Underwater acoustic technology: review of some recent developments

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***Abstract* - It is a truism to say that the relationship of science and technology is push-pull. This is illustrated regularly throughout the fields of ocean engineering and ocean science. It underlies this review for the particular case of underwater acoustics over the past decade. Developments are summarized apropos of the interests of the OES Technology Committee on Underwater Acoustics: (1) design, fabrication, and testing of acoustic instrumentation such as transducers, transducer arrays, hydrophones, sound sources, transponders, and recording systems; (2) use of acoustic instrumentation in the form of active and passive sonar systems for such applications as bottom mapping, underwater imaging, ocean measurement, observation and quantification of biological organisms, target surveillance and tracking; (3) modeling and prediction of ocean acoustic parameters, such as multipath arrival structure, scattering, reverberation, and noise, which influence sonar system performance. Related topics such as underwater acoustic communication, navigation, and positioning; sonar image processing; and inference of ocean acoustic parameters are addressed in separate, independent reviews. This review is a contribution to the 40th anniversary celebration of the OES.**

I. INTRODUCTION

Underwater acoustics is a vast discipline, as it treats the primary modality of underwater sensing and communication, namely sound. The interest of the IEEE Oceanic Engineering Society (OES) in underwater acoustics is in its technological aspects. The subject is still vast, which is apparent from cursory inspection of any Ocean Conference Proceedings or any volume of the IEEE Journal of Oceanic Engineering (JOE). The value of the occasional review is thus evident.

The present aims are to describe areas of active research and development, and to identify trends and directions, all with respect to technology. More specifically, the attempt is made to review the subject within the context of the Technology Committee (TC) on Underwater Acoustics.

It is noted at the outset that at least ten of the other fifteen TCs also have an interest in underwater acoustics, thus the matter of overlap is first addressed. The particular approach taken in this review is then defined, and an overview given at a high level. Some trends and directions are identified.

II. IMPORTANCE OF UNDERWATER ACOUSTICS TO THE OES

Underwater acoustics is a traditional subject of major interest to the OES. It is largely addressed within the scope of the TC on Underwater Acoustics. However, particular aspects are also addressed by or within other TCs too.

(1) The TC on Current, Wave, and Turbulence Measurement recognizes the contributions of Acoustic Doppler Current Profilers, acoustic Doppler velocimeters, acoustic Doppler and acoustic-pulse time-of-flight current meters, and correlation sonars. (2) The TC on Environmental Acoustics is concerned with the influence of the environment on sound propagation and scattering, and acoustic measurement of the environment, usually by so-called inverse methods. (3) The TC on Environmental Technology considers a range of oceanic engineering sensors and systems, including acoustic devices. Thus performance prediction of acoustic sensors as modified by the natural environment is of interest, as is the level of disturbance of these systems on the ocean, e.g., through sonar-induced effects on marine mammal behavior.

(4) Numerous data types are considered by the TC on Information Processing and Data Fusion. These include sonar imagery, which is explicitly mentioned in the statement of focus. The evolution of models that optimally classify acoustic signals from marine mammals is also part of the remit of this TC. (5) The TC on Maritime Security and Critical Infrastructure Protection encompasses all devices associated with monitoring, observation, and protection of, among other things, ocean infrastructure, resources, and ecosystems. Applicable technologies for gathering and processing acoustic information are addressed in the annual Homeland Security Technology Workshop. (6) By its nature, the TC on Oceanographic Instrumentation, Communication, Navigation, and Positioning is interested in new developments in oceanographic instrumentation, as well as standards for oceanographic measurements and data acquisition. Sonars and hydrophones are prominent oceanographic instruments and sources of data.

(7) In many respects, underwater acoustics and sonar signal processing are intrinsically connected. The TC on Sonar Signal and Image Processing emphasizes sonar data processing, for example, in connection with detection, classification, localization, tracking, inversion, and synthetic aperture sonar, but focusing on the signal and image processing aspects. (8) Acoustic systems of all frequencies are of interest to the TC on Underwater Communication, Navigation, and Positioning. Systems that determine location include long- and short-baseline acoustic systems. Positioning systems might exploit similar acoustic baselines, as well as Acoustic Doppler Current Profilers. (9) A growing area of interest identified by the TC on Unmanned Maritime Vehicles and Submersibles is that of

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sensors, which define the capabilities of autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs). Sidescan sonars, pencil-beam-scanning sonars, multibeam sonars, Acoustic Doppler Current Profilers, and towed arrays of hydrophones, are routinely being deployed on or from AUVs and ROVs.

(10) The TC on Ocean Policy and Education has a declared interest in issues associated with ocean resources management. Thus the effects of man-made sound on marine mammals, fish, and other organisms, which are currently and increasingly being regulated through legislation, fall within its scope.

