

Review Article

Advanced Applications for Underwater Acoustic Modeling

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Changes in the ocean soundscape have been driven by anthropogenic activity (e.g., naval-sonar systems, seismic-exploration activity, maritime shipping and windfarm development) and by natural factors (e.g., climate change and ocean acidification). New regulatory initiatives have placed additional restrictions on uses of sound in the ocean: mitigation of marine-mammal endangerment is now an integral consideration in acoustic-system design and operation. Modeling tools traditionally used in underwater acoustics have undergone a necessary transformation to respond to the rapidly changing requirements imposed by this new soundscape. Advanced modeling techniques now include forward and inverse applications, integrated-modeling approaches, nonintrusive measurements, and novel processing methods. A 32-year baseline inventory of modeling techniques has been updated to reflect these new developments including the basic mathematics and references to the key literature. Charts have been provided to guide soundscape practitioners to the most efficient modeling techniques for any given application.

1. Introduction

Over the past several decades, the soundscape of the marine environment has responded to changes in both natural and anthropogenic influences. A soundscape is a combination of sounds that characterize, or arise from, an ocean environment. The study of a soundscape is sometimes referred to as acoustic ecology. The idea of a soundscape refers to both the natural acoustic environment (consisting of natural sounds including animal vocalizations, the sounds of weather, and other natural elements) and anthropogenic sounds (created by humans) including sounds of mechanical origin associated with the use of industrial technology. The disruption of the natural acoustic environment results in noise pollution.

This paper is concerned with the underwater soundscape. The field of underwater acoustics enables us to observe quantitatively and predict the behavior of this soundscape and the response of the natural acoustic environment to noise pollution. Specifically, underwater acoustics entail the development and employment of acoustical methods to image underwater features, to communicate information via the oceanic waveguide, or to measure oceanic properties. In the present context, underwater acoustics encompasses

both the science and the technology necessary to deploy functioning acoustical systems in support of naval and commercial operations.

Broadly defined, modeling is a method for organizing knowledge accumulated through observation or deduced from underlying principles. Modeling applications fall into two basic categories: prognostic and diagnostic. *Prognostic applications* include prediction and forecasting functions where future oceanic conditions or acoustic sensor performance must be anticipated. *Diagnostic applications* include system-design and analysis functions typically encountered in engineering tradeoff studies.

The challenges of managing the underwater soundscape are being met by enabling technologies and by emerging solutions. Throughout this paper, the utility of the available inventory of models is stressed and relevant examples from the recent literature are provided in support.

After a brief background in Section 1, the balance of this paper is divided into three main sections. Section 2 addresses evolving challenges. Section 3 discusses enabling technologies. Section 4 reviews emerging solutions. Finally, Section 5 summarizes the notable advances in underwater acoustic modeling that support management of the underwater soundscape.

2. Evolving Challenges

2.1. Background. The soundscape baseline is defined by ambient noise, which is the prevailing background of sound at a particular location in the ocean at a given time of the year. It does not include transient sounds such as the noise of nearby ships and marine organisms, or of passing rain showers. In practice, ambient noise excludes all forms of self-noise, such as the noise of current flow around the sonar. For sonar processing, however, it is the background of noise (including interfering sounds), typical of the time, location, and depth against which an acoustic signal must be detected.

2.2. Naval Operations in Coastal Environments

2.2.1. The Coastal Environment. Coastal environments are generally characterized by high spatial and temporal variabilities. When coupled with attendant acoustic spectral dependencies of the surface and bottom boundaries, these natural variabilities make coastal regions very complex acoustic environments. Specifically, changes in the temperature and salinity of coastal waters affect the refraction of sound in the water column. These refractive properties have a profound impact on the transmission of acoustic energy in a shallow-water waveguide with an irregular bottom and a statistically varying sea surface. Thus, accurate modeling and prediction of the acoustic environment is essential to understanding sonar performance in coastal oceans.

Physical processes controlling the hydrography of shelf waters often exhibit strong seasonal variations. Annual cycles of alongshore winds induce alternating periods of upwelling and downwelling. The presence of coastal jets and the frictional decay of deep-water eddies due to topographic interactions further complicate the dynamics of coastal regions. Episodic passages of meteorological fronts from continental interiors affect the thermal structure of the adjacent shelf waters through intense air-sea interactions. River outflows create strong salinity gradients along the adjacent coast. Variable bottom topographies and sediment compositions with their attendant spectral dependencies complicate acoustic bottom boundary conditions. At higher latitudes, ice formation complicates acoustic surface boundary conditions near the coast. Waves generated by local winds under fetch-limited conditions, together with swells originating from distant sources, conspire to complicate acoustic surface boundary conditions and also create noisy surf conditions. Marine life, which is often abundant in nutrient-rich coastal regions, can generate or scatter sound. Anthropogenic sources of noise are common in coastal seas including fixed sources such as drilling rigs and mobile sources such as merchant shipping and fishing vessels. Surface weather, including wind and rain, further contribute to the underwater noise field. Even noise from low-flying coastal aircraft can couple into the water column and add to the background noise field.

2.2.2. Littoral Operations. Over the past decade, naval mission requirements have shifted from open-ocean operations to shallow-water (or littoral) scenarios. For convenience,

shallow water will be defined by water depths less than 200 meters. This has not been an easy transition for sonar technologists since sonar systems that were originally designed for operation in deep water seldom work optimally in coastal regions. This has also held true for modeling and simulation (M&S) technologies, which have undergone a redefinition and refocusing to support a new generation of multistatic naval systems that are intended to operate efficiently in littoral regions while still retaining a deepwater capability. Shallow-water geometries increase the importance of boundary interactions, which diminish acoustic energy through scattering and also complicate localization of diesel submarines and coastal mines due to multipath propagation. Moreover, the higher levels of interfering noises encountered in coastal regions combined with higher levels of boundary reverberation mask signals of interest. In advance of naval deployments, synoptic meteorological and oceanographic (METOC) measurements are often required in remote or hostile (i.e., harsh or heavily defended) coastal environments to forecast acoustic sensor performance. Coupled atmosphere-ocean-acoustic models could reduce the need for hazardous *in situ* data collection by numerically computing initial states for the embedded acoustic models.

In support of naval operations in littoral regions, acoustical oceanographers have employed ocean-acoustic models as adjunct tools that can be used to conduct rapid environmental assessments (REAs) in remote locations. Due to an increased awareness of the potential technological impacts on marine life, naval commanders and acoustical oceanographers must also be aware of new environmental regulations governing the acoustic emissions of their sonar systems.

In shallow water, interactions of the acoustic fields with the sea bed require an understanding of the sedimentary structure of the bottom to a level of detail that is usually not required in deep-water environments. In the forward-propagation case, this means that a significant amount of information is necessary to properly characterize the bottom boundary to ensure the generation of high-fidelity model outputs. This generally requires a good understanding of the physics of bottom-interacting acoustics in diverse ocean environments.

Sonar clutter, particularly in shallow-water environments, introduces false targets that change the statistics of the reverberation signal. Specifically, clutter increases the probability of false alarm for a given probability of detection. This is because clutter adds to the length of the tails of the reverberation-envelope PDF (probability distribution function), moving the statistics away from the Rayleigh canonical form. Clutter can be caused by target-like features, either natural or man-made, or by non-Gaussian distributions of the scatterers. Typically, high-bandwidth or highly directive systems (or both) have more problems with clutter since, as the size of the scattering patch is reduced, the PDF of the generally non-Gaussian scatterer distributions becomes resolved by the system [1].

2.2.3. Training Ranges. At issue here is operational naval training with active sonars. These high-power multistatic

sonars have become more important in the face of improved diesel-electric submarine threats operating in complex coastal environments.

The US Navy has explored the environmental consequences of installing and operating an undersea warfare training range (USWTR) in conjunction with appropriate coordination and consultation with the National Marine Fisheries Service (NMFS) and in compliance with applicable laws and executive orders including the Marine Mammal Protection Act (MMPA), the Endangered Species Act (ESA), the National Environmental Policy Act (NEPA), and the Coastal Zone Management Act (CZMA).

2.2.4. Underwater Networks. Ocean-bottom sensor nodes are used for oceanographic data collection, pollution monitoring, offshore exploration, tactical surveillance applications, and rapid environmental assessments [2, 3]. Factors that determine the temporal and spatial variability of the acoustic channel also limit the available bandwidth of the ocean channel and make it dependent on range and frequency. Specifically, long-range systems (~ 10 km) have bandwidths of a few kilohertz while short-range systems (~ 0.1 km) have bandwidths on the order of a hundred kilohertz. A moored-buoy ocean observatory system comprising oceanographic sensors was linked by acoustic communications to retrieve data from sensors in the water column at ranges of approximately 3 km [4]; the observatory was deployed off Vancouver Island in the northeastern Pacific Ocean in May 2004 (for 13 months) to study the correlation of seismicity and fluid flow in a seep area along the Nootka fault.

Underwater networks consist of variable numbers of sensors and vehicles deployed in concert to perform collaborative monitoring tasks over a given area. Underwater sensor networks comprise nodes that communicate via acoustic waves over multiple wireless hops to perform collaborative tasks such as environmental monitoring, naval surveillance, and oceanic exploration. Nodes in underwater sensor networks are constrained by harsh physical environments. Data delivery schemes originally designed for terrestrial sensor networks are unsuitable for use in the underwater environment. Relatively few new schemes have been proposed for underwater use, and no single scheme has yet emerged as the *de facto* standard.

Underwater acoustic communications are influenced by spreading loss, noise, multipath discrimination, Doppler spread, and high and variable propagation delays. Moreover, underwater acoustic channels normally have low data rates and time-varying fading. These factors determine the temporal and spatial variability of the acoustic channel and make the available bandwidth of the ocean channel both limited and dependent on range and frequency. Challenges due to the presence of fading, multipath, and refractive properties of the sound channel necessitate the development of precise underwater-channel models. Some existing channel models are simplified and do not consider multipaths or fading. Multipath interference due to boundary reflection in shallow-water acoustic communications poses major obstacles to reliable high-speed underwater communication systems.

Cooperative transmission is a new wireless communication technique in which diversity gain can be achieved by utilizing relay nodes as virtual antennae. These transmission techniques have been investigated for underwater acoustic communications. First, the performance of several cooperative transmission schemes was studied in an underwater scenario. Second, by taking advantage of the relatively low propagation speed of sound in water, a new wave cooperative transmission scheme was designed in which the relay nodes amplified the signal received from the source node and then forwarded the signal immediately to the intended destination. The goal was to alter the multipath effect at the receiver. Third, the upper bound of performance was derived for the proposed wave cooperative transmission scheme. The simulation results showed that the proposed wave cooperative transmission had significant advantages over both the traditional direct transmission and the existing cooperative transmission schemes originally designed for radio wireless networks [5].

Localization algorithms are relevant to underwater sensor networks, but there are challenges in meeting requirements imposed by emerging applications for such networks in offshore engineering [6]. Localization algorithms can be broadly categorized into *range-based* and *range-free* schemes. Range-based schemes use precise distance or angle measurements to estimate the location of nodes in a network. Range-free schemes are simpler than range-based schemes, but they only provide a coarse estimate of a node's location.

Underwater networking is an enabling technology for the operation of autonomous underwater vehicles. In particular, *ad hoc* networks entail wireless communications for mobile hosts called nodes. In these networks, there is no fixed infrastructure. Mobile nodes that are within range communicate directly via wireless links, while those that are far apart rely on other nodes to relay messages as routers. Node mobility in an *ad hoc* network causes frequent changes of the network topology. Since *ad hoc* networks can be deployed rapidly with relatively low cost, they are attractive for military, emergency, commercial and scientific applications [2, 3]. A channel simulator was developed for testing the performance of unmanned undersea vehicle (UUV) communications [7].

2.2.5. Unmanned Underwater Vehicles. Autonomous underwater vehicles (AUVs), or unmanned undersea vehicles (UUVs), constitute part of a larger group of undersea systems known as unmanned underwater vehicles, a classification that includes nonautonomous remotely operated vehicles (ROVs) that are controlled and powered from the surface by an operator (or pilot) via an umbilical connection.

