Celebrating a Half Century of Signal Processing

The Past, Present, and Future of Underwater Acoustic Signal Processing

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The Future of Signal Processing in the Ocean: A Personal Perspective

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The future of acoustics, and more generally of signal processing in the ocean, will explore many of the same problems that have occupied signal-processing researchers in the past and present, but will undoubtedly do so in

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more general contexts, branching out in new directions and areas, stretching current methods, and posing new challenges. I will build on the past and present (albeit in directions different from the ones covered in [1, 2]), to address my perspective of the future. My emphasis is, of course, in areas that I have worked on or know better. My references are not to be interpreted as exhaustive nor do I claim them to be complete. I will freely quote from the literature. First I will address briefly acoustic signal processing in the ocean in the framework of passive localization to provide some context to my perspective and then provide my view of current and future promising areas of work.

Background

The past was mostly concerned with acoustic submarine warfare (ASW) issues: detection and localization of noisy sources in the deep ocean. The challenges in underwater work were characteristically derived from passive systems.

Bearings Only

Prior to the 1970s, the passive detection and localization problem was very much reduced usually to a "bearings only" problem, e.g., determination of the direction of arrival of a single source from the source signature as received by a linear array of sensors [3]. The common assumptions were single source, narrowband signature, linear array, additive white Gaussian noise, planar wavefront propagation, and homogeneous propagation channel. In other words, the source is in the far field of the array and the propagation is in "free" space, reduced to a single direct path between the source and the receiver.

The major goals of the ASW signal-processing work were the design of processing algorithms (detectors and bearing estimators) and performance evaluation. The techniques used were often adapted from the literature for active radar and extended to the passive context, usually by assuming random signals. Major tools for the design and analysis of the performance of detectors and estimators were the ambiguity function, first introduced by Woodward [4], for radar, and the Cramér-Rao bound (CRB). The CRB for the bearings-only problem is, for example, developed in [5]. The state of the art of detection and localization for active and passive systems in the late 1960s is captured in the two volumes by Van Trees [6, 7], which still endure as standard texts for detection and estimation.

Ranging and Spatial Curvature

In the 1970s, passive localization became concerned not only with bearing but also ranging. Large linear arrays, mounted or towed, enabled exploiting the wavefront curvature of the traveling waves. The framework was still that of the homogeneous deep ocean: linear array, single target, narrowband signature, white Gaussian noise, single-path propagation, high signal-to-noise ratio, but the hypothesis of planar wavefront was no longer held. Much effort was expended in understanding how to exploit the wavefront curvature and in determining performance bounds. The effort focused on extracting bearing and range and on local bounds by Cramér-Rao techniques [8-10] as well as on joint localization and tracking (estimating the target velocity and motions) and on global bounds using the ambiguity function, e.g., [11-13]. To achieve higher resolution, the array and target motions were used to synthesize larger arrays [14], very much like early radar systems used synthetic aperture radar (SAR) and inverse SAR [15].

While this work showed the theoretical feasibility of passive ranging, the simplicity of the underlying propagation model limited its theoretical and practical significance. As acousticians developed a better understanding of wave propagation in the water channel and more efficient numerical codes were developed for ray tracing and the wave equation, in the mid-late 70s and 80s the role of channel propagation took central stage. The free-space and single-direct path assumptions were replaced by waveguide propagation concepts and an inhomogeneous ocean with a complex sound velocity profile (SVP). Modal analysis and waveguide propagation led to the first application of waveguide concepts in source localization in underwater with a vertical array in [16, 17]. This precedes what became known as matched-field processing (MFP), coupling complex propagation models, derived from the wave equation, to array and signal-processing methods. Early papers include [18, 19]. Reference [20] studies the accuracy of localization by MFP methods using the CRB.

The Present And The Future: The 1990s And Beyond

Continuing the trends of the 1980s, the emphasis is to capture the physics governing the ocean behavior in more sophisticated models and make these an integral part of the signal-processing algorithms. The interest shifts from the strict ASW applications of the past to exploring the ocean in several broad dimensions. Detection and localization of sources, as well as their classification, continue to be of major relevance. Other areas are also taking center stage. I will now address a few of the current trends.

