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RECENT ADVANCES IN UNDERWATER ACOUSTIC MODELLING AND SIMULATION

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A comprehensive review of international developments in underwater acoustic modelling is used to construct an updated technology baseline containing 107 propagation models, 16 noise models, 17 reverberation models and 25 sonar performance models. This updated technology baseline represents a 30% increase over a previous baseline published in 1996. When executed in higher-level simulations, these models can generate predictive and diagnostic outputs that are useful to acoustical oceanographers or sonar technologists in the analysis of complex systems operating in the undersea environment. Recent modelling developments described in the technical literature suggest two principal areas of application: low-frequency, inverse acoustics in deep water; and high-frequency, bottom-interacting acoustics in coastal regions. Rapid changes in global geopolitics have opened new avenues for collaboration, thereby facilitating the transfer of modelling and simulation technologies among members of the international community. This accelerated technology transfer has created new imperatives for international standards in modelling and simulation architectures. National and international activities to promote interoperability among modelling and simulation efforts in government, industry and academia are reviewed and discussed.

1. INTRODUCTION

1.1. BACKGROUND

Progress in the area of underwater acoustic modelling has been documented at 3-year intervals starting in 1978 with the publication of an extensive survey of models and databases under US Navy sponsorship [1]. Literature reviews were published in 1981 [2], 1984 [3], 1987 [4] and 1990 [5] to provide periodic progress reports on technological advances. A technical report was issued in 1993 [6] to bridge the gap between the now-discontinued series of literature reviews and publication of the second edition of the book *Underwater Acoustic Modelling: Principles, Techniques and Applications* in 1996 [7]. This book brought together under one cover the substance of all previous reviews, thus forming a comprehensive baseline (hereafter referred to as the 1996 baseline).

The present paper reviews progress since 1996 and concentrates on techniques of interest to acoustical oceanographers and sonar technologists. Accordingly, this paper should be considered in conjunction with the 1996 baseline [7] since that book also established the mathematical foundations of the modelling techniques discussed here. An abbreviated summary of post-1996 developments was presented at the 138th meeting of the Acoustical Society of America in November 1999 [8]. The details of all developments reported herein are derived from open-literature sources including scientific and trade

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journals, technical reports or product descriptions. Developments controlled by proprietary or international-security restrictions were excluded from consideration. For the benefit of the reader, Appendix B defines the many acronyms and abbreviations used throughout this paper.

1.2. MODELLING AND SIMULATION

Broadly defined, modelling is a method for organizing knowledge accumulated through observation or deduced from underlying principles. Simulation refers to *a method for implementing a model over time.* Models have become embedded in increasingly sophisticated simulations which are, in turn, used to analyze increasingly complex sonar systems. In the present context, the term *modelling, simulation and analysis* (MS&A) refers collectively to techniques that can predict and diagnose the performance of complex systems operating in the undersea environment.

Consistent with previous reviews, the principal categories of underwater-acoustic modelling comprise environmental, propagation, noise, reverberation and sonar performance. Discussions of simulation and analysis reflect the ultimate application of models and databases to the assessment of sonar-system performance in virtual ocean environments.

Over the past several years, naval mission requirements have shifted from open-ocean operations to littoral (or coastal) scenarios. This has not been an easy transition for sonar technologists since systems that were originally designed for operation in deep water seldom work optimally in coastal regions. This has also held true for MS&A technologies, which have undergone a redefinition and refocusing to support a new generation of naval systems that are intended to operate efficiently in littoral regions while still retaining a deep-water capability.

Computational capabilities have increased dramatically over the past several decades, and so too have the expectations placed on software performance. Consequently, software efficiency still remains a very critical issue—we cannot look to unlimited computing power as a panacea for inefficient software. Furthermore, with the dramatic increase in autonomous, self-guided systems such as AUVs and UUVs [9, 10], many of which use self-contained MS&A technologies, issues of verification, validation and accreditation (VV&A) will assume even greater importance in maintaining and improving system reliability.

For naval sonar applications, MS&A can be decomposed into four fundamental levels: engineering, engagement, mission and theater (see Table 1) [11]. Engineering-level MS&A comprises the aforementioned categories of environmental, propagation, noise, reverberation and sonar performance models. Engagement-level MS&A executes (simulates) engineering-level models to generate estimates of system performance in a particular spatial and temporal ocean environment when operating against (engaging) a particular target. Mission-level MS&A aggregates multiple engagements to generate statistics useful in evaluating system concepts within the context of well-defined mission scenarios. Finally, theater-level MS&A aggregates mission-level components to analyze alternative system-employment strategies. Figure 1 illustrates the hierarchical relationship between engineering-level simulations and underwater-acoustic models.

Tactical decision aids (TDAs) represent a form of engagement-level MS&A products that blend environmental information with tactical rules garnered from higher-level, aggregate simulations. These decision aids guide system operators and scene commanders alike in planning missions and allocating resources by exploiting knowledge of the operating

TABLE 1

Four principal levels of modelling and simulation (M&S)

Level	Output	Applications
Theater	Force dynamics	• Evaluate force structures • Evaluate strategies
Mission	Mission effectiveness	• Evaluate force employment concepts
Engagement	System effectiveness	• Evaluate system alternatives • Train system operators • Evaluate tactics
Engineering	System performance	• Design and evaluate systems/subsystems • Support testing

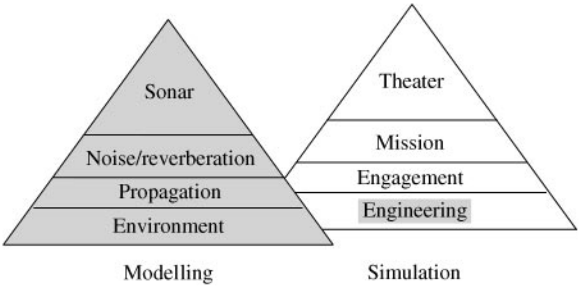

Figure 1. M&S hierarchies illustrating relationship of underwater acoustic models (left) to simulations (right). In this context, engineering-level simulations comprise environment, propagation, noise, reverberation, and sonar models [8].

environment. While TDAs are usually associated with naval applications, the conceptual approach is valid in research and commercial applications as well.

1.3. TECHNICAL DEVELOPMENTS

Developments reported in the literature since 1996 have generally utilized frequencies toward the practical extremities of the underwater-acoustic spectrum: at low frequencies, basic research in inverse methods has been prominent; at high frequencies, applied research in coastal processes has been more evident.

While seemingly unrelated, these developments in fact reflect a consistent movement either from deep-sea to shallow-water measurements or from direct to inverse measurements. These underlying themes offer useful contexts for interpreting recent progress in underwater acoustic modelling and simulation.

Technology-investment strategies, driven by the geopolitical realities of the past several years, have greatly influenced the direction of R&D in general, and of MS&A in particular. The broad trends outlined above have continued the shift in technology investment patterns that began in the early 1990s; this shift has diminished the budgets for naval undersea research thus reducing the number of field experiments, reducing at-sea-training time and limiting asset modernization. This situation creates new opportunities and challenges for MS&A.

1.4. TRAINING

Reductions in at-sea-training time have particularly encouraged (even necessitated) increased reliance on simulations for sonar-related training. For example, the use of computer-based training (CBT) has grown extensively, and sonar models have become common elements of simulations used in such learning environments. Two problems continue to plague advances in this area, however. First, the cost of developing quality courseware often becomes a limiting factor; consequently, the best-intentioned training products can quickly degenerate into *page-turner* programs that are useful for drill and practice among students of dissimilar educational backgrounds but do not challenge students of more advanced topics. Second, the rapid evolution in computer technology often renders training systems prematurely obsolete by outpacing the financial capacity of educational centers to update their equipment; moreover, installing upgraded software on aging equipment aggravates student–computer interactions by slowing computer response times, thereby frustrating students' experiences with CBT.

2. MODELS

2.1. ENVIRONMENTAL

Environmental models are used within the framework of propagation, noise, reverberation and sonar performance models to characterize the behavior of the ocean as an acoustic medium. Environmental models compute the volumetric properties of the ocean and also quantify boundary conditions at the sea surface and the sea floor.

General developments in environmental modelling have been directed at refining and simplifying empirical relationships between observed oceanographic parameters and derived acoustic parameters. For example, Millero and Li [12] corrected the earlier Chen–Millero sound speed formula [7] to improve its applicability to low temperatures and high pressures; this correction is especially important for tomographic applications. In work of a related nature, Leroy and Parthiot [13] developed convenient equations for converting pressure to depth and *vice versa*.

Further advances were provided by Ainslie and McColm [14] who simplified a version of the Francois–Garrison equations for viscous and chemical absorption in sea water [15, 16] by making explicit the relationships among acoustic frequency, depth, sea-water absorption, pH, temperature and salinity. An older data set that has received renewed attention is that reported by Skretting and Leroy [17], which summarized measurements of sound attenuation in the western Mediterranean Sea.

Medwin and Clay [18] emphasized the utility of acoustical sensing in oceanographic research. Along this line of investigation, Wiebe *et al.* [19] described an autonomous acoustic platform for long-term measurement of marine biomass.

The Naval Oceanographic Office [20] updated the Oceanographic and Atmospheric Master Library (OAML) summary of models and databases, including resources suitable for application to underwater acoustics. The Applied Physics Laboratory at the University of Washington [21] documented high-frequency (approximately 10–100 kHz) acoustic models with potential application to simulation and system-design efforts in torpedo and mine-countermeasure programs. These models treat: volumetric sound speed, absorption and backscattering; boundary backscatter and forward loss for the sea surface and the sea floor; ambient-noise sources and levels; and Arctic attenuation and under-ice losses. In a recent book, Ziomek [22] discussed fundamental topics in linear acoustics of interest to both atmospheric and oceanographic researchers.

2.2. PROPAGATION

2.2.1. *Reviews*

A number of historical reviews have been assembled that provide useful insights into technological developments not only over the past several years but also over the much broader horizon of sonar developments in the 20th century. Lee and Pierce [23] traced the historical development of the parabolic equation (PE) method in underwater acoustics while Piskarev [24] provided a first-hand account of state-of-the-art Soviet research in underwater acoustic propagation modelling up to 1989. Vaccaro [25] edited a useful collection of papers that reviewed past progress and future challenges in underwater acoustic signal processing; specific applications included sonar signal processing, time-delay estimation and underwater acoustic communications. Tolstoy [26] summarized progress and challenges in the modelling of acoustic propagation in three-dimensional ocean environments.

2.2.2. *General applications*

Propagation models are integral to the higher-level modelling of noise, reverberation and, ultimately, sonar performance. The categorization of propagation models into five distinct techniques follows that of Etter [7]: Ray Theory, Normal Mode, Multipath Expansion, Fast Field (or Wavenumber Integration) and Parabolic Equation. Since all five techniques are derived from the wave equation by restricting solutions to the frequency domain, the resulting models are appropriate for traditional sonar applications. (Solutions obtained in the time domain would be appropriate, for example, for modelling 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. The balance of this section will review general applications according to these five categories of modelling techniques. New or modified models will be discussed in section 2.2.5.

2.2.2.1. *Ray Theory.* A versatile, range-dependent, ray-tracing program (RAY) has been developed by Bowlin *et al.* [27] that is available via the Internet (see section 2.2.3). Yan [28] noted that the incorporation of spherical-earth-curvature corrections into 2-D (two-dimentional) ray equations considerably extended the applicability of 2-D equations in certain classes of 3-D problems.

2.2.2.2. *Normal mode.* D'Spain *et al.* [29] developed an adiabatic normal-mode model to analyze broadband, matched-field-processing data collected in shallow water. The model incorporated the concept of "effective depth", which was first introduced by Weston [30] for a Pekeris waveguide and later extended by Chapman *et al.* [31] to include shear waves. In essence, the phase change associated with the reflection of a plane wave from a fluid–elastic interface at the bottom is equal to that from a pressure-release boundary that is offset a distance below the true bottom. This offset, which is virtually independent of the grazing angle, can be calculated from available waveguide parameters. Thus, the normal-mode wave numbers are now provided by a closed-form expression rather than by more cumbersome numerical complex-root-finding techniques.

Tindle and Zhang [32] developed an adiabatic normal-mode solution for the benchmark wedge problem (including both fluid and solid attenuating bottom boundaries). The continuous-mode contribution was treated as a sum of leaky modes, and each trapped mode gradually transitioned into a leaky mode as the water depth decreased.

