Evolving Trends and Challenges in Applied Underwater Acoustic Modeling

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Abstract - **Prominent trends and challenges in applied underwater acoustic modeling have been motivated largely by marine-mammal protection research focused on the mitigation of naval-sonar, seismic-source, and pile-driving noise. Channel modeling, underwater-acoustic networks, and communications technologies have evolved to support the increased bandwidths needed for undersea data collection. Energy-flux models, not traditionally used in naval sonar applications, have proved useful for assessing marine-mammal impacts. Developments in inverse sensing include seismic oceanography, which employs low-frequency marine seismic reflection data to image ocean dynamics. Interest in the polar regions has increased due to the well-publicized effects of global warming. Collectively, these trends have added new analytical tools to the existing inventory of propagation, noise, reverberation, and sonar performance models.**

I. Introduction

This paper identifies evolving trends and challenges in applied underwater acoustic modeling. The most prominent trends have arisen in response to new regulatory initiatives that place restrictions on uses of sound in the ocean. The mitigation of marine-mammal endangerment is now an integral consideration in acoustic-system design and operation. Marine-mammal protection research has focused on simulating naval-sonar, seismic-source, and pile-driving noise. Channel modeling, underwater-acoustic (UWA) networks, and advanced communications technologies have evolved to accommodate the increased bandwidths needed for undersea data collection and transfer. Energy flux models, not traditionally used in naval sonar applications, have proved useful in characterizing and predicting the propagation of acoustic signals in support of marine-mammal protection efforts. These recent trends have added to the existing inventory of modeling tools [1].

II. Evolving Challenges

A. Passive Acoustic Technologies

Passive acoustic technologies have advanced in terms of hardware and software. Archival and real-time passive acoustic arrays now constitute economical approaches for mesoscale monitoring of marine areas; these arrays can be used to monitor vocal marine life in areas otherwise difficult to survey by traditional visual methods. Fixed autonomous passive-acoustic arrays can sample continuously for prolonged periods of time in all weather conditions, thus allowing for assessments of seasonal changes in both the distribution and acoustic behavior of individual animals without the disturbance of survey vessels or aircraft. Passive acoustic monitoring (PAM) is most useful when employed in the context of the acoustic behavioral ecology of the animals in regionally and seasonally appropriate contexts. The utility of PAM is improved when adequate information is available regarding individual, group, population, and species sound-level usage [2].

B. Seismic Oceanography

Seismic oceanography (SO) employs low-frequency marine seismic reflection data to image thermohaline fine-structure in the oceanic water column [3]. Reflection seismology can image such fine structure over large areas based on oceanic temperature contrasts of only a few hundredths of a °C. The resulting images illuminate diverse oceanic phenomena including thermohaline fine structure, fronts, water-mass boundaries, internal-wave displacements, internal-tides, eddies, turbulence, and lee waves [4, 5]. These low-frequency reflections can be further processed to produce quantitative estimates of sound speed (and thus ocean temperature), turbulence dissipation, and vertical-mode structure over full ocean depths, provided oceanic fine-structure reflections are present [3].

Seismic-reflection profiling was applied to the study of large-scale physical oceanographic processes in the Gulf of Cadiz and along the western Iberian coast [6]. This location coincided with the path of the Mediterranean Undercurrent. The multi-channel seismic reflection method provided clear images of the thermohaline fine structure with a horizontal resolution approximately two orders of magnitude higher than conductivity-temperature-depth (CTD) casting. Three distinct seismic reflectivity zones were identified: North Atlantic Central Water, Mediterranean Water, and North Atlantic Deep Water.

C. Arctic Acoustics

An overview of the acoustic properties of sea ice assessed the influence of ice-canopy and water-column properties on acoustic transmission loss for propagation within 20 km of a sound source situated at a depth of 20 m [7]. The influence of the ice canopy was first assessed as a perfectly flat surface, and then as a statistically rough surface. A Monte Carlo method was used for the inclusion of ice deformation and roughness. This involved the creation of sets of synthetic ice profiles based on a given sea-ice thickness distribution followed by statistical methods for combining the output of individually evaluated ice realizations. The experimental situation considered was that of an AUV operating within 50 m of the surface. This scenario was associated with the frequency band 9-12 kHz and a horizontal range up to 20 km. The situation was evaluated for a set of typical ice statistics using ray and

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beam acoustic propagation techniques. The observed sound speed profile resulted in a strong defocusing of direct-path signals at ranges of 9-20 km and depths shallower than 50 m. The reduction in signal strength of the direct path created areas where the influence of surface-reflected paths became significant. At ranges of 9-20 km, the inclusion of a perfectly flat ice layer reduced the transmission loss by 15-50 dB. When the ice layer was included as a rough surface layer, the results showed an increase of signal strength of up to 8 dB in the small regions of maximum defocusing.

The Navy operational global atmospheric prediction system (NOGAPS) was replaced in March 2013 by the Navy global environmental model (NAVGEM) as the US Navy's operational atmospheric-forecast system [8]. As part of this transition, both GOFS (global ocean forecast system) and ACNFS (Arctic cap nowcast/forecast system) switched from using NOGAPS to NAVGEM for atmospheric forcing.

