1aID1. Studying the sea with sound

Stan E. Dosso* and Jan Dettmer

*Corresponding author’s address: University of Victoria, Victoria, V8W 3P6, B.C., Canada, sdosso@uvic.ca

Because electromagnetic radiation is strongly attenuated in seawater while sound propagates efficiently to long (even global) ranges, scientists and engineers have devised many ingenious methods to use acoustics in the ocean in place of light, radio, and microwaves. Myriad underwater acoustic applications include remote sensing, remote control, communications, navigation, and source detection/localization. This talk will present a semi-historical overview of the use of sound to study the sea (including the seabed), from ancient times, through two world wars, and into the modern era of advanced measurement technologies and computer analysis. A final emphasis involves on-going research to estimate seabed geophysical properties and quantify their uncertainty and variability using a variety of ocean acoustic measurements and probabilistic inversion theory.

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

Although the study of underwater sound might seem at first blush to be a somewhat arcane investigation to those unfamiliar with the field, it is, in fact, of immense scientific and practical importance. Since seawater is electrically conductive, electromagnetic radiation is strongly attenuated while sound propagates efficiently to long (in some cases, global) ranges. Hence, scientists and engineers have devised ingenious methods to use sound underwater in place of light, radio, or microwaves, including applications in remote sensing, remote control, communications, detection/localization/tracking, navigation, and in studying the sea (including the seabed). To introduce the topic to a general audience, the first part of this paper presents a brief, semi-historical, illustrated overview of the development and study of acoustics in the ocean. This is not intended to be systematic/complete or to survey the current state-of-the-art (enormous tasks), but rather represents a narrative of items and ideas which the authors found interesting and hope readers will as well (a more complete historical review is given in [1] and an excellent educational website in [2]). The latter part of this paper considers contributions to the field by the authors (and collaborators) in geoacoustic inversion for seabed properties.

OCEAN ACOUSTICS: AN ILLUSTRATED OVERVIEW

Any historical overview of ocean acoustics must acknowledge at the outset that many forms of marine life, particularly marine mammals, have been far ahead of humans for eons, and remain so in many ways. As well-known examples: humpback whale songs transmit complex information to others of its kind over ocean-basin scales (1000s of kilometers); echo-locating dolphins adapt the frequency content of their “clicks” to best determine the location, size, shape, and composition (density) of potential prey (sometimes eavesdropping on other dolphins’ clicks to steal prey); and snapping shrimp acoustically stun or kill their prey (small fish and crabs) using a sharp cracking sound produced by a collapsing cavitation bubble created by rapidly closing their large claw (Fig. 1). Notwithstanding these and other impressive underwater-acoustic capabilities from the animal kingdom, the remainder of this paper will consider ocean acoustics from an anthropocentric viewpoint.

Possibly the earliest recorded musings on ocean acoustics were by Greek philosopher and polymath Aristotle (384–322 BC) who noted that sound traveled underwater as it did in air, and questioned whether fish could hear. Jumping ahead to the Renaissance, Leonardo da Vinci wrote in 1490 “If you cause your ship to stop and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you.” In 1870 Jules Verne wrote speculatively (but accurately) about underwater sound in his science-fiction novel 20,000 Leagues Under the Sea: “The slightest sounds were transmitted with a speed to which the ear is unaccustomed on the earth. Indeed, water is a better vehicle for sound than air... Deep sounds, clearly transmitted by this liquid medium, reverberated majestically.”

Among the early scientific investigations in underwater acoustics, in 1826 Swiss physicist J. D. Colladon and French mathematician J. K. F. Sturm measured the speed of sound in Lake Geneva using an ingenious experiment illustrated in Fig. 2. The sound source was a bell suspended in the lake from a row boat. The bell was struck with a

**FIGURE 1.** Three notable under-water acousticians of the animal kingdom, left to right: humpback whale [3], bottle-nose dolphin [3], and snapping shrimp [4].
hammer operated by Sturm in the boat using a lever which was also connected by a pulley to a candle, such that at
the instant the bell was struck the flame ignited a pan of gun powder, producing a simultaneous underwater tone and
above-water flash. Collandon, in a second row boat 16-km distant, was listening with an underwater ear-trumpet
and noted the time difference on his watch between the flash and bell tone (~11 s). From this they estimated the
speed of sound in fresh water at 8°C to be 1435 m/s, remarkably close to modern measurements of 1438 m/s.