2.2.2.3. *Wavenumber integration.* One approach to range-dependent modelling partitions the ocean environment into a series of range-independent sectors called *super elements* by Schmidt *et al.* [33]. Goh and Schmidt [34] extended the spectral super-element approach for acoustic modelling in fluid waveguides to include fluid–elastic stratifications. Their method used a hybridization of finite elements, boundary integrals and wavenumber integration to solve the Helmholtz equation in a range-dependent ocean environment. It provided accurate, two-way solutions to the wave equation using either a global multiple scattering solution or a single-scatter, marching solution.

Grilli *et al.* [35] combined boundary element methods (BEM) and eigenfunction expansions to solve acoustic wave propagation problems in range-dependent, shallow-water regions. Their hybrid BEM technique, or HBEM, was validated by comparing outputs to analytical solutions generated for problems with simple boundary geometries including rectangular, step and sloped domains. HBEM was then used to investigate the transmission of acoustic energy over bottom bumps while emphasizing evanescent modes and associated "tunnelling" effects.

2.2.2.4. *Parabolic equation.* The parabolic equation (PE) method factors an operator to obtain an outgoing wave equation that can be solved efficiently as an initial-value problem in range. This factorization is exact when the environment is range independent. Range-dependent media can be approximated as a sequence of range-independent regions from which backscattered energy is neglected. Transmitted fields can then be generated by using energy-conservation and single-scattering corrections. Through appropriate approximations, Collins and Siegmann [36] extended energy-conservation corrections from the acoustic case to the elastic case.

The parabolic equation method has been further extended to handle range-dependent poro-acoustic waveguides. Lingevitch and Collins [37] argued that a poro-acoustic medium is, in fact, the limiting case of a poro-elastic medium in which the shear wave speed vanishes. In related work, Collins [38] improved the self-starter (a PE technique for generating initial conditions) by removing a stability problem associated with evanescent modes.

A high-angle, elastic PE model was used by Tielbürger *et al.* [39] to investigate the acoustic field properties in an oceanic waveguide where the sound speed had a deterministic, time-independent component and two stochastic components induced by internal-wave activity. In related work on internal waves, Macaskill and Ewart [40] refined numerical solutions of the fourth-moment equation for acoustic intensity correlations, particularly the temporal cross-correlation between acoustic signals of different frequencies propagating through the same medium.

Tang and Tappert [41] used the broadband model UMPE to explain the lack of multipath replicas of the transmitted pulse in broadband acoustic experiments in the Straits of Florida. The observed single broad cluster was attributed to the effects of internal waves,

TABLE 2

Propagation models and other information available from the current contents of the Ocean Acoustics Library (*http://oalib.saic.com*)

Category	Models
Rays	BELLHOP, HARPO, RAY, TRIMAIN
Normal modes	AW, COUPLE, KRAKEN, MOATL, NLAYER, WKBZ
Wavenumber integration	OASES, RPRESS, SCOOTER, SPARC
Parabolic equation	FOR3D, MMPE, PDPE, RAM/RAMS, UMPE
Other	Related modelling software and data sets to support oceanographic and acoustic analyses

which produced moving acoustic "footprints" on a rough seafloor. This version of UMPE has two space dimensions and two time dimensions (travel time and geophysical time). UMPE, and its predecessor MIPE, are now collectively referred to as PE-SSF (Parabolic Equation—Split-Step Fourier Algorithm). PE-SSF thus represents a wide class of PE models [42].

2.2.3. *Web sites*

With the explosive growth of the Internet, there are now numerous web sites dealing with ocean acoustics, underwater sound and related subjects. One site, the *Ocean Acoustics Library* (see Table 2), provides access to some of the stand-alone propagation models reviewed in this paper. This access is provided directly to downloadable software or indirectly by reference to other authoritative web sites. The reader is cautioned, however, that the addresses for these web sites sometimes change or disappear entirely. In such cases, web searches using appropriate key words may help in locating new addresses or alternate sources.

The US Navy Modeling and Simulation Management Office (NAVMSMO) maintains the Navy Modeling and Simulation Catalog, which allows users to find and obtain modelling and simulation resources in support of assessments and training (http://navmsmo.hq.navy.mil).

2.2.4. *Shallow water*

The Shallow Water Acoustic Modeling (SWAM) Workshop, held in Monterey, CA, in September 1999, provided a forum for the comparison of single-frequency (CW) and broadband (pulse) propagation models in synthetic (i.e., virtual) environments. Test cases included up-sloping, down-sloping, flat and 3-D bathymetries; additional cases considered the effects of internal waves and a shelf break. The goal was to determine which shallow-water environmental factors challenged existing propagation models and what details were important for constructing accurate, yet efficient, solutions. The results of this workshop, designated SWAM '99, are to be published in a proceedings volume.

2.2.5. *Models*

Twenty-six new or modified underwater acoustic propagation models are summarized in Table 3. The letters following each model are keyed to brief synopses and pertinent references to the available literature (refer to Notes to Table 3). The categorization of

Table 3

Summary of new or modified underwater acoustic propagation models

Technique	Range independent	Range dependent
Ray theory	Use single environmental specification	BELLHOP {a} Coherent DELTA {b} GRAB {c} HARVEST {d} LYCH {e} MIMIC {f}
Normal mode	MODELAB {g} ORCA {h}	C-SNAP {i} MOCTESUMA {j} PROSIM {k} WKBZ {l}
Multipath expansion	No new developments	No existing solutions
Fast field or wavenumber integration	RPRESS {m} SCOOTER {n} SPARC {o}	CORE {p} RD-OASES {q} RDOASP {r} RDOAST {s}
Parabolic equation	Use single environmental specification	AMPE/CMPE {t} CCUB/SPLN/CNP1 {u} FDHB3D {v} FEPE-CM {w} IMP3D {x} PDPE {y} RAM/RAMS {z}

Notes.

{a} BELLHOP computes acoustic fields in range-dependent environments [116] via Gaussian beam tracing [117].

{b} Coherent DELTA is an extension of a ray-theoretic algorithm developed by A.L. Piskarev, which computes acoustic intensity without calculating eigenrays or focusing factors in caustics. The original algorithm has been modified to sum ray contributions coherently in a range-dependent environment [118].

{c} GRAB computes high-frequency (10–100 kHz) transmission loss in range-dependent, shallow-water environments. The model is based on Gaussian ray bundles, which are similar in form (but somewhat simpler) than Gaussian beams [119]. The US Navy standard GRAB model (under OAML configuration management) is a subset of CASS [120].

{d} HARVEST is a general hybrid technique that solves the two-dimensional acoustic-viscoelastic equations for bottom-interacting acoustics in water depths exceeding 1 km in the frequency range 100–500 Hz. The model comprises three methods: a Gaussian-beam method is used to propagate the source wave field vertically through the water column; a viscoelastic, finite-difference grid is used to compute the complex acoustic–anelastic interaction of the incident wave field with the rough sea floor; and the backscattered wave field is extrapolated to a distant receiver array using the Kirchhoff integral [121].

{e} LYCH calculates transmission loss on the basis of ray tracing in an environment where both sound speed and bathymetry vary as functions of range [122].

{f} MIMIC is a wave-like ray summation model that treats propagation at low frequencies (<150 Hz) and short ranges (<CZ ranges) in range-dependent ocean environments. The environment is modelled as a water column overlying a sedimentary seabed with an acoustically hard bottom [123].

{g} MODELAB is an efficient and numerically robust algorithm for calculating acoustic normal modes in a fluid-layered ocean. Each layer has a sound speed profile for which the mode functions can be expressed analytically in terms of Airy functions. Attenuation is included as a perturbation. The form of the propagator matrices avoids the numerical instabilities associated with evanescent fields [124].

{h} ORCA uses a normal-mode method to model propagation in acousto-elastic ocean waveguides. Leaky modes and seismic interface modes such as the Scholte and Stonely modes are also computed [125].

{i} C-SNAP is a coupled-mode version of the SNAP normal-mode model [126]. The numerical solution technique for one-way mode coupling was obtained from KRAKEN.

{j} MOCTESUMA is a coupled normal mode model developed by Thomson Sintra—Activités Sous Marines, France (Dr Alain Plaisant). There are two versions: one for 2-D environments with fluid/elastic sediments and one for 3-D environments with fluid sediments [127], [128].

{k} PROSIM is a broadband adiabatic normal-mode propagation model, the kernel of which is based on the range-independent normal-mode propagation model called ORCA. Using PROSIM, calculation of broadband transfer functions at frequencies up to 10 kHz in shallow water is attainable in a few minutes on a modern workstation [129].

{l} WKBZ is an adiabatic normal-mode model based on a uniform WKB approximation to the modes [130].

{m} RPRESS uses a high-order, adaptive integration method for efficient computation of the Hankel-transform integral for the wave field in a laterally homogeneous fluid–solid medium [131]. This model has been used to investigate frequency-dependent propagation losses in shallow water caused by shear losses in the sediment [132].

{n} SCOOTER is a finite-element FFP code for computing acoustic fields in range-independent environments. It is recommended for use when the horizontal range is less than 10 water depths [133].

{o} SPARC is a time-marched FFP model that treats problems dealing with broadband or transient sources (i.e., pulses) [116, 133].

{p} CORE is a coupled version of OASES for range-dependent environments. It belongs to the new spectral super-element class of propagation models for range-dependent waveguides. This approach is a hybridization of the finite-element and boundary-element methods. The ocean environment is divided into a series of range-independent sectors separated by vertical interfaces [134].

{q} RD-OASES is a range-dependent version of OASES [135]. RD-OASES extends to fluid–elastic stratifications the development of a spectral super-element approach for acoustic modelling in fluid waveguides using a hybridization of finite elements, boundary integrals and wave-number integration to solve the Helmholtz equation in a range-dependent ocean environment. The ocean environment is divided into a series of range-independent sectors separated by vertical interfaces. This model provides accurate, full two-way solutions to the wave equation using either a global multiple scattering solution or a single-scatter, marching solution.

{r} RDOASP is a pulse version of RD-OASES [34]. (http://acoustics.mit.edu/arctic0/henrik/www/rd_oases.html).

{s} RDOAST refers to the specific combination of RD-OASES and VISA [34]. The virtual source algorithm (VISA) uses the marching, local single-scatter approximation to the transmission and reflection problem at the sector boundaries; thus, a virtual array of sources and receivers is introduced on each sector boundary. (http://acoustics.mit.edu/arctic0/henrik/www/rd_oases.html).

{t} AMPE was developed to solve global-scale ocean acoustic problems that are too large to solve with other existing three-dimensional codes. The PE method was used to solve two-dimensional wave equations for the adiabatic mode coefficients over latitude and longitude [136]. CMPE is a generalization of AMPE that includes mode-coupling terms. It is practical to apply this approach to large-scale problems involving coupling of energy between both modes and azimuths [137].

{u} The Foundation for Research and Technology—Hellas, Institute of Applied and Computational Mathematics, Greece, developed a family of higher-order, finite-element (FE) PE methods: CCUB, SPLN and CNP1 [128].

{v} FDHB3D is a hybrid 3-D, two-way propagation model for solving 3-D backscattering problems. It is based on the implicit finite difference (IFD) parabolic equation (PE) approach [138].

{w} FEPE-CM combines the FEPE code with the PERUSE surface scattering formulation to model the forward scattering from both periodic and single realizations of randomly rough sea surfaces; a conformal mapping technique converts the rough-surface scattering problem into a succession of locally flat-surface problems [139]. Norton and Novarini [140] used FEFE-CM to investigate the effect of sea-surface roughness on shallow-water waveguide propagation.

{x} IMP3D extends the FOR3D model by including a simplified elastic impedance bottom boundary condition [128].

{y} PDPE is a pseudodifferential parabolic equation model; the documentation contains a numerical algorithm for its implementation [141].

{z} RAM incorporates an improved elastic parabolic equation [142] together with a stable self-starter [143]. A companion version called RAMS is available for acousto-elastic problems. Both RAM and RAMS use the split-step Padé solution, which is approximately two orders of magnitude faster than the Crank-Nicolson solution of the wide-angle PE [144].

modelling techniques in Table 3 follows that of Etter [7]: Ray Theory, Normal Mode, Multipath Expansion, Fast Field (or Wavenumber Integration) and Parabolic Equation. A further division can be made according to range-independent (1-D, or depth-dependence only) or range-dependent environmental specifications, where environmental range-dependence can be 2-D (depth and range) or 3-D (depth, range and azimuth). No new developments have been reported for multipath-expansion techniques. Also, note that range-dependent models can be applied to range-independent environments by specifying a single environmental input set. Table A1 updates and revises the 1996 baseline [7] to provide the latest comprehensive listing of 107 stand-alone underwater acoustic propagation models.