Localization

The focus is to move away from the single-source, single-path, planar wavefront, high signal-to-noise ratio framework, and incorporate in the signal processing as much as possible the complex propagation models or the interaction of the sound waves with the scattering objects. With the interest in detection and localization shifting from the deep ocean to coastal waters, several authors considered localization in multipath environments, generalizing the single-ray propagation of the earlier work. Ranging is now to be obtained by exploiting both the multipath structure and the wavefront curvature measured by the array of hydrophones. In [21], a vertically inhomogeneous sound-velocity profile is approximated by a multilinear profile, which is then used to derive the ray structure of the multipath and the detector that makes optimal use of the direct path, the refracted paths, and the reflected bounces. In [22], the Cramér-Rao bound is studied for a two-sensor array and two straight-line propagation paths (direct path and surface or bottom reflected path). In [23], the importance of the multipath contribution for the "range only" estimation problem is studied with two straight-line coherent paths. In [24, 25], the closely related problem of delay estimation for a single wideband source, a single sensor, and three straight line paths is considered. In [26, 27], global (ambiguity based) and local (CRB) bounds are studied for localization (range and depth) with an arbitrary array of sensors, an arbitrary number of not necessarily straight-line paths in the propagation (besides bottom, surface, surface/bottom bounces, the study includes refracted paths), and an arbitrary number of partially correlated sources. The bounds in [27] quantify the range performance gain achieved when several groups of paths can be resolved. This leads to the concept of "virtual" sensors, also known as "multipath ranging" [28], where the temporal diversity is thought of as extending the physical array: each secondary path arriving at a sensor is assimilated to a virtual sensor whose position relative to the physical sensor is determined by the differential delay between that path and the principal reference path. These works have shown that combining the information provided by the spatial structure in the wavefield (curvature) with the temporal structure (virtual arrays), leads to increased estimation accuracy. For example, [23], when only the wavefield curvature is used, passive range error performance goes roughly as $(R/L)^4$, where R and L are, respectively, the range and array baseline. When the wavefield spatial curvature and the temporal "virtual" sensors are used, passive ranging resolution is of the order of $R^4/(LH)^2$ where H is the water channel depth. When $H >> L$ this can represent a substantial improvement. Reference [27] discusses that when the array of K sensors separates the multiple paths in r clusters of resolved paths, the multipath contribution to the Fisher information matrix (the inverse of the Cramér-Rao bound matrix) is equivalent to the contribution of K fictitious arrays, each one with size equal to the number, r, of ray clusters.

Using the temporal diversity provided by the channel propagation structure is highly sensitive to complete knowledge of the channel parameters. The effects of incompletely known environmental conditions like the SVP on the location parameter errors are considered in [27], the effects of not completely known channel depth are studied in [29], and uncertainty in the sensor positions calibration is taken up in [30].

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Detection

Signal processing has to take advantage of all available transmitted energy. Multipath can no longer be ignored or treated as a nuisance that limits the performance of the receivers. Rather, multipath is to be used to advantage by processing and combining coherently the energy in the sound channel. Designing signal-processing algorithms that make maximum usage of the complexity of the ocean environment poses several challenges: for example, the computational complexity associated with integrating forward propagation models or the sensitivity of these algorithms to model mismatches. Approaches to reduce this sensitivity have led to developing detectors that are robust to environmental mismatches. Reference [31] introduces a multiconstraint beamformer to improve the robustness of MFP to incomplete knowledge of the channel and aimed at coping with inhomogeneous deterministic range-dependent ocean environments. Reference [32] considers minimum-variance beamforming techniques to achieve robustness of MFP to random inhomogeneities in the SVP. Reference [33] uses wavelets to design robust detectors while avoiding the channel inversion problem that is essentially performed by MFP. Studying the expected performance and determining performance bounds will continue to be of major interest. Reference [34] extends the concept of ambiguity function to applications where there is an incomplete specification of the model, such as when the channel is not completely known. References [35, 36] consider bounds on the accuracy of estimating the environmental parameters as well as localization.

Classification

There is a large amount of knowledge accumulated in the literature detailing the nature and generation of sounds in the ocean. However, these sounds change significantly with the time of the year and the geographic location. In addition, sounds from similar sources experience a wide variability in propagation characteristics that differ in deep water from shallow water and depend on other environmental conditions. The sounds of interest are usually immersed in a background of noise that includes traffic

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and shipping noise, sea-surface noise like the breaking of waves, wind, rain drops, bubble formation, sound from seismic activities, turbulence, biological activities, and off-shore activities, [37]. The spectral range of these sounds is large. For example, shipping lies in the 20 Hz-400 Hz range. Surface noise, depending on the wind strength and sea state, may go from 8 Hz to 3 or 4 kHz. Biological sources generate sounds in the range 20 kHz to 150 kHz. In deep water, the principal biological sources of low-frequency sounds are vocalizations from mammals (e.g., whales and porpoises). In shallow water, toad fish, croakers, and catfish all contribute to biological sound, often at dawn or in the evening. Ice fracturing generates spiky sounds in the frequency range of 1 Hz-300 Hz. Ship noise may come from the propulsion system, the propeller, auxiliary machinery, hydrodynamic effects, or movements of the hull. Noise levels of mechanical origin may vary significantly. Submarines may produce only about 10 mW of acoustic power, while surface ships may generate up to 100 W.

