History of Environmental Acoustics, 1960's to 2000's

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Abstract - **Building on oceanographic and wave physics knowledge bases assembled over the prior century, environmental acoustics research has made steady progress since the 1960's. Developments in waveguide propagation theory, acoustic theory of heterogeneous media, data acquisition electronics, data storage capability, navigational precision and computational power have each enabled this progress. An overview of these developments and the resultant scientific progress is given here.**

I. Introduction

Environmental acoustics is a field with a long history dating back roughly to the late 1930's. This paper presents some of the history of that field. It is one of a group of papers on the history of ocean engineering sub-disciplines contributed by the IEEE-Oceanic Engineering Society Technology Committees (OES-TCs) to the Quebec City Oceans '08 Conference, marking the 40th anniversary of the OES.

Prior to the 1930's, use of sound in the sea, although marked by great utility, essentially disregarded departures from straight-line propagation. Possibly the first step was recognition of how refractive effects of vertical temperature gradients of magnitudes regularly found in the ocean were able to focus sound, duct sound, or create shadow zones, including the so-called "afternoon-effect". An excellent although brief summary of these early developments can be found in the book by Urick [1]. Next, during World War II, another event recognized as a milestone in understanding how the intricate details of the ocean environment controlled sound propagation was the discovery of the deep-ocean sound channel. This was done independently by American and Soviet scientists [2,3]. After these ground-breaking early studies of the complexity of underwater sound propagation, including effects of sound-speed gradients in the water, of a rough surface, and of a rough and volumetrically heterogeneous seabed, research and development led to a steady stream of developments over many decades. We focus here on the last 40 years, the OES years. A recent article on the history of underwater acoustics does a very good job of covering the period prior to the founding of OES, and provides additional information on the period covered here [4].

The Environmental Acoustics TC is one of two IEEE Oceanic Engineering Society TCs that focus on undersea acoustics research from a natural science point of view, the other being the Underwater Acoustics TC. Many other TCs coordinate activities in fields involving acoustics, such as undersea positioning or communication. However, these activities generally depend on fundamental acoustics research results for their purposes, rather than produce such results.

For the purposes of this historical review, ocean environmental acoustics is defined as ***the study of acoustic effects that are governed in fundamental ways by spatially and temporally varying phenomena within and adjoining the ocean***. As a corollary, the use of sound to measure these features is also included. The sound can be from known sources or from sources generally called noise: distributed natural sources, concentrated natural sources, and distributed man-made sources. This is a somewhat broader definition of environmental acoustics than is used in civil and mechanical engineering. In those fields, the term refers to studies of noise, noise abatement, and effects on organisms subject to such noise (very often the effect on humans). Our extension of the definition to include basic propagation physics stems from the reality of a heterogeneous underwater environment, which can concentrate, scatter or attenuate sound, meaning that environmental influences on propagation play an active role in shaping the undersea sonic environment. Stated another way, the environment exerts fundamental control on effects of any sound generated beneath the sea or transmitted into the sea through boundaries. Studies of undersea propagation effects are an inherent part of any study of the undersea sonic environment or on the effects of sound on organisms, and can not be isolated. Studies of propagation effects are in fact fundamental to the degree that they stand alone and fill a large literature, providing a solid basis for studies of a more applied nature.

There has been a steady advance in our collective knowledge of sound propagation in the sea since the founding of OES. Many of these advances have depended on technological advances pervasive throughout society, such as increases in computational power, satellite GPS (navigation and time keeping), and digital data storage. Advancement of this discipline due to improvements in materials and electronics, including digital computers, is analogous to progress in other

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technical pursuits. There has been a virtual avalanche of opportunities in ocean acoustics because of new technologies. In addition to advances stemming from physical technologies, other advances in our field have been brought about by new physical insight or research methodologies.

