Acoustical sensing of biology in the sea

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Abstract

During the last decade the scope of science issues addressed by the bioacoustics community has broadened notably. This contribution deals with two active fields of research: 1) increasing the ability of acoustical sensors to resolve biological structures, both spatially and temporally; and 2) adapting acoustical methods to observations of benthic habitat and life.

1. Introduction

Acoustical oceanography is inherently a multi-disciplinary science. Fisheries scientists, biological oceanographers and marine ecologists have long found that mathematics, especially statistics, is an essential tool with which they must gain considerable familiarity if they are to successfully pursue their chosen trade and the diverse scientific issues that bear on their investigations. Over the last three decades biologists working to describe life in the sea have determined that it is also helpful, if not essential, to acquire at least an elementary understanding of several sub-disciplines of physics. Some knowledge of acoustics and optics is increasingly required if one is to make optimal use of available technology in pursuit of knowledge about life in aquatic environments. Likewise, sensing life in the sea is a challenging scientific endeavor for physicists, chemists, geologists and a wide variety of engineers, providing numerous exciting new opportunities to those willing to learn the language and culture of biological and fisheries oceanography and marine ecology. A relatively small, dedicated group of physical scientists are actively addressing measurement challenges facing ocean scientists with an interest in aquatic life. Acoustical oceanographers often have a formal background in physics or a related engineering discipline, but increasingly their interests and abilities span several relevant disciplines in oceanography. Good ecosystems research addresses not only individual animals and populations, but involves an assessment of the overall physical, chemical and biological environment. Good research in acoustical oceanography demands familiarity with not only acoustics, but also demands knowledge of a wide variety of abiotic and biotic factors that affect the propagation and scattering of sound.

The first attempts to develop underwater acoustics as a tool for studying life in the sea, specifically fish, took place in the 1920's [1-3]. During the ensuing decades fisheries acoustics has benefited from major technological advances in acoustical oceanography. The future continues to offer exciting prospects for those interested in understanding how and why fish biomass varies over time and space. In an era when there are both increasing demands on the sea for protein and continuing concern for the environment, achieving a better understanding of the marine ecosystem is socially relevant as well as scientifically important. Over the last few decades, the interests of scientists involved with bio-acoustical oceanography have expanded far beyond the original applications in fisheries science (biomass assessment and surveys) to describe distribution and seasonality. Internationally, basic and applied research efforts can now be identified which examine detection, enumeration and definition of spatial and temporal pattern for numerous taxonomic groups ranging from whales to protists. Although it stresses contributions made by scientists associated with the International Council for the Exploration of the Sea (ICES), a comprehensive review of the history of uses of acoustics in fisheries science and in biological oceanography has been prepared as a part of the celebration of the 100th anniversary of ICES [4]. This document is particularly valuable for its extensive list of references.

The uses of acoustics that apply to the sensing of biological organisms in the marine environment are now so diverse and numerous that only a few current research themes can be addressed in this contribution. We briefly highlight only two from among many promising areas of active research. Even though we do not include it explicitly, much of the progress we will discuss is relevant to attacks on the Grand Challenge in bioacoustics -- remote species identification [5]. These developments in research also bear on a Grand Challenge in fisheries science and biological oceanography – an accurate, data-based description of animal behavior in the sea, leading to the formulation and validation of a predictive capability.

2. High Resolution Bioacoustics

2.1 Stimuli for Developing Systems with High Acoustical Resolution

In marine ecology, one of the most exciting technological developments of the last decade has been a very substantial increase in the spatial and temporal resolution that can be achieved with acoustic sensors. Improvements in systems designed to examine distributions of small zooplankton and micronekton are approaching resolutions three orders of magnitude better than those available only five years ago. Since about 1985, new deployment methods and advances in acoustical transducer technologies have resulted in an ability to resolve small zooplankton and micronekton at vertical scales of tens of centimeters, an improvement of more than twenty times. Temporal sampling rates for acoustical sensors used to detect small zooplankton have increased from nominally once an hour to intervals of less than a minute. Estimates of zooplankton biomass and abundance, sorted by size, can now be routinely made with such spatial and temporal resolutions.

The advent of affordable multi-beam acoustics offers similar improvements that can be applied in fisheries science. Although the application of multi-beam technology to problems in marine ecosystems science is still in its infancy, such sounders and sonars can now clearly define the three dimensional shapes of fish schools and aggregations. The application of high resolution acoustic systems to studies of fish behavior should make it possible to improve substantially our confidence in traditional acoustic methods now used for the assessment of over 20 major fish stocks in the North Atlantic alone. Similar use of these methods for assessment can be found in most of the world's oceans. The present evolution and future potential for 3-D acoustics in fisheries applications is certainly a candidate for any list of the most exciting developments in acoustical oceanography for the next decade.