Underwater gliders actually constitute a new class of autonomous underwater vehicles that glide by controlling their buoyancy and attitude using internal actuators [8]. Gliders have useful applications in oceanographic sensing and data collection because of their low cost, autonomy, and capability for long-range extended-duration deployments. They serve as adjuncts to ship-based hydrographic casts, towed sensors, UUV/AUV and satellite-based sensors, but they also present challenges in communications common to all untethered subsurface sensors.

2.3. Marine Seismic Operations

2.3.1. Seismic Exploration. Marine seismic surveys are used to assess the location of hydrocarbon resources, including gas and oil. There are two acquisition methods: 2D and 3D. The 2D method tows a single seismic cable (or streamer) behind the seismic vessel, together with a single source. The reflections from the subsurface of the sea floor are assumed to lie directly below the path (sail line) of the vessel. In a 3D survey, groups of sail lines (or swathes) are used to acquire orthogonal or oblique lines relative to the acquisition direction. By utilizing more than one source together with many parallel streamers towed by the seismic vessel, the acquisition of many closely spaced subsurface 2D lines can be achieved by a single sail line. Computationally intensive processing is necessary to produce a 3D image of the subsurface of the sea floor. The source arrays are powered by high-pressure air that is compressed onboard the seismic vessel. These compressors are capable of recharging the airguns rapidly and continuously, enabling the airgun source arrays to be fired at approximately 10-second intervals for periods of up to 12 hours. Typical towing depths range from 4–5 meters for shallow high-resolution surveys or 8–10 meters for deeper penetration, lower-frequency targets in open waters. Typical source outputs are approximately 220 dB re 1 $\mu\text{Pa}/\text{Hz}$ at 1 m. Other types of seismic sources include water guns and marine vibrators.

2.3.2. Marine Mammal Impacts. In 2002, the International Association of Geophysical Contractors (IAGC) hosted an informal meeting to discuss future *Acoustics Research* relevant to seismic operations related to the effects of seismic exploration on sperm whales in the Gulf of Mexico [9]. The IAGC offered its support for sperm-whale research through the contribution of a seismic-source vessel for controlled-exposure experiments. In response, a proposed sperm whale seismic study (SWSS) was approved by the Minerals Management Service (MMS) in 2002. (The MMS is now the Bureau of Ocean Energy Management, Regulation and Enforcement, or BOEMRE.) In subsequent years, IAGC was joined by a number of oil and gas companies to form the Industry Research Funders Coalition (IRFC) that has continued to provide contributions in support of SWSS studies.

Long-term (monthly to seasonal) movements and distributions of sperm whales were studied using satellite-tracked radio telemetry tags (S-tags). Short-term (hours) diving and swimming behavior and vocalizations of sperm whales were examined using recoverable digital-recording acoustic tags (D-tags) that logged whale orientation (i.e., pitch, roll, heading) and depth, as well as the sounds made by the whale and received at the whale from the environment. Diving depths and movements were examined using 3D passive acoustic tracking techniques.

To examine potential changes in the behavior of sperm whales when subjected to seismic airgun sounds, controlled exposure experiments (CEEs) were conducted using the D-tags in conjunction with a seismic-source vessel. The location and level of airgun sounds delivered at the tagged sperm

whales were controlled by the science team. These CEEs provided data on the immediate and short-term (hours) response of sperm whales to airgun sounds. Longer-term avoidance or displacement behaviors of sperm whales to seismic vessel airgun sounds were examined using location data from the S-tags and from proprietary commercial seismic shot data.

The 3D tracking method requires at least two widely separated hydrophones to obtain the horizontal range and depth of acoustically active sperm whales and would thus be suited for eventual use on a standard seismic vessel, where the passive acoustic arrays (streamers) can be over a kilometer long. Instead of relying on four hydrophones deployed as a three-dimensional array (which would be difficult to deploy and process), the method used here exploited surface multipath (or “ghosts”) to reduce the number of required hydrophones to three and further permitted the phones to be deployed along a single towed cable. The horizontal separation between the widely-spaced hydrophones needed to be at least 200 m in order to obtain adequate range and depth resolution at 1 km horizontal ranges. The method did not require the use of multipath from the ocean bottom, but when such bottom returns were detected they could provide an independent confirmation of these tracking procedures [10].

2.4. Shipping Activity. Shipping lanes, a term used to indicate the general flow of merchant traffic between two ports, are routes that historically have been optimized for shortest distances and travel times, and which are modified to avoid extreme weather events [11]. Noise from distant shipping generally occupies the frequency band 20–500 Hz.

A comparison of time-series measurements of ocean ambient noise over two periods (1963–1965 and 1994–2001) revealed that noise levels from the latter period exceeded those of the earlier period by about 10 dB in the frequency ranges 20–80 Hz and 200–300 Hz, and by about 3 dB at 100 Hz [12]. The observed increase was attributed to increases in shipping. Ambient noise measurements collected at the same site but separated by an interval of nearly 40 years (1964–1966 and 2003–2004) revealed an average noise increase of 2.5–3 dB per decade in the frequency band 30–50 Hz [13, 14].

2.5. Windfarm Development. Wind power, as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, and produces no greenhouse gas emissions during operation. A wind farm, which is a group of wind turbines in the same location used for production of electric power, may be located offshore. The installation of ocean wind farms requires medium water depths (<30 m) and construction logistics such as access to specialized vessels to install the turbines. Economic wind generators require wind speeds of 16 km/h or greater.

A concerted effort has been made by industry to minimize any undesirable effects relating to windfarm development and operation [15]. One potential effect of offshore windfarm development is the creation of underwater noise.

Knowing the length of time the marine environment is exposed to an underwater noise source is useful when assessing environmental effects. Measurements of offshore wind turbine noise showed low-frequency sound levels with a maximum of 153 dB re $1 \mu\text{Pa}$ at 1 m at 16 Hz. These measurements were of individual turbines of a relatively low power (less than 1 MW). Despite the low-level and low-frequency nature of the sound, behavioral reactions of marine mammals have been observed in response to the reproduction of wind-turbine noise.

2.6. Ocean Acidification. Climate change also affects the ocean soundscape. The emission of carbon into the atmosphere through the effects of fossil-fuel combustion and industrial processes increases atmospheric concentrations of carbon dioxide (CO_2). Ocean acidification, which occurs when CO_2 in the atmosphere reacts with water to create carbonic acid (H_2CO_3), is increasing.

The attenuation of low-frequency sound in the sea is pH dependent; specifically, the higher the pH, the greater the attenuation. Thus, as the ocean becomes more acidic (lower pH) due to increasing CO_2 emissions, the attenuation will diminish and low-frequency sounds will propagate farther, making the ocean noisier.

Recent investigations modeled what effect the increasing acidity of the ocean would have on ambient-noise levels in shallow water in the presence of internal waves [16]. This model assumed an isotropic distribution of noise sources. Exploring a scenario typical of the East China Sea, the noise at 3 kHz was predicted to increase by 30%, or about one decibel, as the pH decreased from 8.0 to 7.4. These results are representative of other contemporaneous investigations into this matter.

3. Enabling Technologies

3.1. Background

3.1.1. Regulatory Initiatives. An examination of anthropogenic sound in a global context considered the need for new regulatory initiatives to deal with the conflicting uses of ocean space related to noise [17]. This study identified the existing legal, economic, and political barriers to the creation and implementation of a new international regime designed to manage anthropogenic noise in the ocean.

The Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals was charged by the Ocean Studies Board of the US National Research Council to assess the state of our knowledge of underwater noise and recommend research areas to assist in determining whether noise in the ocean adversely affects marine mammals [18]. One of the findings of this committee was that models describing ocean noise are better developed than are models describing marine mammal distribution, hearing, and behavior. The biggest challenge lies in integrating the two types of models. The National Research Council [19] also examined what constitutes *biologically significant* in the context of Level B harassment as used in the latest amendments to the

US Marine Mammal Protection Act (MMPA). The MMPA separates harassment into two levels. Level A harassment is defined as “any act of pursuit, torment, or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild.” Level B harassment is defined as “any act of pursuit, torment, or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering.” The MMPA, enacted in 1972, was the first legislation that called for an ecosystem approach to natural-resource management and conservation; it specifically prohibited the *take* (i.e., hunting, killing, capture, and/or harassment) of marine mammals.

The ocean biogeographic information system (OBIS) is an on-line worldwide atlas for accessing, modeling and mapping marine biological data in a multidimensional geographic context [20]. Also see the website at <http://www.iobis.org/home>.

3.1.2. Modeling Uncertainty. *Uncertainty* has been defined as a quantitative measure of our lack of knowledge of the sound-speed field and boundary conditions constituting the waveguide information necessary for simulation of the acoustic field [21]. This uncertainty is distinct from any errors related to numerical solution of the wave equation. Existing methods typically solve a deterministic wave equation separately over many realizations, and the resulting set of pressure fields is then used to estimate statistical moments of the field. Proper sampling may involve the computation of thousands of realizations to ensure convergence of the statistics.

A study of the effects of uncertainty in the modeling of anthropogenic impacts suggested a precautionary approach to regulation [22]. It was further noted that due to the complex patterns of sound propagation encountered in diverse shelf regions, some marine mammals may not necessarily encounter the average sound exposure conditions predicted for any given seismic survey.

3.2. Numerical Modeling Techniques. Four types of models will be discussed: propagation, noise, reverberation, and sonar performance. The order of presentation will follow that indicated in Figure 1. This box-type format will be used throughout the text to present compact summaries of methods that have been developed in detail elsewhere [23].

3.2.1. Propagation Models. As sound propagates through the ocean, the effects of spreading and attenuation diminish its intensity. Spreading loss includes spherical and cylindrical spreading losses in addition to focusing effects. Attenuation loss includes losses due to absorption, leakage out of ducts, scattering, and diffraction. Propagation losses increase with increasing frequency due largely to the effects of absorption. Sound propagation is profoundly affected by the conditions of the surface and bottom boundaries of the ocean as well as by the variation of sound speed within the ocean volume.

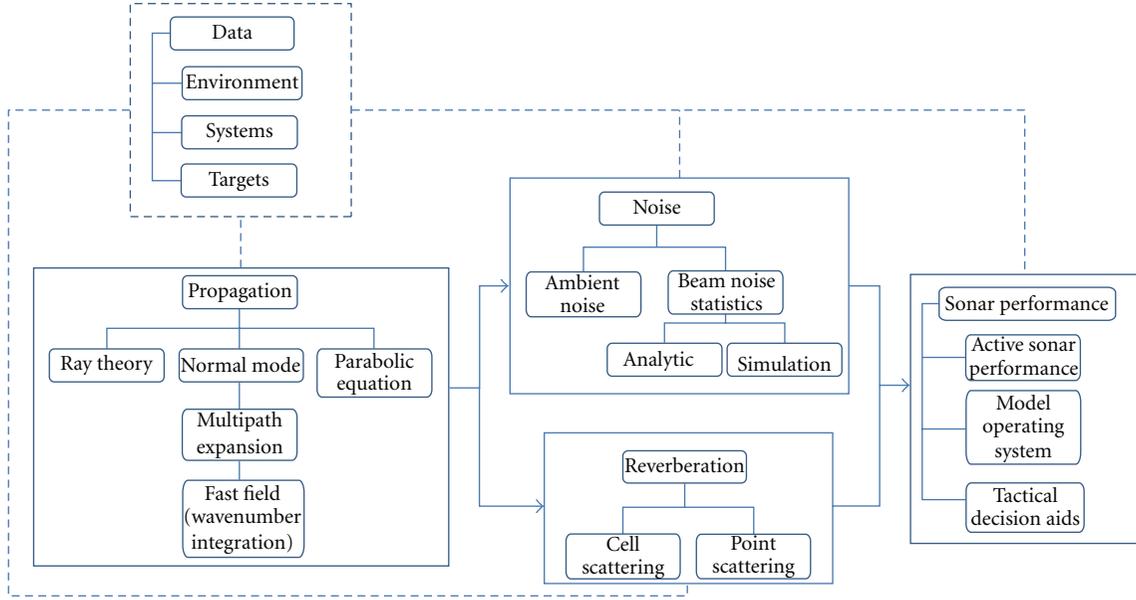


FIGURE 1: Flow of underwater acoustic modeling from propagation, through noise and reverberation, to sonar performance.