The interwoven history of our field and its technology is approached in a couple of ways, and this paper is organized as follows: Sections II and III discuss technical developments in computational, theoretical, and field-based ocean acoustic research, including shifts in approach and method. Section IV contains historical information about the Journal of Oceanic Engineering. Section V gives a chronological account of how the new tools and techniques, as well as new theoretical constructs, have fostered progress. Section VI describes some important accomplishments and recent developments. Section VII summarizes and comments on future directions and opportunities.

II. Technical Developments

Technological advances in materials, digital electronics (may be considered materials also, at a fundamental level), and computer software have served to revolutionize (or at least speed up) many aspects of ocean environmental acoustics research. Perhaps the opportunistic application of new technology within our field could be viewed as expected, not worthy of note, and having parallels in every other research discipline. On the other hand, the expense and difficulty of oceanographic field work, and the harsh physical environment, demand that efficiencies be developed and incorporated into practice. Furthermore, the broad range of effects, time scales, and spatial scales at play in ocean acoustics means that increases in dynamic range of computer simulated propagation and data collection are very important.

A. Computers

Computational power has improved throughout the entire 1960's and onward period, following the oft-cited Moore's Law. Prior to this, in the 1950's, large groups were dedicated to computations such as long-range ocean ray traces, which can now be done in the blink of an eye. Since then, the computational power available to specialized top-end computational experts, and to less-computationally specialized investigators, have both accelerated. In the 1960's mainframe computers allowed some standardization of computing methods across all walks of life, reducing the cost. This trend continued in the 1970's with mini-computers capable of operation outside of special rooms. The 1980's saw further gains, based on dual revolutions of microprocessor-based PC's for everyday users and centralized supercomputers for specialists, such as those built by Cray Research. As a result, the late 1980's state of the art speed of a propagation simulation (parabolic equation, see following section), performed on a desktop PC with an array processor board, was about one minute for a 15-km deep-water propagation run (500 by 400 grid points) [5]. Such a computation now takes seconds on a desktop or laptop PC, and a fraction of a second on current generation of supercomputer or computer cluster (Input/output functions can contribute significantly to clock time of runs, so massive amount of computer memory now becoming standard also serve to speed things up. To illustrate the progress, propagation variability analyses done by modern investigators with no capitalization of specialized equipment typically involve multiple linked simulations. These might be ensemble averages, Monte-Carlo studies, time-series simulation, or broadband waveform simulation. Studies of this type could only be dreamed of 20 years ago.

B. Digital Sound Sources

Digitally controlled sound sources were introduced in this time period. Now, this procedure is only a matter of connecting a computer (small enough to put into the sea, if required) with the power amplifier circuitry. Digital control allows better management and reproducibility of experimental conditions. Reproducibility of conditions allows time-series analysis and had other benefits. Finally, flexibility of waveforms, bandwidth, and so on enable more effective experiments. (By the way, sound source design in general has benefited from new materials and methods, such as finite element modeling [6]. This is more within the purview of the Underwater Acoustics TC.)

C. Data Acquisition

Increasingly powerful digital electronics has been incorporated into receiver circuitry and data acquisition systems. Synchronized receivers such as vertical and horizontal line arrays have benefited in particular, having increased size and capabilities such as sampling rate and signal to noise ratio [7,8]. Miniaturization has allowed small preamps to be positioned close to hydrophones without adding undue flow noise. Digital data transmission and storage have sped-up operations immensely and added reliability and redundancy.

D. Offshore Industrial Technology

Developments in the offshore industrial sector have driven down the costs and improved design and reliability of components such as underwater housings, rigging, and housing thru-hull fittings. This has reduced cost and down-time, and has increased efficiency of field work.

III. New Approaches

Developments in approach and methodology within wave propagation theory, and within inverse methods, have been key in the progress of the field. Here are some examples well known to the rank-and-file in ocean acoustics:

A. Propagation regimes

In the 1960's the method of normal modes was extended to "almost stratified" media, allowing adiabatic normal mode propagation theory to be applied to many commonly encountered ocean conditions [9,10]. This led to creative thinking regarding the union of the observational and theoretical branches of ocean acoustics. The division of shallow-water propagation into strictly layered, adiabatic normal mode, and coupled-mode regimes has facilitated computational approaches and experimental interpretation.