Higher resolution multi-beam and side-scan sonars are also beginning to find niches in research programs that address benthic ecology. Evolving applications in this area include the detailed, remote sensing and description of habitat and the potential for detecting, enumerating, sizing and tracking individual organisms during their daily (or longer) ambits. Most of what we know about the benthic communities is based on very sparse data. Much of it is limited to shallow, clear water where divers or cameras can operate. Turbid waters (e.g., mud bottoms with resuspension), deep waters and places with high standing stocks of phytoplankton are all poorly described with conventional methods. Good data collected at night are especially sparse for all bottom environments since the introduction of light may rapidly change behavior in animals that depend on the dark to hide and only emerge at night to forage.

Marine scientists cannot yet enumerate or follow individuals and observe behavior over relevant parts of the life cycle of most organisms in the sea. As a consequence, simple descriptive measures such as encounter rates between predator, prey, and individuals of the same species are not known for most species and environments. Nevertheless, the higher spatial and temporal resolutions we are beginning to achieve with some acoustical technologies are finally approaching that needed to measure biomass and distribution on time and space scales similar to the ambit of the animals we are studying. The ability to observe animals in their natural setting at these scales is an advantage that terrestrial ecologists have long enjoyed. Observing individual animals as they interact with their environment and with each other is, after all, an important part of the process that can lead to understanding how and why some populations thrive and grow, and others do not.

In the marine sciences, our inability to make *in situ* observations of changing distributions and behaviors has forced us to do ecosystem analyses in which inference based on severely under-sampled data rather than a continuum of direct observations is the rule. It is a rare instance in which observations of an individual animal or even a specific individual, layer, "patch", aggregation, or assemblage would even approach the "lifetime" of the distributional feature, much less a significant part of the organism's life cycle. The limits imposed by conventional sampling technologies place serious constraints on progress in marine ecology. Research, stimulated by recognition of the importance of these limits, has resulted in the development of an increasing number of innovative sensor systems characterized by a relatively high spatial resolution. Some of these systems can collect data on time scales that approach the rate at which changes take place, and some can be used for periods that are long relative to a typical cruise (nominally two weeks) on an oceanographic vessel. In a few cases, deployment periods of only a few months have led to observation of natural cycles that had not been previously studied, and to an understanding of the biological response to those cycles.

2.2 Fisheries Acoustics

Advances in the resolution achievable with medium and low frequency sensors are becoming evident in fisheries acoustics, where methods for calibrating and using new multi-beam systems are under development at several institutions. Although multi-beam systems are hardly new technological developments in acoustics, their application in fisheries science is still novel [6]. This new ability to observe school shapes and changes in behavior under a variety of stresses is drawing renewed attention to issues that we could not really even address, other than by speculation, several years ago.

A longstanding issue of substance is how the behavior of fish in schools or layers impacts estimates of abundance made from a moving ship with tools such as an echo sounder [7]. Avoidance of the echo sounder beam transmitted from an approaching survey ship, by the simple act of the fish swimming laterally as a ship approaches, has long been recognized as a probable bias that affects the precision and accuracy of acoustic surveys done in support of fisheries management efforts. The light associated with a survey vessel can be minimized, but bioluminescence stimulated by the mixing and turbulence associated with an approaching ship, when present, can potentially be a visible cue that fish could use to move away. Noise radiated by a moving ship can be minimized, but not eliminated, effectively providing another cue that may lead to fish moving laterally and being missed by an echo sounder beam.

It has long been suspected that the noise and light associated with an approaching survey vessel could cause fish and micronekton to attempt to avoid the vessel [8]. An effect that is more subtle than successful total avoidance may be a tendency for a fish (or a layer or school) to move downward or change swimming direction in the water column in response to an approaching survey vessel [9-11]. A relatively small change in behavior may have substantial impacts on the accuracy and precision of current methods for determining fish biomass. The simple act of swimming down to avoid an approaching survey ship, even at a slight angle, changes the orientation of the animals with respect to the angle at which they are insonified by an acoustic beam (i.e., their tilt angle). Even if the echo sounder registers the presence of an individual, the acoustic reflectivity may be significantly different than one has assumed, leading to a bias in the estimation of biomass. There is a strong possibility that multi-beam, or 3-dimensional, acoustic sensors can be used to observe and describe both the natural and anthropogenically-induced behavior of marine animals. It is also likely that these systems will eventually be used to quantify these behavioral sources of variance, if not bias, in traditional fisheries acoustics.