The degree of overlap in interests in underwater acoustics within the ten TCs mentioned above may be judged by comparison with the statement of focus of the TC on Underwater Acoustics, whose domain encompasses many aspects of acoustics in the subsea environment. The principal concerns of this TC include: (1) design, fabrication, testing, and calibration of acoustic instruments such as transducers, transducer arrays, hydrophones, sound sources, sonar systems, and transponders; (2) use of acoustic instrumentation in the form of active and passive sonar systems for such applications as bottom mapping, underwater imaging, ocean measurement, observation and quantification of biological organisms, and target surveillance and tracking; (3) modeling and prediction of ocean acoustic characteristics, such as propagation, scattering, reverberation, and noise, which influence sonar system performance.

III. Approach Taken in Review

Clearly there are many ways to organize a review such as this. In light of a survey of Ocean Conference Proceedings and JOE over the past decade, it was decided to base the review on themes of special issues of JOE, supplemented by reference to other concurrent work reported in JOE.

In deciding what themes to include, the problem of overlap is encountered anew, but this time because of the multi-faceted nature of developments in underwater acoustics technology. For instance, a particular work [1] assesses the performance of the parametric sonar, based on the parametric acoustic array [2], in underwater communications. The work involves issues of transduction, nonlinear generation of the secondary difference-frequency signal in the medium, optimization of parameters, and determination of the signal-to-noise ratio, thus involving much more than the nominal subject of underwater acoustics. Ultimately, underwater communications may be improved, as through higher signal-to-noise ratio or less chance of interception, as in use of the sonar to excite a single mode.

Another work [3] describes manufacturing of rough surfaces for experimental studies of seafloor scattering. While the focus of the paper is on a fabrication method, the ultimate subject is testing of models for the propagation and scattering of sound over a rough seafloor.

In a third exemplary paper [4], four different methods for assessing bubble size *in situ*. This involves issues of propagation and scattering, including absorption, in a dispersive environment. Inversion of acoustic scattering data for bubble size distribution and concentration is important for sonar performance prediction, as well as the complex of problems associated with air-sea interactions.

IV. Themes of Special Issues of JOE, 1997-2007

These themes are listed in chronological order together with the guest editors and respective JOE volume and issue numbers and year.

Image processing for oceanic applications
C. de Moustier, E. J. Sullivan, and S. E. Hammil
JOE 22(1) 1997

Shallow-water acoustics
J. F. Lynch, D. Tang, and W. M. Carey
JOE 22(2, 3) 1997

Long-range propagation
E. S. Livingston, A. Tolstoy, and P. F. Worcester
JOE 24(2) 1997

Underwater acoustic communications
D. B. Kilfoyle, J. C. Preisig, and M. Stojanovic
JOE 25(1) 2000

Underwater Technology ‘98
H. Maeda, T. Ura, R. L. Wernli, and A. J. Healey
JOE 25(1) 2000

High-frequency acoustics
J. Stanic, and R. R. Goodman
JOE 26(1) 2001

Autonomous ocean-sampling networks
T. B. Curtin and J. G. Bellingham
JOE 26(4) 2001

Underwater Technology 2000
T. Ura and R. L. Wernli
JOE 27(1) 2000

Oceanic observatories
J. B. Edson, A. D. Chave, M. Dhanak, and
F. K. Duennebier
JOE 27(2) 2002

High-frequency sediment acoustics
E. I. Thorsos and M. D. Richardson
JOE 27(3) 2002

Marine mammals and noise
P. L. Tyack and J. Potter

JOE 28(1, 2) 2003

Geoacoustic inversion in range-dependent shallow-water environments
N. R. Chapman, S. A. Chin-Bing, D. King, and R. Evans
JOE 28(3) 2003; 29(1) 2004

Underwater image and video processing
H. Singh, X. Tang, E. Trucco, and D. Lane
JOE 28(4) 2003

Non-Rayleigh reverberation and clutter
D. A. Abraham and A. P. Lyons
JOE 29(2) 2004

Biology-inspired science and technology for autonomous underwater vehicles
P. R. Bandyopadhyay
JOE 29(3) 2004

Science and engineering advances in exploring the Asian marginal seas
J. F. Lynch and P. Dahl
JOE 29(4) 2004

Open ocean aquaculture engineering
D. W. Fredriksson, I. Tsukrov, and W. Paul
JOE 30(1) 2005

Archival papers
W. M. Carey
JOE 30(2) 2005

Synthetic aperture radar imaging of the ocean surface
R. Garello, R. Romeiser, and R. L. Crout
JOE 30(3) 2005

Interaction of low- to mid-frequency sound with the ocean bottom
C. W. Holland, R. Gauss, G. Frisk, and N. Makris
JOE 30(4) 2005

Capturing uncertainty in the tactical ocean environment
E. S. Livingston, J. A. Goff, S. Finette, P. Abbot, J. F. Lynch, and W. S. Hodgkiss
JOE 31(2) 2006

HF/VHF ocean surface radar
L. R. Wyatt, M. L. Heron, and R. Garello
JOE 31(4) 2006

Mine burial processes
R. H. Wilkens and M. D. Richardson
JOE 32(1) 2007

Many of these are directly concerned with underwater acoustics. Others may support developments in underwater acoustics or draw on these to advance the principal theme.