B. *Parabolic Wave Equation*

The parabolic equation (PE) approximation first came into ocean acoustics use in the 1970s. Since then, this computationally advantageous method for computing acoustic fields emanating from a source quickly became very popular as an alternative to adiabatic and coupled mode methods. The method was adapted from use in the fields of seismic and electromagnetic wave propagation [11]. Efficient implementation of the method, first in 2-D vertical ocean slices allowed, for example, repeated forward calculations for reasonably realistic (i.e. physically complicated) situations. Simulations enabled experimental findings to be explained and interpreted. In one respect, propagation modeling with the PE and other methods are bold approaches because no backscatter is allowed, but this approximation is frequently valid and the applicability of the methods is proven.

C. *Applied Mathematical Methods*

Some mathematical methods of quantum mechanics have been successfully adopted, ranging from the WKB approach, to solutions to the PE, which shares form with the Schrödinger equation in three dimensions. A paper is available [12] which cites many of the original articles on the relationship between this branch of classical physics and quantum physics. Of note is the physics of coupled-mode propagation [13], which has gained recognition through experiment [14] and simulation [15-17]. Adoption of Hamiltonian methods has also added insight [18]. By the late 90's, the new methods and new computational resources provided new insights into the structure and stability of acoustic fields [19, 20]. Path-integral scattering formalisms and moment equation methods were adapted to deep-water propagation in the 1980's [21]. Finally, perturbation methods have been frequently applied in geoacoustic inverse experiments [22]. Other methods have been applied; those mentioned here are the ones commonly used in propagation and inversion studies, the emphasis of environmental acoustics.

D. *Inverse theory*

Linear and nonlinear inverse methods are widely applied in all branches of experimental science. The sensitive dependence of acoustic fields to details of the environment means that sometimes a good starting model of the environment is not known, thus linear methods would not be applicable. Nonlinear methods including global search techniques have been implemented in the very active field of geoacoustic parameter inversion [23,24]. Many challenges remain because of the complexity commonly found in the seafloor, and the resulting complexity of the acoustic field. Many inversion advances stem from new computational algorithms and accelerating computer power. For instance, many inverse methods involve repeated direct comparisons of computed predictions with data.

IV. Journal of Oceanic Engineering

A. *Early Years: 1976-1996*

In its first 21 years of publication the *Journal of Oceanic Engineering (JOE)* contained a healthy number of articles on environmental acoustics. Larger numbers of papers began appearing in the mid 80's. These can be grouped according to theme. The papers in each theme were sometimes published in waves. The themes and years of appearance are

(1) Remote sensing, 1986-1994 [25-32]
(2) Bubbles and noise, 1990 [33-42]
(3) Inversion and seafloor properties, 1988-1994 [43-48]
(4) Seismic frequencies, 1988 [49-50]
(5) Propagation, 1986-1995 [51-58]
(6) Scattering, 1989 [59-61]
(7) Reverberation, 1984-1995 [62-66]
(8) Instrumentation, 1990 [67-70]

B. *Special Issues: 1988-2007*

JOE has included many special issues in its 30-years plus of publication. The majority of the special issues have covered acoustics or acoustic propagation-based topics. A few of the special issues relevant to environmental acoustics appeared in what we have called the early years, with the rate of appearance increasing thereafter. Here is a list of the acoustics-based special issues and the guest editors. The individual papers in the special issues are more numerous than the papers of the early years and are not cited here.