2.3. NOISE

2.3.1. *General applications*

Buckingham and Potter [43] documented the proceedings of the Third International Meeting on Natural Physical Processes Related to Sea Surface Sound, which was held in March 1994. Richardson *et al.* [44] presented a broad survey of the sounds produced by machines and mammals, the sensitivity of marine mammals' hearing, and the reactions of marine mammals to various noise sources; this work is particularly relevant to the use of high-intensity sources in ocean tomographic applications as well as multistatic naval operations.

Felizardo and Melville [45] concluded that ambient noise correlated well with wind speed (in the Knudsen range) but correlated poorly with significant wave height. The poor correlation with wave height was attributed to the disproportionate effect of swell on the frequency of breaking waves, which are considered the primary source of wind-dependent noise in the ocean.

Nystuen and Medwin [46] proposed a new bubble-entrapment mechanism to account for a missing component in the modelling of underwater sound levels produced by raindrops. Vagle *et al.* [47] made further measurements in support of *Weather Observation Through Ambient Noise* (WOTAN), which is a technique for inferring oceanic winds from underwater ambient sound.

Hamson [48] reviewed techniques for modelling shipping and wind noise over the frequency range 50–3000 Hz, concentrating mainly on work performed after 1980. Noise level, horizontal and vertical directionality, and the noise responses of arrays were used to describe characteristics of ambient noise.

Harrison [49] used a simple ray approach to approximate the full-wave treatment of noise levels and coherence in range-independent ocean environments. Bjørnø [50] provided a general summary of ambient-noise characteristics in littoral waters.

Zedel *et al.* [51] modified an *Acoustic Doppler Current Profiler* (ADCP) to record ambient sound in the frequency range 1–75 kHz. The resulting instrument package called OASIS (Ocean Ambient Sound Instrument System) inferred wind speeds and directions from these acoustic measurements that were determined to be in good agreement with direct observations made at Ocean Weather Station Mike in the Norwegian Sea.

2.3.2. *Models*

Noise models can be segregated into two categories: ambient-noise models and beam-noise statistics models. Ambient-noise models are applicable over a broad range of frequencies and consider noise originating from surface weather, biologics, shipping and other commercial activities. Beam-noise statistics models predict the properties of low-frequency shipping noise using either analytic (deductive) or simulation (inductive) methods. All developments noted subsequent to the 1996 baseline concern only ambient-noise models.

Three new or modified underwater acoustic noise models are summarized in Table 4. The letters following each model are keyed to brief synopses and pertinent references to the available literature (refer to Notes to Table 4). These models are all categorized as ambient-noise (versus beam-noise statistics) models [7]. Table A2 updates the 1996 baseline [7] to provide the latest comprehensive listing of 16 stand-alone underwater acoustic noise models.

TABLE 4

Summary of new or modified underwater acoustic noise models

Noise models
ANDES {a}
CANARY {b}
RANDI 3.1 {c}

Notes:

{a} ANDES (Version 4.2) addresses issues related to shallow-water ambient-noise modelling including upgrades to the shipping-density and sound-speed databases, in addition to a new capability to model fluctuations in noise directionality due to changes in wind speed and the movement of discrete sources through the transmission-loss field [145, 146].

{b} CANARY is a ray-based model of ambient noise and noise coherence that is used to estimate the performance of hull-mounted sonars in range-dependent and azimuth-dependent environments [147, 148].

{c} RANDI (Version 3.1) predicts ambient-noise levels and directionalities at low-to-mid frequencies in both shallow and deep water. Shipping noise can be calculated for highly variable environments using either the finite-element or split-step parabolic equation method. Local wind noise is computed using the range-independent theory of Kuperman–Ingenito, including both discrete normal modes and continuous spectra. U.S. Navy standard and historical databases are used to describe the environment [149, 150]. Version 3.3 is a modified version of RANDI 3.1 for use in shallow water; this version provides the user with the option to supply the model with measured or estimated environmental information in areas where the U.S. Navy standard databases may not provide coverage [151].

2.4. REVERBERATION

2.4.1. *General applications*

Recent developments in reverberation modelling have emphasized bistatic applications in littoral regions where there are enhanced opportunities for bottom interactions. Love *et al.* [52] noted that variability is the principal feature of volume reverberation in littoral waters. Smith *et al.* [53] used measurements and models to correlate reverberation events with bathymetric features.

2.4.2. *Models*

Reverberation models can be categorized according to cell-scattering or point-scattering techniques. Cell-scattering formulations divide the ocean into cells, where each cell contains a large number of uniformly distributed scatterers. Point-scattering formulations assume a random distribution of (point) scatterers. All recent developments reviewed here have been categorized as cell-scattering techniques.

Four new or modified underwater acoustic reverberation models are summarized in Table 5. The letters following each model are keyed to brief synopses and pertinent references to the available literature (refer to Notes to Table 5). The reverberation models are segregated according to their ability to handle monostatic (i.e., collocated source/receiver) or bistatic (i.e., spatially separated source/receiver) geometries. Table A3 updates the 1996 baseline [7] to provide the latest comprehensive listing of 17 stand-alone underwater acoustic reverberation models.

TABLE 5

Summary of new or modified underwater acoustic reverberation models

Monostatic	Bistatic
PEREV {a}	BiKR {b} BiRASP {c} OGOPOGO {d}

Notes:

{a} PEREV (Tappert's PE reverberation model), together with the UMPE (now MMPE) propagation model, are described by Smith *et al.* [53].

{b} BiKR is a bistatic reverberation model [152] based on the KRAKEN propagation model.

{c} BiRASP extended the RASP model to handle arbitrary (bistatic) source and receiver configurations in a three-dimensional, range-dependent environment [153]. RASP had been previously modified to predict range-dependent, monostatic reverberation at higher frequencies (up to 10 kHz) and in water shallower than originally intended; this modification is referred to as the *Shallow Water RASP Upgrade* [154].

{d} OGOPOGO is based on the Bucker–Morris method for computing shallow-water boundary reverberation using normal modes to calculate the acoustic energy propagating from the source to the scattering area and back to the receiver. Ray-mode analogies and empirical scattering functions are used to compute the scattered energy at the scattering area [74]. The normal-mode model PROLOS computes the propagation loss. Travel times of the reverberation signals are derived from the modal-group velocities. Volume reverberation from either the water column or the subbottom is not currently included, but boundary reverberation is computed using empirical scattering functions and ray-mode analogies. Both monostatic and bistatic geometries can be handled, and horizontal or vertical arrays can be specified for the source and receiver. OGOPOGO was used to interpret reverberation measurements from shallow-water sites in the frequency range 25–1000 Hz [76].

2.5. SONAR PERFORMANCE

2.5.1. *General applications*

Sonar performance models combine environmental models, propagation models, noise models, reverberation models and appropriate signal-processing models to solve the sonar equation [7]. Recent developments have emphasized applications in littoral regions. For example, Baggenstoss [54] described a technique for reducing false-alarm rates in highly reverberant shallow-water environments using two separate normalization processes to produce different output statistics: *cross-range* (*or sector*) *normalization*—a given beam energy output is normalized by an average of adjacent beam energy estimates; and *down-range normalization*—equivalent to traditional split-window average normalizer, which is accomplished using an average of the beam energy at past and future times.

In other work, Wazenski and Alexandrou [55] used optimal detection and estimation theory to improve detection and localization performance over standard matched-filtering techniques. The Generic Sonar Model (GSM) provided the simulation environment.

2.5.2. *Models*

Twelve new or modified sonar performance models (subcategorized as active sonar performance, model-operating systems and tactical decision aids) are summarized in Table 6. The letters following each model are keyed to brief synopses and pertinent references to the available literature (refer to Notes to Table 6). Model-operating systems [7] provide a framework for the direct linkage of data-management software with computer-implemented codes of acoustic models, thus facilitating the construction of versatile MS&A capabilities. Model Operating Systems are further distinguished from (stand-alone) active sonar performance models by virtue of their ability to conduct

TABLE 6

Summary of new or modified sonar performance models

Active sonar performance	Model-operating systems	Tactical decision aids
ALMOST {a}	CAAM {i}	IMAT {k}
GASS {b}	GSM Bistatic {j}	NECTA {l}
HODGSON {c}		
INSIGHT {d}		
INSTANT {e}		
MINERAY {f}		
MSASM {g}		
SWAT {h}		

Notes:

{a} ALMOST, which was developed for the Royal Netherlands Navy, is a complete sonar performance prediction model for active and passive systems. ALMOST contains three modules: PROPLOSS for transmission loss; REPAS for passive sonar range predictions; and REACT for active sonar range predictions. The transmission-loss component is based on range-dependent ray tracing [155]. Dreini *et al.* [156] compared the transmission-loss component of ALMOST with similar models.

{b} GASS is a simulator/stimulator for air ASW systems trainers. GASS contains an environmental-acoustics (EVA) server that provides underwater acoustic propagation, noise and reverberation characteristics based on U.S. Navy standard acoustic models (ASTRAL and ANDES) and environmental databases from OAML. These characteristics are provided in the form of parameters that control the generation and propagation of time-series signals in other parts of GASS. The models used are range-dependent, and seamlessly support a wide operating envelope in frequency, range and water depth. The EVA server was designed to be responsive to real-time systems and therefore should be suitable for a wide range of other acoustic prediction, simulation and modelling applications [157, 158].

{c} HODGSON, which was originally developed by Lt.Cdr. J.M. Hodgson of the Royal Navy, treats a fully range-dependent (sound speed and bathymetry) ocean environment; the transmission-loss component is based on range-dependent ray tracing [159]. The U.K. Ministry of Defence has formally validated the propagation model for both shallow and deep water. Dreini *et al.* [156] compared the transmission-loss component of HODGSON with similar models. HODGSON also contains a reverberation module that computes surface and bottom reverberation. This model is available commercially from Ocean Acoustic Developments, Ltd.

{d} INSIGHT has been upgraded with improvements in the calculation of reverberation within the active-sonar model component [160, 161].

{e} INSTANT computes transmission loss in range-dependent ocean environments using a hybrid of ray and mode concepts. The formulation is based on the conservation of energy flux and the exploitation of the ray invariant to model weak range dependence [162].

{f} MINERAY was initially developed in the 1970s to predict the performance of submarine minehunting sonars. There are three distinct generations of the MINERAY model. The first generation (1970s) was appropriate for modelling high-frequency sonars in deep-water environments. The second generation (mid-1980s) was extended to allow multipath sound propagation via bottom and surface bounces [163]. The third generation (mid-1990s) has been extended to support modelling in littoral environments [164]. (http://www.arlut.utexas.edu/ ~ asdwww/xmineray/about.html)

{g} MSASM assesses the effectiveness of air-deployed, multistatic-acoustic sonobuoy fields [165].

{h} Shallow water acoustics toolset (SWAT) was developed to support mine-countermeasure (MCM) sonars [166]. SWAT actually comprises two models: one for detection sonars and one for classification sonars. The detection model is hosted on a personal computer and is designated PC SWAT. The classification model is designed to run on a workstation and is referred to as SWAT. Inputs and commands are menu driven in PC SWAT. Surface and bottom reverberation are computed by considering the multipath contributions, which are important in shallow and very-shallow littoral environments. A three-dimensional, coherent acoustic scattering model of mines is also incorporated. Both PC SWAT and SWAT include the latest high-frequency environmental models [21].

{i} CAAM is a flexible R&D tool for sonar technologists [165]. It integrates the OAML environmental databases [20] together with selected propagation models including PE, ASTRAL and RAYMODE.

{j} Generic sonar model (GSM) has been extended to include a bistatic active signal excess model (Powers [71]). Version G (updated through December 1996) removed unsupported propagation models (RAYMODE, FACT and MULE) and added bistatic scattering strength tables, among other features.

{k} Interactive multisensor analysis tool (IMAT) was developed to integrate training, operational preparation, tactical execution, and post-mission analysis into a seamless support system [61].

{l} NECTA supports oceanographic and environmental data analysis as well as sensor performance predictions. The open and modular design of the system allows the ready inclusion of additional environmental data and tactical guidance to meet changing demands [167].

sensitivity analyses by computing components of the active-sonar equation [7] using alternative solution techniques. Tactical decision aids, discussed earlier in section 1.2, constitute a newly introduced subcategory. Table A4 updates the 1996 baseline [7] to provide the latest comprehensive listing of 25 sonar performance models.