D. Advanced Computational Techniques

1) Cellular Automation (CA): CA is an alternative computational technique that can be used to model the behavioral response of dynamic systems. Since this method allows flexibility in the application of various types of boundary conditions, it is particularly attractive for use in developing alternative propagation models for ocean acoustics. The modeling scheme creates a profile of propagation loss versus range in an acoustic medium. It was shown that modeling complex boundary conditions could be performed easily with CA methods. As with other modeling methods, however, the computational time increased when solution refinement increased. An alternative multi-grid modeling scheme was shown to increase the performance time of the CA method significantly. This improvement was dependent upon the total number of global grid points inside the multi-grid domain. The end result showed that a multi-grid system (with fewer nodal points) produced accurate results that could replicate a uniform grid that utilized a larger number of nodal points [9].

2) Ocean-acoustic interferometry: The Green's function was approximated from the cross-correlation of sound recorded at two locations in a shallow-water oceanic waveguide; this approach was referred to as ocean-acoustic interferometry [10]. Both active-source and ship-dominated ambient noise interferometry were considered. A stationary-phase argument was used to relate cross-correlations from active sources to the Green's function between hydrophones. A vertical line source, a horizontal line source, and a horizontal hyperbolic source were considered. The theory and simulations were found to be in agreement with those presented by previous investigators. Empirical Green's function approximations were determined from ship-dominated ocean noise cross-correlation. Direct and secondary path travel times between hydrophones were determined; these results compared favorably with simulated data. Averaging the cross-correlations between equi-spaced horizontal line array hydrophone pairs was shown to increase the signal-to-noise ratio (SNR). Analysis of temporal variations in the cross-correlations confirmed that, at any given time, the signal is generally dominated by one or two sources. Cross-correlations obtained from data collected during a tropical storm were shown to be clearer than those collected at other times. This was thought to be due to a reduction in nearby shipping and an increase in the overall sound levels caused by increased wave action resulting from the storm. Two practical applications were derived from this work: (1) diagnosis of a multichannel hydrophone array; and (2) array hydrophone self-localization.

3) Adjoint models: Adjoint models are powerful tools for many studies that require an estimate of the sensitivity of model output with respect to input. Actual fields of sensitivity are produced directly and efficiently, which can then be used in a variety of applications, including data assimilation, parameter estimation, stability analysis, and synoptic studies. The use of adjoint models as a tool for sensitivity analysis can be described using simple mathematics [11].

4) Statistical robustness: Statistical robustness deals with deviations from fundamental distributional assumptions [12]. Many practical engineering problems rely on the Gaussian distribution of the data, which in many situations is well justified. This enables a simple derivation of optimal estimators. However, this nominal situation is useless if the estimator was derived under distributional assumptions on the noise and signal that do not hold in practice. Measurement campaigns in both radar and sonar have confirmed the presence of impulsive (heavy-tailed) noise, which can cause optimal signal processing techniques (especially those derived using the nominal Gaussian probability model) to be biased or to break down. Measures of robustness can be defined including the influence function (IF), the breakdown point (BP), and the maximum bias curve (MBC). Collectively, robust estimators are useful in locating parameters instead of the conventional sample mean.

E. Energy Flux Formulations

Simple derivations of transmission-loss formulas based on an energy-flux approach also allow for boundary losses [13]. A universal graph was provided to delineate five acoustic-propagation regions: (1) spherical spreading; (2) cylindrical spreading; (3) three-halves spreading due to mode stripping; (4) single mode; and (5) bottom path. An integral formula was derived to estimate the averaged steady-state transmission loss for a source-receiver pair in a channel whose environmental parameters varied slowly with range [14]. The derivation was based on the theory of ray acoustics with lossy specular reflection from the boundaries. The averaging process eliminated all but gradual changes with range of the transmission loss, and dependence on the depth of each point was retained.

The range-averaged intensity model (RAIM) [15], originally developed by Weston [13], is based on a probabilistic description of the intensity field in terms of cyclic ray beams. The contributions of these cyclic ray beams are functions of their probability of presence at the receiver depth (as obtained from their cycle length) and of the classical geometrical spreading factor.

The energy-flux formulation of waveguide propagation is closely related to the incoherent mode sum, and its simplicity has led to development of efficient computational algorithms for reverberation and target echo strength [16]. However, the formulation lacks the effects of convergence or modal interference. By starting with the coherent mode sum, rejecting the most rapid interference, and retaining beats on a scale of a ray-cycle distance, it was shown that convergence could be included in a hybrid formulation requiring minimal extra computation. Three solutions were offered by evaluating the modal intensity cross terms using Taylor expansions: (1) in the most efficient approach, the double summation of the cross terms was reduced to a single numerical sum by solving the other summation analytically; (2) a local range average; and (3) a local depth average. Favorable comparisons were made between these three solutions and the wave model Orca with, and without, spatial averaging in an upward refracting duct. It was also shown that the running range average was very close to the mode solution (excluding its fringes), given a relation between averaging window size and effective number of modes which, in turn, is related to the waveguide invariant.

Integrating the energy-flux (angular-spectrum) method for shallow-water reverberation with physics-based rough-bottom scattering and sediment-volume scattering models resulted in a simple relationship between the classic seabed scattering cross sections and the modal scattering matrix in waveguides [17]. The shallow-water reverberation expression in the angular domain could be used for predicting reverberation in a Pekeris waveguide. Moreover, a corresponding expression in the modal domain could be used for predicting shallow-water reverberation in a non-Pekeris waveguide.

