stop your ship, then put one end of a blowpipe in the water and the other in your ear, you will hears ships far from yourself." [1] [2].

Fraunhofer and Jean Fresnel studied on interference between waves. Sound propagation in water were described mathematically during the 17th through 19th centuries. In 1743, J.A. Nollet conducted a series of experiments to prove that water is compressible. The scientists' ears usually served as receivers . During the latter half of the 19th century, main concern about maritime was navigation in fog and the danger of collision with other ships or icebergs. John Tyndall in England and Joseph Henry in the USA in separate investigations found sound propagation in air to be unreliable and in 1876 recommended to the lighthouse authorities in both countries that they adopt high power siren warning installations at all major lighthouses. Elisha Gray, who was working with Edison on improving the telephone, recognized that the carbon button microphone in a suitable waterproof container could be used as a hydrophone to receive underwater bell signals. In 1899, Gray and A.J. Mundy were granted a patent on an electrically operated bell for underwater signaling [2][3][4].

The outbreak of World War I, In France the Russian electrical engineer Constantin Chilowsky produced the first successful underwater acoustic signals that were sent across the river Seine in Paris below the Pont National by the end of 1915. In 1917 several members of Lord Rutherford's group were carried out research and development related to underwater echolocation and passive listening under the top secret "ASDIC" project. ASDIC is an acronym for "Allied Submarine Detection Investigation Committee". The first practically working active sonar, or ASDICS as the British preferred to name it, was built by Boyle in November 1918. It was successfully tested out fitted to a trawler a few days after the armistice on November 11, 1918. Dr. Harvey C. Hayes and his group developed the towed hydrophone assembly called "the Eel," and a passive sonar installation

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using 48 hydrophones hull mounted and towed was tested on a US destroyer. This installation was the most advanced passive sonar system produced during World War I. [4] [5].

The knowledge of speed of sound in the sea is crucial for understanding underwater sound propagation In 1924, Heck and Service [5] published tables on the dependence of sound speed on temperature, salinity, and pressure. Sound propagation under the influence of vertical variation in sound speed was investigated and modeled using the "ray theory" borrowed from the theory of light. Sound propagation in layered media such as the water column and seafloor was calculated by using the normal mode theory, developed by C.L. Pekeris in 1941 [6]. Ewing is credited with first predicting and then making the first measurements on the sound fixing and ranging ("SOFAR") sound channel, created by decreasing temperature and increasing pressure with depth in the deep ocean, thus creating a minimum in the sound speed depth profile. The first application of this discovery was aimed at providing a rescue system for downed at sea airmen. From his inflated rubber boat, the airman should drop small cartridges over the side set to explode on the axis of the SOFAR channel situated at about 1200 m depth in the North Atlantic. Ewing, together with J.L. Worzel and several other colleagues at Woods Hole Oceanographic Institute studied long range sound propagation in shallow and deep water by using underwater explosions. Chaim Pekeris improved his normal mode propagation theory and was able to interpret the shape of the mean dispersion curves measured by Ewing and Worzel [7]. Geometrical dispersion was also described by Tolstoy in a fluidesolid layer. The concept of elastic wave propagation has allowed underwater acousticians to model and understand complex shallow water acoustics. Ewing and Worzel's research also formed the basis for a series of seabed geological structure studies performed mostly in shallow water off the East Coast of the USA. Liebermann explained the deviation from the Stokes based viscous absorption dependence on the square of the frequency by the presence of a dilatational viscosity and the influence of relaxational effects [6][7][8][9][10][11] [3].

The comprehensive research and development efforts in underwater acoustics after World War II and the development in computer technology after 1960 formed the basis for the nearly explosive development in underwater acoustics from 1960. Among the main trends in underwater acoustics research and development are underwater sound propagation modeling involving mode theory, parabolic equations and finite element methods to include realistic range dependence and surface and bottom effects, reverberation studies, and ambient noise source and directivity studies coupling between acoustics, oceanography, and meteorology to lead to long term reliable weather forecasts, acoustical studies of biomass in the sea including detection of sea mammals [3] [12] [13] [14].