The long-range propagation of sound underwater was exploited in the late 19th Century for ship warnings and
navigation aids along the British and U.S. Atlantic coasts. Underwater bells deployed near lighthouses and from
(moored) lightships were detected by passing ships as warning/navigation signals at much larger distances (10–20
km) and with less weather-related variability than in-air sound or light transmissions. Further, the bearing to the
sound source could be determined using a binaural system consisting of two in-water detectors (ear horns or water-
tight microphones) on either side of the ship fed to the right and left ears of a trained operator.

The 1912 sinking of the RMS Titanic, with 1500 deaths, due to a night-time collision with an ice berg in the
foggy North Atlantic (Fig. 3), provided strong impetus for the development of underwater acoustic approaches to ice
berg detection and ranging. That same year, working for the Submarine Signal Company, Canadian Reginald
Fessenden (1866–1932) designed the Fessenden oscillator, an electro-acoustic moving-coil transducer which could
produce and receive underwater sound signals at about 1 kHz (Fig. 4). Using this device, Fessenden was able to
echo-locate ice bergs to about 3-km range, representing one of the first applications of what came to be called sonar
(sound navigation and ranging). The oscillator was later also used to communicate underwater via Morse code, and
installed on Royal Navy submarines. In 1915, Fessenden invented the fathometer (an acoustic depth echo-sounder),
for which he later won the Scientific American Gold Medal. Fessenden also carried out pioneering work in radio (he
is credited with the first audio and first two-way trans-Atlantic radio transmissions), and held over 500 patents for
diverse inventions including reflection seismology, paging and television systems, and tracer bullets. In 1986 the
Canadian Acoustical Association established the annual Fessenden Student Prize in Underwater Acoustics based on
proceeds from the 12th ICA Symposium on Underwater Acoustics held in Halifax, Nova Scotia.

World War I (1914–1918) provided intense motivation for sonar developments in anti-submarine warfare
(submarines sank more than 4800 merchant ships during the war), and significantly accelerated underwater acoustics
advancements. Both passive sonar systems (listening for noise generated by a target) and active sonar systems
(transmitting a “ping” and listening for the echo off a target) were developed with the goal of detecting, classifying,
localizing, and tracking submarines. Important instrumentalations for underwater sound reception and
transmission were based on the piezoelectric effect (originally discovered in 1880 by Jacques and Pierre–husband of
Marie–Curie), that some crystals (notably quartz) develop an electric potential across their faces when subjected to a
mechanical pressure, and, conversely, the application of an electric field results in mechanical expansion/contraction
of the crystal. Most modern hydrophones and many acoustic sources are still based on piezoelectric transducers.

Another advancement during the First World War was the hydrophone array, typically a horizontal (towed or hull-
mounted) line of sensors which provides directional capabilities by electronically steering the array response in
angle through appropriate inter-sensor time delays, as well as providing array gain to boost the signal to noise ratio.

FIGURE 2. Colladon and Sturm’s 1862 experiment to measure the speed of sound in Lake Geneva [5].
After WWI, echo-sounding sonar systems were applied to the challenge of mapping the ocean abysses, which cover over 70% of the earth’s surface. The first systematic acoustic survey of bathymetry (underwater topography) was carried out by the German ship Meteor, which traversed the Atlantic 13 times in 1925–27 (at a 600-km north-south line spacing), resulting in 70,000 echo-soundings over total track length of 130,000 km track (echo-soundings were regularly checked against the trusted but extremely slow procedure of lead-line sounding). The Meteor survey produced the first detailed bathymetric chart of an ocean basin (Fig. 5), and clearly mapped the Mid-Atlantic Ridge running from pole to pole, mimicking the shape of the continental coastlines. Global-scale bathymetric features, such as mid-ocean ridges (in all oceans) and deep oceanic trenches along some coastlines, were mapped acoustically in the 1920s–1950s, and played a key role in the understanding of seafloor spreading and the development of plate tectonic theory in the 1960s.