F. Shallow Water Acoustics

Shallow-water ambient noise measurements were conducted in a brackish-water environment where hydrophones were located at depths of 15-20 m [18]. The measurement site was well isolated from ship traffic noise, which made it possible to study wind-generated effects also at lower frequencies. Due to the near-field conditions, the ambient-noise levels were not significantly distorted by propagation effects. The measured ambient noise spectra showed a distinctive bandpass structure characteristic of the dipolar source distribution formed by bubbles in breaking waves. The observed sharp spectral declines below 500 Hz were most likely caused by the resonances of oscillating bubble clouds created by breaking waves. The low-frequency range of the declines may be attributed to the larger bubble sizes in fresh and brackish waters compared to saline water. High-frequency ambient noise spectra exhibit a dual-slope spectral pattern above 1 kHz due to increased attenuation above 10 kHz at intermediate and high wind speeds. The study demonstrated that absorption in brackish and fresh water, unlike in ocean water, tends to decrease above a frequency of 10 kHz due to the low proportion of small bubbles in a bubbly mixture created by breaking waves. The excess high-frequency attenuation in the spectra cannot therefore be directly attributed to the effects of absorption in a bubbly mixture. Measured ambient noise spectra were modeled as a cumulative power spectrum of individual resonating bubbles distributed in a radius range of 0.01-3.3 mm using a model for the sound generated by breaking waves. The dual-slope pattern observed in the brackish water spectra was mostly explained with a bubble-size distribution that has a distinctive maximum at radii between 0.1 and 0.3 mm, and a relative drop in bubble density below a radius of 0.1 mm. A physical explanation for this is the fact that small bubbles have a tendency to coalesce more in fresh and brackish water than in sea water.

G. Biological Noise Impacts

Studies of fish hearing and physical sound propagation models can be used to predict the detection distance of reefs for settling larval fish, and the potential impact of anthropogenic noise [19].

Very-low-frequency sounds 1-100 Hz propagate over long distances in the ocean sound channel. Weather conditions, earthquakes, marine mammals, and anthropogenic activities influence sound levels in this frequency band [20]. Weather-related sounds result from interactions between waves, bubbles entrained by breaking waves, and the deformation of sea ice. Earthquakes generate sound in geologically active regions, and earthquake T-waves propagate throughout the oceans. Blue and fin whales generate long-duration sounds near 20 Hz that can dominate regional ambient noise levels seasonally. Anthropogenic sound sources include ship propellers, energy extraction, and seismic air guns, and have been growing steadily. The increasing availability of long-term records of ocean sound now provide new opportunities for a deeper understanding of natural and anthropogenic sound sources and potential interactions among them.

Underwater acoustic recordings were examined for six floating production storage and offloading (FPSO) vessels moored off Western Australia [21]. Monopole-source spectra were computed for use in environmental impact assessments of underwater noise. Given that operations on the FPSOs varied over the period of recording, and were sometimes unknown, a statistical approach was used to estimate the noise levels. No significant or consistent aspect dependence was found for the six FPSOs; furthermore, noise levels did not scale with FPSO size or power.

The quadrature method was utilized to solve the wave equation with van der Pol boundary conditions [22]. These particular boundary conditions create chaotic acoustical vibrations typical of those generated by noise signals radiated from underwater vehicles.

A computer model was developed to simulate low-frequency (< 1000 Hz) acoustic signals produced by a wave energy device in coastal environments [23]. These signals were analyzed with the aid of the audiogram of marine mammals, in this case the harbour seal. This enabled an estimate of the levels of acoustic noise experienced by marine mammals due to the presence of ocean-deployed devices. Propagation of the underwater acoustic signals was modeled using the finite-element method with appropriate boundary conditions at the sea surface and the sea floor.

Underwater noise sources associated with horizontal-axis tidal turbines were modeled to assess their potential impact on shallow-water marine environments [24]. The requirement for device-noise prediction as part of environmental impact assessment was considered in light of the limited amount of measurement data available. Noise sources included self noise, interaction noise, and hydro-elastic noise. In future studies, machinery (generator) noise and cavitation noise also need to be considered. The dominant flow-generated noise sources were modeled using empirical techniques. These preliminary assessments indicated that this noise source alone is not expected to cause permanent or temporary threshold shift in the marine animals studied.

The OAWRS (ocean acoustic waveguide remote sensing) approach for studying marine life was first demonstrated in 2003 in the Mid-Atlantic Bight off the northeast US coast [25]. Using a single 1-second duration transmission of a linear frequency modulated (LFM) waveform, OAWRS surveyed an area as large as the state of Connecticut. The imaging was effectively instantaneous because the entire region was surveyed in less time than it would take a marine organism to traverse a single OAWRS resolution cell. The OAWRS approach was used again with the National Marine Fisheries Service (NMFS) annual herring survey of the Gulf of Maine and Georges Bank to study herring group behavior associated with spawning in September-October 2006. In both experiments, a vertical source array transmitted sound in the frequency range 390 - 1400 Hz, which is near the swimbladder resonance frequency for many fish species in the survey regions. Echoes scattered from fish were received by a towed horizontal receiving array. Instantaneous snapshots of the ocean environment over thousands of km^2 were then formed by charting acoustic returns in horizontal range and bearing by temporal matched filtering and beamforming. A detailed technical description of the OAWRS approach was provided in a set of six appendices.