3. DATABASES

Databases serve two principal functions in MS&A: model initialization and model evaluation. Moreover, where no formal models yet exist, tentative empirical models can be formulated on the basis of limited observational data.

The Naval Oceanographic Office [20] updated the OAML summary of models and databases, including resources suitable for underwater-acoustic model initialization and evaluation. Ocean Acoustic Developments Ltd [56] created the WADER global ocean information system, which is based on DBDB5 bathymetry and the Levitus temperature–salinity data [7].

4. SIMULATIONS

4.1. FOUNDATION TECHNOLOGY

The National Research Council [11] portrayed modelling and simulation as a foundation technology for many developments that will be central to the U.S. Navy over the next several decades. Bracken *et al.* [57] edited a useful collection of papers co-ordinated by the Military Operations Research Society (MORS) that covered a broad spectrum of modelling and simulation.

4.2. DEFENSE MODELLING AND SIMULATION OFFICE

The Defense Modeling and Simulation Office (DMSO) was established in 1991 to provide a focal point for information concerning U.S. Department of Defense (DOD) modelling and simulation (M&S) activities (refer to the DMSO web site at http://www.dmso.mil/). DMSO is leading an effort to establish a *common technical framework* (CTF) to facilitate the interoperability and reuse of all types of models and simulations. The foundation for this effort is the High Level Architecture (HLA), the highest priority effort within the DOD M&S community. The HLA has been proposed for acceptance by the North Atlantic Treaty Organization (NATO) as the standard for simulations used within the NATO Alliance and has also been proposed as IEEE Standard 1516.

Two other elements of the CTF include Conceptual Models of the Mission Space (CMMS) and Data Standards. When completed, CMMS will provide simulation-independent descriptions of real-world processes, entities, environments and relationships. The Data Standards program will provide the M&S community with certified data to promote interoperability of models and simulations, thus improving the credibility of M&S results.

DMSO also offers a series of Common Services to complement the CTF including VV&A procedures and environmental databases. Regarding environmental databases, planned representations of the Natural Environment will include terrain, oceans, atmosphere and space.

4.3. GENERAL APPLICATIONS

For the purposes of discussion, general applications of simulations in underwater acoustics focus on *simulation testing* and *simulation technology*. *Simulation testing* encompasses laboratory testbeds and at-sea tests. Testbeds allow the simultaneous use of high- and low-detail system representations (i.e., variable resolution) in a single simulation. This flexibility enables an analyst to simulate a key system in high detail while simulating the less-critical contextual environment in lower detail. At-sea tests provide engineers the opportunity to validate sonar-system performance in real (versus synthetic) ocean environments. *Simulation technology* includes the transitioning of mature simulation technologies from research-and-development (R&D) environments to operational applications. Also considered is the development of commercial-off-the-shelf (COTS) simulation systems.

The Tactical Oceanography Simulation Laboratory (TOSL) provides a testbed for the development, testing and validation of high-fidelity underwater acoustic models and supporting databases (see reference [58]). The Littoral Warfare Advanced Development (LWAD) project provides at-sea tests (including platforms and co-ordination) to identify and resolve undersea technical issues that arise from operating undersea warfare, surface warfare, and mine warfare systems in littoral environments (see reference [59]). Sea tests can range from simple focused technology experiments (FTE) to more complex system concept validations (SCV).

The Interactive Multisensor Analysis Tool (IMAT) was originally developed to enhance the training of naval-aviation ASW operators [60], but has since been expanded to include surface-ship and submarine ASW operators as well. IMAT products include classroom multimedia systems and integrated curricula, PC-based learning systems (promoting highly visual cause-and-effect training), operator-console and tactical simulation [61]. The US Navy is presently considering IMAT for use as an operational Tactical Decision Aid (TDA).

Whitman [62] reviewed defense-conversion opportunities in marine technology and made a distinction between *dual use* and *conversion*. *Dual use* suggests the deliberate pursuit of new research, development or economic activity that is applicable within both military and civilian domains. *Conversion* implies seeking new uses for existing defense resources. Veenstra [63] demonstrated the feasibility of using commercial off-the-shelf (COTS) hardware and software to build advanced sonar simulation–stimulation systems at costs that are significantly lower than traditional approaches.

5. EVALUATION

5.1. HEURISTIC VALUE

Oreskes *et al.* [64] argued that the primary value of models in the earth sciences is heuristic (i.e., an aid to learning, as through trial-and-error methods) and that the demonstration of agreement between observation and prediction is inherently partial since natural systems are never closed. The ocean is a natural system and, as an acoustic medium, it is not a closed (i.e., deterministic) system. Most underwater acoustic models treat the ocean as a deterministic system, however, and this can create problems when evaluating models against field data that are, by nature, non-deterministic (i.e., stochastic or chaotic). In-depth discussions of theoretical and applied approaches to model evaluation have been provided elsewhere [7]. These discussions emphasized the importance of configuration-management practices in constructing and maintaining reliable model-evaluation histories. The application of verification, validation and accreditation (VV&A) techniques in the M&S development process is an important discipline.

5.2. VERIFICATION, VALIDATION AND ACCREDITATION (VV&A)

Rapid changes in global geopolitics have opened new avenues for collaboration, thus greatly facilitating the transfer of modelling and simulation technologies among members of the international community. This accelerated technology transfer has stimulated initiatives for improved international standards in simulation architecture.

The U.S. Department of Defense [65] has assembled a very useful compendium of VV&A techniques from sources in government, industry and academia. This compendium provides practical guidelines for formulating VV&A procedures in a wide range of modelling and simulation environments. Furthermore, requirements for the development, documentation and implementation of a software quality program have also been outlined [66].

Definitions for VV&A that originated from the efforts of the Military Operations Research Society (MORS) were officially adopted by the Department of Defense [67]: *Verification*: the process of determining that a model implementation accurately represents the developer's conceptual description and specifications; *Validation*: the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model; *Accreditation*: the official certification that a model or simulation is acceptable for a specific purpose.

5.3. STANDARD DEFINITIONS

A consistent vocabulary and system of units is essential for credible model evaluation. Carey [68] clarified the use of SI metric units for measurements and calculations used in underwater acoustics and bioacoustics while Hall [69] re-examined the dimensions of units for source strength, transmission loss, target strength, surface- and volume-scattering strength. An alphabetical listing of definitions for modelling and simulation terms was published by the IEEE [70].

The US Defense Modeling and Simulation Office (DMSO) assembled the *DOD Modeling and Simulation* (*M&S*) *Glossary* that prescribes a uniform modelling and simulation (M&S) terminology, particularly for use throughout the Department of Defense. In addition to the main glossary of terms, this highly useful manual includes a list of M&S-related abbreviations, acronyms, and initials commonly used within the Department of Defense. Copies can be obtained from the U.S. Department of Commerce, National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, U.S.A. Copies may also be downloaded directly from the DMSO web site at http://www.dmso.mil/.

6. APPLICATIONS

This section discusses specific applications segregated according to *direct* and *inverse* methods. *Direct methods* include traditional sonar applications. *Inverse methods* extract information from direct measurements of the physical properties of the ocean [7].

6.1. DIRECT METHODS

6.1.1. *Bistatic modelling*

The Generic Sonar Model (GSM) has been extended to handle bistatic geometries [71]. Reise and Etter [72] used this bistatic version of GSM to investigate the utility of bistatic sonar configurations operating in littoral scenarios; bistatic configurations were found to offer improved performance over their monostatic counterparts when operating against targets of unknown depth.

6.1.2. *Shallow-water reverberation*

A collection of papers dealing with high-frequency acoustics in shallow water was edited by Pace *et al.* [73]; these papers addressed issues relating to scattering and reverberation in shallow water.

Ellis [74] built upon the method of Bucker and Morris [75] for computing shallow-water boundary reverberation using normal modes to calculate the acoustic energy propagating from the source to the scattering area and back to the receiver. Ray-mode analogies and empirical scattering functions were used to compute the scattered energy at the scattering area. Continuing along this line of investigation, Desharnais and Ellis [76] developed the bistatic normal-mode reverberation model OGOPOGO, which is a further extension of the method of Bucker and Morris [75]. The propagation was described in terms of normal modes computed by the normal-mode model PROLOS. Travel times of the reverberation signals were derived from the modal-group velocities. Volume reverberation from either the water column or the subbottom is not currently included, but boundary reverberation is computed by using empirical scattering functions and ray-mode analogies. The OGOPOGO model was used to interpret reverberation measurements from shallow-water sites in the frequency range 25–1000 Hz.

6.1.3. *Coupled-wedge modes*

Fawcett *et al.* [77] described an efficient coupled-mode method based on the concept of *wedge modes*, which are identical to the usual normal modes of a range-invariant waveguide except that the mode functions are referenced to the arc of a circle rather than a vertical line. This derives from use of a polar co-ordinate system with its origin at the apex of the wedge rather than the usual range-depth co-ordinate system in a wedge domain. Leaky modes were included because of their importance in range-dependent waveguide geometries.

For shallow-water acoustic propagation, the wavelength is commensurate with the water depth, but short compared to the horizontal extent of the problem. Under these conditions, a sloping bottom causes the development of normal modes having wavefronts that are curved in the vertical direction. When using simple slopes, for example, such wedge modes were found to propagate with cylindrical wavefronts by Mignerey [78]. Tindle and Zhang [32] developed an adiabatic normal-mode solution for the benchmark wedge problem for both fluid and solid attenuating ocean bottoms.

6.1.4. *Chaos*

Time-domain analysis of ocean ambient-background pressure fluctuations collected at the Atlantic Undersea Test and Evaluation Center (AUTEC) during a mine-deployment exercise (MINEX) revealed a positive Lyapunov exponent, which identified the system as chaotic. The prediction horizon was confined to a few samples. Determination of the degrees of freedom was important for the construction of physical models and non-linear noise-reduction filters, which were based on characteristics of the observed degrees of freedom (in this case, 9) from the background acoustic source. The magnitude of the largest Lyapunov exponent provided a measure of confidence for signal-state prediction [79].

In non-separable, range-dependent environments, ray paths can be chaotic, thus placing a fundamental limit on tracing rays by the classical *shooting* approach in which the launch angles of rays from a source point are varied until the rays intersect the receiver endpoint within specified tolerances. To circumvent this problem, Mazur and Gilbert [80, 81] used Rayleigh–Ritz and simulated-annealing methods rather than minimizing the travel-time integral indirectly.

The effects of ocean internal waves on long-range acoustic pulse propagation were analyzed from the geometrical-optics viewpoint by Simmen *et al.* [82], who also investigated the chaotic behavior of rays and the microfolding of timefronts. The extent of the region of the timefront in which strongly chaotic rays appear, and the strength of the rays' sensitivity to initial conditions, were found to depend on the average sound-speed profile, the source-to-receiver range, and the internal-wave spectral model.

Tappert and Tang [83] found that groups of chaotic eigenrays tended to form *clusters* having stable envelopes. Sundaram and Zaslavsky [84] studied the dispersion of wave packets using a parabolic approximation to the wave equation; they noted that, in a manner similar to that observed in quantum chaos, enhanced dispersion due to chaotic ray dynamics was counterbalanced by wave coherence effects.

6.1.5. *Three-dimensional modelling*

Tolstoy [26] stressed the point that $N \times 2$-D (sometimes called $2\frac{1}{2}$-D) approximations to full three-dimensional modelling will fail whenever the out-of-plane energy is significant, as in the case of bottom topography (wedges, ridges and seamounts), eddies and fronts. Lee and Schultz [85] prepared a monograph describing a stand-alone three-dimensional ocean acoustic propagation model.

6.1.6. *Boundary interactions*

6.1.6.1. *Ice cover.* Kapoor and Schmidt [86] developed a canonical model in which the under-ice scattering surface was represented as an infinite elastic plate with protuberances.

6.1.6.2. *Sea surface.* Kuo [87] reviewed and clarified earlier formulations of sea-surface scattering losses based on perturbation methods. Kuo also presented new predictions based on numerical integration in a complex domain.

Ogden and Erskine [88] extended the range of environmental parameters (principally wind speed) used in modelling sea-surface backscattering strengths in the critical sea test (CST) experiments. Related work (with minimal analysis) summarized bottom-backscattering strengths that had been measured during the CST program over the frequency range 70–1500 Hz for grazing angles ranging from 25 to 50° [89]. Nicholas *et al.* [90] extended the analysis of surface-scattering strengths that were measured during the CST experiments over the approximate frequency range 60–1000 Hz; unexplained variations between measured and modelled scattering strengths were attributed to an incomplete parameterization of subsurface bubble clouds. A numerical procedure was developed by Norton *et al.* [91] to parameterize bubble clouds in terms of an effective complex index of refraction for use in high-fidelity models of forward propagation.