Sound-speed gradients introduce refractive effects that may focus or defocus the propagating acoustic energy.

Formulations of acoustic propagation models generally begin with the three-dimensional, time-dependent wave equation. For most applications, a simplified linear, hyperbolic, second-order, time-dependent partial differential equation is used:

$$\nabla^2 \Phi = \frac{1}{c^2} \frac{\partial^2 \Phi}{\partial t^2}, \quad (1)$$

where $\nabla^2 = (\partial^2/\partial x^2) + (\partial^2/\partial y^2) + (\partial^2/\partial z^2)$ is the Laplacian operator, Φ is the potential function, c is the speed of sound, and t is the time.

Subsequent simplifications incorporate a harmonic (single-frequency, continuous wave) solution in order to obtain the time-independent Helmholtz equation. Specifically, a harmonic solution is assumed for the potential function Φ :

$$\Phi = \phi e^{-i\omega t}, \quad (2)$$

where ϕ is the time-independent potential function, ω is the source frequency ($2\pi f$), and f is the acoustic frequency. Then the wave equation (1) reduces to the Helmholtz equation:

$$\nabla^2 \phi + k^2 \phi = 0, \quad (3)$$

where $k = (\omega/c) = (2\pi/\lambda)$ is the wavenumber and λ is the wavelength. Equation (3) is referred to as the time-independent (or frequency-domain) wave equation.

Propagation models are integral to the higher-level modeling of noise, reverberation, and, ultimately, sonar performance. The graphic in Figure 1 shows the flow of sonar modeling from propagation, through noise and reverberation, through to sonar performance. Estimates of passive

sonar performance would require the input of propagation and noise while active sonar performance would require inputs of both noise and reverberation.

Propagation models can be categorized into five distinct techniques [23].

- (a) Ray-theoretical models calculate propagation loss on the basis of ray tracing.
- (b) Normal-mode solutions are derived from an integral representation of the wave equation.
- (c) Multipath expansion techniques expand the acoustic field integral representation of the wave equation in terms of an infinite set of integrals, each of which is associated with a particular ray-path family. Thus, each normal mode can then be associated with corresponding rays.
- (d) In underwater acoustics, fast-field theory is also referred to as “wavenumber integration.” In seismology, this approach is commonly referred to as the “reflectivity method” or “discrete-wavenumber method.”
- (e) The parabolic approximation approach replaces the elliptic reduced wave equation with a parabolic equation (PE). Use of the parabolic approximation in wave propagation problems can be traced back to the mid-1940s when it was first applied to long-range tropospheric radio wave propagation.

As shown in Figure 2, 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

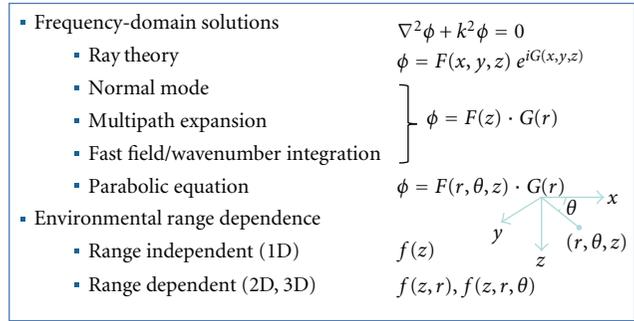


FIGURE 2: Organization of propagation models into five distinct techniques. A further division is made according to range-independent (1D) or range-dependent (2D or 3D) environmental specifications.

are appropriate for traditional sonar applications. (Solutions obtained in the time domain would be appropriate, e.g., for modeling shock propagation in the ocean.) 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. Hybrid formulations obtained by combining two or more different techniques are often developed to improve domain robustness.

Table 1 provides a summary of stand-alone propagation models. Superscript letters identify those models that have been added to the inventory since 2003. These letters refer to a brief summary and appropriate documentation. Model documentation can range from informal programming commentaries to journal articles to detailed technical reports containing a listing of the actual computer code. Corresponding information on the legacy models is provided in the 2003 baseline [23] and is not repeated here.

In Table 1: (*Propagation models*), (a) FeyRay was developed to accommodate the speed, fidelity, and implementation requirements of sonar trainers and simulators. It is a broadband, range-dependent, point-to-point propagation model optimized for computational efficiency. FeyRay utilizes the Gaussian-beam approximation, which reduces the acoustic wave equation (a partial differential equation) to a more tractable system of ordinary differential equations [24–28], (b) PlaneRay provides a unique sorting and interpolation routine for efficient determination of a large number of eigenrays in range-dependent environments. No rays are traced into the bottom since bottom interaction is modeled by plane-wave reflection coefficients. The bottom structure is modeled as a fluid sediment layer over a solid half-space. This approach balances two conflicting requirements: ray tracing is valid for high frequencies while plane-wave reflection coefficients are valid for low frequencies where the sediment layers are thin compared with the acoustic wavelength [29–33], (c) PWRC is a ray-based model that performs geoacoustic inversions in range-dependent ocean waveguides. The pressure field is modeled approximately by separating the ocean propagation ray paths from the layered bottom interaction. The bottom interaction is included by using a

full-wave description, making PWRC a hybrid model, in contrast to a full-ray theory approach that traces rays into the bottom layers. The field contribution from the bottom interactions partially includes beam-displacement effects associated with internally reflected or refracted returns from the sediment since the complex bottom reflection coefficients are obtained from a full-wave solution. This method is comparable in accuracy to normal mode and analytic solutions (in range-dependent environments) for frequencies >100 Hz [34], (d) Ray5, developed by Trond Jenserud at the Forsvarets forskningsinstitutt (Norwegian Defence Research Establishment), uses direct integration in a sound-speed field specified either analytically or by interpolation from measured data. The Ray5 program is well suited for ray-tracing calculations in acoustic fields described analytically. It needs the sound-speed values, their spatial derivatives and second derivatives at all points within the field. Hence, if these values can be given analytically as functions of the oceanographic and bathymetric parameters, no interpolation is necessary and the program reduces its computing time. Further developments in Ray5 have made it possible to calculate eigenrays. This allows phase information to be retained for a given frequency so that coherent pressure values can be summed for the rays arriving at the receiver. The actual pressure values for the individual rays are calculated by assuming the pressure distribution in the direction normal to the ray to have a Gaussian behavior (i.e., Gaussian beams). It is also possible to calculate the incoherent sound levels [35]. A separate report includes the MATLAB code for Ray5 [36], (e) RAYSON was developed by Semantic (France) to solve the Helmholtz equation using a ray-theoretic approximation for high frequencies. In a stratified (range-independent) environment, analytic solutions are obtained for ray paths that are portions of circles. In range-dependent environments, the ray equations are numerically integrated using a fourth-order Runge-Kutta method to propagate the rays along the range axis. The bottom composition can vary with range and the state of the sea surface can vary in time as well as in range. The software is coded in C++ and is available commercially [37–40], (f) XRAY combines ray tracing in a range-dependent water column with local full-field modeling of interactions with a seabed composed of multiple range-dependent layers of fluid

or solid materials [41], (g) POPP is a range-independent version of the PROLOS normal-mode propagation model [42], (h) IECM is a two-way coupled-mode formalism that provides an exact solution to the wave equation [43]. This model was used to establish a benchmark solution that is an exact numerical solution for the reverberation time series for an environment with a range-dependent, fine-scale rough bottom boundary that induces mode coupling and generates a scattered field. The solution includes scattering effects to all orders in that it sums the infinite series of forward and backward contributions at each range point and maintains energy conservation, (i) SWAMP is a range-dependent normal-mode model that contains closed-analytical forms of the vertical mode functions, which facilitate computation of one-way mode-coupling coefficients between adjacent range-independent regions by neglecting weak backscattering components [44, 45]. The model was used to understand the physics of pulse propagation in double-ducted shallow-water environments where precursors have been observed. The pulse temporal response is modeled using Fourier synthesis in the frequency domain. The model accounts for scattering events along the acoustic signal propagation path and has been extended to model acoustic pulse scattering by spherical elastic-shell targets in inhomogeneous waveguides within the T-matrix approach [46], (j) Integrated Mode extends the multipath expansion method to range-dependent environments [47]. This approach accounts for horizontal variations in bottom depth, bottom type, and sound speed using the stationary phase approximation, (k) OASES-3D target modeling framework is used to investigate scattering mechanisms of flush buried spherical shells under evanescent insonification [48–51], (l) The Cartesian 3D parabolic equation program implements a split-step Fourier algorithm with a wide-angle PE approximation, and is thus a 3D variant of the PE model of Thomson and Chapman [52]. The advantage of employing Cartesian coordinates in the numerical scheme is that the model resolution is uniform over the computational domain [53, 54], (m) MONM3D incorporates techniques that reduce the required number of model grid points. The concept of tessellation (i.e., covering the plane with a pattern in such a way as to leave no region uncovered) is used to optimize the radial grid density as a function of range, reducing the required number of grid points in the horizontal planes of the grid. The model marches the solution out in range along several radial propagation paths emanating from a source position. Tessellation, as implemented in MONM3D, allows the number of radial paths in the model grid to depend on range from the source. In addition, the model incorporates a higher-order azimuthal operator which allows a greater radial separation and reduces the required number of radial propagation paths [55], (n) NSPE, the Navy Standard PE model, consists of two methods of solving the acoustic parabolic wave equation: split-step Fourier parabolic equation model (SSFPE); and split-step Padé (finite-element) parabolic equation (SSPPE) known as RAM. [<http://www.nrl.navy.mil/content.php?P=03REVIEW212>], (o) OWWE [56] is based on the innovative one-way wave

equation developed by Godin [57]. This equation was generalized by Godin to include the source terms and also to account for motion of the medium. The solutions of the differential OWWE are strictly energy conserving and reciprocal. The derivation presented for the multiterm Padé PE model is applicable to a broad class of finite-difference PE models, (p) RAMGEO is a version of RAM modified to handle sediment layers that are range dependent and parallel to the bathymetry [58], (q) RMPE is a ray-mode parabolic-equation solution that is expressed in terms of normal modes in the vertical direction and mode coefficients in the horizontal direction. The model is based on the beam-displacement ray-mode (BDRM) theory and the parabolic equation (PE) method. The BDRM theory is used to analyze the local normal modes. The PE method is used to solve the wave equations for mode coefficients [59], and (r) 3DWAPE incorporates higher-order finite-difference schemes to handle the azimuthal derivative term in a three-dimensional (3D) parabolic equation model [60]. Broadband pulse propagation problems were solved in a 3D waveguide using a Fourier synthesis of frequency-domain solutions (3DWAPE) in a penetrable wedge-shaped waveguide [61]. The 3DWAPE model includes a wide-angle paraxial approximation for the azimuthal component. This version of 3DWAPE was used to investigate broadband sound pulse propagation in two shallow-water waveguides: the 3D ASA benchmark wedge and the 3D Gaussian canyon [62].

The specific utility of these categories is further explained below. In applying ocean-acoustic propagation models, the analyst is normally faced with a decision matrix involving water depth (deep versus shallow), frequency (high versus low), and range-dependence (range-independent versus range-dependent ocean environments). The following assumptions and conditions were imposed in construction of Figure 3, which was originally adapted from F. B. Jensen (see [23]).

- (1) Shallow water includes those water depths for which the sound can be expected to interact significantly with the sea floor. Typically, a maximum depth of 200 m is used to delimit shallow water regions. A more accurate definition of shallow water would be expressed in terms of water depth and acoustic wavelength [23].
- (2) The threshold frequency of 500 Hz is somewhat arbitrary, but it does reflect the fact that above 500 Hz, many wave-theoretical models become computationally intensive. Also, below 500 Hz, the physics of some ray-theoretical models may become questionable due to restrictive assumptions.
- (3) A solid circle indicates that the modeling approach is both applicable (physically) and practical (computationally). Distinctions based on speed of execution may change as progress is made in computational capabilities. A partial circle indicates that the modeling approach has some limitations in accuracy or in speed of execution. An open circle indicates that the modeling approach is neither applicable nor practical.