Songs of humpback whales (*Megaptera novaeangliae*) in the Stellwagen Bank National Marine Sanctuary (in the Gulf of Maine) were reduced concurrent with transmissions of an OAWRS experiment approximately 200 km away during an 11-day period in the autumn of 2006 [26]. The occurrence of songs was observed for 11 days before, during, and after the experiment and then compared with songs over the same 33 calendar days two later years. The lack of humpback-whale songs during the OAWRS experiment was the most substantial signal in the data. These findings demonstrated the greatest distance over which anthropogenic sound has been shown to affect vocalizing baleen whales, and the first time that active acoustic fisheries technology has been shown to have this effect. It was suggested that the suitability of OAWRS technology for *in-situ*, long-term monitoring of marine ecosystems should be reconsidered in light of its possible effects on non-target protected species. These findings were disputed [27] by showing that humpback-whale vocalization behavior was synchronous with peak annual Atlantic herring spawning processes in the Gulf of Maine. With a passive, wide-aperture, densely-sampled, coherent hydrophone array towed north of Georges Bank in an autumn 2006 OAWRS experiment, vocalizing whales could be instantaneously detected and localized over most of the Gulf of Maine ecosystem in a roughly 400-km diameter area by introducing array gain of 18 dB, orders of magnitude higher than previously available in acoustic sensing of whales. With humpback-whale vocalizations consistently recorded at roughly 2000 d^{-1}, it could be shown that a constant humpback-whale song occurrence rate indicated that the OAWR transmissions had no effect on humpback songs. It was suggested that the reported song occurrence variation [27] was consistent with natural causes other than sonar.

Underwater noise is now classed as pollution in accordance with the European Union’s Marine Strategy Framework Directive (Directive 2008/56/EC dated 17 June 2008) [28]. Noise from shipping is a major contributor to the ambient noise levels in ocean, particularly at low (< 300 Hz) frequencies. Patterns and seasonal variations of underwater noise in the Celtic Sea were studied using a coupled ocean model (POLCOMS - Proudman Oceanographic Laboratory Coastal Ocean Modelling System) and an acoustic model (HARCAM) in the year 2010. Two sources of sound were considered: (i) noise representing a typical large cargo ship, and (ii) noise from pile-driving activity. In the summer, when the source of sound is on the onshore side of the boundary front, the sound energy is mostly concentrated in the near-bottom layer. In winter, the sound from the same source is distributed more evenly in the vertical. The difference between the sound level in summer and winter at 10 m depth is as high as 20 dB at a distance of 40 km. When the source of sound is on the seaward side of the boundary front, the sound level is nearly uniform in the vertical. The transmission loss is also greater (~ 16 dB) in the summer than in the winter for a shallow source, while it is up to ~ 20 dB for a deep source at 30 km.

Ramp-up (or soft-start procedures) employ a gradual increase in the source level in order to mitigate the effects of sonar transmissions on marine mammals [29]. The levels of sound that killer whales (*Orcinus orca*) were exposed to from a generic sonar operation were preceded by different ramp-up schemes. In this model, ramp-up procedures were shown to reduce the risk of killer whales receiving sounds of sufficient intensity to affect their hearing. The effectiveness of the ramp-up procedure depended strongly on the assumed response threshold and differed with ramp-up duration, although extending the duration of the ramp up beyond 5 min did not add much to its predicted mitigating effect. The main factors that limited effectiveness of ramp up in a typical antisubmarine warfare (ASW) scenario were high source level, rapid-moving sonar source, and long silences between consecutive sonar transmissions. It was suggested that this exposure-modeling approach could be used to evaluate, and optimize, mitigation procedures.

H. Seismic Source Modeling

Modeling sound propagation in the ocean is an essential tool to assess the potential risk of air-gun shots on marine mammals [30]. Based on a 2½D finite-difference code, a full waveform modeling approach was presented that determined both sound-exposure levels of single shots and cumulative sound-exposure levels of multiple shots fired along a seismic line. Band-limited point-source approximations of compact air-gun clusters deployed in polar regions were used as sound sources. Marine mammals were simulated as static receivers. Applications to deep- and shallow-water models, including constant and depth-dependent sound velocity profiles of the Southern Ocean, showed dipole-like directivities in the case of single shots, and tubular cumulative sound exposure level fields beneath the seismic line in the case of multiple shots. Compared to a semi-infinite model, an incorporation of seafloor reflections enhanced the seismically induced noise levels close to the sea surface. Refraction due to sound velocity gradients and sound channeling in near-surface ducts were evident, but affected only low-to-moderate levels. Therefore, exposure-zone radii derived for different hearing thresholds were almost independent of the sound-velocity structure. With decreasing thresholds, radii increased according to a spherical (20 $\log_{10} r$) law in case of single shots and according to a cylindrical (10 $\log_{10} r$) law in case of multiple shots. A doubling of the shot interval diminished the cumulative sound exposure levels by 3 dB and halved the radii. The ocean bottom properties only slightly affected the radii in shallow waters if the normal incidence reflection coefficient exceeded 0.2.