6.1.6.3. *Sea floor*. Ellis and Crowe [92] combined Lambert's law scattering with a surface-scattering function based on the Kirchhoff approximation to obtain a new functional form that allowed a reasonable extension from backscattering to a general, three-dimensional scattering function useful in bistatic–reverberation calculations. This new functional form was tested in a bistatic version of the Generic Sonar Model (GSM) and was shown to be an improvement over two other commonly used methods, neither of which includes azimuthal dependence: the separable approximation, and the half-angle approximation.

Ainslie *et al.* [93] demonstrated the importance of leaky modes in range-dependent environments with variable water depth. In this particular investigation, the bottom-interacting field was computed by mode summation.

Greaves and Stephen [94] determined that seafloor dip on the scale of a few hundred meters influenced, but did not determine, scattering strength. This suggested that other characteristics of steeply dipping areas, such as subsurface properties or smaller-scale surface features, strongly affected the level of backscattered signals.

A new bottom-scatter modelling approach was proposed by Holland and Neumann [95] to account for artifacts observed in field data when the subbottom plays a role in the scattering process. LeMond and Koch [96] developed a normal-mode scattering formulation that was useful in computing single-frequency bottom reverberation for bistatic and monostatic scattering geometries in both shallow- and deep-water environments.

In a theoretical study, Shenderov [97] treated acoustical scattering by algae as the diffraction of sound waves on a random system of three-dimensional, bent, elastic bodies. This approach considered the statistical properties of algae.

Tindle and Zhang [98] demonstrated that the acoustic-reflection coefficient for a homogeneous fluid overlying a homogeneous solid with a low shear speed could be approximated by replacing the solid with a fluid having different parameters. Zhang and Tindle [99] subsequently simplified these expressions by approximating the acoustic-reflection coefficients of solid layers with a fluid described by suitably chosen (proxy) parameters.

6.2. INVERSE METHODS

6.2.1. *Concepts*

In the present context, inverse methods combine direct physical measurements of the ocean with theoretical models of ocean acoustics. The principal objective is to estimate detailed ocean-acoustic fields from sparse physical measurements by using the theoretical models as guides.

Collins and Kuperman [100] presented a broad discussion of inverse problems in ocean acoustics and methods for solving them. Parameters of interest included sound speed in the water column, sediment properties and boundary roughness. The importance of forward models in solving inverse problems was stressed.

6.2.2. *Acoustic daylight*

A general introduction to imaging underwater objects with ambient noise was presented by Buckingham *et al.* [101]. Buckingham *et al.* [102] further described the results of an experiment with acoustic daylight ocean noise imaging system (ADONIS), which operates in the frequency range 8–80 kHz and relies on ambient noise to provide the acoustic contrast between look angles on-target and off-target. Epifanio *et al.* [103] described results from the ORB experiments, which were conducted with targets at ranges between 20 and 40 m using ADONIS' 126 receive-only beams spanning the vertical and horizontal. Makris *et al.* [104] conducted a careful analysis of this noise-imaging concept and concluded that it pressed the limits of current technology. Furthermore, they traced similar approaches back to 1985 when the possibility of detecting submarines solely by their noise absorbing and scattering properties (*acoustic contrast* versus *acoustic glow*) had been investigated by S. Flatté and W. Munk.

Potter and Chitre [105] extended the concept of *acoustic daylight* (which uses the mean intensity of backscattered ambient-noise energy to produce images of submerged objects, and is thus analogous to *vision*) by exploring the information contained in higher moments. Specifically, information embodied in the second temporal and spatial moments of intensity, for which there are no visual analogs like *acoustic daylight*, was referred to as Ambient Noise Imaging (ANI), a broader imaging approach.

6.2.3. *Field Inversion*

The proceedings of a conference sponsored by the NATO SACLANT Undersea Research Centre in Italy in June 1994 were documented by Diachok *et al.* [106]. It was demonstrated that inversion methods could exploit the amplitude and phase information detected on hydrophone arrays or geophone arrays to infer environmental information about the ocean.

A recent book by Munk *et al.* [107] provided a comprehensive review of the oceanography and mathematics necessary to understand and develop ocean-acoustic tomographic systems. Methods for computing and plotting tomographic inversions in ocean environments have been described by Nesbitt and Jones [108–110]. In related work, Weickmann and Jones [111] described computer programs used to perform ocean-acoustic tomography inversions based on a non-perturbative-inversion method. Harrison *et al.* [112] described a localization technique that was an efficient approximation to the maximum *a posteriori* probability (MAP) estimator intended for use in matched-field source-localization methods.

6.2.4. *Phase conjugation and time-reversal mirrors*

Kuperman *et al.* [113] experimentally demonstrated that a time-reversal mirror (or phase-conjugate array) could spatially and temporally refocus an incident acoustic field back to its origin. This work was extended by Song *et al.* [114] to refocus an incident acoustic field at ranges other than that of the probe source. The basic idea of the approach was that the sound field maxima could be shifted to different ranges by appropriately increasing or decreasing the source frequency for a specific propagation environment.

Time-reversal acoustics can be applied in shallow water to focus energy back to a source location. This refocusing produces spatial intensification of the field (through removal of multipath spreading) as well as temporal convergence of the signal. These properties suggested potential applications in underwater acoustic communication systems [115].

7. CONCLUSION

Progress in underwater acoustic modelling and simulation can be categorized according to *techniques* and *applications*. One aspect that transcends both categories is the opening of new avenues for collaboration, stimulated in large part by rapid changes in global geopolitics. This new openness has facilitated the transfer of modelling and simulation technologies among members of the international community. This accelerated technology transfer has stimulated initiatives for improved international standards in simulation architecture, thus promoting the interoperability of both software and hardware.

7.1. TECHNIQUES

Researchers in environmental modelling have endeavored to refine and simplify empirical formulas relating observed oceanographic parameters to derived acoustic parameters. Such advances serve to reduce both the size and execution time of the models and simulations within which these formulas are embedded.

Notable accomplishments in propagation modelling include introduction of the spectral super-element approach in the wavenumber-integration technique, and extension of the parabolic-equation technique to handle poro-acoustic waveguides.

The sensitivity of marine mammals' hearing and the reactions of marine mammals to various noise sources have advanced through additional fieldwork. This work provides guidelines for the design and operation of high-intensity sources (especially in multistatic and tomographic experiments) that are compliant with governing environmental regulations.

The further maturing of modelling and simulation technologies has facilitated the commercialization of such products, many of which are tailored to training applications. For example, the use of computer-based training (CBT) has grown extensively, and sonar performance models have become common elements of simulations used in such learning environments.

7.2. APPLICATIONS

In *direct* methods, work has continued in bistatic modelling, shallow-water reverberation using normal-mode approaches, coupled-wedge modes for analysis of shallow-water propagation, chaos and its limitations on prediction horizons, three-dimensional modelling and volumetric visualization, and ocean-boundary interactions.

In *inverse* methods, research has continued on full-field inversion methods and on *acoustic daylight* (and expanded into the broader imaging approach termed *ambient-noise imaging*). New research initiatives have investigated the application of phase conjugation and time-reversal mirrors to problems in underwater acoustics; this work may have relevance to underwater communications, particularly in shallow-water environments.

REFERENCES

1. P. C. ETTER and R. S. FLUM SR 1978 *ASW Systems Project Office ASWR*-78-117. A survey of marine environmental/acoustic data banks and basic acoustic models with potential application to the Acoustic Performance Prediction (APP) program.
2. P. C. ETTER 1981 *The Shock and Vibration Digest* **13**(2), 11–20. Underwater acoustic modeling techniques.

3. P. C. ETTER 1984 *The Shock and Vibration Digest* **16**(1), 17–23. Underwater acoustic modeling techniques.
4. P. C. ETTER 1987 *The Shock and Vibration Digest* **19**(2), 3–10. Underwater acoustic modeling techniques.
5. P. C. ETTER 1990 *The Shock and Vibration Digest* **22**(5), 3–12. Underwater acoustic modeling techniques.
6. P. C. ETTER 1993 *Radix Systems, Inc. Technical Report TR*-93-082. Recent developments in computational ocean acoustics.
7. P. C. ETTER 1996 *Underwater Acoustic Modeling: Principles, Techniques and Applications*. London: E&FN Spon, second edition.
8. P. C. ETTER 1999 *Journal of the Acoustical Society of America* **106**, 2298. Updated technology baseline in underwater acoustic modeling, simulation, and analysis (Abstract).
9. P. C. ETTER 2000 *Acoustic Interactions with Submerged Elastic Structures. Part 2: Propagation, Ocean Acoustics and Scattering* (A. Guran, J. Ripoche and F. Ziegler, editors). Progress in underwater acoustic modeling (in press), chapter 13.
10. NATIONAL RESEARCH COUNCIL 1996 *Undersea Vehicles and National Needs*. Washington: National Academy Press.
11. NATIONAL RESEARCH COUNCIL 1997 *Technology for the United States Navy and Marine Corps*, 2000–2035. *Becoming a 21st-Century Force*, Vol. 9: *Modeling and Simulation*. Washington: National Academy Press.
12. F. J. MILLERO and X. LI 1994 *Journal of the Acoustical Society of America* **95**, 2757–2759. Comments on "On equations for the speed of sound in seawater".
13. C. C. LEROY and F. PARTHIOT 1998 *Journal of the Acoustical Society of America* **103**, 1346–1352. Depth-pressure relationships in the oceans and seas.
14. M. A. AINSLIE and J. G. MCCOLM 1998 *Journal of the Acoustical Society of America* **103**, 1671–1672. A simplified formula for viscous and chemical absorption in sea water.
15. R. E. FRANCOIS and G. R. GARRISON 1982 *Journal of the Acoustical Society of America* **72**, 896–907. Sound absorption based on ocean measurements: Part I: pure water and magnesium sulfate contributions.
16. R. E. FRANCOIS and G. R. GARRISON 1982 *Journal of the Acoustical Society of America* **72**, 1879–1890. Sound absorption based on ocean measurements: Part II: boric acid contribution and equation for total absorption.
17. A. SKRETTING and C. C. LEROY 1971 *Journal of the Acoustical Society of America* **49**, 276–282. Sound attenuation between 200 Hz and 10 kHz.
18. H. MEDWIN and C. S. CLAY 1998 *Fundamentals of Acoustical Oceanography*. San Diego: Academic Press.
19. P. H. WIEBE, K. E. PRADA, T. C. AUSTIN, T. K. STANTON and J. J. DAWSON 1995 *Sea Technology* **36**(2), 10–14. New tool for bioacoustical oceanography.
20. NAVAL OCEANOGRAPHIC OFFICE 1999 *OAML-SUM-21G*. Oceanographic and atmospheric master library summary.
21. APPLIED PHYSICS LABORATORY, UNIVERSITY OF WASHINGTON 1994 *APL-UW TR* 9407 (also *Office of Naval Research Technical Report AEAS* 9501). APL-UW high-frequency ocean environmental acoustic models handbook.
22. L. J. ZIOMEK 1995 *Fundamentals of Acoustic Field Theory and Space–Time Signal Processing*. Boca Raton, FL: CRC Press.
23. D. LEE and A. D. PIERCE 1995 *Journal of Computational Acoustics* **3**, 95–173. Parabolic equation development in recent decade.
24. A. L. PISKAREV 1992 *EG&G Technical Report No. 6K1-011A*. Soviet research in underwater acoustic propagation modeling.
25. R. J. VACCARO (editor) 1998 *IEEE Signal Processing Magazine* **15**(4), 21–51. The past, present, and future of underwater acoustic signal processing.
26. A. TOLSTOY 1996 *Journal of Computational Acoustics* **4**, 243–271. 3-D propagation issues and models.
27. J. B. BOWLIN, J. L. SPIESBERGER, T. F. DUDA and L. F. FREITAG 1992 *Woods Hole Oceanographic Institution Technical Report WHOI*-93-10. Ocean acoustical ray-tracing software RAY.
28. J. YAN 1999 *Applied Acoustics* **57**, 163–177. Effects of earth curvature on two-dimensional ray tracing in underwater acoustics.