## 2. Review of Related Works

### *2.1. Underwater Wave Propagation*

Weinberg studied application of ray theory to acoustic propagation. Generalized Wentzel–Kramers– Brillouin–Jeffreys solutions are used to solve the depth dependent wave equation. By applying numerical integration in conjunction with stationary phase, the problem of caustics is eliminated. Computed predictions are compared with theoretical results and another computer model. Tindle introduced relatively new method of calculating waveforms in underwater sound propagation. The method is based on a Hankel transform generalized Wentzel–Kramers–Brillouin (WKB) solution of the wave equation. The resulting integral leads to a new form of ray theory which is valid at relatively low frequencies and allows evaluation of the acoustic field on both the illuminated and shadow sides of caustics and at cusps where two caustics meet to form a focus. The description of all other ray arrivals corresponds to simple ray theory. The method can handle range dependence but is illustrated here in long distance propagation in deep water where the ray paths do not pass close to surface or bottom [14][15].

Scott and Cogan [16][17] investigated the numerical simulation of wave propagation in bounded space using differential based models. They emphasized that the model generally encounter spatial discretization problems when the boundaries of the computation space do not fall on exact multiples of the models discretization. While the accuracy can be improved by refinement of the model, the computational load can increase exponentially, often making the problem unsolvable. They studied to describe a novel approach which compares well with TLM numerical method and differential based models with a significantly reduced computational load. Scott and Cogan also studied acoustic wave propagation in underwater shallow channel environments. They investigated the need for an accurate boundary conforming description and demonstrate why mesh refinement strategies are not appealing in this situation. Our approach can be used to account for the distortions in the received signal in an underwater channel and we highlight the influence of both surface state and receiver position [16] [17].

Holland and Ellis examined shallow water environments where the uppermost sediment layer is a fine grained fabric (e.g. clay or silty clay), the observed reverberation may be dominated by scattering from the sub bottom. Reverberation predictions from normal mode and energy flux models are compared for the case where the scattering arises from a sub bottom half space under a fine grained sediment layer. The model comparisons, showing some differences, illuminate the result of different approximations in the two approaches. Holland also studied propagation in a waveguide with range dependent seabed properties. He described the impact of spatial variability of seabed properties on propagation. Incoherent range dependent propagation depends upon the geometric mean of the seabed plane wave reflection coefficient and the arithmetic mean of the cycle distance. Thus, only the spatial probability distributions (pdfs) of the sediment properties are required. Also, it is shown that the propagation over a range dependent seabed tends to be controlled by the lossiest, not the hardest, sediments. The theory may be useful for other (non oceanic) waveguides [18] [19].

Sertlek and Ainslie investigated the accurate and stable calculation of underwater acoustic propagation. In this work, some widely used acoustic propagation models, based on different methods such as normal mode, ray tracing, parabolic equation and flux theory are tested. The effects of each method's characteristic parameters on propagation loss are also studied. Propagation loss results and run times of each model are compared at the different frequencies, ranges and receiver depths. The comparisons provide insight to the optimal choice of running parameters and performance of each model. Sertlek and Ainslie also investigated analytical solution is derived in terms of the Faddeeva function by converting a normal mode sum into an integral based on a hypothetical continuum of modes. In shallow water propagation, the sound field depends on the proximity of the receiver to the sea surface, the seabed, the source depth, and the complementary source depth. While normal mode theory can predict this depth dependence, it can be computationally intensive. For a Pekeris waveguide, this approach provides accurate depth dependent propagation results (especially for the surface decoupling) without requiring complex calculation methods for eigenvalues and corresponding eigen functions. Cristini et al., studied time domain full wave simulations in underwater acoustics using a spectral element method which is capable take advantage of the possibilities offered by high performance computing and accurate numerical simulations require a high computational power. They examined Shallow water propagation, deep water propagation as well as diffraction by objects in complex environments [20] [21] [22] [22].

Ainslie studied effect of wind generated bubbles on fixed range acoustic attenuation in shallow water. He mentioned that the effect of wind is to increase propagation loss due to rough surface scattering and the interaction with near surface bubble clouds. The bubbles are found to play an important catalytic role, not by scattering or absorbing sound, but by refracting it up towards the sea surface and thus enhancing the scattering loss associated with the rough air–sea boundary [23].