As man-made targets become quieter, the level of their reflected (active systems) or radiated (passive sonars) narrowband or broadband energy is significantly reduced. Passive transients become increasingly relevant. Transients like a hatch slamming shut, active sonar pinging, or increased cavitation through sudden maneuvers may signal the presence of a man-made target. It is important to distinguish these from the diversity of the other ambient acoustic sounds. Human operators are trained to use their expert knowledge to discriminate among these. However, the quieting of targets requires raising the threshold of detectability, which in turn increases the rate of false alarms and thus overwhelms the human operator. Automating these tasks by extracting classification features that cue the operator to relevant targets is important. Neural-network technologies have been applied to these problems; an early paper is [38]. Understanding how dolphins, who exhibit remarkable biosonar capability, can discriminate among various underwater objects is another avenue of research that may one day lead to improved and efficient classification algorithms (see [39]). For a review of some of the significant developments in similar areas see [40].

Active classification and recognition is also increasingly important, and not just for military applications. In commercial fisheries, narrowband and wideband systems are being designed and tested to identify species and the size and volume of schools. This requires that signal-processing methods be developed that are insensitive to small variations of the species signature to a variety of factors including shape, size, or tilt angle [41]. Detailed studies of the interaction and scattering of sound with rigid and elastic bodies have to be pursued, relevant features like acoustic resonances identified, and their results incorporated into the classification algorithms. Time-frequency analysis, multiresolution techniques, and wavelets are finding increased utilization.

Acoustic Tomography

Ocean acoustic tomography (OAT) is essentially the inverse of the localization and time-delay estimation problems. OAT was originally proposed in [42]. Its goal is to infer from measurements of the travel time and other acoustic propagation properties the state of the ocean as traversed by the acoustic waves [43]. Travel time is a function of ocean temperature, circulation velocities, salinity, and other ocean physical properties. Many important phenomena in the ocean, e.g., eddies, have spatial scales of tens of kilometers and time scales of tens of weeks. OAT provides a viable technique to study these mesoscale phenomena by solving an inverse problem. While MFP and localization algorithms assume knowledge about the channel, say the SVP, to determine the position of a source, OAT determines the state of the ocean (for example, the temperature) from accurate measurements of the travel time delays or other properties of the sound propagation in the ocean. For a comprehensive overview and historical remarks on OAT see [43]. A review of the development of the use of acoustic tomography to detect and map climatic temperature changes in the ocean over basin scales is in [44]. This reference also reviews the history of the use of sound over long distances in the ocean.

Much activity in the 80s developed the technology and apparatus with the required precision and stability to make the technique a viable one. Programs have shown their applicability. For example, the Greenland Sea program [45] measured the temperature, heat content, and other ocean quantities in the Arctic environment. The Heard Island Feasibility Test [46, 47] used sound propagating over 5 to 6 thousand miles, from a source placed in the vicinity of the Heard Island in the Southern Indian Ocean and detected in North America, to study issues of ocean warming. European programs, such as Thetis I and Thetis II [48-50] and now Octopus, are aimed at studying the deep winter convection in the Mediterranean Sea and demonstrating the feasibility of OAT on the whole Western Mediterranean basin. The overall goal of these programs is to determine climate changes on a long-term basis. These and other efforts have successfully demonstrated OAT. In the future, the increased utilization of OAT to improve our scientific knowledge of the ocean will present a fertile field for the development of advanced signal-processing algorithms.

Physical Oceanography

Given the sensitivity of matched-field processing to the precise knowledge of the physical environment, it is increasingly important to combine these signal-processing methods with physical oceanography modeling. Physical oceanographers couple models describing ocean fields with measurements provided by instrumentation on board satellites or on drifting buoys. They refer to this as data assimilation. These models can be used to predict physical processes in marginal seas and in the global ocean and can be coupled to acoustic propagation models to provide better determination of the acoustic propagation environment in a particular ocean region.

Ocean fields include circulation velocities, pressure fields, sea surface height (SSH), ocean temperature, or salinity. Of course the sound velocity profile is in turn related to these quantities. Challenges here relate to the large ocean basins, to the highly nonlinear models, and to the sparseness of the measurements. In ocean-circulation models the dynamics of the physical quantities are described by discretizations of the so called set of primitive equations. These are derived from Navier-Stokes equations through scale analysis: global models can be on resolution scales of hundreds of miles and many months; mesoscale or synoptic phenomena relate to spatial and time scales on the order of tens of miles and tens of weeks; and so called fleet models present resolutions of a few miles. The dynamical models are driven by exogenous variables like the wind. Average winds are extracted from historical records. The grids discretizing the basins may have several layers and millions of nodes, leading to state vectors of several million variables.