V. Some Recent Developments

Apropos of the TC on Underwater Acoustics, some recent developments are reviewed, as documented in JOE over the period 1997-2007. The cited developments are necessarily limited and should only be viewed as indicative, for no attempt is made to be comprehensive. The developments are grouped by broad category according to the principal concerns of the TC as listed above.

A. Design, fabrication, and testing of acoustic instruments

Developments in transducers, hydrophones, arrays of these, and larger sonar systems are ongoing. This may be suggested by some of the following examples. Vector hydrophones are being applied in direction-finding [5,6]. The effects of vector sensor placement on accuracy is being assessed [7]. Triplet arrays of hydrophones, with elements at the vertices of an equilateral triangle, are being used in reverberation analysis and inversion [8]. A planar hydrophone array is being focused in the nearfield to enhance the performance of a scanning sonar designed to search for buried objects [9]. Shading weights are being optimized for velocity sonar arrays conforming to hulls [10]. A sheet of polyvinyldifluoride (PVDF) is being used as the acoustic source of a chirp signal for backscattering measurement [11].

Commercially available parametric sonars are being used as sources in studies of seafloor scattering [12,13]. Parametric sonars are also being developed for special applications involving imaging of the seafloor and sub-bottom with respect to buried objects such as dumped munitions [14]. In the case of [12] and [13], the receiver array projects from the nose of an AUV, akin to the sword of a swordfish. In addition, the parametric sonar is mounted on a quasi-stationary structure, and the AUV is used bistatically to form a synthetic aperture. The same parametric sonar has been used in conjunction with horizontal and vertical receiving arrays to enhance detection of sub-bottom echoes [15].

Bistatic scattering geometries are also being used in studies of volumetric scattering from sediments [16]. Similar geometries are being studied to determine localization accuracy for various geometries and measurement errors [17]. A specific case of bistatic scattering, namely forward scattering, is being considered to detect inhomogeneities passing through a sonar beam [18].

B. Use of acoustic instruments

Two prominent classes of applications of acoustic instruments concern marine organisms and measurements of oceanographic properties. Some examples drawn from JOE are given.

Acoustic detection of zooplankton is well established, as is acoustic quantification under certain conditions [19]. New acoustic methods are being developed for the classification of zooplankton by means of scientific echo sounders operating at multiple ultrasonic frequencies [20,21]. A particular statistical approach based on measurement of the echo amplitude is being pursued *vis-à-vis* classification for both zooplankton and fish [22].

Acoustics is also being used in connection with behavioral studies of fish. Fish-tracking is an important element of such studies. In some cases, this is done by recording the position of fish echoes with split-beam echo sounder or multibeam sonar. An algorithm to track fish with a multibeam sonar is being experimentally tested [23]. A radically different form of fish-tracking is being considered: by tagging fish with passive acoustic receivers, which can then receive periodic signal transmissions from one or more sources. The design of the receiver is presented in [24].

Sound scattering is being used to detect benthic organisms too. One source of bottom reverberation, that of shell fragments, is being studied [25]. The contribution of shelled animals to both volumetric and bottom reverberation has been noted elsewhere [26].

Vocalization is inherent to many if not all marine mammals. It may be a primary means of communication. Certainly the song of the humpback whale is well known [27]. The hypothesis that the song is used by male humpback whales as a sonar to locate other whales on the breeding grounds is examined in detail in one work [28], and challenged in another [29].

Whales are innately sensitive to sound, and may be harmed by sound produced by human activities. This is acknowledged in two special issues of JOE, cited above in Section IV. In a more recent study, the effects of seismic sources used in geophysical explorations on whale behavior are observed [30].

Ocean measurements, or measurements of oceanographic properties, are of considerable interest to the TC on Underwater Acoustics, as sonar performance depends on these. Thus, the JOE special issues on "Shallow-water acoustics," "Long-range propagation," "High-frequency acoustics," "High-frequency sediment acoustics," "Geoacoustic inversions in range-dependent shallow-water environments," and "Interaction of low- to mid-frequency sound with the ocean bottom" are of interest insofar as ocean properties are being determined.