29. G. L. D'SPAIN, J. J. MURRAY, W. S. HODGKISS, N. O. BOOTH and P. W. SCHEY 1999 *Journal of the Acoustical Society of America* **105**, 3245–3265. Mirages in shallow water matched field processing.
30. D. E. WESTON 1960 *Journal of the Acoustical Society of America* **32**, 647–654. A Moiré fringe analog of sound propagation in shallow water.
31. D. M. F. CHAPMAN, P. D. WARD and D. D. ELLIS 1989 *Journal of the Acoustical Society of America* **85**, 648–653. The effective depth of a Pekeris ocean waveguide, including shear wave effects.
32. C. T. TINDLE and Z. Y. ZHANG 1997 *Journal of the Acoustical Society of America* **101**, 606–609. An adiabatic normal mode solution for the benchmark wedge.
33. H. SCHMIDT, W. SEONG and J. T. GOH 1995 *Journal of the Acoustical Society of America* **98**, 465–472. Spectral super-element approach to range-dependent ocean acoustic modeling.
34. J. T. GOH and H. SCHMIDT 1996 *Journal of the Acoustical Society of America* **100**, 1409–1420. A hybrid coupled wave-number integration approach to range-dependent seismoacoustic modeling.
35. S. GRILLI, T. PEDERSEN and P. STEPANISHEN 1998 *Engineering Analysis with Boundary Elements* **21**, 131–145. A hybrid boundary element method for shallow water acoustic propagation over an irregular bottom.
36. M. D. COLLINS and W. L. SIEGMANN 1999 *Journal of the Acoustical Society of America* **105**, 687–692. A complete energy conservation correction for the elastic parabolic equation.
37. J. F. LINGEVITCH and M. D. COLLINS 1998 *Journal of the Acoustical Society of America* **104**, 783–790. Wave propagation in range-dependent poro-acoustic waveguides.
38. M. D. COLLINS 1999 *Journal of the Acoustical Society of America* **106**, 1724–1726. The stabilized self-starter.
39. D. TIELBÜRGER, S. FINETTE and S. WOLF 1997 *Journal of the Acoustical Society of America* **101**, 789–808. Acoustic propagation through an internal wave field in a shallow water waveguide.
40. C. MACASKILL and T. E. EWART 1996 *Journal of the Acoustical Society of America* **99**, 1419–1429. Numerical solution of the fourth moment equation for acoustic intensity correlations and comparison with the mid-ocean acoustic transmission experiment.
41. X. TANG and F. D. TAPPERT 1997 *IEEE Journal of Oceanic Engineering* **22**, 245–255. Effects of internal waves on sound pulse propagation in the Straits of Florida.
42. F. D. TAPPERT 1998 *Journal of the Acoustical Society of America* **103**, 2990. Parabolic equation modeling with the split-step Fourier algorithm in four dimensions (Abstract).
43. M. J. BUCKINGHAM and J. R. POTTER (editors) 1996 *Sea Surface Sound* '94. Singapore: World Scientific Publishing.
44. W. J. RICHARDSON, C. R. GREENE JR, C. I. MALME and D. H. THOMSON 1995 *Marine Mammals and Noise*. San Diego: Academic Press.
45. F. C. FELIZARDO and W. K. MELVILLE 1995 *Journal of Physical Oceanography* **25**, 513–532. Correlations between ambient noise and the ocean surface wave field.
46. J. A. NYSTUEN and H. MEDWIN 1995 *Journal of the Acoustical Society of America* **97**, 1606–1613. Underwater sound produced by rainfall: secondary splashes of aerosols.
47. S. VAGLE, W. G. LARGE and D. M. FARMER 1990 *Journal of Atmospheric and Oceanic Technology* **7**, 576–595. An evaluation of the WOTAN technique of inferring oceanic winds from underwater ambient sound.
48. R. M. HAMSON 1997 *Applied Acoustics* **51**, 251–287. The modeling of ambient noise due to shipping and wind sources in complex environments.
49. C. H. HARRISON 1996 *Journal of the Acoustical Society of America* **99**, 2055–2066. Formulas for ambient noise level and coherence.
50. L. BJØRNØ 1998 *Archives of Acoustics* **23**, 211–225. Sources of ambient noise in littoral waters.
51. L. ZEDEL, L. GORDON and S. OSTERHUS 1999 *Journal of Atmospheric and Oceanic Technology* **16**, 1118–1126. Ocean ambient sound instrument system: Acoustic estimation of wind speed and direction from a subsurface package.
52. R. H. LOVE, C. H. THOMPSON and R. W. NERO 1996 *Journal of the Acoustical Society of America* **100**, 2799. Volume reverberation in littoral waters (Abstract).
53. K. B. SMITH, W. S. HODGKISS and F. D. TAPPERT 1996 *Journal of the Acoustical Society of America* **99**, 1387–1404. Propagation and analysis issues in the prediction of long-range reverberation.
54. P. BAGGENSTOSS 1994 *Sea Technology* **35**(11), 59–62. Active sonar processing for shallow water ASW.

55. M. Wazenski and D. Alexandrou 1997 *Journal of the Acoustical Society of America* **101**, 1961–1970. Active, wideband detection and localization in an uncertain multipath environment.
56. Ocean Acoustic Developments Ltd 1999 *Product description literature*. WADER global ocean information system.
57. J. Bracken, M. Kress and R. E. Rosenthal (editors) 1995 *Warfare Modeling*. New York: John Wiley.
58. J. W. Ellis, J. E. Miller and M. R. Fernandez 1996 *Sea Technology* **37**(5), 31–37. NRL's tactical oceanography simulation lab.
59. C. H. Spikes, F. T. Erskine, J. F. McEachern and D. A. Backes 1997 *Sea Technology* **38**(6), 71–77. Littoral warfare technology testing.
60. J. A. Foret, M. S. Korman, J. W. Schuler and E. Holmes 1997 *Journal of the Acoustical Society of America* **101**, 3097. Design and development of PC-IMAT: teaching strategies for acoustical oceanography (Abstract).
61. US Department of The Navy 1999 *Joint publication of the SPAWAR Systems Center and the Naval Surface Warfare Center, Carderock Division*. Interactive multisensor analysis training.
62. E. C. Whitman 1994 *Sea Technology* **35**(11), 21–25. Defense conversion in marine technology.
63. D. Veenstra 1998 *RTC* **VII**(12), 135–137. A COTS approach to sonar simulation/stimulation.
64. N. Oreskes, K. Shrader-Frechette and K. Belitz 1994 *Science* **263**, 641–646. Verification, validation, and confirmation of numerical models in the earth sciences.
65. US Department of Defense 1996 *Office of the Director of Defense Research and Engineering, Defense Modeling and Simulation Office*. Verification, validation and accreditation (VV&A) recommended practices guide [http://www.dmso.mil/home/vva/].
66. US Department of Defense 1988 *DOD-STD*-2168. Military standard: defense system software quality program.
67. US Department of Defense 1994 *DoD Directive* 5000.59. DoD modeling and simulation management.
68. W. M. Carey 1995 *IEEE Journal of Oceanic Engineering* **20**, 109–113. Standard definitions for sound levels in the ocean.
69. M. V. Hall 1995 *Journal of the Acoustical Society of America* **97**, 3887–3889. Dimensions and units of underwater acoustic parameters.
70. Institute of Electrical and Electronics Engineers, Inc. 1989 *IEEE Std* 610.3–1989. IEEE standard glossary of modeling and simulation terminology.
71. W. J. Powers 1987 *Naval Underwater Systems Center Technical Memorandum* 871025. Bistatic active signal excess model—an extension of the Generic Sonar Model.
72. B. Reise and P. C. Etter 1997 *Proceedings of the Undersea Defence Technology Conference, Hamburg, Germany*. Performance assessment of active sonar configuration options.
73. N. G. Pace, E. Pouliquen, O. Bergem and A. P. Lyons (editors) 1997 *SACLANTCEN Undersea Research Centre Conference Proceedings CP*-45. High frequency acoustics in shallow water.
74. D. D. Ellis 1995 *Journal of the Acoustical Society of America* **97**, 2804–2814. A shallow-water normal-mode reverberation model.
75. H. P. Bucker AND H. E. Morris 1968 *Journal of the Acoustical Society of America* **44**, 827–828. Normal-mode reverberation in channels or ducts.
76. F. Desharnais and D. D. Ellis 1997 *IEEE Journal of Oceanic Engineering* **22**, 309–316. Data-model comparisons of reverberation at three shallow-water sites.
77. J. A. Fawcett, E. K. Westwood and C. T. Tindle 1995 *Journal of the Acoustical Society of America* **98**, 1673–1681. A simple coupled wedge mode propagation method.
78. P. C. Mignerey 1995 *Journal of the Acoustical Society of America* **98**, 2912. Horizontal refraction of 3-D curvilinear wedge modes (Abstract).
79. T. W. Frison, H. D. I. Abarbanel, J. Cembrola and B. Neales 1996 *Journal of the Acoustical Society of America* **99**, 1527–1539. Chaos in ocean ambient "noise".
80. M. A. Mazur and K. E. Gilbert 1997 *Journal of the Acoustical Society of America* **101**, 174–183. Direct optimization methods, ray propagation, and chaos. I. Continuous media.
81. M. A. Mazur and K. E. Gilbert 1997 *Journal of the Acoustical Society of America* **101**, 184–192. Direct optimization methods, ray propagation, and chaos. II. Propagation with discrete transitions.
82. J. Simmen, S. M. Flatté and G.-Y. Wang 1997 *Journal of the Acoustical Society of America* **102**, 239–255. Wavefront folding, chaos, and diffraction for sound propagation through ocean internal waves.

83. F. D. TAPPERT and X. TANG 1996 *Journal of the Acoustical Society of America* **99**, 185–195. Ray chaos and eigenrays.
84. B. SUNDARAM and G. M. ZASLAVSKY 1999 *Chaos* **9**, 483–492. Wave analysis of ray chaos in underwater acoustics.
85. D. LEE and M. H. SCHULTZ 1995 *Numerical Ocean Acoustic Propagation in Three Dimensions*. Singapore: World Scientific Publishing.
86. T. K. KAPOOR and H. SCHMIDT 1997 *Journal of the Acoustical Society of America* **102**, 256–265. Acoustic scattering from a three-dimensional protuberance on a thin, infinite, submerged elastic plate.
87. E. Y. T. KUO 1988 *IEEE Journal of Oceanic Engineering* **13**, 229–234. Sea surface scattering and propagation loss: review, update, and new predictions.
88. P. M. OGDEN and F. T. ERSKINE 1994 *Journal of the Acoustical Society of America* **96**, 2908–2920. Surface and volume scattering measurements using broadband explosive charges in the Critical Sea Test 7 experiment.
89. P. M. OGDEN and F. T. ERSKINE 1997 *Naval Research Laboratory Report NRL/FR*/7140-97-9822. Bottom scattering strengths measured using explosive sources in the Critical Sea Test Program.
90. M. NICHOLAS, P. M. OGDEN and F. T. ERSKINE 1998 *IEEE Journal of Oceanic Engineering* **23**, 81–95. Improved empirical descriptions for acoustic surface backscatter in the ocean.
91. G. V. NORTON, J. C. NOVARINI and R. S. KEIFFER 1998 *Journal of the Acoustical Society of America* **103**, 3256–3267. Modeling the propagation from a horizontally directed high-frequency source in shallow water in the presence of bubble clouds and sea surface roughness.
92. D. D. ELLIS and D. V. CROWE 1991 *Journal of the Acoustical Society of America* **89**, 2207–2214. Bistatic reverberation calculations using a three-dimensional scattering function.
93. M. A. AINSLIE, M. N. PAKCMAN and C. H. HARRISON 1998 *Journal of the Acoustical Society of America* **103**, 1804–1812. Fast and explicit Wentzel–Kramers–Brillouin mode sum for the bottom-interacting field, including leaky modes.
94. R. J. GREAVES and R. A. STEPHEN 1997 *Journal of the Acoustical Society of America* **101**, 193–208. Seafloor acoustic backscattering from different geological provinces in the Atlantic Natural Laboratory.
95. C. W. HOLLAND and P. NEUMANN 1998 *Journal of the Acoustical Society of America* **104**, 1363–1373. Sub-bottom scattering: a modeling approach.
96. J. E. LEMOND and R. A. KOCH 1997 *Journal of the Acoustical Society of America* **102**, 266–277. Finite correlation and coherent propagation effects in the normal-mode description of bottom reverberation.
97. E. L. SHENDEROV 1998 *Journal of the Acoustical Society of America* **104**, 791–800. Some physical models for estimating scattering of underwater sound by algae.
98. C. T. TINDLE and Z. Y. ZHANG 1992 *Journal of the Acoustical Society of America* **91**, 3248–3256. An equivalent fluid approximation for a low shear speed ocean bottom.
99. Z. Y. ZHANG and C. T. TINDLE 1995 *Journal of the Acoustical Society of America* **98**, 3391–3396. Improved equivalent fluid approximations for a low shear speed ocean bottom.
100. M. D. COLLINS and W. A. KUPERMAN 1994 *Inverse Problems* **10**, 1023–1040. Inverse problems in ocean acoustics.
101. M. J. BUCKINGHAM, C. L. EPIFANIO and M. L. READHEAD 1996 *Journal of the Acoustical Society of America* **100**, 2736. Passive imaging of targets with ambient noise: experimental results (Abstract).
102. M. J. BUCKINGHAM, J. R. POTTER and C. L. EPIFANIO 1996 *Scientific American* **274**(2), 86–90. Seeing underwater with background noise.
103. C. L. EPIFANIO, J. R. POTTER, G. B. DEANE, M. L. READHEAD and M. J. BUCKINGHAM 1999 *Journal of the Acoustical Society of America* **106**, 3211–3225. Imaging in the ocean with ambient noise: the ORB experiments.
104. N. C. MAKRIS, F. INGENITO and W. A. KUPERMAN 1994 *Journal of the Acoustical Society of America* **96**, 1703–1724. Detection of a submerged object insonified by surface noise in an ocean waveguide.
105. J. R. POTTER AND M. CHITRE 1999 *Journal of the Acoustical Society of America* **106**, 3201–3210. Ambient noise imaging in warm shallow seas; second-order moment and model-based imaging algorithms.