### 2.2. Underwater Acoustic Communication

Stojanovic et al., investigated a theoretically optimal multichannel receiver for inter symbol interference communication channels, and its suboptimal versions with linear and decision feedback equalizer. The shallow water acoustic communication channel is characterized by a long delay spread and a high Doppler spread. Coherent modulation schemes such as phase shift keying (PSK) along with adaptive decision feedback equalizers (DFE) and spatial diversity combining have been shown to be an effective but computationally complex way of communication in such channels. Xi et al., studied a direct adaptation based bidirectional turbo equalizer (DA BTEQ) for underwater acoustic communications. In their study they proposed scheme incorporates a forward direct adaptation based turbo equalizer (DA TEQ) with a backward DA TEQ to exploit bidirectional diversity gain and combat error propagation, thereby enabling faster convergence rate and better symbol detection performance. They underlined that DA BTEQ is effective against error propagation and clearly outperforms the traditional single direction DA TEQ for both single input multiple output and single input single output systems [24] [25].

Due to the symmetry of the linear wave equation, sound transmitted from one location received at other locations, reversed and retransmitted, focuses back at the original source location. Edelmann et al. [26], did an experiment at sea to measure the focus of a 3.5 kHz centered time reversal mirror (TRM) that was conducted in three different environments: an absorptive bottom, a reflective bottom, and a sloping bottom. The experiment included a preliminary exploration of using a TRM to generate binary phase shift keying communication sequences in each of these environments. A comparison of the results was made and time reversal was shown to be an effective approach for mitigating inter symbol interference caused by channel multipath. Hursky et al., studied passive phase conjugation (PPC) – uses the cross correlation of two consecutive signals transmitted from the transmitter to the receiver to convey information. In one such system which uses pulse position modulation (PPM) with PPC for communication, the spacing between a linear frequency modulated (LFM) signal and its mirror image is used to encode the data. Luan et al., developed an improved Doppler estimation algorithm using virtual time reversal mirror. According to their study any communication system transmitting signal by frame can employ the algorithm without additional assisting signals, and with acceptable increase in computational cost as well. The results of the sea experiment in Qingdao show the great reliability of this algorithm, and the Doppler shift can be estimated correctly in different types of time varying multipath channels [26] [27] [28].

Frassati et al. [29], investigated robust and reliable horizontal long range acoustic communications in littoral water environment. They addresses experimental results recently obtained with two other approaches which both aim at providing robust transmissions with higher bit rate: first is a set of OFDM (orthogonal frequency division multiplex) modulations in which data are transmitted by modulating a large number of orthogonal carriers, second approach is an application of DSSS (direct sequence spread spectrum) techniques where the transmitted symbols are spread over the used bandwidth with a pseudo noise binary. Chitre et al., developed coded OFDM in a very shallow water channel in Singapore waters. This technique OFDM (orthogonal frequency division multiplexing), a communication technique widely used in wired and wireless systems, divides the available bandwidth across a number of smaller carriers, each of which experiences flat fading. This simplifies the equalizer structure and provides robustness against time varying frequency selective fading. Another source of signal degradation is impulsive noise from snapping shrimp, which affects several OFDM carriers at the same time. OFDM, when coupled with coding, can provide robustness against impulsive noise by distributing the energy for each bit over a longer period of time. Li et al., investigated the method of cyclic cumulants and autocorrelation characteristics for OFDM signal modulation recognition and detected the signal in multipath condition. The purpose of underwater communication pattern recognition, is to recognize the modulation pattern from the received underwater acoustic communication signal. This technique has great influence on underwater acoustic communication interference spectrum monitoring, signal receiving and acknowledgment, communication management. The results showed that autocorrelation characteristics still a best approach for recognizing the OFDM modulated signal [29] [30] [31].