The Bureau Veritas Rule Note [31] addressed the underwater radiated noise (URN) emitted by any self-propelled ship. It aimed to control and limit the environmental impact on marine fauna in both shallow and deep waters. The measurement procedures focused on uncertainty, with the goal to improve measurement repeatability and to control measurement uncertainty. Three classes of vessels were addressed: controlled, advanced, and specified. The maximum underwater radiated noise levels corresponding to the notation URN-controlled vessel were the lowest (most stringent), with levels being progressively relaxed for advanced and specified vessels. Regarding bioacoustic impacts, the introduction of underwater noise in the marine environment was linked to the impact on the marine fauna. In reference to the European Directive 2008/56/EC and Commission Decision 2010/477/EU, the Descriptor 11.2 "Continuous low frequency sound" was to be assessed. [Directive 2008/56/EC of 17 June 2008 established a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive); Commission Decision 2010/477/EU of 1 September 2010 established criteria and methodological standards on good environmental status of marine waters.] For that purpose, a dedicated assessment of the pressure levels of the ⅓-octave bands centered at 63 Hz and 125 Hz are to be performed. The measurement procedure and post-processing described in this Rule Note implicitly enable this assessment. For specific cases of vessels operating in a restricted and defined area, an additional report on the species of underwater noise concern could be requested.

Underwater noise levels were predicted using an integrated modeling approach incorporating: (1) an airgun array source model; (2) a broadband Nx2D propagation model based on a modified version of RAM; and (3) environmental databases comprising high-resolution bathymetry, historical CTD casts, and geoacoustic properties of the seabed [32]. An airgun array source signature model was developed for use in predicting the acoustic source levels of seismic arrays; this model was based on the physics of the oscillation and radiation of airgun-generated bubbles and was validated against actual airgun data. Broadband sound propagation was approximated by modeling transmission losses at ⅓-octave band center frequencies. Noise levels were then computed by subtracting the transmission losses from the respective ⅓-octave band airgun array source levels. Seasonal variations in the sound-speed profiles were derived using principal-component analysis of a large collection of historical CTD data. The resulting noise level estimates were used to define impact zones around survey vessels where marine mammals could be expected to exhibit disturbance reactions to airgun noise.

I. Pile-Driving Noise

Subacoustech Environmental undertook a study on behalf of Royal Haskoning DHV to assess the impact of underwater noise produced during pile-driving operations in the installation of wind-turbine foundations at the Dudgeon Wind Farm site in the North Sea (this site is situated north of Norfolk). The levels of underwater noise from the installation of jacket piles and monopiles were estimated and assessed using a semi-empirical underwater sound propagation model INSPIRE (currently version 3.4.2). This model enabled the behavior of noise (versus range from the pilings) to be estimated for varying water depths, pile sizes, blow energies and piling locations utilizing archival measurements of piling noise in UK waters. The model was validated against these archival measurements. INSPIRE was used to predict expected noise levels on 180 transects radiating outwards from the various piling locations at the Dudgeon site, and the results were further synthesized to produce impact-range contours [33].

Offshore windfarm developments may impact protected marine-mammal populations and thus require appropriate assessment under the EU Habitats Directive [34]. A framework was developed for assessing population-level impacts of disturbance from piling noise on a protected harbour seal population in the vicinity of a proposed wind farm development in the North Sea off northeast Scotland. The predicted propagation of noise resulting from the piling operations required to install the wind turbine foundations was modeled using INSPIRE. The frequency-weighted scale [dBht(species)] was validated as a metric for the assessment of the behavioral and audiological effects on underwater animals of anthropological underwater noise [35].

J. Underwater Acoustic Networks and Communications

Four pervious reviews of acoustic communications (Acomms) were updated [36]. Specifically addressed were: (1) channel models; (2) equalizers; (3) time reversal and passive phase conjugation; (4) OFDM and MIMO; (5) diversity; (6) acquisition and synchronization; (7) coding; (8) networks; and (9) stealth. A comprehensive technology assessment of the current state-of-the-art in underwater acoustic sensor networks was organized according to physical layer, MAC (or data link) layer, and routing (or network) layer [37]. A recent review of underwater acoustic networking served both as an introduction to the subject and a summary of existing protocols, and further described the state-of-the-art for all networking facets that are relevant to underwater applications [38].

An acoustic communication system is inherently wideband in the sense that the bandwidth is not negligible with respect to its center frequency [39]. The channel can have a sparse impulse response, where each physical path acts as a time-varying low-pass filter, and motion introduces additional Doppler spreading and shifting. Surface waves, internal turbulence, fluctuations in the sound speed, and other small-scale phenomena contribute to random signal variations. There are presently no standardized models for the acoustic channel fading, and experimental measurements are often conducted to assess the statistical properties of the channel at particular deployment sites.

A collection of systematic measurements was reviewed to characterize shallow-water acoustic propagation channels for application to underwater communications [40]. The objective of channel sounding is to measure the channel impulse response as a function of time and time delay. *In situ* measurements were performed in different frequency bands, geographical areas, seasons, deployment geometries, and used different probe-signal parameters. The survey comprised measurements from northern Europe covering the continental shelf, Norwegian fjords, a sheltered bay, a channel, and the Baltic Sea. These measurements were conducted in frequency bands between 2 and 32 kHz. The study compared a variety of channels that differed in many ways, frustrating attempts to define a typical acoustic communication channel. Forward-propagation effects are relevant to channel models suitable for the design of modulation schemes, network protocols, and simulation environments.