106. O. Diachok, A. Caiti, P. Gerstoft and H. Schmidt (editors) 1995 *Full Field Inversion Methods in Ocean and Seismo-Acoustics* (Modern Approaches in Geophysics, Vol. 12). Dordrecht: Kluwer Academic Publishers.
107. W. Munk, P. Worcester and C. Wunsch 1995 *Ocean Acoustic Tomography*. New York: Cambridge University Press.
108. L. Nesbitt and R. M. Jones 1994 *NOAA Technical Memorandum ERL ETL*-242. A C program for generating publication-quality plots.
109. L. Nesbitt and R. M. Jones 1994 *NOAA Technical Memorandum ERL ETL*-243. A FORTRAN program for performing nonperturbative ocean acoustic tomography inversion.
110. L. Nesbitt and R. M. Jones 1994 *NOAA Technical Memorandum ERL ETL*-245. A FORTRAN program to generate comparison data to test tomography inversion programs.
111. A. Weickmann and R. M. Jones 1994 *NOAA Technical Memorandum ERL ETL*-244. A FORTRAN program for performing Abel transforms.
112. B. F. Harrison, R. J. Vaccaro and D. W. Tufts 1998 *Journal of the Acoustical Society of America* **103**, 3721–3724. Robust matched-field localization in uncertain ocean environments.
113. W. A. Kuperman, W. S. Hodgkiss, H. C. Song, T. Akal, C. Ferla and D. R. Jackson 1998 *Journal of the Acoustical Society of America* **103**, 25–40. Phase conjugation in the ocean: experimental demonstration of an acoustic time-reversal mirror.
114. H. C. Song, W. A. Kuperman and W. S. Hodgkiss 1998 *Journal of the Acoustical Society of America* **103**, 3234–3240. A time-reversal mirror with variable range focusing.
115. A. A. M. Abrantes, K. B. Smith and A. Larraza 1999 *Journal of the Acoustical Society of America* **105**, 1364. Examination of time-reversal acoustics and applications to underwater communications (Abstract).
116. M. Porter 1991 *SACLANT Undersea Research Centre Memorandum SM*-245. The KRAKEN normal mode program.
117. M. B. Porter and H. P. Bucker 1987 *Journal of the Acoustical Society of America* **82**, 1349–1359. Gaussian beam tracing for computing ocean acoustic fields.
118. L. Dozier and P. Lallement 1995 *Full Field Inversion Methods in Ocean and Seismo-Acoustics* (O. Diachok, A. Caiti, P. Gerstoft and H. Schmidt, editors), 45–50. Parallel implementation of a 3-D range-dependent ray model for replica field generation. Dordrecht: Kluwer Academic Publications.
119. H. Weinberg and R. E. Keenan 1996 *Journal of the Acoustical Society of America* **100**, 1421–1431. Gaussian ray bundles for modeling high-frequency propagation loss under shallow-water conditions.
120. R. E. Keenan, H. Weinberg and F. E. Aidala Jr 1998 *US Naval Oceanographic Office Software Test Description*. GRAB: Gaussian ray bundle (GRAB) eigenray propagation model version 2.0.
121. J. O. A. Robertsson, A. Levander and K. Holliger 1996 *Journal of Geophysical Research* **101**, 11225–11241. A hybrid wave propagation simulation technique for ocean acoustic problems.
122. A. M. Plotkin 1996 *ISDCO unpublished manuscript*. LYCH 2-D ray program functional description.
123. Ocean Acoustic Developments Ltd 1999 *Product description literature*. Global sonar assessment and range prediction system.
124. S. J. Levinson, E. K. Westwood, R. A. Koch, S. K. Mitchell and C. V. Sheppard 1995 *Journal of the Acoustical Society of America* **97**, 1576–1585. An efficient and robust method for underwater acoustic normal-mode computations.
125. E. K. Westwood, C. T. Tindle and N. R. Chapman 1996 *Journal of the Acoustical Society of America* **100**, 3631–3645. A normal mode model for acousto-elastic ocean environments.
126. C. M. Ferla, M. B. Porter and F. B. Jensen 1993 SACLANT Undersea Research Centre Memorandum SM–274. C-SNAP: coupled SACLANTCEN normal mode propagation loss model.
127. E. Noutary and A. Plaisant 1996 *Theoretical and Computational Acoustics* "95 (D. Lee, Y.-H. Pao, M. H. Schultz and Y.-C. Teng, editors), 61–74. 2D and 3D propagation modeling with coupled modes.
128. J. S. Papadakis, V. A. Dougalis, N. A. Kampanis, E. T. Flouri, B. Pelloni, A. Plaisant, E. Noutary, L. Bjørnø, P. Nielsen and D. Zhu 1998 *Acustica — Acta Acustica* **84**, 1031–1041. Ocean acoustic models for low frequency propagation in 2D and 3D environments.
129. F. Bini-Verona, P. L. Nielsen and F. B. Jensen 1999 *SACLANT Undersea Research Centre Memorandum SM*-358. PROSIM broadband normal-mode model.

130. R. Zhang, Y. He, H. Liu and V. A. Akulichev 1995 *Journal of Sound and Vibration* **184**, 439–451. Applications of the WKBZ adiabatic mode approach to sound propagation in the Philippine Sea.
131. S. Ivansson and I. Karasalo 1992 *Journal of the Acoustical Society of America* **92**, 1569–1577. A high-order adaptive integration method for wave propagation in range-independent fluid-solid media.
132. S. Ivansson 1994 *Journal of the Acoustical Society of America* **96**, 2870–2875. Shear-wave induced transmission loss in a fluid-solid medium.
133. M. B. Porter 1990 *Journal of the Acoustical Society of America* **87**, 2013–2023. The time-marched fast-field program (FFP) for modeling acoustic pulse propagation.
134. J. T. Goh, H. Schmidt, P. Gerstoft and W. Seong 1997 *IEEE Journal of Oceanic Engineering* **22**, 226–236. Benchmarks for validating range-dependent seismo-acoustic propagation codes.
135. H. Schmidt 1999 *Department of Ocean Engineering, Massachusetts Institute of Technology*. OASES, Version 2.2 user guide and reference manual (http://acoustics.mit.edu/arctic0/henrik/www/oases.html).
136. M. D. Collins 1993 *Journal of the Acoustical Society of America* **94**, 2269–2278. The adiabatic mode parabolic equation.
137. A. T. Abawi, W. A. Kuperman and M. D. Collins 1997 *Journal of the Acoustical Society of America* **102**, 233–238. The coupled mode parabolic equation.
138. D. Zhu and L. Bjørnø 1999 *Journal of Computational Acoustics* **7**, 133–145. A hybrid 3-D, two-way IFD PE model for 3-D acoustic backscattering.
139. G. V. Norton, J. C. Novarini and R. S. Keiffer 1995 *Journal of the Acoustical Society of America* **97**, 2173–2180. Coupling scattering from the sea surface to a one-way marching propagation model via conformal mapping: validation.
140. G. V. Norton and J. C. Novarini 1996 *Journal of the Acoustical Society of America* **99**, 2013–2021. The effect of sea-surface roughness on shallow water waveguide propagation: a coherent approach.
141. K. V. Avilov 1995 *Acoustical Physics* **41**, 1–7. Pseudodifferential parabolic equations of sound propagation in the slowly range-dependent ocean and their numerical solutions.
142. M. D. Collins 1998 *Journal of the Acoustical Society of America* **104**, 1808. New and improved parabolic equation models (Abstract).
143. R. J. Cederberg and M. D. Collins 1997 *IEEE Journal of Oceanic Engineering* **22**, 102–109. Application of an improved self-starter to geoacoustic inversion.
144. M. D. Collins 1993 *Journal of the Acoustical Society of America* **93**, 1736–1742. A split-step Padé solution for the parabolic equation method.
145. W. Renner 1995 *Science Applications International Corporation Technical Report*. Software requirements specification for the ANDES model (Version 4.2).
146. W. Renner 1995 *Science Applications International Corporation Technical Report*. User's guide for the ANDES model (Version 4.2).
147. C. H. Harrison 1997 *Applied Acoustics* **51**, 289–315. CANARY: a simple model of ambient noise and coherence.
148. C. H. Harrison 1997 *Journal of the Acoustical Society of America* **102**, 2655–2662. Noise directionality for surface sources in range-dependent environments.
149. J. E. Breeding, L. A. Pflug, M. Bradley, M. Hebert and M. Wooten 1994 *Naval Research Laboratory Report NRL/MR*/7176-94-7552. RANDI 3.1 user's guide.
150. J. E. Breeding Jr, L. A. Pflug, M. Bradley, M. H. Walrod and W. McBride 1996 *Naval Research Laboratory Report NRL/FR*/7176-95-9628. Research ambient noise directionality (RANDI) 3.1 physics description.
151. L. A. Pflug 1996 *Naval Research Laboratory Report NRL/MR*/7176-96-8003. Modification of the RANDI model for shallow-water applications.
152. D. M. Fromm 1999 *Proceedings of the 28th Meeting of the Technical Cooperation Program, Technical Panel MAR TP-9, Naval Research Laboratory*. Multistatic active system performance modeling in littoral waters.
153. D. M. Fromm, J. P. Crockett and L. B. Palmer 1996 *Naval Research Laboratory Report NRL/FR*/7140-95-9723. BiRASP—the bistatic range-dependent active system prediction model.
154. J. K. Fulford 1991 *Naval Oceanographic and Atmospheric Research Laboratory Technical Note* 135. Shallow water RASP upgrade.
155. P. Schippers 1995 *Proceedings of the Undersea Defence Technology Conference, Cannes, France*. The ALMOST PC-model for propagation and reverberation in range dependent environments.

156. G. Dreini, C. Isoppo and F.B. Jensen 1995 *SACLANT Undersea Research Centre Report SR*-240. PC-based propagation and sonar prediction models.
157. US Navy Air Asw Project Office 1996 *Program Executive Office*, *Air ASW*, *Assault*, *and Special Mission Programs* (*PMA*-264). User's guide for the environmental acoustics server software package.
158. US Navy Air ASW Project Office 1996 *Program Executive Office*, *Air ASW*, *Assault*, *and Special Mission Programs* (*PMA*-264). Operating system interface description for the environmental acoustics server software package.
159. UK Ministry of Defence, Director Naval Surveying, Oceanography and Meteorology 1995 *User Guide*. Hodgson propagation loss model version 4.0.
160. M. A. Ainslie, C. H. Harrison and P. W. Burns 1994 *Proceedings of the Institute of Acoustics* **16** (Part 6), 105–112. Reverberation modeling with INSIGHT.
161. M. A. Ainslie, C. H. Harrison and P. W. Burns 1996 *IEE Proceedings* (*Radar*, *Sonar and Navigation*) **143**, 190–195. Signal and reverberation prediction for active sonar by adding acoustic components.
162. M. N. Packman, C. H. Harrison and M. A. Ainslie 1996 *IEE Proceedings* (*Radar*, *Sonar and Navigation*) **143**, 184–189. Rapid calculations of acoustic propagation loss in range dependent oceans.
163. C. E. Jaster and H. Boehme 1984 *Applied Research Laboratories*, *The University of Texas at Austin*, *Technical Report ARL-TR*-84-9. The MINERAY sonar performance prediction computer model baseline description.
164. R. S. Bailey, M. A. Beck, I. M. Fink, M. L. Garcia, G. Kaduchak and M. Z. Lawrence 1997 *Applied Research Laboratories*, *The University of Texas at Austin*. Installation and user's guide for Mineray 3 sonar performance prediction model, X-Windows version (XMineray).
165. Navy Modeling and Simulation Management Office 1999 *Navy M&S Catalog* [http://navmsmo.hq.navy.mil/].
166. G. S. Sammelmann 1998 *Coastal Systems Station*, *Dahlgren Division*, *Naval Surface Warfare Center*. SWAT acoustic modeling [http://www.ncsc.navy.mil/css/papers/swat.htm].
167. BAeSEMA Ltd 1998 *Product description literature*. Tactical support systems.