C. Modeling and prediction of ocean acoustic characteristics

As in the case of measurements of oceanographic properties, modeling and prediction of ocean acoustic characteristics are important in studies of sonar performance. The way in which these properties affect propagation, scattering, and reverberation is of direct interest, as is the effect of ambient noise.

These subjects are frequently addressed in special issues of JOE. In addition to those cited in the previous section apropos of ocean measurements, the special issues on "Marine mammals and noise" and "Archival papers" are noteworthy. A number of contributions on the theme of "Capturing uncertainty in the tactical ocean environment" address, implicitly or explicitly, effects of oceanographic properties on sonar performance.

VI. Trends and Directions

The themes alone of the majority of JOE special issues indicate significant areas of development within or contributing to underwater acoustics. Further examination of regular contributions to JOE and papers to Ocean Conference Proceedings over the past decade supports the currency of interest in these developments and define trends and directions. Some of these are addressed in summary fashion here, again without attempting to be comprehensive. Basic documentation in each mentioned area is provided in special issues of JOE.

Marine mammals and other marine organisms are receiving increasing attention because of their innate and remarkable acoustic sensing capabilities and evident or potential sensitivity to sound, especially that from human activities, e.g., geophysical explorations using seismic arrays; offshore oil, gas, and mineral extractions; shipping; and some sonar use. At the same time, biomimetic sonar may achieve substantially enhanced performance with respect to the detection and classification of objects. It is believed, with very good reason, that there is much for the sonar designer to learn from animal sonars.

The shallow-water zone defines much of the worldwide coastal zone. Understanding propagation and scattering of sound in shallow water is essential to many applications, including bathymetric mapping, underwater communications, and application of inverse methods to determine environmental properties both in the water column and in the sub-bottom.

High-frequency acoustics is widely used for sensing marine organisms in the water column. It is being increasingly used for sensing benthic organisms and biological disturbances, such as bioturbation, on the seafloor, in all cases with high spatial and temporal resolution. It is also providing information on suspended sediment and its movement. Understanding processes of sediment accretion and erosion is essential to many coastal environmental studies, buried-object detection, and marine ecosystem function through interaction with the benthic habitat.

Uncertainty in knowledge of the physical properties of the marine environment, including for example sound speed profile, seafloor characteristics, and the influence of internal and solitary waves, is being treated with increasing rigor. Far from being ignored in so-called mean-field, or mean-environment, analyses, it is being incorporated routinely in analyses. A tacit aim of many of these analyses is determination of the quality and stability of modeling results.

Major advances have been made in the field of unmanned underwater vehicles over the past several decades, literally effecting a revolution in oceanographic measurement. The past decade has witnessed profound leaps in AUV technology, with significant documentation in Ocean Conference Proceedings. As platforms for acoustic sensors, AUVs are supporting very high-resolution mapping operations, for example, of the seafloor and hydrothermal vents, including their plumes.

Advances in signal and image processing, as in the processing of sidescan sonar images, is encouraging the application of sidescan sonar in studies of the seafloor and seafloor processes. These applications are steadily accompanied by discoveries, as of ancient shipwreck sites and now-submerged human settlements.

Three prominent areas of neglect in this review, among others, are those of quality assurance of acoustic measurements, applications of image processing in acoustic detection and classification, and redundancy in acoustic measurements. The community is very cognizant of the importance of the first, which is being actively pursued through calibration studies, as in the development and application of protocols. Image processing methods are significantly refining acoustic detection and classification methods for certain problems and/or certain operating conditions. Redundancy in acoustic measurements is being addressed through instrument bandwidth, whether done through multiple narrow bands or through genuinely wideband operations. These and other important areas deserve explicit attention in future reviews.

VII. Summary Comments

Advances in underwater acoustics technology are occurring in many areas. Just a few are noted in the previous section. Outstanding sources of information on these advances are contained in the Ocean Conference Proceedings and the IEEE Journal of Oceanic Engineering (JOE). The first documents immediate and ongoing advances; the second presents information on advances through archival publication.

It is appreciated that some works-in-progress presented at Oceans Conferences do ultimately reach JOE, thanks especially to guest editors working cooperatively with the JOE Editor-in-Chief. Much other work remains in the Ocean Conference Proceedings. This literature, while unreviewed, serves the purpose of timely communication, and the busy ocean engineer may choose to pursue the next development or project, recognizing the value of the working product, for example, a new instrument or other tool. Professional ocean engineers generally appreciate the value of a rigorous peer review of work and the benefits of documentation of new work in an archival journal.

The mentioned publications are literally treasure troves of information on the technology of underwater acoustics, not to mention the broader subject of ocean engineering. Students are encouraged to explore these to acquaint themselves with important technological developments.

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