Information theoretic studies have shown that the capacity of a channel increases linearly with the minimum of the number of transmit and receive antennas. This increase in capacity translates to a corresponding increase in achievable data rate through the use of multiple input multiple output (MIMO) processing techniques and space time coding. Roy et al., investigates the feasibility and effectiveness of space time trellis and layered space time codes for the shallow water, acoustic, frequency selective channel. They mentioned that an effective approach for increasing data rate over wireless channels is to employ coding techniques appropriate for multiple transmit antennas, namely space time coding. Space time trellis codes (STTC) and layered space time codes (LSTC) can be used with sub optimal decoding techniques. Proakis et al., considered several aspects in the design of shallow water acoustic networks that maximize throughput and reliability while minimizing power consumption. Underwater acoustic networks are generally formed by acoustically connected ocean bottom sensor nodes, autonomous underwater vehicles (AUVs), and surface stations that serve as gateways and provide radio communication links to on shore stations. The quality of service of such networks is limited by the low bandwidth of acoustic transmission channels, high latency resulting from the slow propagation of sound, and elevated noise levels in some environments. Carlson et al., studied location aware source routing (LASR), our modification of the dynamic source routing (DSR) protocol to add location awareness and link quality metrics. A new protocol was needed because of the unique difficulties of underwater networking: radio links do not work through water, and the acoustic links that are used instead have much lower data rates and much higher latency. Specifically designed for use in underwater acoustic networks, LASR is explained, and initial simulation results are presented to show that the new protocol performs better than two existing techniques [32] [33] [34] [35].

### 2.3. Sonar

SONAR is the acronym for Sound Navigation And Ranging. Sonar technology is similar to other Technologies such as: RADAR (Radio Detection And Ranging) ultrasound, which typically is used with higher frequencies in medical applications; seismics, which typically uses lower frequencies in the sediments. The first active sonar designed in the same way modern sonar is, was invented and developed as a direct consequence of the loss of Titanic in 1912, where the basic requirement was to detect icebergs in 2 miles distance [36].

Originally, natural materials were used for the transducers, but by the 1930s sonar systems incorporating piezoelectric transducers made from synthetic materials were being used for passive listening systems and for active echo-ranging systems. These systems were used to good effect during World War II by both submarines and anti-submarine vessels [37].

In the 1960s, sonar designers began to test the application of digital signal processing. Although the very preliminary work involved only a 1-bit system, it was the beginning of the digitized procedures of modem sonar. The 1-bit system included DELTlC (delay line time compressor), DIMUS and thereafter DICANNE (digital interference canceling adaptive network nulling equipment). The rapid growth of digital sonar techniques is also benefitting from the development of LSIC large scale integration and VLSI very largescale integration. Many specific digital signal processing chips have been launched which can meet a range of application requirements. The digitization of sonar signal processing resulted in substantial changes in sonar systems. A digital signal is more convenient for transmission, and processing. Therefore, it provides the possibility to design new concept sonar systems with friendlier human/machine interfaces and better performance. Also, the extensive application of digital signal processing technique in sonar systems considerably advanced the development of digital signal processing theory itself, microcomputer design, and even the semiconductor industry [38][39][40][41].

Schock et al. examined buried object scanning. According to their study A sonar, designed to scan for objects buried in the seafloor, generates images of pipe and cable sections and ordnance buried in sand. The sonar operates by illuminating a broad swath of the seabed using a line array of acoustic projectors while acoustic backscattering from the illuminated sediment volume is measured with a planar hydrophone array. The sonar uses a steerable transmission beam to minimize the scattering noise and to allow targets to be illuminated at various aspect angles. Wettergren and Traweek explained optimization shading weights for velocity sonar arrays conforming to hulls. Edwards et al., studied seafloor scattering by using parametric sonars. Jones and Jackson, studied volumetric scattering from sediments by using bistatic scattering geometries. Matveev et al., examined detection of inhomogeneities passing through a sonar beam [42] [43] [44] [45] [46].

Acoustics is also being used in connection with behavioral studies of fish. Fish-tracking is an important element of such studies. Passive SONAR using acoustic energy produced by the fish themselves has also been developed as a significant research tool. Passive acoustics takes advantage of sounds produced by fishes to eavesdrop on their behavior. Most fish sounds are associated with aggression, courtship, and spawning. In some cases, this is done by recording the position of fish echoes with split-beam echo sounder or multibeam sonar. Schell and Linder, experimentally tested an algorithm to track fish with a multibeam sonar [47] [48] [49].