Channel simulators can be grouped according to simulation method: (1) direct replay – reproduce measured channel conditions; (2) stochastic replay – generate channel conditions with statistical properties similar to field measurements; and (3) model-based simulation – generate channel conditions by physical modeling based on marine environmental information [41]. The meaning of the term *channel conditions* can vary from simulator to simulator; while it often refers to the time-varying impulse response (TVIR), it may also denote noise models or more elaborate channel-characterization methods. One channel simulator for underwater acoustic channels (MIME) mimics the acoustic channel by passing the transmit signal through a channel modeled as a TVIR, where delay and time both are sampled at the sampling rate of the signal. Three simulation modes were included: direct replay of a measured TVIR; stochastic replay of a measured TVIR; and model-based simulation. Validation used data from two sea experiments in concert with a diverse selection of communication schemes. Good agreement was found between bit-error rates and packet-error rates of *in situ* transmissions and simulated transmissions. Long-term error statistics of *in situ* signaling were also reproduced in simulation when a single channel measurement was used to configure the simulator. The implication is that this type of channel simulator can be used to test new modulation schemes in a realistic fashion without going to sea, except for the initial data collection.

In many emerging applications, underwater-acoustic networks (UANs) are integrated into larger networks comprising terrestrial, radio, and satellite networks [42]. A cross-disciplinary project called Coastal and Arctic Maritime Operations and Surveillance (CAMOS) sensor networks, developed at NTNU (Norwegian University of Science and Technology), has been developing a robust communication framework that integrates underwater, terrestrial radio and satellite communications in a resilient infrastructure with specific attention given to Denial-of-Service (DoS) attacks. In this way, a multitude of applications can be supported with specific attention given to sensor networking in the Arctic region. Denial-of-Service attacks are designed to prevent UAN nodes from utilizing all or part of their network connectivity. Countermeasures comprise two basic approaches: each node monitors the packet-forwarding activities of its neighbors and rates the transmission reliability of all alternative routes to a particular destination node; and the neighbors of any single node collaborate in rating the node according to how well the node executes the functions requested of it [43].

Underwater acoustic (UWA) communications are complicated by doubly-spread channels (i.e. large time spreads resulting from multipath and Doppler). This ill-conditioned problem exists for conventional orthogonal signal-division multiplexing (OSDM), which employs a single transducer in the receiver. The introduction of a multichannel receiver was found to be effective against the ill-conditioned problem [44]. A UWA communication system using OSDM was proposed that measured the multipath profile without an adaptation or interpolation process to achieve stable communication in doubly-spread channels. It was shown that OSDM with a multichannel receiver was attractive in terms of communication quality. Moreover, ODSM achieved a far better bit-error rate (BER) performance compared to the other schemes in both static and dynamic channels with various input signal-to-noise ratios. However, the complexity was less than that achieved using a single-carrier with a decision-feedback equalizer. They suggested that OSDM may be a reliable communication alternative for UWA under conditions of multipath and Doppler spread, as in shallow water.

A statistical model for UWA channels was developed that took into account physical aspects of acoustic propagation as well as the effects of inevitable random channel variations [45]. Channel variations were classified into small scale and large scale based on the notion of the underlying random displacement being on the order of a few, or many wavelengths, respectively. Based on this model, a computationally efficient channel simulator was proposed in which each path's small-scale coefficient was represented by an autoregressive Gaussian process itself; further provision was made to account for frequency correlation across the signal bandwidth. Large-scale modeling focused on the channel gain, which offered a measure of the received signal strength averaged locally over small-scale phenomena. A log-normal model was proposed for the large-scale gain, the mean of which followed a log-distance dependence. Experimental data from four deployment sites with varying degrees of mobility were used for a statistical analysis. Probability distributions and correlation functions of the salient small- and large-scale parameters demonstrated a good match with the theoretical models. The present model was based on the Gaussian assumption for the underlying processes, which is a starting point from a statistical point of view.

The AquaTools simulation toolkit supports simulation of underwater acoustic networks using either static or mobile nodes [46]. Three different channel models provide flexibility in accommodating transmission frequency, distance between nodes, depth, ambient temperature, salinity and acidity. AquaTools is based on the ns2 simulator and thus provides a flexible scripting interface to set up the simulations. The simulated results include detailed packet traces. A high degree of similarity in the channel characteristics predicted by AquaTools compared to numerical and published models validated the reliability of the simulator. The ability to test different protocols and systems with AquaTools makes it a valuable tool in place of at-sea testing.

Accurate acoustic channel models are critical for the study of underwater acoustic networks. Existing models include physics-based models and empirical-approximation models: the former enjoy good accuracy, but incur heavy computational load, rendering them impractical in large networks; the latter are computationally inexpensive but inaccurate since they do not account for the complex effects of boundary reflection losses, multi-path phenomenon and ray bending in the stratified ocean medium. The Stratified Acoustic Model (SAM) is based on frequency-independent geometrical ray tracing, accounting for each ray's phase shift during the propagation [47].