APPENDIX A: UPDATED MODEL BASELINE

This appendix presents four summary tables listing all underwater-acoustic models contained in the 1996 baseline [7] as updated with the models identified in this paper and in related work [8]. The four tables are segregated according to stand-alone Propagation Models (Table A1), stand-alone Noise Models (Table A2), stand-alone Reverberation Models (Table A3) and Sonar Performance Models (Table A4). The Sonar Performance

Table A1

Comprehensive summary of propagation models

Technique	Range independent	Range dependent	
Ray theory	CAPARAY	ACCURAY	MEDUSA
	FACT	BELLHOP	MIMIC
	FLIRT	Coherent DELTA	MPC
	GAMARAY	FACTEX	MPP
	ICERAY	GRAB	Pedersen
	PLRAY	GRASS	RAYWAVE
	RANGER	HARPO	RP-70
		HARVEST	SHALFACT
		LYCH	TRIMAIN

TABLE A1

Continued

Technique	Range independent		Range dependent	
Normal mode	AP-2/5	ORCA	ADIAB	MOCTESUMA
	COMODE	PROTEUS	ASERT	PROLOS
	DODGE	SHEAR2	ASTRAL	PROSIM
	FNMSS	Stickler	CENTRO	SNAP/C-SNAP
	MODELAB		CMM3D	WEDGE
	NEMESIS		COUPLE	WKBZ
	NLNM		Kanabis	WRAP
	NORMOD3		KRAKEN	3D Ocean
	NORM2L		MOATL	
Multipath expansion	FAME		No existing solutions	
	MULE			
	NEPBR			
	RAYMODE			
Fast field or wavenumber integration	FFP	RPRESS	CORE	SAFRAN
	Kutschale FFP	SAFARI	RDFFP	
	MSPFFP	SCOOTER	RD-OASES	
	OASES	SPARC	RDOASP	
	Pulse FFP		RDOAST	
Parabolic equation	Use single environmental specification		AMPE/CMPE	OS2IFD
			Corrected PE	PAREQ
			CCUB/SPLN/CNP1	PDPE
			DREP	PE
			FDHB3D	PE-FFRAME
			FEPE	PESOGEN
			FEPE-CM	PE-SSF (UMPE/MMPE)
			FEPES	RAM/RAMS
			FOR3D	Spectral PE
			HAPE	TDPE
			HYPER	Two-Way PE
			IFD Wide Angle	ULETA
			IMP3D	UNIMOD
			LOGPE	3DPE (NRL-1)
			MaCh1	3DPE (NRL-2)
			MIPE	3D TDPA
			MOREPE	

TABLE A2

Comprehensive summary of noise models

Ambient noise	Beam-noise statistics
ANDES	*Analytic*
AMBENT	BBN shipping noise
CANARY	BTL
CNOISE	USI array noise
DANES	Sonobuoy noise
DUNES	
FANM	*Simulation*
Normal mode ambient noise	BEAMPL
RANDI—I/II/III	DSBN
	NABTAM

TABLE A3

Comprehensive summary of reverberation models

Cell scattering		Point scattering	
Monostatic	Bistatic	Monostatic	Bistatic
DOP	BAM	REVGEN	Under-ice reverberation simulation
EIGEN/REVERB	BiKR		
MAM	BiRASP		
PEREV	BISAPP		
REVMOD	BISSM		
REVSIM	OGOPOGO		
TENAR	RASP		
	RUMBLE		

TABLE A4

Comprehensive summary of sonar performance models

Active sonar performance	
ALMOST	LORA
Active RAYMODE	MINERAY
ASPM	MOCASSIN
CASTAR	MSASM
CONGRATS	NISSM—II
GASS	SEARAY
HODGSON	SONAR
INSIGHT	SST
INSTANT	SWAT
LIRA	
Model-operating systems	Tactical decision aids
CAAM	IMAT
CASS	NECTA
GSM—bistatic	
PRISM	

Models are further divided into three functional subcategories: Active Sonar Performance (stand-alone models); Model-Operating Systems; and Tactical Decision Aids. Acronyms for the 1996 baseline models were defined previously [7].

Relative to the 1996 baseline [7], the number of propagation models increased from 83 to 107, ambient-noise models increased from 15 to 16, reverberation models increased from 14 to 17, and sonar performance models increased from 14 to 25. In all, this represents a 30% increase over the 1996 baseline.

APPENDIX B: ACRONYMS AND ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
ADONIS	Acoustic Daylight Ocean Noise Imaging System
AEAS	Advanced Environmental Acoustic Support
ALMOST	Acoustic Loss Model for Operational Studies and Tasks

AMPE	Adiabatic Mode PE
ANDES	Ambient Noise Directionality Estimation System
ANI	Ambient-Noise Imaging
APL/UW	Applied Physics Laboratory/University of Washington
ASEPS	Automated Signal Excess Prediction System
ASTRAL	ASEPS Transmission Loss
ASW	Anti-Submarine Warfare
AUTEC	Atlantic Undersea Test and Evaluation Center
AUV	Autonomous Undersea Vehicle
AW	Acoustic Mode Generation Program Using Chebyshev Polynomials as Basis Functions
BELLHOP	Gaussian-Beam, Finite-Element, Range-Dependent Propagation Model
BEM	Boundary Element Method
BiKR	Bistatic Shallow-Water Reverberation Model Based on KRAKEN
BiRASP	Bistatic Range-Dependent Active System Prediction Model
CAAM	Composite Area Analysis Model
CANARY	Coherence and Ambient Noise for Arrays
CASS	Comprehensive Acoustic Simulation System
CBT	Computer-Based Training
CCUB	Finite Element PE Model
CMMS	Conceptual Models of the Mission Space
CMPE	Coupled Mode PE
CNP1	Finite Element PE Model
Coherent DELTA	3-D Range-Dependent Ray Model
CORE	Coupled OASES for Range-Dependent Environments
COTS	Commercial Off-the-Shelf
COUPLE	Coupled Mode Model
C-SNAP	Coupled SNAP
CST	Critical Sea Test
CTF	Common Technical Framework
CW	Continuous Wave
CZ	Convergence Zone
DBDB	Digital Bathymetric Database
DMSO	Defense Modeling and Simulation Office
DOD	Department of Defense
EFEPE	Exponential FEPE (superseded by RAM)
EVA	Environmental Acoustics
FACT	Fast Asymptotic Coherent Transmission
FAME	Fast Multipath Expansion Model
FDHB3D	Hybrid 3D, Two-Way IFD PE Model for Computing 3D Backscattering
FE	Finite Element
FEPE	Finite Element Parabolic Equation
FEPE-CM	FEPE with Conformal Mapping
FFP	Fast Field Program
FOR3D	Finite Difference Method, Ordinary Differential Equations, and Rational Function Approximations to Solve the LSS 3D Wave Equation
FTE	Focused Technology Experiments
GASS	Generic Acoustic Stimulator System
GRAB	Gaussian Ray Bundles
GSM	Generic Sonar Model
HARPO	Hamiltonian Acoustic Raytracing Program—Ocean
HARVEST	Hybrid Adaptive Regime Visco-Elastic Simulation Technique
HBEM	Hybrid BEM
HLA	High-Level Architecture
HODGSON	Range-Dependent Ray Theoretical Propagation Model
IEEE	Institute of Electrical and Electronics Engineers
IFD	Implicit Finite Difference
IMAT	Interactive Multisensor Analysis Tool
IMP3D	Finite Difference PE Model with Elastic Impedance Bottom Boundary

INSIGHT	Active Sonar Model for Range-Independent Environments
INSTANT	Active Sonar Model for Range-Dependent Environments
KRAKEN	Adiabatic/Coupled Normal Mode Model
LSS	Lee–Saad–Schultz Method
LWAD	Littoral Warfare Advanced Development
LYCH	Range-Dependent, Ray-Theoretical Propagation Model
MAP	Maximum *a posteriori* Probability
MCM	Mine Countermeasures
MIMIC	Low-Frequency, Range-Dependent, Ray-Theoretical Propagation Model
MINERAY	Active Sonar Model Used in Mine-Hunting Scenarios
MINEX	Mine Deployment Exercise
MIPE	(University of) Miami PE
MMPE	Monterey-Miami PE (formerly UMPE; now PE-SSF)
MOATL	Modal Acoustic Transmission Loss Model
MOCTESUMA	Coupled Normal Mode Model
MODELAB	Normal Mode Model
MORS	Military Operations Research Society
M&S	Modelling and Simulation
MS&A	Modelling, Simulation and Analysis
MSASM	Multistatic Active System Model; Multistatic Anti-Submarine Model
MULE	Multilayer Expansion
NATO	North Atlantic Treaty Organization
NAVMSMO	Navy Modeling and Simulation Management Office
NECTA	Naval Environmental Command Tactical Aid
NLAYER	N-Layer Normal Mode Model
NRL	Naval Research Laboratory
OAML	Oceanographic and Atmospheric Master Library
OASES	Ocean Acoustics and Seismic Exploration Synthesis
OASIS	Ocean Ambient Sound Instrument System
OGOPOGO	Normal-Mode Reverberation Model
ORB	Research Platform
ORCA	Normal Mode Model for Acousto-Elastic Ocean Environments
PDPE	Pseudo-Differential PE
PE	Parabolic Equation
PEREV	PE Reverberation Model
PERUSE	PE Rough Surface
PE—SSF	PE—Split-Step Fourier
PROLOSS	Propagation Loss Model
PROPLOSS	Transmission Loss Module in ALMOST
PROSIM	Broadband Adiabatic Normal-Mode Propagation Model
RAM	Range-Dependent Acoustic Model
RAMS	RAM for Acousto-Elastic Problems
RANDI	Research Ambient Noise Directionality Model
RASP	Range-Dependent Active System Performance Model
RAY	Range-Dependent Raytracing Program
RAYMODE	Ray/Normal Mode
R&D	Research and Development
RD-OASES	Range-Dependent OASES
RDOASP	Pulse Version of RD-OASES
RDOAST	RD-OASES with VISA
REACT	Active Sonar Range Prediction Module in ALMOST
REPAS	Passive Sonar Range Prediction Module in ALMOST
RPRESS	Model for Computing Seismoacoustic Wavefields
SACLANTCEN	Supreme Allied Commander Atlantic (SACLANT) Undersea Research Centre
SCOOTER	FFP, Finite-Element, Range-Independent Propagation Model
SCV	System Concept Validation
SI	Système International [d'Unités] (International System [of Units])
SNAP	SACLANTCEN Normal-Mode Acoustic Propagation Model
SONAR	Sound Navigation and Ranging
SPARC	SACLANTCEN Pulse Acoustic Research Code

SPLN	Finite Element PE Model
SuperSNAP	Enhanced SNAP
SWAM	Shallow Water Acoustic Model (Workshop)
SWAT	Shallow Water Acoustics Toolset
TDA	Tactical Decision Aid
TOSL	Tactical Oceanography Simulation Laboratory
TRIMAIN	Range-Dependent Acoustic Propagation Model Based on Triangular Segmentation of the Range-Depth Plane
TRM	Time-Reversal Mirror
UK	United Kingdom
US	United States
UMPE	University of Miami PE (now MMPE)
UUV	Unmanned Undersea Vehicle
VISA	Virtual Source Algorithm
VV&A	Verification, Validation and Accreditation
WADER	Global Ocean Information System
WHOI	Woods Hole Oceanographic Institution
WKB	Wentzel, Kramers and Brillouin
WKBZ	Adiabatic Normal Mode Model
WOTAN	Weather Observation Through Ambient Noise