World War II (1939–45) again provided intense impetus for advancements in ocean acoustics. In addition to the development of new weapon systems (acoustic-homing torpedoes, sound-triggered mines) and improved sonars, acoustics studies also advanced knowledge of the ocean. For example, studies carried out to explain sonar operators’ observations of diffuse, variable-depth echoes from a mysterious deep horizon lead to the discovery of the deep scattering layer, prevalent worldwide, which consists of a population of marine organisms (zooplankton, krill, small fish) which rise to the surface at night to feed on phytoplankton (and on each other) and descend to depth during daylight hours to avoid larger predators. Another example is the discovery of the deep sound channel (DSC), which explained the mechanism for extremely long-range propagation. Sound speed in the ocean depends primarily on temperature and pressure. Descending from the surface, sound speed initially decreases with depth due to decreasing water temperature through a layer known as the thermocline. Below the thermocline the sound speed increases with depth due to increasing pressure in deep isothermal water. The result is the DSC, with a minimum (axis) at the base of the thermocline (Fig. 6), which varies from ~1000 m in the tropics, to 500 m in temperate waters, to the surface in the Arctic (i.e., a half-channel). Sound traveling in the DSC is refracted downward above.
FIGURE 5. Bathymetry of the Atlantic Ocean based on acoustic echo-soundings of the 1925-27 Meteor expedition, delineating the Mid-Atlantic Ridge (green) through the entire ocean [7].

The channel axis and refracted upward below the axis, cycling within the DSC without lossy boundary interactions (Fig. 6 shows original ray predictions for DSC propagation by Maurice Ewing in the 1940s). In a 1960 experiment, an explosive source detonated in the DSC near Perth, Australia, was detected near Bermuda 3.6 hours later after following a 20,000-km path [8]. DSC propagation was exploited to locate WWII airmen downed at sea: An explosive sound source was dropped from the life raft, detonated at the DSC axis, and was detected at widely-spaced coastal stations, allowing triangulation of the source location to within 10–20 km. Due to such applications the DCS was also referred to as the SOFAR (sound fixing and ranging) channel, and the airmen’s sound sources referred to as SOFAR bombs.

Following WWII, the requirement to detect and track submarines during the Cold War continued to push sonar developments. Among these was the U.S. Navy’s deployment of the SOSUS (sound surveillance system) arrays in the 1950s. These coastline-length arrays of bottom-mounted sensors listening to DSC propagation represented enormous advancements in electrical/marine engineering and signal processing (highly classified at the time). Following the end of the Cold War in the early 1990s, the SOSUS arrays have been directed to other applications, including tracking vocalizing whales and recording earthquakes.

FIGURE 6. Left: Typical oceanic sound-speed profile illustrating the deep sound channel (SOFAR channel). Right: Ewing’s original ray prediction of sound-channel propagation [9].
In the 1970s, Walter Munk and Carl Wunsch proposed the idea of measuring ocean properties over large regions via acoustic tomography [10], analogous to the X-ray-based medical CT (computed tomography) scan used to image the human body. In ocean acoustic tomography, acoustic travel-times are measured between a series of sources and receivers at known locations. The sound speed integrated over the propagation path can be inferred from measured travel-times, and a series of measurements for suitable source-receiver geometries can be inverted for a model of the sound-speed distribution. An example of acoustic tomography is shown in Fig. 7 from the AMODE-MST experiment off southern Florida in 1991, which used a receiver array towed in a 1000-km diameter circle around six moored acoustic sources to record tomographic data inverted for the sound-speed field and investigate mesoscale variability [11, 12]. Since ocean sound-speed variations depend primarily on temperature, tomographic results may be interpreted as a model of the oceanic temperature distribution, from which different water masses, etc., can often be identified. The ocean current field can be estimated from reciprocal tomography in which two-way transmissions from a series of transceivers (instruments acting as both source and receiver) are measured. Since reciprocal measurements include signals travelling both with and against ocean currents, the difference between reciprocal measurements removes the dominating effect of temperature and allows inversion for water-current structure.