K. Databases

The bottom sediment type (BST) database describes sediment-type provinces by identifying an integer value that has a one-to-one relationship with a particular sediment type. These descriptors consider the grain size, origin, and placement of bottom deposition. The BST data are provided at high- and low-spatial resolution. The high-resolution set derives from multiple sources including the analyses of grabs and cores collected during surveys conducted by the Naval Oceanographic Office and from National Imagery and Mapping Agency (now National Geospatial-Intelligence Agency) charts, side-scan imagery, seismic, bathymetry, and public literature. The low-resolution set is assembled from various high-level sources, including maps, atlases, and regional studies of ocean basins. The gathered sediment information exists in a variety of diverse and sometimes incompatible formats including sample point data, areal coverage, and acoustic data. The 5-minute resolution database provides an estimate of the most likely sediment to be found on a broad, regional basis. Although the database resolution is 5 minutes, the underlying source-data resolution is uneven and far lower, typically by an order of magnitude. Therefore, the database cannot guarantee that the sediment category identified in any cell is absolutely correct, only that the category represents the prevailing sediment within the defined region [48].

III. Numerical Modeling Techniques

A. Propagation Models

Propagation models can be categorized into five distinct techniques [1]: ray theory, normal mode, multipath expansion, fast field (or wavenumber integration) and parabolic equation. A further division can be made according to range-independent (1D, or depth-dependence only) or range-dependent environmental specifications, where environmental range-dependence can be 2D (depth and range) or 3D (depth, range and azimuth). Since all five techniques are derived from the wave equation by restricting solutions to the frequency domain, the resulting models are appropriate for traditional sonar applications. Each of the five techniques has a unique domain of applicability that can be defined in terms of acoustic frequency and environmental complexity. These domains are determined by the assumptions that were invoked in deriving each solution from the wave equation. Hybrid formulations obtained by combining two or more different techniques are often developed to improve domain robustness.

Table I provides a summary of stand-alone propagation models. Bold underlined names refer to those models added to the inventory after 2013 and which are documented in the text below; the remaining legacy models are documented in the 2013 baseline [1]. Five new models have been added to the inventory since 2013: VSTACK [49], CDPE [50], CRAM [51], FWRAM [49], and RAMSURF [52].

B. Noise Models

Noise models can be segregated into two categories: ambient-noise models and beam-noise statistics models. Ambient-noise models are applicable over a broad range of frequencies and consider noise originating from surface weather, biologics, shipping and other commercial activities. Beam-noise statistics models predict the properties of low-frequency shipping noise using either analytic (deductive) or simulation (inductive) methods.

Table II provides a summary of noise models. Bold underlined names refer to those models added to the inventory after 2013 and which are documented in the text below; the remaining legacy models are documented in the 2013 baseline [1]. One new model has been added to the inventory since 2013: INSPIRE [33].

C. Reverberation Models

Reverberation models can be categorized according to cell-scattering or point-scattering techniques. Cell-scattering formulations divide the ocean into cells, where each cell contains a large number of uniformly distributed scatterers. Point-scattering formulations assume a random distribution of (point) scatterers. A further segregation can be made according to monostatic and bistatic source/receiver geometries.

Table III provides a summary of reverberation models. Bold underlined names refer to those models added to the inventory after 2013 and which are documented in the text below; the remaining legacy models are documented in the 2013 baseline [1]. Two new models have been added to the inventory since 2013: REV3D [53] and TAMAR [54].

D. Sonar Performance Models

Sonar performance models combine environmental models, propagation models, noise models, reverberation models and appropriate signal-processing models to solve the sonar equations.

Sonar performance models can be further categorized as active sonar models, model operating systems and tactical decision aids. Model-operating systems provide a framework for the direct linkage of data-management software with computer-implemented codes of acoustic models, thus facilitating the construction of versatile simulation capabilities. Tactical decision aids represent a form of engagement-level simulation that blends environmental information with tactical rules. These decision aids guide system operators and scene commanders in planning missions and allocating resources by exploiting knowledge of the operating environment.

Table IV provides a summary of sonar performance models. Bold underlined names refer to those models added to the inventory after 2013 and which are documented in the text below; the remaining legacy models are documented in the 2013 baseline [1]. Two new models have been added to the inventory since 2013: HARCAM [55], and SAKAMATA [56].

IV. SUMMARY

Prominent trends and challenges in applied underwater acoustic modeling have been motivated by marine-mammal protection research focused on the mitigation of naval-sonar, seismic-source, and pile-driving noise. Channel modeling, underwater-acoustic networks, and communications technologies have evolved to support the increased bandwidths needed for undersea data collection. These developments have added new analytical tools to the existing inventory of propagation loss, noise, reverberation, and sonar performance models.

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TABLE I. SUMMARY OF UNDERWATER ACOUSTIC PROPAGATION MODELS. BOLD UNDERLINED NAMES REFER TO THOSE MODELS ADDED TO THE INVENTORY AFTER 2013 AND WHICH ARE DOCUMENTED IN THE TEXT; THE REMAINING LEGACY MODELS ARE DOCUMENTED IN THE 2013 BASELINE [1].