1. **Low-frequency acoustics in the ocean**
   October 1988, vol. 13(4)
   M. A. Deaett
2. **Ocean Acoustic Data Telemetry** *
   January 1991, vol. 16(1)
   J. A. Catipovic
3. **Inversion Techniques and the Variability of Sound Propagation in Shallow Water**
   October 1996, vol. 21(4)
   J. H. Wilson, S. Rajan, J. M. Null
4. **Shallow-water acoustics**
   April 1997, vol. 22(2) and July 1997, vol. 22(3).
   J. F. Lynch, D. Tang and W. M. Carey.
5. **Long-range propagation**
   April 1999, vol. 24(2)
   E. S. Livingston, A. Tolstoy and P. F. Worcester
6. **High-frequency acoustics**
   January 2001, vol. 26(1).
   J. A. Simmen, S. J. Stanic and R. R. Goodman
7. **High-frequency sediment acoustics**
   July 2002, vol. 27(3)
   E. I. Thorsos and M. D. Richardson

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* Intellectual overlap with contemporary TC: Underwater Communication, Navigation and Positioning

8. **Marine mammals and noise**
   January 2003, vol. 28(1) and April 2003, vol. 28(2).
   J. Potter and P. L. Tyack
9. **Geoacoustic inversion in range-dependent environments**
   July 2003, vol. 28(3) and January 2004, vol. 29(1).
   N. R. Chapman, S. Chin-Bing, D. King and R. Evans
10. **Non-Rayleigh reverberation and clutter**
   April 2004, vol. 29(2).
   D. A. Abraham and A. P. Lyons
11. **Science and engineering advances in exploring the Asian marginal seas**
   October 2004, vol. 29(4).
   J. F. Lynch and P. H. Dahl
12. **Archival papers on ambient noise, bottom loss and fluctuation**
   April 2005, vol. 30(2)
   W. M. Carey
13. **Interaction of low- to mid-frequency sound with the ocean bottom**
   October 2005, vol. 30(4)
   C. W. Holland, R. Gauss, G. Frisk and N. Makris
14. **Capturing uncertainty in the tactical ocean environment**
   April 2006, vol. 31(2)
   E. S. Livingston, J. A. Goff, S. Finette, P. Abbot, J. F. Lynch and W. S. Hodgkiss

C. Other activity: 1988-2007

Other papers covering environmental acoustics were published in the journal apart from the special issue solicitations. Many of these were in the field of shallow water propagation, which saw growing activity in the 1990's. The connection of environmentally-induced acoustic field fluctuations with underwater system performance made *JOE* a suitable place for these articles. Other fields that are represented include acoustic measurement methods and computation modeling.

V. TIMELINE

A glance at the tables of contents of *IEEE JOE* and other journals covering ocean environmental acoustics gives one a sense of the progress of the overall subject, and how the emphasis has shifted (and expanded) over the decades. Additionally, there has been progress within specific sub-disciplines of environmental acoustics, such as surface-scattering or low-frequency transmission loss variability, which we will generally outline.

In the 1960's and 70's, the mathematical method improvements mentioned earlier were made. At this time, use of the parabolic form of the wave equation allowed efficient numerical solutions for theoretical investigations and practical predictions in strongly range-dependent environments. This extended capabilities beyond what was allowable with the adiabatic mode approximation, applicable to weakly range-dependent. Coupled-mode models were also developed and used, taking advantage of faster computers.

In the 1980's and 90's, vertical line array improvements led to significant advances in acoustic field structure and coherence studies. Also at this time, new oceanographic environmental sensors and vehicles were coming online, based in part on the same advances that led to the new acoustic systems, allowing more comprehensive experiments with better environmental measurements [71,72]. Furthermore, improved modeling capabilities in the 90's and new detailed observations of physical ocean features led to more accurate understanding of precise effects of specific features of realistically small dimension. Features contributing to acoustic field complexity and variability that had been difficult to effectively model became the subject of new investigation: heterogeneous seafloor layering, tilted seafloors, ocean fronts, turbulence-driven anomalies, internal waves of various types (these have wide frequency and wavelength spectra), fronts, and eddies.