Model type	Applications							
	Shallow water				Deep water			
	Low frequency		High frequency		Low frequency		High frequency	
	RI	RD	RI	RD	RI	RD	RI	RD
Ray theory	○	○	◐	◑	◐	◐	◑	◑
Normal mode	◑	◐	◑	◐	◑	◐	◐	○
Multipath expansion	○	○	◐	◐	◐	◐	◑	◐
Fast field	◑	◐	◑	◐	◑	◐	◐	◐
Parabolic equation	◐	◑	○	○	◐	◑	◐	◐

Low frequency (<500Hz) RI: range-independent environment
 High frequency (>500Hz) RD: range-dependent environment

- ◑ Modeling approach is both applicable (physically) and practical (computationally)
- ◐ Limitations in accuracy or in speed of execution
- Neither applicable or practical

FIGURE 3: Domains of applicability of underwater acoustic propagation models.

To provide compact summaries, propagation models are arranged in categories reflecting the basic modeling technique employed (i.e., the five canonical approaches) as well as the ability of the model to handle environmental range dependence (Figure 3). Such factors define what is termed *domains of applicability*. Hybrid models occasionally compromise strict categorization, and some arbitrariness has been allowed in this classification process. The environmental range dependence considers variations in sound speed or bathymetry. Other parameters may be considered to be range dependent by some of the models, although they are not explicitly treated in this paper.

Figure 3 has been modified in two important respects relative to previous versions [23]. Specifically, a range-dependent capability has been added to the multipath-expansion and to the fast-field (or wavenumber integration) approaches. This change is warranted by the substantial progress made by modelers over the past several years.

Taken together, Figure 3 and Table 1 provide a useful mechanism for selecting a subset of candidate models once some preliminary information is available concerning the intended applications. Note that range-dependent models can also be used for range-independent environments by inserting a single environmental description to represent the entire horizontal range.

3.2.2. Noise Models. Noise is the prevailing, unwanted background of sound at a particular location in the ocean at a particular time. The local noise field is thus characterized by temporal, spatial, and spectral variabilities. The noise generated by natural or anthropogenic point sources is diminished through the effects of propagation to the sonar receiver.

Noise models can be segregated into two categories: ambient-noise models and beam-noise statistics models, as

illustrated in Box 1. Ambient-noise models are applicable over a broad range of frequencies and consider noise originating from surface weather, biologics, shipping, and other commercial activities [63]. Beam-noise statistics models [64] predict the properties of low-frequency shipping noise using either analytic (deductive) or simulation (inductive) methods. Table 2 provides a summary of noise models. Superscript letters identify those models that have been added to the inventory since 2003. These letters refer to a brief summary and appropriate documentation. Model documentation can range from informal programming commentaries to journal articles to detailed technical reports containing a listing of the actual computer code. Corresponding information on the legacy models is provided in the 2003 baseline [23] and is not repeated here.

In Table 2: (Noise models), (a) ARAMIS consists of a number of FORTRAN, C++ and MATLAB codes that integrate US Navy standard databases with user-provided sonar system parameters to assess the performance of passive spatial processors [65], (b) DANM is the successor to ANDES. DANM predicts the azimuthal dependence of noise in the 25–5,000 Hz band [18]. The dynamic ambient noise model (DANM) provides a realistic simulation of the temporal noise field in which a passive receive array operates. The total noise field is obtained by separately calculating wind and shipping noise. The temporal variability of the noise field is simulated by moving merchant ships along major shipping lanes. Shipping databases provide seasonal information about shipping lanes between the world’s major ports, as well as the type and number of ships that move in the lanes, (c) ISAAC uses a Gaussian ray-tracing approach to determine the acoustic ray paths between source and target, including those reflected from the sea surface and sea bed. The ray paths may refract with changes in bathymetry, water density, salinity, temperature, and sea-bed type. ISAAC

Ambient noise	
Given: the directional noise intensity per unit solid angle $[N_s(\theta, \phi)]$.	
(i) The horizontal noise directionality $[N(\phi)]$ is calculated from $[N_s(\theta, \phi)]$ as:	
$N(\phi) = \int_{-\pi/2}^{\pi/2} N_s(\theta, \phi) \cos \theta d\theta.$	
(ii) The vertical noise directionality $[N(\theta)]$ is calculated from $[N_s(\theta, \phi)]$ as:	
$N(\theta) = (1/2\pi) \int_0^{2\pi} N_s(\theta, \phi) d\phi.$	
(iii) The omnidirectional noise level (N) is then calculated as:	
$N = \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} N_s(\theta, \phi) \cos \theta d\theta d\phi,$	
or	
$N = \int_0^{2\pi} N(\phi) d\phi.$	
(iv) The horizontal angle (ϕ) is measured positive clockwise from true North while the vertical angle (θ) is measured positive upward from the horizontal plane. No receiver beam patterns were convolved with the noise levels $N(\theta)$ and $N(\phi)$.	
Beam-noise statistics	
The averaged noise power at the beamformer output (Y) can be expressed as:	
$Y = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^{A_{ij}} S_{ijk} Z_{ijk} B_{ijk},$	
where m : number of routes in the basin; n : number of ship types; A_{ij} : number of ships of type j on route i (a random variable); S_{ijk} : source intensity of the k th ship of type j on route i (a random variable that is statistically independent of the source intensity of any other ship); Z_{ijk} : intensity transmission ratio from ship ijk to the receiving point; B_{ijk} : gain for a plane wave arriving at the array from ship ijk	

Box 1: Organization of underwater acoustic noise models into two categories.

TABLE 2: Summary of underwater acoustic noise models. Super-script letters identify those models that have been added to the inventory since 2003.

Ambient noise	Beam-noise statistics
ANDES	<i>Analytic</i>
AMBENT	BBN shipping noise
ARAMIS ^a	BTL
CANARY	Sonobuoy noise
CNOISE	USI Array noise
DANES	
DANM ^b	<i>Simulation</i>
DINAMO	BEAMPL
DUNES	DSBN
FANM	NABTAM
ISAAC ^c	SIAM-I/II ^c
MONM ^d	
Normal mode ambient noise	
RANDI-I/II/III	

allows sensitive marine areas such as marine mammal locations, migratory routes and fisheries to be displayed in the GIS alongside acoustic propagation results. Noise impacts on individual species can be assessed by comparing the sound pressure levels generated from anthropogenic activities with sensitivity thresholds to perform environmental risk assessments. The system has been configured specifically for use by offshore industries, environmental agencies, regulators and others to help assess the environmental impact of underwater noise. The *dBht (species)* approach provides a measurement of sound that accounts for interspecies differences in hearing

ability by passing the sound through a filter which mimics the hearing ability of the species. (The *dBht (species)* metric is a pan-specific metric incorporating the concept of “loudness” by using a frequency-weighted curve based on the species’ hearing threshold as the reference unit for a dB scale. A large number of both field and controlled-laboratory measurements have been made of the avoidance of a range of idealized noises, using fish with greatly different hearing as a model. All data, irrespective of source or species, indicate a dependence of avoidance reaction on the *dBht(species)* level. The data indicate three regions: no reaction below 0 *dBht* (i.e., below the species’ threshold of hearing), a cognitive avoidance region where increasing numbers of individuals will avoid the noise from 0 to 90 *dBht*, and instinctive reaction at and above 90 *dBht* where all animals will avoid the noise. This probabilistic model allows the behavioral impact of any noise source to be estimated [66].) This approach provides an indication of the noise level that will be received for the species at various distances from the noise source. These values can then be compared to published data to indicate distances at which a species will demonstrate a strong avoidance reaction, a temporary elevation of hearing threshold or a permanent elevation of hearing threshold [67]. (d) MONM (marine operations noise model) incorporates a range-dependent, split-step parabolic equation acoustic model including a shear-wave computation capability. MONM has been used for precise estimation of noise produced by subsea construction noise, marine facilities operation, and seismic exploration, particularly in complex coastal regions. The core algorithm in MONM computes frequency-dependent acoustic transmission loss parameters along fans of radial tracks originating from each point in a specified set of source positions. The modeling is performed in individual one-third octave spectral bands

covering frequencies from 10 Hz to several kHz, which covers the overlap between the auditory frequency range of marine mammals and the spectral region in which sound propagates significantly beyond the immediate vicinity of the source. The MONM software makes use of geo-referenced databases to automatically retrieve the bathymetry and acoustic-environmental parameters along each propagation traverse, and incorporates a tessellation algorithm that increases the angular density of modeling segments at greater ranges from a source to provide more computationally efficient coverage of the area of interest. The grid of transmission-loss values produced by the model for each source location is used to attenuate the spectral acoustic output levels of the corresponding noise source to generate absolute received sound levels at each grid point. These are then summed across frequencies to provide broadband levels. A further step of Cartesian resampling and summing of the received noise levels from all the sources in a modeling scenario yields the aggregate noise level for the entire operation on a regular grid from which contours can be drawn on a GIS map. The model can either generate contours at evenly spaced levels or draw boundaries representing biologically significant threshold levels [68], and (e) SIAM II (S.C. Wales, unpublished manuscript) was designed to provide many replications of surface-ship noise for horizontal array systems, particularly narrow-beam systems, but could also be used for omnidirectional systems. Its predecessor, SIAM I [69, 70], predicted ship-generated noise over the band 20–120 Hz by generating many replications so that ensemble statistics could be examined. A review report provides more details on SIAM (I/II) in addition to other legacy beam-noise statistics models [71]. Plotting packages for SIAM were described elsewhere [72].

3.2.3. Reverberation Models. Reverberation is sound that is scattered by the ocean boundaries (sea surface and sea floor) or by the volumetric inhomogeneities. Reverberation is produced by the sonar itself; therefore, the spectral characteristics are essentially the same as the transmitted sonar signal. The intensity of reverberation varies with the range of the scatterers (due to propagation loss) and also with the intensity of the transmitted signal.

Most traditional active sonars are configured in what is termed a monostatic geometry, meaning that the source and receiver are at the same position. In some sonar systems, however, the source and receiver are separated in range or depth, or both, in what is termed a bistatic configuration. Bistatic geometries are characterized by a triangle of source, target and receiver positions, and by their respective velocities. Such geometries are commonly employed in sonobuoy applications and also in active surveillance applications. Geometries involving multiple sources and receivers are termed multistatic.

Reverberation models can be categorized according to cell-scattering or point-scattering techniques (Box 2). Cell-scattering formulations divide the ocean into cells, where each cell contains a large number of uniformly distributed

scatterers [73]. Point-scattering formulations assume a random distribution of (point) scatterers. Table 3 provides a summary of stand-alone reverberation models. Superscript letters identify those models that have been added to the inventory since 2003. These letters refer to a brief summary and appropriate documentation. Model documentation can range from informal programming commentaries to journal articles to detailed technical reports containing a listing of the actual computer code. Corresponding information on the legacy models is provided in the 2003 baseline [23] and is not repeated here.

In Table 3: (Reverberation models), (a) C-SNAP-REV computes reverberation using the C-SNAP range-dependent normal-mode model. Range dependence of the environment is treated as a one-way coupled-mode solution. Surface and bottom reverberation is obtained by integrating the received intensity over the area insonified by the emitted pulse and that contributes to the reverberation at a given time. An average sound speed is assumed for all the paths (i.e., no group-velocity dependence). The scattering is described by a mode-coupling matrix that is equivalent to the plane-wave scattering function evaluated at discrete angles corresponding to the modes. The incident and scattered mode angles are modified to take into account the local slope and are given by the local phase velocity and the sound speed at the interface. Coherent summation of mode contributions is used to correctly model the effects of deep-water convergent zones. The empirical scattering function is based on Lambert's rule. The model deals mainly with the monostatic case, though the technique is extendable to bistatic geometries. (Unpublished notes by Ellis, SACLANT Undersea Research Centre, La Spezia, Italy, various dates.) (b) HYREV is a high-frequency, monostatic reverberation model suitable for shallow-water environments. Arrival times and transmission losses from the source to scatterers are obtained from the appropriate eigenrays. The composite-roughness theory is used to predict the boundary scattering [74], (c) NOGRP first runs the normal-mode program POPP (a variant of PROLOS), which calls the normal mode subprogram MODES and writes out a binary file of mode information that is then read by the monostatic reverberation code. ROSELLA, an extension of NOGRP, is used to execute the reverberation calculations with beam patterns [75, 76], (d) PAREQ-REV is a range-dependent wave-theory model based on the parabolic approximation of the wave equation. The numerical method uses the split-step Fourier marching solution with automatic interpolation of environmental data with range. The code allows a choice of either the standard Tappert-Hardin parabolic equation or the wide-angle equation of Thomson-Chapman. Several choices of starting fields are provided, including a Gaussian source beam of varying width and tilt with respect to the horizontal. Reverberation from the ocean boundaries is computed using standard scattering laws: Lambert's rule for bottom backscatter, and either Chapman-Harris curves or Lambert's rule for sea-surface backscatter. The computational scheme uses reciprocity of propagation to compute the reverberation field for arbitrary receiver depths at the source range. (Unpublished notes by Schneider, SACLANT Undersea Research Centre,

Cell scattering:

Cell-scattering models assume:

- (1) a homogeneous distribution of scatterers throughout the area or volume producing reverberation at any given time;
- (2) a sufficiently high density of scatterers to ensure that a large number of scatterers occurs in an elemental volume (dV) or area (dA) at range r .