Technique	Range Independent			Range Dependent				
Ray Theory	CAPARAY	PLRAY		ACCURAY	GRASS	MIMIC	Ray5	TV-APM
	FACT	RANGER		BELLHOP	HARORAY	MPC	RAYSON	XRAY
	FLIRT			Coherent DELTA	HARPO	MPP	RAYWAVE	
	GAMARAY			FACTEX	HARVEST	Pedersen	RP-70	
	ICERAY			FeyRay	LYCH	PlaneRay	SHALFACT	
				GRAB	MEDUSA	PWRC	TRIMAIN	
Normal Mode	AP-2/5	MODELAB	ORCA	ADIAB	CPMS	MOCTESUMA	SWAMP	
	BDRM	NEMESIS	POPP	ASERT	FELMODE	NAUTILUS	WEDGE	
	COMODE	NLNM	PROTEUS	ASTRAL	IECM	PROLOS	WKBZ	
	DODGE	NORMOD3	SHEAR2	CENTRO	Kanabis	PROSIM	WRAP	
	FNMSS	NORM2L	Stickler	CMM3D	KRAKEN	SHAZAM	3D Ocean	
				COUPLE	MOATL	SNAP / C-SNAP		
Multipath Expansion	FAME	NEPBR		Integrated Mode				
	MULE	RAYMODE						
Fast Field or Wavenumber Integration	FFP	Pulse FFP	SPARC	CORE	RD-OASES	SAFRAN		
	Kutschale FFP	RPRESS	**VSTACK**	OASES-3D	RDOASP			
	MSPFFP	SAFARI		RDFFP	RDOAST			
	OASES	SCOOTER						
Parabolic Equation	Use Single Environmental Specification			AMPE / CMPE	FEPE-CM	MaCh1	PECan	TDPE
				Cartesian 3DPE	FEPES	MONM3D	PE-FFRAME	Two-Way PE
				CCUB / SPLN / CNP·	FOR3D	MOREPE	PESOGEN	ULETA
				CDPE	**FWRAM**	NSPE	PE-SSF (UMPE / MMPE)	UNIMOD
				Corrected PE	HAPE	OS2IFD	RAM / RAMS / RAMGEO	3DPE (NRL-1)
				CRAM	HYPER	OWWE	**RAMSURF**	3DPE (NRL-2)
				DREP	IFD Wide Angle	PAREQ	RMPE	3DTDPA
				FDHB3D	IMP3D	PDPE	SNUPE	3DWAPE
				FEPE	LOGPE	PE	Spectral PE	

TABLE II. SUMMARY OF UNDERWATER ACOUSTIC NOISE MODELS. BOLD UNDERLINED NAMES REFER TO THOSE MODELS ADDED TO THE INVENTORY AFTER 2013 AND WHICH ARE DOCUMENTED IN THE TEXT; THE REMAINING LEGACY MODELS ARE DOCUMENTED IN THE 2013 BASELINE [1].

Ambient Noise			Beam-Noise Statistics	
			Analytic	
AMBENT	DANES	**<u>INSPIRE</u>**	BBN Shipping Noise	USI Array Noise
ANDES	DANM	ISAAC	BTL	Sonobuoy Noise
ARAMIS	DINAMO	MONM	*Simulation*	
CANARY	DUNES	Normal Mode Ambient Noise	BEAMPL	NABTAM
CNOISE	FANM	RANDI - I / II / III	DSBN	SIAM - I / II

TABLE III. SUMMARY OF UNDERWATER ACOUSTIC REVERBERATION MODELS. . BOLD UNDERLINED NAMES REFER TO THOSE MODELS ADDED TO THE INVENTORY AFTER 2013 AND WHICH ARE DOCUMENTED IN THE TEXT; THE LEGACY MODELS BELOW ARE DOCUMENTED IN THE 2013 BASELINE [1].

Cell Scattering				Point Scattering	
Monostatic		*Bistatic / Multistatic*		*Monostatic*	*Bistatic / Multistatic*
C-SNAP-REV	PERM-2D	ARTEMIS	BISTAR	REVGEN	BORIS-SSA
DOP	**<u>REV3D</u>**	BAM	MURAL	RITSHPA	Under-Ice Reverberation Simulation
EIGEN / REVERB	REVMOD	BiKR	OGOPOGO		
HYREV	REVPA	BiRASP	RASP		
MAM	REVSIM	BISAPP	RUMBLE		
NOGRP / ROSELLA	R-SNAP	BISSM	S-SCARAB		
PAREQ-REV	**<u>TAMAR</u>**				
PEREV	TENAR				

TABLE IV. SUMMARY OF SONAR PERFORMANCE MODELS. BOLD UNDERLINED NAMES REFER TO THOSE MODELS ADDED TO THE INVENTORY AFTER 2013 AND WHICH ARE DOCUMENTED IN THE TEXT; THE REMAINING LEGACY MODELS ARE DOCUMENTED IN THE 2013 BASELINE [1].

Active Sonar Models			
Active RAYMODE	HODGSON	MINERAY	SONAR
ALMOST	INSIGHT	MOCASSIN	SST
ASPM	INSTANT	MOC3D	SUPREMO
CASTAR	LIRA	MODRAY	SWAMI / DMOS
CONGRATS	LORA	MSASM	SWAT
ESPRESSO	LYBIN	NISSM - II	UAIM
GASS		SEARAY	
Model Operating Systems		**Tactical Decision Aids**	
CAAM	**<u>HARCAM</u>**	ASPECT	
CALYPSO	HydroCAM	IMAT	
CASS	PRISM	NECTA	
ESME / NEMO	SPPS	**<u>SAKAMATA</u>**	
GSM - Bistatic			