The ATOC (acoustic thermometry of ocean climate) program is based on applying acoustic tomography on an ocean-basin scale to average out mesoscale and internal-wave variability and provide a stable measure of ocean temperature which can be monitored over time as an indicator of global climate change. Measurements were made from 1996–2006 in the North Pacific and provided ocean temperatures along mega-meter propagation paths with uncertainties much smaller than other measurement approaches of this scale. The TAP (trans-Arctic propagation) experiment considered warming in the Arctic basin by making acoustic measurements in 1994 and comparing them to direct sound-speed measurements made from 1970–1980 [13]. By considering the change in travel-times of three propagating modes which are concentrated at different depths, it was concluded that a 0.4°C warming had occurred in Atlantic intermediate water flowing into the Arctic at depth (see Fig. 8). This result was later verified by temperature measurements along an icebreaker transit.

Starting in the 1970s, the idea was developed to observe large-scale ocean currents by acoustically tracking neutrally-buoyant sub-surface floats (Langrangian drifters) over time periods of months to years and distances of up to 1000s of kilometers. In the initial approach, the drifters consisted of sound sources that transmitted a coded signal at regular intervals which were detected at a series of moored receiving stations, determining the drifter’s position as a function of time. Since the long-range propagation occurred within the SOFAR channel, the drifters were referred to as SOFAR floats. Later, to decrease fabrication costs, this design was reversed with the drifters consisting of receivers which recorded arrival times of transmissions from moored sources (drifters surface periodically to
transmit data to satellite). In this case the acronym was reversed, and the drifters referred to as RAFOS floats. Figure 9 shows SOFAR and RAFOS floats and an example of drift patterns in the Atlantic Ocean off Brazil.

In the late 1980s, acoustic Doppler current profilers (ADCPs) were developed to measure current profiles in the water column. These instruments send high-frequency acoustic beams vertically through the water and measure the acoustic backscatter from suspended particles moving with water currents. The travel-time of the backscattered arrivals gives an estimate of distance, and the Doppler frequency shift indicates the velocity of the scatters (3 or more acoustic beams are required to determine the three-dimensional velocity field). Figure 10 shows an east-west cross-section the Newfoundland Sub-Polar Current at 41°N based on 17 ADCP stations, delineating the boundary between warm northward and cold southward currents.

Technology and techniques for seafloor acoustic surveys also improved dramatically from the 1970s to the present. While standard echo-sounders determine the water depth directly beneath a ship from the echo return-time of a single vertical beam, multi-beam sonars provide much greater efficiency by mapping a lateral swath of seafloor. Multi-beam sonars are hull-mounted systems which send out a lateral fan of acoustic beams and determine water depth along a cross-track swath of seafloor from echo return times beamformed into narrow receive beams (swath widths at the seafloor are typically 2-4 times the water depth and frequencies are 20-100 kHz). High-precision bathymetry mapping with multi-beam systems require accurate measurements of ship location as well as ship motion (heave, pitch, roll). Alternatively, side-scan sonars create an image of seafloor reflectors by measuring the backscatter strength for a lateral fan of acoustic beams transmitted and received from a “tow-fish” ~100 m off the bottom (fan-widths are typically 100–500 m, frequencies 100–500 kHz). Finally, bottom-penetrating sonars provide an image of the sub-bottom along a ship track by measuring echo-return times off sub-bottom layers using an acoustic source and hydrophone array towed behind the ship (frequencies of 0.1–40 kHz). Example results from multi-beam, side-scan, and bottom-penetrating sonars are shown in Fig. 11.
FIGURE 9. Left: SOFAR and RAFOS floats onboard ship (top and bottom, respectively) [14]. Right: Drift paths of SOFAR and RAFOS floats off Brazil [15].

FIGURE 10. North-south subpolar current section across the continental slope south of the Grand Banks of Newfoundland from 17 ADCP stations. Northward currents defined as positive.

FIGURE 11. Left, top and bottom: Multi-beam and bottom-penetrating sonar results, respectively, for a submarine sand dune field in Juan de Fuca Strait [16]. Above: Side-scan sonar image of the wreck of the *Herbert D. Maxwell* [7].
The past two decades have continued to see impressive developments in underwater acoustics science and technology, which has furthered our understanding of the oceans. Important areas of development include the use remotely-operated and autonomous underwater vehicles; cabled ocean observatories; measurements and modeling of bottom-interacting acoustics including scattering, reverberation, and poroelastic effects; and the inversion of ocean acoustic data for seabed geoacoustic properties. Some recent contributions of the authors to the latter topic are briefly presented in the following section.