In the 2000's, incredible data storage leaps enabled autonomous multi-channel measurements at high rate (dozens of channels at 10-kHz rate for many weeks). Systems were used aboard ships and in short-term moorings looking at short-period environmental effects [73]. They were also deployed autonomously on the seafloor, fostering advances in studies of acoustic effects of mesoscale-driven and tidal interference-driven (fortnightly) phenomena [74-78]. Computers continued to improve. Three-dimensional PE simulation, formerly difficult and costly, has accelerated in use over the last decade, with recognition in recent years that deflection of sound out of radial two-dimensional slices originating at a source may be more common than had been recognized.

The fundamentals of ocean environmental acoustics have not changed during the last 40 years, but new tools created over that time, mentioned earlier, have led to substantial progress in our understanding and our ability to document natural phenomena in the field. Observational verification is fundamental in ocean acoustics, as with all sciences. Steady improvement to digital acquisition systems, reduced power consumption, improved timing control and synchronization, and data storage capability, have each enhanced field efforts. In particular, studies involving sensor arrays and array processing have benefited. As a result of steady computer advances, ever more detailed definitive studies of scattering and propagation effects in ocean sound-speed structures too complex to yield to analytical methods have appeared throughout the period.

VI. EXAMPLE SUBDISCIPLINES

Many notable new findings or advances have been made over the 40-year time period. Here are some research threads that are now relatively mature, with many generations of papers available. Many of the citations given here refer to the seminal papers and other important papers in each field. Papers published more recently are cited here to allow interested readers the opportunity to examine progress.

- New theories and observations describing fluctuating basin-scale acoustic propagation [79,80].
- New inverse methods to determine seafloor properties (geoacoustic parameters) [81].
- Improved physical understanding of sub-bottom geo-acoustic effects. (Examples are permeable material effects, elastic media, shear/pressure wave interactions.) [82-84]
- New understanding of surface phenomena including sound generation, scattering and ducting effects of bubble clouds [85,86].
- Identification of stable long-range propagation qualities of potential use in acoustical monitoring of ocean climate state [87-89].
- Application of time reversal and matched field coherent processing [90].
- Marine mammal behavior and sound sensitivity [91,92].

In addition to those mature fields, there are some novel and creative new results in the recent literature, some applied. These are fields of rapid recent development. Representative recent articles are cited.

- Analysis of backscatter of low-frequency sound from distant fish schools [93].
- Establishment of array-based studies of sub-seafloor structure using ambient noise [94].
- Studies of coupled-mode or strongly horizontally refracted sound in coastal internal waves [95].
- Microseisms and seismic T-phase [96].

Many of these eleven example environmental acoustic sub-disciplines have a great deal of overlap, sharing investigators, data sets, and equipment. This is testimony to the broad curiosity of the scientists as well as the fact that many aspects of environmental ocean acoustics are closely intertwined and can be effectively studied in a comprehensive fashion.

VII. Summary

In the introduction of this brief history we have outlined the current purview of the OES Environmental Acoustics TC. A few ideas about how enabling technologies and the creative talents of engineers and scientists have fostered progress in this field have been presented. Activities of the *Journal of Oceanic Engineering* in this area were shown to accelerate between the mid 1980's and the present day. Many special issues on this subject were published, containing dozens of papers often written by coordinated investigators, with the papers often having important links to each other. A brief examination of how advancing technology fostered new research results was given, along with a short list of example fields of strong activity and progress.

The link between advancing technology of oceanographic measurements and data collection and research progress in this and other disciplines is strong. New tools coming on line, for example autonomous vehicles, ocean gliders, acoustically quiet sensor placements, and signal processing methods, ensure that this trend will continue.

Although achievements over the last 40 years in each and every area of environmental acoustics have been facilitated by technological advances, they have fundamentally resulted from the talents and efforts of the researchers.

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