The projector beam pattern is denoted by $b(\theta, \phi)$ and the axial intensity at unit distance is I_0 .

The receiver beam pattern is denoted by $b'(\theta, \phi)$ and s_v is the ratio of the intensity of the scattering produced by a unit volume at a distance of 1 m from the volume to the intensity of the incident sound wave.

The equivalent plane-wave volume reverberation level (RL_v) is

$$RL_v = 10 \log_{10} [(I_0/r^4) s_v \int_v b(\theta, \phi) b'(\theta, \phi) dV].$$

The plane-wave level of boundary reverberation is

$$RL_b = 10 \log_{10} [(I_0/r^4) s_b \int b(\theta, \phi) b'(\theta, \phi) dA].$$

Point scattering:

Point-scattering models are based on a statistical approach that assumes the scatterers are randomly distributed throughout the ocean. The echoes from each individual scatterer are then summed to compute the reverberation level.

Box 2: Organization of underwater acoustic reverberation models into two categories.

La Spezia, Italy, various dates.), (e) PERM-2D computes backscatter from range-dependent bathymetry in the oceanic waveguide [77]. This technique extends the approach of Collins and Evans [78] to problems involving small-scale and large-scale boundary roughness. The PERM-2D model subdivides the oceanic waveguide into range-independent regions and applies the single-scattering approximation (i.e., multiple forward and backward coupling in the scattered fields is neglected) to formulate a scattering problem for the reflected and transmitted pressure field at each range step. Forward-scattering loss, which can be significant at long ranges and very rough surfaces, is included in the solution. Wide-angle operators, which are accurate for the propagating and evanescent spectrum, are applied to yield stable and convergent iteration formulas for the reflected and transmitted fields [79]. Unlike perturbative methods that are restricted to small-roughness amplitudes, the PERM-2D model is valid for arbitrary roughness subject to the single-scattering approximation, (f) REVPA is a parabolic-equation reverberation model intended for shallow-water applications [80], (g) R-SNAP is a coherent monostatic reverberation model employing the range-dependent propagation model SNAP [81, 82], (h) ARTEMIS (adiabatic reverberation and target echo mode incoherent sum) is a general-purpose numerical model of bistatic target echo level and surface and bottom reverberation for bistatic arrangements in an arbitrary range-dependent environment with arbitrary sound-speed variation [83]. The model minimizes computation time while retaining a reasonably accurate power envelope. The approach is based on the adiabatic normal-mode approximation, but with the modal series treated as a continuum and with WKB mode amplitudes (excluding the oscillatory modulation). Outputs are three-dimensional and they can be presented in map form as target echo, reverberation or signal-to-reverberation ratio. Given sparse environmental data, the tradeoff between accuracy and speed is negotiated by intelligent interpolation. This is done by constructing quantities (functions of the desired variables, such as cycle distance, ray angles, etc.) that are more or less linear in space or in mode number. These are converted

back to the original variables after linear interpolation, (i) BISTAR is a bistatic, range-dependent reverberation model based on the method of coupled normal modes. The environment is discretized into range-independent segments and the outward propagating field is coupled at the interfaces under the single-scatter hypothesis. The propagation theory and implementation are those of C-SNAP. In order to implement the reverberation prediction, the CW field estimate of C-SNAP has been augmented with a narrowband time-series estimator. The time-domain estimates for the range-dependent environment are available separately and are also used to obtain the reverberation estimates. The scattering process itself can be modeled either as a parametric scattering strength such as Lambert's law or via perturbation theory. The model includes coherent propagation to and from the scattering patch [84–87]. (Also, unpublished notes by K.D. LePage, SACLANT Undersea Research Centre, La Spezia, Italy, various dates.), (j) MURAL, the multistatic reverberation algorithm, supports trainer development, and can be used with any propagation model that produces range-sampled grids of transmission loss, travel time, launch and grazing angles. MURAL contains functions that calculate propagation, scattering and beam patterns. The operation of MURAL couples the algorithm controls to the requested resolution of the prediction with the goal of self-optimizing its performance for the requested resolution [88], (k) S-SCARAB is a range-independent raytracing model for calculating both forward propagating and reverberant acoustic fields. Features include improved algorithms to calculate the coherent forward propagating field, the inclusion of upward refracting rays in the sediment, definition of bistatic source-receiver geometries, and the possibility of specifying 3D beam patterns of the source and receivers. The forward and back propagating acoustic fields are calculated by tracing rays both in the water column and sediment. Only contributions from the ocean bottom are considered in calculation of the reverberation. The local scattering properties of the seabed are described by known power-law expressions for both the interfaces of stratified sediment layers and volume inhomogeneities in the sediment. These scattering kernels

TABLE 3: Summary of underwater acoustic reverberation models. Superscript letters identify those models that have been added to the inventory since 2003.

Cell scattering	
Monostatic	Bistatic/multistatic
C-SNAP-REV ^a	ARTEMIS ^h
DOP	BAM
EIGEN/REVERB	BiKR
HYREV ^b	BiRASP
MAM	BISAPP
NOGRP/ROSELLA ^c	BISSM
PAREQ-REV ^d	BISTAR ⁱ
PEREV	MURAL ^j
PERM-2D ^e	OGOPOGO
REVMOD	RASP
REVPA ^f	RUMBLE
REVSIM	S-SCARAB ^k
R-SNAP ^g	
TENAR	
Point scattering	
Monostatic	Bistatic/multistatic
REVGEM	BORIS-SSA ^m
RITSHPA ^l	Under-ice reverberation Simulation

are dependent on physical descriptors of the bottom such as seabed roughness. S-SCARAB is computationally efficient compared to other reverberation tools based on normal-mode or parabolic equation approaches, particularly at higher frequencies [89], (l) RITSHPA is a reverberation module intended for use in high-resolution, wideband sonar simulators [90] in which reverberation is stochastic (non-Rayleigh) and follows the K-distribution [91]. Hybrid multipaths, in which the return path is different from the transmit path, are also considered. RITSHPA assumes spherical propagation loss (i.e., isovelocity water column) and uses widely known formulas to compute reflection and scattering at boundaries, and (m) BORIS-SSA (bottom reverberation from inhomogeneities and surfaces small-slope approximation) simulates time series resulting from acoustic scattering off various seafloor types involving various source-receiver geometries [92–96]. This package is an upgrade of BORIS-3D. The model parameters characterize the sonar directivity and pulse shape, the geometrical configuration of the scattering problem and the geophysical characteristics of the seafloor, the sea surface, or other surfaces. These surfaces can have various statistical behaviors or can be obtained from deterministic data based on measured surface heights.

3.2.4. 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. A further segregation can be made according to source/receiver geometry into monostatic and bistatic categories (Box 3). The monostatic formulation of the sonar equations follows a traditional format [73], while the bistatic formulation is adapted from H. Cox (see [23]). The performance of passive

sonars (i.e., those that detect sound emitted from a target of interest) could be modeled using the appropriate environmental descriptors together with suitable propagation-loss and noise models. The performance of active sonars (i.e., those that transmit an interrogation signal and then detect the echo returned from a target of interest) could be modeled similarly with the addition of suitable reverberation models.

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. Model-operating systems are further distinguished from stand-alone active sonar performance models by virtue of their ability to conduct sensitivity analyses by computing components of the active-sonar equation using alternative solution techniques. Since sonar model operating systems normally utilize existing ocean-acoustic models and standard oceanographic databases, these systems are unique only in the sense of the number and types of models and databases included, and the particular architectures, graphical user interfaces (GUIs), and other features employed. 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 4 provides a summary of sonar performance models. Superscript letters identify those models that have been added to the inventory since 2003. These letters refer to a brief summary and appropriate documentation. Model documentation can range from informal programming commentaries to journal articles to detailed technical reports containing a listing of the actual computer code. Corresponding information on the legacy models is provided in the 2003 baseline [23] and is not repeated here.

In Table 4: (Sonar performance models), (a) ESPRESSO is a minehunting sonar performance assessment tool developed as a NATO standard for interfacing with NATO planning and evaluation tactical decision aids [97]. It uses BELLHOP as a propagation submodel, which has also been modified to calculate beam-based, high-frequency reverberation [98]. Espresso exists in two versions: one intended for scientific use and the other for military use. The scientific version of Espresso provides greater flexibility than the military version, including the ability to select sub-models and view the results of any sub-model. A user guide addresses the user interface for Espresso and describes the underlying software models and data output options available within Espresso [99]. There is a separate user guide for the military version, Espresso (m), which provides greater tailoring of the user interface, including the ability to customize parameters [100]; (b) LYBIN is a range-dependent, ray-theoretical model developed by Svein Mjølunes of the Norwegian Defence Logistic Organization [101–103]. Range-dependent environmental inputs include bottom type and topography, volume backscatter, sound speed, temperature, salinity, wind speed, and wave height. Choices of

Active sonar equations (monostatic)

(i) Noise background

$$SL - 2TL + TS = NL - DI + RD_N.$$

(ii) Reverberation background

$$SL - 2TL + TS = RL + RD_R.$$

Passive sonar equation

$$SL - TL = NL - DI + RD.$$

SL: source level; TL: transmission loss; TS: target strength; NL: noise level; DI: receiving directivity index;

RL: reverberation level; RD: recognition differential.

Active sonar equations (bistatic)

The signal excess (SE) can be represented as:

$$(i) SE = ESL - TL_1 - TL_2 - [(N_0 - AG_N) \oplus R_0] + TS - \Lambda - L,$$

the energy source level (ESL) is related to the intensity source level (SL) as:

$$(ii) ESL = SL + 10\log_{10} T$$

where T is the duration of the transmitted pulse,

The echo energy level (EEL) received from the target at a hydrophone on the receiver array is then:

$$(iii) EEL = ESL - TL_1 - TL_2 + TS,$$

where TS is the target strength, N_0 is the noise spectral level, R_0 represents the reverberation spectral level, AG_N is the array gain against noise, Λ is the threshold on the signal-to-noise ratio (SNR) required for detection,

L is a loss term to account for time spreading and system losses,

\oplus represents power summation, TL_1 is the transmission loss from source (S) to target (T),

and TL_2 is the transmission loss from target (T) to receiver (R).

Box 3: Sonar performance models are based upon the sonar equations, which are the basic building blocks for both monostatic and bistatic sonar geometries.

calculation outputs include ray trace, transmission loss, reverberation (surface, volume, and bottom), noise, signal excess, probability of detection, travel time, and impulse response. The transmission-loss module was evaluated by NURC [104]. LYBIN is available commercially from the Forsvarets forskningsinstitutt (FFI), (c) MOC3D [105] is a 3D model developed from the 2D model MOCASSIN [106]. MOC3D was used to investigate the importance of out-of-plane sound propagation in a shallow-water experiment in the Florida Straits [107], (d) MODRAY was developed in conjunction with DSTO (Australia) to simulate the propagation of sound through the underwater environment [108, 109]. MODRAY uses classical ray-tracing theory to produce sound-pressure time series at one or more receivers. The marine environment is range-independent. Seafloor composition can be specified, the sound-speed profile can be arbitrary, noise includes wind, rain, biological and shipping sources, and scattering by marine organisms is included. MODRAY can model an arbitrary number of sound sources, reflectors and receivers stationed on moving platforms. MODRAY has been used extensively to model the effectiveness of underwater communications algorithms

[110, 111], (e) SUPREMO is a multistatic sonar performance model that includes propagation, target echoes, reverberation and noise, all plotted as a function of delay time and bearing using an equivalent map projection. A modular propagation section makes it possible to separate the effects of propagation modeling (e.g., theoretical basis and range-dependence) from those of scattering computations (e.g., computational efficiency, bottom slope and scattering law). Special attention is paid to problems of interference from multiple sources firing in sequence, target aspect dependence from multiple receivers, mixed FM and CW, mismatched source and receivers, multiple displays (one for each bistatic pair), and presentation of results [82, 112–115]. Predictions of acoustic reverberation and target echo intensity made by the SUPREMO sonar performance model were compared with measured data gathered in the Malta Plateau region of the Mediterranean Sea. The observed model-measurement agreement demonstrated the suitability of SUPREMO for use with an environmentally adaptive, low-frequency, active sonar system [116]. Version 2.0 of SUPREMO has been documented [117, 118], (f) SWAMI models range-and-azimuth dependence ($N \times 2D$) via adiabatic modes [119].