**PROBABLISTIC GEOACOUSTIC INVERSION**

This section provides a brief overview, with examples, of the authors’ research program at the University of Victoria with the aim to study seabed geoacoustic properties and processes via the inversion of ocean acoustic measurements. The remote sensing of seabed parameters with acoustic data represents an important problem with geophysical, geological, geotechnical, and defense applications. Geoacoustic inversion provides a convenient *in-situ* alternative to direct sampling (e.g., coring), but requires solving a nonlinear inverse problem which is inherently non-unique (i.e., a range of solutions acceptably fit the data). Although often neglected due to computational complexity, rigorous uncertainty estimation is of key importance to meaningfully interpret recovered parameters in nonlinear inversion. Only with quantitative uncertainty estimates can issues such as resolving parameter spatial and temporal variability or frequency dependence be meaningfully addressed.

The problem of remote sensing of the properties of a physical system (e.g., the seabed) is ubiquitous in the sciences: A signal interacts with the system under investigation and is influenced in a manner dependent on the properties of the system. Observations of the altered signal (data) contain information regarding system properties which is not directly accessible to the observer, but must be inferred by formulating an inverse problem. The system is described by a model which specifies the physical theory for the signal-system interaction, an appropriate system parameterization, and a statistical representation for the error processes. Parameters of the error model (e.g., variances, covariances) which are not known independently can also be included as unknowns in the problem. The goal is to estimate parameter values and uncertainties (or, better, probability distributions) which are consistent with the data according to the physical/statistical model.

A probabilistic (Bayesian) approach to inversion treats unknown model parameters as random variables constrained by data and prior information, with the goal of quantifying the posterior probability density (PPD). The PPD represents the multi-dimensional probability distribution over the model parameters, and is typically interpreted in terms of simplifying properties such as marginal probability densities (e.g., one-dimensional probability distributions in which all but one parameter are integrated out). In nonlinear problems (such as acoustic inversion), analytic solutions are not available, and numerical sampling of the PPD must be applied. Such sampling is usually based on Markov-chain Monte Carlo (MCMC) methods [17] which, while powerful and general, can be numerically intensive. Hence, developing efficient algorithms is of practical importance.

As a first example, consider the inversion of seabed acoustic reflection coefficients (ratio of reflected to incident amplitude) as a function of angle as measured with a towed source/receiver system (Fig. 12, top right) in the Baltic Sea [18]. Measurements were carried out at two sites where the uppermost seabed sediments were known to consist of soft mud and harder till, to determine if acoustic reflection data can differentiate between the seabed types. Plane-wave visco-elastic reflection theory is applied, and frequency-averaged data are time windowed to consider <1-m penetration depth so seabed layering is not considered. Residual errors are assumed Gaussian distributed with variance included as a parameter in the inversion. The seabed properties estimated from the reflection data consist of the compressional-wave (sound) and shear-wave speeds, $V_P$ and $V_S$, compressional- and shear-wave attenuations, $\alpha_P$ and $\alpha_S$, and density, $\rho$. The inversion applied Metropolis-Hastings sampling [17] in a principal-component parameter space for efficiency. Prior information consisted of bounded uniform intervals which constrained the inversion to physically reasonable values. Figure 12 (left) shows the inversion results in terms of marginal probability distributions for the geoacoustic parameters. This plot indicates that $V_P$, $V_S$, and $\rho$ are resolved by the acoustic data (i.e., have reasonably small uncertainties), while $\alpha_P$ and $\alpha_S$ are essentially unconstrained by this data set. The geoacoustic parameters recovered at the two sites are consistent with known values for mud and till. Importantly, the differences in both $V_P$ and $V_S$ estimates between the two sites clearly exceed their uncertainties, differentiating definitively between the sediment types at the sites. The relationships between parameters can be investigated in terms of joint marginal distributions (Fig. 12, lower right). For example, the positive correlation between $V_P$ and $V_S$ (positive slope to the marginal density peak) indicates that the physics of the problem does not see these parameters as fully independent, but admits a range of solutions in which both $V_P$ and $V_S$ increase in an appropriate ratio.
The above example was designed to consider a simple uniform (half-space) model for the seabed. However, in many cases the goal is to resolve the depth variation of geoacoustic properties in terms of a layered seabed model. In such cases the model parameterization (number of layers) that is consistent with the resolving power of the data is generally not known a priori. Traditionally, subjective assumptions are often made for the parameterization in inverse problems, and the consequences are rarely investigated. However, the assumed model can profoundly affect the information which can be recovered, particularly uncertainty estimates. In the general case where an appropriate model is not known independently, it can (and should) be included in the inverse problem, i.e., be estimated from the data, a procedure known as model selection. Trans-dimensional (trans-D) inversion represents an automated approach to model selection which samples over a range of model parameterizations according to their support by the data, yielding a probability distribution over the model set which is interpreted as an ensemble solution. This approach can be shown to satisfy parsimony (favors simple parameterizations consistent with the data resolution), and has the advantage that the uncertainty in the choice of model is quantified and included in the uncertainty of the solution.