Besides the approximations induced by the scaling analysis, there are numerous sources of uncertainties, such as the random components of the winds, the imprecise specification of the boundary conditions, and the lack of knowledge of the initial conditions. Often, the global models are used to predict the flow across the physical boundaries of a regional model, e.g., studying the ocean circulation or the physical properties in the California current, the Gulf Stream, the Sea of Japan, or the Yellow Sea. For example, models studying the ocean circulation in the Japan East Sea are usually driven by winds and flows in the Tsushima Strait and the Tsugaru Strait that connect the Japan Sea to the North Pacific [51, 52]. Likewise, the Gulf Stream needs boundary conditions derived from global models that provide information regarding the Rossby waves and eddies crossing the boundaries. In turn, the regional models determine the boundary conditions for the fleet models.

Data assimilation is desired to keep these boundary conditions accurate and in track with measured data. Global measurement programs (satellites and floating buoys) have been launched in the last decade, corresponding essentially to SSH and sea surface temperature (SST) data. Assimilation of SST and SSH data plays a major role in providing global modeling capability to enable nowcast capability to fleet models. Current methods used for data assimilation include simple methods such as nudging [53], approximate Kalman-Bucy filtering [54], inverse methods [55], or adjoint techniques [56]. For the state of the art on data assimilation techniques as used by physical oceanographers see [57, 58].

There is ample room for the development of sophisticated data assimilation techniques by researchers with more of a signal-processing bent. There is some work along these lines for assimilation of satellite measurements (Eulerian data): [59] uses multiresolution analysis and wavelets for highly efficient interpolation of large ocean data sets in a multiscale fashion; [60] uses wavelets coupled to Kalman-Bucy filters to develop expedite data-assimilation algorithms; and [61-63] use the block structure of the discretized partial differential equation models and the sparseness of the satellite measurements to derive efficient implementations for Kalman-Bucy assimilation algorithms.

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Synthetic Aperture

The principles of SAR [64] and synthetic aperture sonar (SAS) are well understood. Reference [65] first suggested a tomography interpretation for spotlight-mode SAR. High-resolution aircraft-borne SAR systems provide high-quality images and can achieve range and cross-range (or azimuth) resolutions in the range of 1 ft at slant ranges of over 30 miles and altitudes of 10 km. To create an image with SAR, e.g., [66], a wideband pulsed signal (usually a chirp) is transmitted with a given pulse transmission frequency as the SAR platform moves along a straight line path. The echoes are measured and phase compensated for the relative motions between the radar antenna phase center and the center of the scene (in spotlight). Finally, the data is formatted and compressed in range and azimuth to achieve the desired resolution.

The simplest image-formation algorithm in SAR is the so called rectangular format algorithm (RFA), [66]. After dechirping, it is essentially equivalent to two FFTs. However, RFA has major problems due to the fact that the range and the cross-range to each scatterer vary over the coherent aperture time required for azimuth resolution. It is common to refer to these effects as motion through resolution cells (MTRCs), [66]. As a result of the phase errors induced by MTRC, the images obtained by RFA are smeared out, the range-azimuth image is blurred, and loss of resolution in the SAR system occurs. The problem is made worse in fine-resolution SAR systems where targets extend over several image cells. In general, the blurring effect is space-variant. This means that the blurred target signature is different for different target locations. This space-variant blurring effect is a major challenge to SAR target detection. The performance of a detector optimally designed for one signature will deteriorate because the target is at a different location, consequently exhibiting a different signature.

Ways of handling the MTRC include accurate motion compensation during the image-formation process. For example, in spotlight SAR, the polar format algorithm (PFA), the range migration algorithm (RMA) [66], the extended coherent processing algorithm (ECP), and the enhanced image-processing algorithm (EIP) [67] are designed to compensate for the MTRC. These algorithms are usually computationally complex because their implementation requires nonuniform interpolation in the Fourier transform domain. Implementing these algorithms in real time is out of reach for on-board processing of phase history data. An alternative to these expensive algorithms is to design detectors that are robust to MTRC, i.e., use the RFA algorithm at the image-formation step and then use a detector that is robust to the types of defocusing induced by MTRC [68].