TABLE 4: Summary of sonar performance models. Superscript letters identify those models that have been added to the inventory since 2003.

Active sonar models	
Active RAYMODE	MINERAY
ALMOST	MOCASSIN
ASPM	MOC3D ^c
CASTAR	MODRAY ^d
CONGRATS	MSASM
ESPRESSO ^a	NISSM-II
GASS	SEARAY
HODGSON	SONAR
INSIGHT	SST
INSTANT	SUPREMO ^e
LIRA	SWAMI/DMOS ^f
LORA	SWAT
LYBIN ^b	UAIM ^g
Model operating systems	
CAAM	GSM - Bistatic
CALYPSO ^h	HydroCAM
CASS	PRISM
ESME/NEMO ⁱ	SPPS ^j
Tactical decision aids	
ASPECT SPPS ^k	
IMAT	
NECTA	

SWAMI has been used to support the towed integrated active-passive sonar (TIAPS), which was developed as a technology demonstrator for the Canadian Forces. Software development utilized a system test bed (STB) comprising a collection of scaleable, portable, and reusable components for constructing sensor-based applications. The toolset contains modules to produce predictions of transmission loss, reverberation (MONOGO), signal excess, and probability of detection. SWAMI includes the capability to model various source and receiver configurations including omnidirectional arrays, line-arrays (both horizontal and vertical) and volumetric arrays [120]. DMOS (DRDC Atlantic Model Operating System) is an evolution of the SWAMI suite of programs that enables a user to model transmission loss, reverberation, signal excess, and probability of detection for active sonars [121]. Originally, the suite was based on normal-mode theory (PMODES); however, normal-mode theory is best suited to shallow water and low acoustic frequencies, and users occasionally need to model reverberation and other parameters under other conditions. DMOS was enhanced to include a Gaussian-beam acoustic propagation model, BELLHOP, as an alternate propagation engine. A DRDC-extended version that included a range-dependent capability was chosen. DMOS may now be used to model both active and passive sonars in shallow or deep water; (g) UAIM is a system of computer algorithms designed to predict multibeam sonar performance and image

the effects of variations in bathymetry, clutter objects, and bottom type, particularly in complex shallow-water environments [122]. The model addresses perceived weaknesses in existing mine-countermeasure (MCM) sonar performance models. The propagation code in UAIM was derived from RASP while the reverberation and signal excess codes were derived from GSM. Modifications were made to these codes to accommodate high-frequency range-dependent applications. A utility package called SoundGuide assists the operator in creating the large input file, executes UAIM and plots the resulting data, (h) CALYPSO (ΚΑΛΥΨΩ) is an integrated computer environment that was developed for the analysis of underwater acoustic detection systems [123]. The communication language is Greek. It can treat passive detection, broadband, or LOFAR, as well as active detection, monostatic or multistatic. The system contains compact databases for environmental (coastline, bathymetry, oceanographic, geological) and operational (system parameters, target characteristics) data. Acoustic propagation calculations are performed using normal-mode, parabolic approximation, and ray-theoretical codes supporting broadband calculations in range-dependent environments. The results include transmission loss, reverberation levels, detection thresholds and probabilities of detection for a variety of user-defined operational scenarios. (This work was supported by the Greek MOD.) (i) ESME (effects of sound on the marine environment) is a multidisciplinary research and development effort to explore the interactions between anthropogenic sounds, the acoustic environment and marine mammals [124, 125]. The “ESME workbench” models the entire sound path including the sound sources (impulsive or explosive), the medium (water column and seafloor), and the temporary threshold shift (TTS) models of the marine mammals. (TTS refers to a temporary increase in the threshold of hearing, i.e., the minimum intensity needed to hear a sound at a specific frequency, but which returns to its preexposure level over time.) The goal is to predict impacts of anthropogenic sounds on marine mammals. This entails three elements: (1) accurate estimates of the sound field in the ocean; (2) accurate estimates of the cumulative sound exposure of the marine mammals; (3) reliable predictions of the incidence of TTS for the species of interest given the estimated cumulative exposure. The flexibility and computational efficiency of the ESME Workbench will be enhanced by merging the NEMO (NUWC exposure model) and ESME approaches into the “One Navy Model,” which is intended to serve as the standard simulation system for use in predicting impacts of anthropogenic sound sources on marine life for environmental compliance purposes, (j) SPPS, the sonar performance prediction system (developed in Germany), evaluates the performance of sonar systems in various naval-warfare scenarios and assists in sonar-system design efforts. The model accommodates active and passive sonar detection problems involving both broadband and narrowband signals using a variety of sonar antennas. The integrated ocean-acoustic propagation model spans the frequency range 10 Hz to 1 MHz by using a hybrid combination of parabolic-equation, coupled-mode, and ray propagation submodels. Environmental databases describe the ocean environment,

targets, platforms and sonar-system characteristics. The reverberation model predicts volume, surface and bottom components. Noise sources include ambient, biological, rain, shipping, ice, seismic exploration, and self-noise [126], and (k) ASPECT, the active system performance estimate computer tool, is a multistatic tactical decision aid (TDA). It computes estimates of system performance for active underwater acoustic sensors. ASPECT was originally designed to satisfy the requirements of mission planning software for the IEER (improved extended echo ranging) system. However, virtually any multistatic or monostatic active acoustic system can be modeled using this software package. ASPECT uses the FAME (fast multipath expansion) model for range-independent calculations of transmission loss and ASPM (active system performance model) for range-dependent transmission loss and reverberation. These computations are then fed into MSASM, which is capable of estimating the performance of active sonar systems for multiple sources, receivers, and targets. It simulates target motion including such features as normal and uniform probability distribution, various speed, and course distributions, as well as target evasion modeling to a limited degree. ASPECT version 2.0 (and beyond) supersedes the MSASM Interactive Execution and Optimization System (MINEOS), which was the first version of mission planning software developed for the IEER program. ASPECT also exists as a standalone version [127].

3.3. Inversion Techniques

3.3.1. Adjunct Tools for Oceanographers. Inverse acoustic sensing techniques presently constitute adjuncts to direct measurement methods. However, the application of inverse acoustic sensing techniques to dynamical studies of the oceans' boundaries and interior show great promise for three reasons. First, such data can be used to establish comparative baselines for other remote sensors, such as satellites, by providing synoptic portraits of the interior oceans together with concurrent ground-truth data at the sea surface. Second, inverse acoustic techniques often afford useful insights into a broad class of oceanic phenomena since their successful employment relies heavily on the use of numerical models first to understand the role of the oceans as an acoustic medium. Third, inverse data provide estimates of spatially integrated and temporally averaged oceanic conditions that are not readily available from traditional oceanographic sensors.

Recently, acoustical oceanographers have employed underwater-acoustic models as adjunct tools for inverse-sensing techniques that can be used to obtain synoptic portraits of large ocean areas or to monitor long-term variations in the ocean.

Useful information about the ocean can be derived from both forward and inverse applications of underwater sound. Direct (or forward) methods include traditional sonar applications. Inverse methods extract information from direct measurements of the physical properties of the ocean. These inverse methods combine the direct physical measurements with theoretical models of underwater

acoustics. The objective is to estimate detailed underwater-acoustic fields from sparse physical measurements using the theoretical models as guides. Inversions of controlled-source, noise, and reverberation fields have been performed successfully (Box 4).

Inverse sensing techniques that employ acoustics have been used in several subdisciplines of geophysics including seismology, meteorology, and oceanography. In oceanography, inverse acoustic data provide estimates of spatially integrated and temporally averaged oceanic conditions that are not readily available from a traditional constellation of point sensors. Forward (or direct) models are important in solving inverse problems.

3.3.2. Propagation (Acoustic Field Measurements). Acoustic propagation characteristics in the deep oceans are determined largely by the refractive properties of the water column and, to a lesser extent, by the surface and bottom boundary conditions. Propagation measurements can be used to infer bulk properties of the water column such as temperature, sound speed, density, and currents. In shallow-ocean areas, where propagation characteristics can be strongly affected by the bottom boundary, propagation measurements can be used to infer properties of the sea floor such as composition and scattering characteristics. A wide spectrum of inverse problems has been addressed in underwater acoustics including estimation of geoacoustic parameters, acoustic thermometry, and shallow-water characterization. Inverse acoustic sensing methods utilizing the propagation characteristics of the oceans include matched field processing, ocean acoustic tomography and deductive geoacoustic inversion [23]. A new technique known as a time reversal mirror (TRM) uses inverse methods to refocus received signals back to the source.

Range-dependent ray-theoretical models are typically used for deep-water applications involving tomographic experiments as well as for high-frequency experiments in shallow water. Range-dependent wave-theoretical models based on normal-mode, fast-field (wavenumber integration), or parabolic-equation approaches are preferred for low-frequency experiments in shallow water.

3.3.3. Noise. The ambient noise field in the oceans is described by the spectral, spatial, and temporal characteristics of sound generated by both natural and industrial sources. Measurements of these characteristics can provide useful information regarding the nature of the noise sources themselves as well as physical features within the oceans. Examples of inverse applications of the noise field include wind speed determination, rainfall measurements, object imaging (*acoustic daylight*), and geoacoustic inversion.

3.3.4. Reverberation. The reverberation field in the oceans is the product of acoustic scattering by the surface and bottom boundaries and by inhomogeneities within the oceans. The utility of the reverberation field as an inverse sensing technique is analogous to that of the ambient noise field. For example, the reverberation field can be inverted to

- Propagation
- (i) Matched field processing:
 - (a) source localization,
 - (b) marine environment characterization.
 - (ii) Ocean acoustic tomography:
 - (a) density field (eddies, currents),
 - (b) temperature (climate monitoring).
 - (iii) Deductive geoacoustic inversion:
 - (a) sediment parameters,
 - (b) sea-floor scattering characteristics.
 - (iv) Time reversal mirror (TRM):
 - (a) signal refocusing.
- Noise
- (i) Field inversion:
 - (a) wind speeds,
 - (b) rainfall rates.
 - (ii) Acoustic daylight:
 - (a) object imaging.
 - (iii) Geoacoustic inversion:
 - (a) seabed acoustics.
- Reverberation
- (i) Field inversion:
 - (a) sea-floor imaging.
 - (ii) TRM nulling:
 - (a) reverberation attenuation.

Box 4: Summary of inverse ocean acoustic sensing techniques.

image the sea floor. A new development uses time reversal mirror (TRM) methods to attenuate reverberant returns.

4. Emerging Solutions

4.1. Background. This section addresses advanced processing methods in addition to novel methods by which to maximize the interpretation, and thus utility, of archival and experimental data.

4.2. Advanced Integrated Modeling Approaches

4.2.1. Acoustic Integration Model. The acoustic integration model (AIM) combines a movement simulator with underwater acoustic models to predict (and thus minimize and mitigate) the potential effect of sound on marine mammals [128]. Simulated sound sources and animals are programmed to move in location and depth over time in a realistic fashion. AIM is a Monte Carlo statistical model based on a whale movement and tracking model and an underwater acoustic backscattering model for a moving source. Currently, AIM incorporates the BELLHOP and PE propagation models in addition to the ETOP05 bathymetry and GDEM sound-speed profile databases. The ETOP05 data set is the highest resolution topographic data set with global coverage that is publicly available, with elevations posted every 5 arc minutes (approximately 10 km) for all land and sea floor surfaces. ETOP05 is distributed without restriction by the National Oceanic and Atmospheric Administration

(NOAA) through its National Geophysical Data Center (NGDC).