An example of trans-D geoacoustic inversion for a seabed model with an unknown number of layers is given in Fig. 13 [19]. In this case high-resolution reflection-coefficient data were collected on the Malta Plateau in the Mediterranean Sea using a single moored hydrophone and ship-towed impulsive source (Fig. 13, left), which provides a greater range of reflection angles and improved ability to correct for source directivity than the towed-array geometry considered in Fig. 12. Multi-frequency reflection coefficient data (500–5000 Hz) were inverted using spherical-wave reflection theory and a poroelastic seabed model (Buckingham’s viscous grain-shearing model [20]), although the results are converted here to compressional-wave (sound) speed, density, and attenuation for comparison with core measurements taken at the site. Residual variances at each frequency were included as unknowns in the inversion. The trans-D inversion applied the reversible-jump Markov-chain Monte Carlo (rjMCMC) algorithm [21] to sample over models with differing numbers of layers. High rejection rates for dimension jumps (changes in the number of layers) can be a problem for rjMCMC algorithms, and is addressed here using parallel tempering [22] which samples from a sequence of distributions which are progressively relaxed compared to the PPD but include probabilistic interchange with the PPD. In addition, spherical-wave data predictions are carried out in parallel using a graphics processing unit (GPU), which sped up computations by a factor of ~200.
Figure 13 (right) shows the high-resolution reflection inversion results in terms of marginal probability profiles for sound speed (velocity), density, and attenuation. The trans-D inversion recovers both discontinuous changes (layering) and gradients in the geoacoustic parameters, as required by the data. Figure 13 shows that the inversion results are in excellent agreement with direct measurements made on a core collected at the same site. In particular, the inversion results closely track the core density profile to ~3-m depth; below this depth discrepancies are likely due to decompression of the bottom 0.5 m of the core in the extraction process which biases the measurements. The inversion and core measurements for sound speed agree closely to 2-m depth. Below this depth the higher-speed sediments are expected to exhibit dispersion (speed varies with frequency) such that the discrepancies are likely due to the much higher frequency (200 kHz) applied in the core measurements (as well as core decompression in the bottom 0.5 m). Hence, in this example remote sensing via acoustic reflection inversion provides \textit{in-situ} geoacoustic profiles at frequencies of interest which may well be more reliable than the core measurements.

The inversion of naturally-occurring ambient noise, as opposed to controlled-source signals, is a topic of recent interest in geoacoustic inversion (and other areas of acoustics). Advantages include simpler experimental configurations with lower power requirements, continuously-available signals, less environmental disruption, and unobtrusive surveys. Geoacoustic reflection inversion in shallow waters can be based on ambient noise by using a vertical line array of sensors to measure the ambient noise field, and beamforming the response into up- and down-looking angles (Fig. 14, left). Assuming surface noise sources (wind and waves) and propagation involving successive bottom and surface reflections, sound in a down-looking beam has always suffered one more bottom reflection than that in an up-looking beam at the same angle [23]. Hence, dividing the down-looking response by the up-looking response provides reflection coefficients, although of somewhat lower angular resolution than controlled-source measurements due to the smearing effect of beamforming. Figure 14 compares marginal probability profiles for sediment sound speed, $c$, density, $\rho$, and attenuation, $\alpha$, from the inversion of ambient-noise (upper right) and controlled-source (lower right) reflection data collected at a site on the Malta Plateau (different site from Fig. 13) [24]. The two results in Fig. 14 are in good agreement, although the controlled-source inversion includes smaller-scale structure. Both results are in good agreement with core measurements at site, which are also included in this figure.