### 2.4. Ambient Noise

Ambient noise is the residual noise background measured at a hydrophone when individual noise sources cannot be identified, or ambient noise is the natural noise environment at a measurement site. Noise is unwanted sound in the ocean, since it generally interferes with the operation of sonar or other underwater sound registration equipment. Ambient noise became an active area of research during World War II because of the availability of calibrated instruments and the necessity to understand the ambient noise levels in coastal waters [1] [50].

Knudsen et al. [51], are summarized in a series of curves describing ambient noise spectra, known as the Knudsen spectra. From a physical and conceptual viewpoint the ambient noise level in the sea is best understood in terms of the characteristic source mechanisms. Wenz [52], illustrated the diversity of ambient noise sources. Studies of the influence of the flow around a hydrophone on noise generation by Strasberg have shown that the spectral density level is dependent on the flow velocity if the hydrophone is in a fixed position in the water column, is resting on the seabed, or is drifting freely with the water current [51][52][53].

Webb [54] discussed seismic activity ranges from large-scale intermittent sources, such as individual earthquakes (seaquakes), distant volcanic eruptions, seismic explorations, and sea mining to microseisms. Theoretical and experimental studies of the relations between ocean surface waves and microseisms have been reported by several scientists [54][55][56][57][58].

Isakovich and Kuryanov discussed low-frequency underwater noise that is produced by turbulent pressure fluctuations in the atmosphere near the ocean surface. The induced noise field in the sea is related, on a one-to-one frequency basis, with the fluctuations in the exciting turbulence field [59][60].

Nystuen [61] has proposed underwater sound measurements as a way for determining the amount of rain falling on the sea surface. A prospective future procedure for rainfall measurements could include underwater ambient noise measurements at certain geographical locations combined with the use of satellite observations and the use of weather radar. Bjorno [62] discussed experimental evidence for the strong influence of surface tension on the noise level produced by real rain.

Cato measured wind-generated waves, when they break, that produced noise through the action of surf on beaches [63].

Glowacki et al. examined the intensity, directionality, and temporal statistics of the underwater noise radiated by melting icebergs in Hornsund Fjord, Svalbard, using a three-element acoustic array. They present the first estimate of noise energy per unit area associated with iceberg melt and demonstrate its qualitative dependence on exposure to surface current. They provided the first quantitative estimates of the acoustic energy density associated with subsurface iceberg melt in units of joules per unit area. Moreover, we demonstrate that the face of a grounded iceberg exposed to surface currents radiates more noise than its sheltered face, which we interpret as a signal of higher melt rate caused by greater heat exchange [64].

Lossent et al. [65], underlined marine renewable energy development raised concerns over the impact of underwater noise and they assessed the acoustic impacts of an operating tidal current turbine (Paimpol-Bréhat site, France) on marine fauna. Their results show that within this area of greatest potential impact, physiological injury of the hearing apparatus of invertebrates, fishes and marine mammals is improbable. Behavioral disturbance may occur up to 1 km around the device for harbor porpoises only. This is of little concern for a single turbine. However, greater concern on turbine noise impact, particularly on behavioral reactions has to be granted for a farm with up to 100 turbine [65].

## 3. Conclusion

- In this paper, the review of underwater wave propagation, ambient noise, sonar systems and acoustic communications are investigated.
- Underwater wave propagation models become a well-developed topic until mid-2000s.
- Improvement of calculation techniques, such as computer aided calculations, let scientist to develop more accurate and more effective wave propagation models.
- Eventually, by using the developed models, a topic attracted scientists' interest as an application; underwater acoustic communication and Sonar systems.
- The past decades has significantly advanced underwater networking research as a branch of underwater acoustic communication.
- Efficient multi hop and ad hoc packet routing protocols for AUV networks are promising research areas for the future. We will also deal with applying some techniques such as but not limited to [66-87].

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