4.2.2. Marine Mammal Movement Models. A method has been developed for modeling marine mammal movement and behavior (3MB) for use in environmental impact assessments [129]. Estimating the impact of anthropogenic sound on marine animals entails consideration of animal location and behavior at the time of sound exposure. The ESME model (see Table 4) incorporates 3MB to provide fine-scale control over simulated marine-animal (animat) movement and behavior. Control over the animats is scaleable to the information available regarding the species of concern. Movement and behavior are stochastically determined by sampling from distributions describing rates of movement in the horizontal and vertical planes, direction of travel, time at the surface between dives, time at depth, and time in and transition between behavioral states. Influence of behavior over each of the other distributions is also permitted.

As part of the NATO Undersea Research Centre (NURC) broadband environmentally adaptive concept, the SUPREMO sonar performance model was incorporated within a feedback mechanism for sonar-parameter optimization for any specified ocean environment [130]. The feasibility of using active sonars to monitor the movement of marine mammals was investigated in order to recommend stand-off distances within which an acoustic source should not be deployed [131].

4.2.3. Energy Flux Models. Some applications, such as work relating to acoustic impacts on marine mammals, do not require extremely high-fidelity model outputs. Transmission losses averaged over depth, for example, are often adequate.

An approach referred to as energy-flux models [132] is useful for rapid calculation of transmission loss where the propagation conditions are dominated by numerous boundary-reflected multipaths and when only the coarse characteristics of the acoustic field are needed.

In specific configurations, especially at long ranges in shallow-water environments, the transmitted field can be viewed as being composed of many paths propagating by successive reflections from the surface and bottom boundaries. Here, the acoustic energy will remain trapped between these two boundaries. Furthermore, if the acoustic frequency is high enough that the field oscillations can be considered to be random, then an average intensity can be calculated using simple algebraic formulas [23].

This concept can be extended to ocean environments where the sound speed is not constant, or where there are slight losses at the boundaries. In such cases, the transmitted field cannot be taken as a volumetric average. Rather, it has to be decomposed into its angular components and the cyclic characteristics of the various beams must be detailed [133].

This approach is very useful for predicting incoherent transmission losses in cases where there are a large number of modes (≥ 6). These flux models are fast because there is no requirement to find modes or eigenrays. They can also lead to

very simple and intuitive expressions. This method has been extended for reverberation [134].

4.2.4. Waveguide Invariant Models. In weakly range-dependent ocean environments, it has been observed that the acoustic wavefield can be described in terms of ray-based or mode-based approaches [135, 136]. Using ray-based descriptions, distributions of the ray amplitude and phase (travel time) are largely controlled by the so-called stability parameter (α). Alternatively, using mode-based descriptions in either purely range-independent environments or in range-independent environments upon which weak (range-dependent) perturbations have been superimposed, many wavefield properties are controlled by the so-called waveguide invariant (β). When β is evaluated using asymptotic mode-theoretical results (in a stratified environment), it was found that $\beta = \alpha$, which is consistent with the well-known ray-mode duality. In weakly range-dependent environments, however, α was found to control ray stability and several measures of travel-time dispersion while β controlled the spread of modal-group delays due to mode coupling.

In essence, the waveguide invariant (β) summarizes the pattern of constructive and destructive interference between acoustic modes propagating in the ocean waveguide. It manifests itself as interference fringes (or striations) in a plot of frequency versus source-receiver separation. The waveguide invariant summarizes in a single scalar parameter the dispersive propagation characteristics in a waveguide.

4.3. Advanced Nonintrusive Measurement Approaches

4.3.1. Acoustic Transmission Options. In *acoustic probing*, transmit signals can be adapted according to *in situ* estimates of channel conditions. Waveform characteristics could be set using returns from the previous transmission as an indicator of channel response. Rapidly modifying processing parameters by analyzing previously received signals addresses the problem of fluctuating acoustic channel response owing to variations in environmental factors. Such optimal matching to the estimated channel response would improve target-echo stability [137].

Since sound level, frequency, and duration are critical parameters in causing physical damage to marine life, transmitting over a wider frequency spectrum using spread-spectrum techniques or noise-like signals could avoid tissue damage by reducing the time spent (or energy transmitted) in particular frequency bands. Spread-spectrum techniques use a pseudorandom spreading code to produce a wide-band source signature. Signals must possess high range and Doppler resolution and minimize cross-talk between different users.

Noise-like signals emulate ambient noise by covertly adapting to the fluctuating ambient noise field. Designers could model pseudo-random signals based on bioacoustic noise, surf noise (when high-frequency broadband transients should be useful [138]) or shipping noise (when near CW would be more useful).

Advances in sonar technologies have rendered modern sonar systems useful for *in situ* measurements of the ambient marine environment. For example, through-the-sensor measurements of the ocean impulse response have enabled modern sonars to perform collateral functions as *tactical environmental processors*.

A recent *through-the-sensor* remote-sensing technique for acoustic-parameter estimation has been referred to as SABLE (sonar active boundary loss estimation) [139]. Bottom scattering strengths were derived from active hull-mounted naval sonar data by using eigenray paths modeled by CASS and GRAB to associate sonar-signal attributes with specific propagation paths.

4.3.2. Collision Avoidance. Cetaceans are prone to collisions with fast-moving vessels. In areas of high cetacean and vessel densities, the sperm whale (*Physeter macrocephalus*) is of great concern. Sperm whales are highly vocal and can be localized with passive sonar; however, when at or near the surface (i.e., when they are at greatest risk of collision), they tend to stop vocalizing. Techniques employing active sonars have proved to be inefficient due to short detection ranges and high closing speeds. The efficiency of a passive-sonar solution was evaluated that used vocalizing whale clicks (at depth) as acoustic sources to detect silent whales [140]. This solution could serve as a noninvasive complement to a more complex passive localization and collision-avoidance system. A wideband $N \times 2D$ (range-and-azimuth-dependent) ray model was used to simulate a passive solution comprising an arbitrary number of active acoustic sources (vocalizing whales), an illuminated object (silent whale) and a passive-sonar receiver, all positioned in three-dimensional space with arbitrary bathymetry. Both curved-line and straight-line ray solutions were implemented, with the latter providing greater computational speeds at the expense of temporal and angular fidelity. The simulation recreated the resultant mixture of direct, reverberated and target-backscattered signals arriving at the receiver for any array configuration, any number of sources and one target. In the vicinity of the Canary Islands, the simulations demonstrated the applicability of the concept with a maximum detection range on the order of 1 km.

4.4. Advanced Processing Methods

4.4.1. Adjoint Modeling. The principal application of adjoint models is sensitivity analysis. When quantitative estimates of sensitivity are desired, a mathematical model of the phenomenon or relationship is required. While models have been used to assess the impacts of perturbations and thus estimate sensitivity, a more efficient approach is to use the model's adjoint to determine optimal solutions. The adjoint operates backward in the sense that it determines a gradient with respect to input from a gradient with respect to output. In a temporally continuous model, this would appear as integration backwards in time. If there are no numerical instabilities associated with irreversible processes in the tangent linear model acting forward in time, there will be

none in the adjoint acting backward in time (a tangent linear model provides a first-order approximation to the evolution of perturbations in a nonlinear forecast trajectory). The greatest limitation to the application of adjoints is that the results are useful only when the linearized approximation is valid. The adjoint operator (matrix transpose) back-projects information from data to the underlying model. Geophysical modeling calculations generally use linear operators that predict data from models. The usual task is to find the inverse of these calculations, that is, to find models (or make maps) from the data. The adjoint operator tolerates imperfections in the data and does not demand that the data provide full information.

The concept of adjoint modeling was introduced in shallow water acoustics for solving inverse problems [141]. In related work, the concept of backpropagation was reviewed in the context of adjoint modeling [142]. The different implementations of this concept were compared and discussed in the framework of experimental acoustic inversion in shallow water with application to source localization, ocean acoustic tomography, geoacoustic inversion and underwater communications. Well-established inversion (or focalization) methods based on matched-field processing, model-based matched filter and time-reversal mirror are related to lesser known techniques such as acoustic retrogradation and other variants of backpropagation. In contrast to the latter, adjoint-based variational inversion approaches make use of the adjoint of a forward model to backpropagate the model-data mismatch at the receiver toward the source.

An adjoint model was derived from a forward-propagation model (e.g., normal mode or parabolic equation) to propagate data-model misfits at the observation point back through the medium to the site of those medium perturbations that were not accounted for in the forward model and which gave rise to the observed data-model misfits [143]. This property makes adjoint models attractive for use in acoustic inversion experiments.

4.4.2. Stochastic Resonance. Stochastic resonance refers to a phenomenon that is manifested in nonlinear systems whereby weak signals can be amplified in the presence of noise [144]. Three components are necessary: a threshold, a periodic signal and a source of noise. The response of the system undergoes resonance-like behavior as the noise level is varied [145]. Stochastic resonance was applied to enhance the detection of target signals masked by shallow-water reverberation [146]. Specifically, parameter-induced stochastic resonance was used to tune system parameters to recover the spatial signal that was corrupted by Gaussian noise. This method also has applicability when processing spatial signals that are corrupted by K -distributed envelope noise (a standard model for radar clutter).

4.4.3. Optimization Techniques. Ant colony optimization (ACO) has elements in common with genetic algorithms [147]. Both are population-based algorithms that search a discrete space and provide uncertainty analyses. The

main difference is the mechanism that handles and recombines components of better candidate solutions (i.e., ant-pheromones trails versus genetic operators). Ant colony optimization is further distinguished by having a form of memory (the ant pheromone trails), while genetic algorithms are without memory. Specifically, when the pheromones evaporate, identifiers of paths with above-average quality fade out. Thus, high rates of evaporation mean that only recent information can be retrieved (typical for short-term memory); alternatively, low rates of evaporation allow recollection of much older information (typical for long-term memory). When applied to inversion, the world of the ants acts as an analogy for the geoacoustic environment.

An efficient and reliable method was proposed for performing the inversion of a neural-network underwater acoustic model to obtain sea-floor parameters [148]. Two different versions of a modified particle-swarm optimization were used: two-step gradient approximation and hierarchical cluster-based approximation. Both approaches worked well.

Tabu search has traditionally been applied to combinatorial optimization problems [149, 150]. The tabu search begins by marching to a local minimum. This approach avoids entrapment in cycles by forbidding (tabu), or penalizing, moves that take the solution in the next iteration to points in the solution space previously visited.

4.4.4. Chaos. In the presence of weak fluctuations in the sound-speed field, it has been observed that ray trajectories in ocean waveguides exhibit a chaotic behavior in which the travel times along eigenrays form compact clusters, the center of which is close to the arrival time of an unperturbed ray with similar geometry [151]. The deep-water acoustic waveguide was modeled by an unperturbed sound-speed profile [$c_0(z)$] combined with weak fluctuations of sound speed [$\delta c(r, z)$] caused by a random field of internal waves conforming to the Garrett-Munk spectrum. Formally, ray equations in a random inhomogeneous medium can be considered as stochastic equations whose parameters are determined by a random function δc . Such nonlinear equations can be solved in the framework of ordinary perturbation theory, but only for short ranges. Instead, the ray structure was analyzed by using the Hamiltonian formalism in terms of action-angle canonical variables whose variation was small under conditions of weak perturbations. It was estimated that ray arrival times at a distance r occupied an interval whose average width increased in proportion with $r^{1.5}$, in agreement with previous investigators. Moreover, for $r < 10^3$ km, the ray trajectories forming the cluster deviated only slightly from the unperturbed ray trajectory and the cluster width grew in proportion with $r^{0.5}$. For $r > 10^3$ km, the width of the cluster grew in proportion with r^2 .