A final problem considered here involves acoustic inversion for seabed and water-column properties which vary in two dimensions (i.e., with depth and horizontal range along a track). For two-dimensional (2D) inversion, parsimonious parameterizations which adapt to resolve local structure are of paramount importance. Our approach applies trans-D inversion using a highly-efficient 2D seabed parameterization based on a self-adjusting grid. In this approach, the parameterization is based on an irregular arrangement of nodal points, with the unknown parameter set consisting of the spatial positions and environmental properties associated with each node as well as the number of nodes [25, 26]. The nodal positions and properties are used to define the 2D seabed model in terms of Voronoi cells (nearest-neighborhood regions about the nodes), as used for forward modeling computations. Trans-D inversion via rjMCMC samples over parameterizations involving differing numbers of nodes, with natural Bayesian parsimony restricting the inversion to simple parameterizations. The number and position of nodes self-adjust to provide high nodal density in regions where the data resolving power and structural variation are high, and low density where resolution or variation is low.
To illustrate this new approach, a simulated example is considered in which the sound speed varies with depth and range in an unknown manner in both the water column and seabed (density and attenuation also vary in the seabed and are inverted for, but results are not shown here) [26]. Figure 15 (top panel) shows the true sound-speed structure (note that different color scales are applied for the water column and seabed due to the different scales of variation). The water-column is strongly stratified in the uppermost part and has a low-speed range-dependent intrusion starting at 2-km range. The bathymetry varies from 100- to 200-m depth over the 4-km range with a flat section near the center (bathymetry is treated as known in the inversion). The seabed has a 10-m thick low-speed (1550 m/s) layer immediately below the water-sediment interface. Below this is a wedge (1600 m/s) extending from 0- to 2-km range and decreasing in thickness from 70 to 10 m. Otherwise, the seabed consists of a basement of 1700 m/s. Synthetic data (frequency-domain acoustic fields) were computed at a vertical array of 32 sensors for sources at five locations (50-m depth and ranges of 1, 2, 3, 3.5, 4 km) and three frequencies (50, 100, 200 Hz) using a split-step parabolic equation propagation model. Complex Gaussian-distributed noise was added to the data with a standard deviation of 15% of the maximum magnitude at each frequency. Full-field inversion was carried out assuming no knowledge of the water-column or seabed structure or of the source spectrum (i.e., incoherent processing).

The inversion results are shown in Fig. 15 in terms of sound-speed estimates (ensemble mean, middle panel) and uncertainties (ensemble standard deviation, lower panel). The middle panel shows that the speed structure is well resolved throughout the water column and seabed. In particular, the thin low-speed layer at the top of the seabed, the intrusion in the water column, and the wedge in the seabed are all recovered with high accuracy. The lower panel shows the largest uncertainties occur deep in the seabed and near the beginning of the wedge. The number of nodes varied between 6–12 for the seabed and 7–9 for the water column, representing a parsimonious parameterization for this complex 2D structure.

**SUMMARY**

Oceans are opaque to electromagnetic fields but transparent to sound. However, with ingenuity, sound can be used in the ocean for myriad practical applications, including the study of the ocean itself. This paper presented a brief semi-historic overview of highlights in the progress in applying acoustics in the ocean, and in understanding the ocean acoustically, including recent work in geoacoustic inversion.
ACKNOWLEDGMENTS

We thank Charles Holland of the Pennsylvania State University for long-term collaborations on geoacoustic inversion, other members of the UVic Ocean Acoustics group (Jorge Quijano and Gavin Steininger) for their contributions to inversion research, and the Office of Naval Research for supporting our work.

REFERENCES

2. www.dosits.org (Discovery of sound in the sea).
7. NOAA Photo Library (photolib.noaa.gov).
14. www.po.gso.uri.edu (University of Rhode Island, Graduate School of Oceanography, Physical Oceanography).