There are two types of SAS: passive SAS and active SAS. Active SAS, e.g., [69-71], is very much similar in principle to SAR systems, except that the corresponding system numbers are quite different, and this fact entails significant practical distinctions: the speeds of propagation are 3×10^8 m/s for SAR versus 1.5×10^3 for SAS; the platform speeds range from several hundred m/s to several thousand m/s for SAR while they are under 10 m/s for SAS, usually much lower; the beamwidths and squint angles are also very different, 1° and up to 8° for SAR versus a beamwidth of 10° and broadside for SAS. For typical numbers for SAS systems see [70]. One issue arising in (swath mode) SAS that is seldom a problem in (strip mode) SAR is undersampling resulting from the low speed of sound propagation in water. One way of avoiding this effect is to reduce the speed of the "towfish" (the platform transporting the active transducer), which conflicts with the requirement of a higher speed to get wide coverage. This low speed also determines a low transmitted pulse repetition rate, meaning a much smaller number of returned echoes are available than in SAR (even though the beamwidth is much smaller in SAR) and so signal-to-noise ratio issues become critical in SAS for effective pulse detection. Other significant problems in SAS include the lack of stability of the platform motion (aperture errors), the noise and reverberation levels encountered in the underwater channel, and inhomogeneities in the propagation channel. These factors compound the problems that are experienced with SAR systems. The motion compensation and focusing of the images that are dealt with by phase correction in SAR (see the previous paragraphs) are usually addressed in SAS by time-delay compensation.

Passive SAS is a much less mature subject than active SAS. For a discussion on the relevant issues see [72] and also [73-76].

Another emerging topic is the interferometric SAR (InSAR) [77], and correspondingly, the interferometric SAS (InSAS), e.g., [78]. The purpose is to provide topographic maps of the scene (add height or the third dimension to the SAR image) being illuminated. These maps are obtained from the phase differences between complex SAS images acquired by two different arrays or by the same array at separate passes. Because the height and the absolute value of the phase difference are in a one-to-one relation (see [77]) the challenge in InSAR and InSAS is to obtain the absolute phase value (phase unwrapping) rather than the phase modulo 2π. Conventional approaches to this problem follow a two-step procedure (see, for example, [79, 80] for the InSAR context). The first step involves the determination of modulo 2π phase values, forming the so-called interferogram or wrapped phase image. The second step consists of phase unwrapping, i.e., determination of the absolute values of the phase from the modulo 2π interferogram by some ad-hoc or heuristic phase-continuity criterion. Statistical methods based on Bayes nonlinear filtering theory have been applied to unwrapping the phase. In particular, [81] developed a Bayes unwrapper to unwrap the phase of signals propagating under the Arctic ice crust. Reference [82], and further work by these authors, formulates absolute phase unwrapping for InSAR as a Bayesian nonlinear surface-reconstruction problem with very significant improvement over alternative heuristic phase unwrappers.

Conclusion

The ocean has been the next frontier and it will remain so. Starting with the first attempt to measure the depth of an ocean basin by the great navigator Fernão de Magalhães (I will keep the spelling he, himself, used and of his mother language, Portuguese. The name has been Anglicized and Galicized to Ferdinand Magellan.) [83, 84], experimentalists and engineers have developed all sorts of intrusive instrumentation to probe its secrets. Due to the characteristics of sound propagation, acoustics has proven a meaningful and reliable tool.

Many topics, areas of activity, and approaches have been left out in this brief overview. For example, as a channel, the ocean poses peculiar and interesting challenges to communications (see the Underwater Acoustic Communications section of this article [85]). It is an adverse environment for data communications due to time fluctuations and multipath propagation, and its channel properties are very sensitive to the environmental parameters that change with time and are location dependent. These factors preclude the direct application of standard communication techniques, especially when transmission power is severely constrained, as is the case in autonomous underwater vehicles (AUVs). Novel approaches are being explored for the design of acoustic data receivers to work with AUVs by adequately modeling the channel and exploiting the spatial diversity induced by the multipath propagation, e.g., [86]. Another topic which I left out but is of continued importance is multitarget tracking and the corresponding data-association issues. I also didn't address acoustic imaging. Along with traditional sidescan [84] and swath bathymetry sonars [87], which still pose many challenges in mapping the seabed, it is conceivable that sophisticated signal-processing beamforming algorithms, together with MEMS technology, will provide small head-mounted sensors enabling divers to "illuminate" turbid waters while searching at small ranges (say 3 m) for mines or inspecting pipelines or drilling towers.

Underwater acoustics has provided the impetus for developing new algorithms and methodologies that now find wide application in other fields. More significantly, its intrinsic perspective of "physics," "matched," or "model" based signal processing has impacted broadly and appeals to many different areas. This is how it should be—and it is how I expect it will continue to be.

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