Chaotic and stochastic nonlinear ray dynamics can occur in underwater-acoustic waveguides with longitudinal variations in the sound speed caused by internal waves [152]. This situation was investigated using a model of a "frozen" medium in which the temporal variations in the environment were neglected and only the spatial variations due to the comparatively small propagation time of sound

in the ocean were considered. Coherent ray clusters were observed in which large fans of rays with close initial conditions preserved close current dynamical characteristics over long distances. The cluster structure could be considered to consist of statistical and coherent parts. Rays belonging to the statistical part propagated in the same areas of phase space with the same value of the Lagrangian, but did not correlate with each other and demonstrated exponential sensitivity to initial conditions. Rays belonging to the coherent part did not demonstrate sensitivity to initial conditions. This coherent clusterization might be a useful property for acoustic tomography in terms of determining spatio-temporal variations in the hydrological environment under conditions of ray chaos [153].

5. Summary

This paper has reviewed changes in the ocean soundscape, changes that have been driven by both anthropogenic activity and natural factors. New regulatory initiatives have placed additional restrictions on uses of sound in the ocean, and mitigation of marine-mammal endangerment is now an integral consideration in acoustic-system design and operation. Emphasis has been placed on leveraging advanced modeling methods to solve emerging scientific and engineering challenges in this field.

Naval sonars have been redesigned as high-power multistatic systems capable of operating in complex coastal environments against quiet submarines. Littoral training ranges to support this new generation of sonar systems must comply with more stringent environmental regulations. Such compliance is often assessed using advanced modeling techniques coupled with *in situ* data collection. Oceanographic data collection is supported by underwater networks consisting of sensors and vehicles deployed in concert. These networks employ nodes that communicate via acoustic channels that have low data rates and time-varying fading.

Seismic exploration has ventured into deeper waters in search of diminishing energy resources using source arrays that are powered by high-pressure air. Controlled-exposure experiments have studied changes in the behavior of nearby whales due to these powerful sources; however, modeling uncertainty complicates the regulatory interpretation of average sound-exposure conditions.

Increased merchant shipping activity has had a measurable impact on the ocean soundscape over the past four decades: the average noise has increased by 2.5–3 dB per decade in the frequency band 30–50 Hz. Moreover, the growing number of wind farms in coastal waters of medium depth (<30 m) has added to the soundscape at low frequencies and resulted in behavioral reactions of nearby marine mammals.

Climate change has also affected the ocean soundscape. The emission of carbon into the atmosphere through the effects of fossil-fuel combustion and industrial processes has increased atmospheric concentrations of carbon dioxide (CO₂). Ocean acidification, which occurs when CO₂ in the atmosphere reacts with water to create carbonic acid

(H₂CO₃), has increased. The attenuation of low-frequency sound in the sea is pH dependent; specifically, the higher the pH, the greater the attenuation. Thus, as the ocean has become more acidic (lower pH) due to increasing CO₂ emissions, the attenuation has diminished and low-frequency sounds propagate farther, making the ocean noisier. Recent investigations have estimated that the noise at 3 kHz would increase by 30% if the pH decreased from 8.0 to 7.4.

Modeling tools traditionally used in underwater acoustics have undergone a necessary transformation; these tools include propagation, noise, reverberation, and sonar-performance models. Advanced modeling techniques now include forward and inverse applications, integrated-modeling approaches, nonintrusive measurements and novel processing methods. The flow of the sonar modeling processes was used to demonstrate advances in modeling technology relevant to assessments of the ocean soundscape. A 32-year baseline inventory of modeling techniques was updated with the latest developments, including basic mathematics and references to the key literature, to guide soundscape practitioners to the most efficient modeling techniques for any given application.

Advanced processing methods included integrated modeling approaches that combine marine-mammal movement simulators with underwater acoustic models to predict (and thus minimize and mitigate) the potential effect of sound on marine mammals. Advances have been achieved using energy-flux and waveguide-invariant techniques that can simplify interpretation of channel models. Nonintrusive measurement approaches included new acoustic transmission options to minimize marine-mammal impacts. Collision avoidance techniques have proved useful in areas of high cetacean and vessel density. Finally, adjoint modeling, stochastic resonance, optimization techniques, and chaos were shown to facilitate understanding of advance underwater acoustic modeling results.

Abbreviations

1D:	One-dimensional
2D:	Two-dimensional
3D:	Three Dimensional
3DWAPE:	3D wide-angle parabolic equation
3MB:	Marine mammal movement and behavior
ACM:	Association for computing machinery
ACO:	Ant colony optimization
AIM:	Acoustic integration model
ARAMIS:	Array response advanced modal integrated simulator
ARTEMIS:	Adiabatic reverberation and target echo mode incoherent sum
ASA:	Acoustical Society of America
ASPECT:	Active system performance estimate computer tool
AUV:	Autonomous underwater vehicle
BISTAR:	Incoherent bistatic reverberation for range-dependent environments

BLM:	Bureau of Land Management (now BOEMRE)	IARIA:	International Academy, Research, and Industry Association
BMT:	British Maritime Technology Ltd	ICC:	International Conference on Communications
BOEMRE:	Bureau of Ocean Energy Management, Regulation and Enforcement (formerly BLM)	IECM:	Integral equation coupled-mode
BORIS-SSA:	Bottom reverberation from inhomogeneities and surfaces-small-slope approximation	IEEE:	Institute of Electrical and Electronics Engineers
CALYPSO:	Model operating system	IEER:	Improved extended echo ranging
Cartesian 3DPE:	3DPE Employing Cartesian Coordinates in the Numerical Scheme	Integrated Mode:	Multipath expansion method extended to range-dependent environments
CEE:	Controlled exposure experiments	IOMEDEX:	Ionian Sea/Mediterranean Sea Exercise (part of LRAPP)
CISE:	Computational intelligence and software engineering	IRFC:	Industry Research Funders Coalition
CMM:	Caractérisation du Milieu Marin	ISAAC:	Impact on Species from Anthropogenic Acoustic Channels
CORDA:	Centre for Operational Research and Defence Analysis	JASA:	Journal of the Acoustical Society of America
COWRIE:	Collaborative Offshore Wind Energy Research Into the Environment	LRAPP:	Long Range Acoustic Propagation Project
C-SNAP-REV:	Reverberation using the C-SNAP Normal-Mode Model	LSMS:	Life system modeling and simulation
CW:	Continuous wave	LYBIN:	Range-dependent ray-theoretical propagation model
CZMA:	Coastal zone Management Act	MATLAB:	Matrix Laboratory (Mathworks, Inc.)
DANM:	Dynamic ambient noise model	MCM:	Mine countermeasures
dB:	Decibel	METOC:	Meteorology and oceanography
DMOS:	DRDC Atlantic model operating system	MINEOS:	MSASM interactive execution and optimization system
DRDC:	Defence Research and Development Canada	MMPA:	Marine Mammal Protection Act
DREA:	Defence Research Establishment Atlantic (Canada)	MMS:	Minerals Management Service
DSTO:	Defence Science and Technology Organisation (Australia)	MOC3D:	3D Version of MOCASSIN
EIA:	Environmental impact assessment	MOCASSIN:	Monte Carlo Schall-Strahlen Intensitäten (Monte Carlo Sound Ray Intensities)
ESA:	Endangered Species Act	MOD:	Ministry of Defence
ESME:	Effects of sound on the marine environment	MODRAY:	Maritime Operations Division Ray-tracer
ESPRESSO:	Extensible performance and evaluation suite for sonar	MONM:	Marine Operations Noise Model
ETOP05:	Earth topography five-minute grid	MONM3D:	3D PE Model for MONM
FeyRay:	Broadband, range-dependent Gaussian-beam propagation model	MONOGO:	Reverberation Module in SWAMI
FFI:	Forsvarets forskningsinstitutt (Norwegian Defence Research Establishment)	M&S:	Modeling and Simulation
FFP:	Fast field program	MTS:	Marine Technology Society
FM:	Frequency modulation	MURAL:	Multistatic reverberation algorithm
FORTTRAN:	Formula translation	$N \times 2D$:	Quasi-3D modeling approach
GDEM:	Generalized digital environmental model	NATO:	North Atlantic Treaty Organization
GIS:	Geographic information system	NEMO:	NUWC Exposure Model
GmbH:	Gesellschaft mit beschränkter Haftung	NEPA:	National Environmental Policy Act
GOATS:	Generic Ocean Array Technology Sonar	NGDC:	National Geophysical Data Center
GUI:	Graphical User Interface	NMFS:	National Marine Fisheries Service
HYREV:	HanYang University Reverberation Model	NOAA:	National Oceanic and Atmospheric Administration
IAGC:	International Association of Geophysical Contractors	NOGRP:	Fast normal mode (monostatic) reverberation model
		NSPE:	Navy Standard Parabolic Equation
		NTNU:	Norwegian University of Science and Technology
		NURC:	NATO Undersea Research Centre (formerly SACLANTCEN)

NUSC:	Naval Underwater Systems Center (now NUWC)	SUPREMO:	Multistatic sonar model
NUWC:	Naval Undersea Warfare Center (formerly NUSC)	SWAMI:	Shallow Water Active-Sonar Modelling Initiative
OASES:	Ocean acoustics and seismic exploration synthesis	SWAMP:	Shallow Water Acoustic Modal Propagation
OASES-3D:	Version of OASES incorporating 3D scattering effects	SWSS:	Sperm Whale Seismic Study
OBIS:	Ocean biogeographic information system	TDA:	Tactical decision aid
OCS:	Outer continental shelf	TIAPS:	Towed integrated active-passive sonar
ONR:	Office of Naval Research	TRM:	Time-reversal mirror
OWWE:	One-way wave equation	TTS:	Temporary threshold shift
PAREQ:	Parabolic equation model	UAIM:	Underwater acoustic imaging model
PAREQ-REV:	Reverberation using the PAREQ parabolic equation model	UDT:	Undersea defence technology
PDF:	Probability density (or distribution) function	USWTR:	Undersea warfare training range
PDPE:	Pseudo-differential PE	UUV:	Unmanned undersea vehicle
PE:	Parabolic equation	WHOI:	Woods Hole Oceanographic Institution
PERM-2D:	Reverberation model	WKB:	Wentzel, Kramers, and Brillouin
PlaneRay:	Eigenray Model for range-dependent environments	WUWNet:	Workshop on Underwater Networks
PMODES:	Range-independent normal-mode transmission-loss module in SWAMI	XRAY:	Range-dependent ray theoretical model combined with full-field modeling of seabed interactions.
POPP:	Range-independent version of PROLOS		
PWRC:	Plane wave reflection coefficient		
RAM:	Range-dependent acoustic model		
RAMGEO:	RAM modified for range-dependent sediment layers		
Ray5:	Range-dependent ray model		
RAYSON:	Range-dependent ray-theoretic model for high frequencies		
RDS:	Rapidly deployable system		
REA:	Rapid environmental assessment		
REVPA:	Parabolic-equation reverberation model		
RITSHPA:	Reverberation including the statistics of hybrid path arrivals		
RMPE:	Ray-Mode Parabolic Equation Model		
ROSELLA:	Extension of NOGRP to handle beam patterns		
ROV:	Remotely operated vehicle		
R-SNAP:	Coherent monostatic reverberation model		
SABLE:	Sonar active boundary loss estimation		
SACLANT:	Supreme Allied Commander, Atlantic		
SACLANTCEN:	SACLANT Undersea Research Centre		
SIAM:	Simulated ambient noise model		
SIGBED:	Special Interest Group on Embedded Systems (ACM)		
SPPS:	Sonar performance prediction system		
S-SCARAB:	SACLANTCEN-scattering reverberation and backscatter		
SSF:	Split-step Fourier		
SSFEPE:	SSF PE Model		
SSPPE:	Split-step Padé PE model		
STB:	System test bed		

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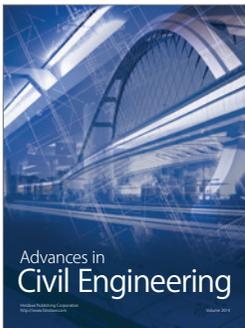
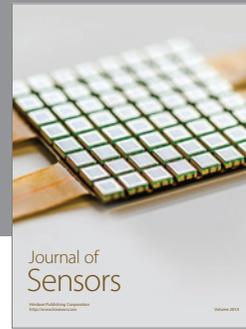
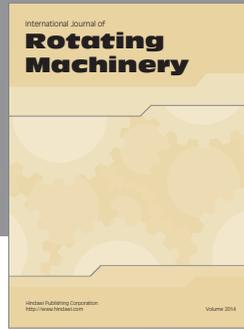
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