2.3 Plankton Acoustics

Acoustical methods for studying micronekton and plankton are now more than a half-century old [12, 13]. Fisheries acoustics benefited greatly from technologies developed in research related to antisubmarine warfare during and after WW II. In a similar way, plankton acoustics can be considered a sibling of fisheries acoustics, drawing on the appropriate methods developed from that discipline within acoustical oceanography. However, the technical approach taken by acousticians interested in plankton diverged materially from that developed by fisheries acousticians during the late 1960's and early 1970's, beginning with an insightful bit of multiple frequency work in the Great Laurentian Lakes by McNaught [14]. Although McNaught did not fully quantify his work, the ideas behind today's multi-frequency methods were clearly outlined. By the mid-90's, the dependencies of acoustical volume scattering on the size of small crustaceans was sufficiently well described that it could be used as a practical tool in marine ecosystems work with plankton [5, 15, 16]. Spatial distributions of plankton and micronekton biomass, with size discrimination, could be resolved at vertical distributions of ca 2 m with casts to nominally 100 m [17]. In 1994, multi-frequency methods of data collection for examining plankton normally involved making a vertical cast with a sensor, often in concert with a CTD. This usually meant stations or individual casts were separated by about an hour. Vertical motions of the ship usually limited vertical resolutions of plankton biomass to about 2 m. Over the next five years, the product of the spatial and temporal resolution of measurements of plankton biomass were substantially improved, especially for application to measurement problems in coastal environments. Transducer technologies were improved, allowing the use of greater bandwidth at higher power levels. Consumer demand for portable computers produced lower power, smaller and more capable integrated circuits, including embedded computers at reasonable prices. These developments allowed the development of new generations of multi-frequency echo ranging bottom mounted and moored sensors that could achieve successively higher resolutions in time and space. By 1998 acoustical technology available for studying small zooplankters supported measurements at vertical resolutions of 12.5 cm or better, at least once a minute. This represented an improvement of about three orders of magnitude in the product of the temporal and spatial resolutions beyond that available in 1994.

As an illustration of these advances, we provide a record (Figure 1) from an inverted multi-frequency echo sounder, a TAPS-6™, moored near the 20 m contour in a shallow fjord (East Sound) located in northern Puget Sound, Washington, USA. Three such sensors were positioned on taut moorings at the corners of a triangular array that measured 300 m on a side. These sensors were used to examine the upper 10 m of the water column for about three months. Data were transmitted at one-minute intervals from each sensor via underwater cables to a shore-base, were recorded there, and then were telemetered to an ftp site for easy access by the principal investigators via the Internet. The bottom panel illustrates the full resolution of the system (0.125 m vertical bins at one minute intervals) for a single 24-hour period in June 1998. In order to illustrate the "state-of-the-art" just two years before these data were collected, the high resolution data were re-sampled to demonstrate how the data would have appeared if measured at the resolutions available in 1996, when the highest resolution possible was only 0.5 m in the vertical at intervals of 15 minutes (center panel, Figure 1). Two years earlier, in 1994, the best temporal and spatial resolutions available were measurements of volume scattering strengths in 2 m vertical bins about once an hour. Data re-sampled at that rate are illustrated in the top panel of Figure 1.

Clearly, the increases in resolution made possible by advances in plankton acoustics during that 5-year period reveal much more structure in the water column biology today than it was possible to see only a few years earlier. For example, in the bottom panel, before midnight, plumes of high scattering were observed at the surface, extending to depths of a few meters. These plumes are correlated with the presence of slicks on the surface revealing Langmuir circulation in the water column. The spectra, as estimated at acoustic frequencies of 265, 420, 700, 1850 and 3000 kHz, are characteristic of the scattering one would get from a combination of crustaceans and small bubbles. These plumes were often observed during times when the wind speeds were well below speeds that cause breaking gravity waves. Several wholly physics-based explanations are plausible, including the mixing of bubbles from breaking capillary waves into the water column by vertically circulating Langmuir cells [18,19, 20]. However, since the entire water column was supersaturated with oxygen during this period, an alternative explanation that involves a biological mechanism is also possible. That explanation would suggest that small bubbles might come out of solution at nucleation sites on phytoplankton or marine snow, both of which were very abundant throughout the entire water column. Diel heating near the surface, low levels of turbulent mixing from wind and tidal currents, or both, could be invoked to bring the bubbles out of solution. Ecologically, such mechanisms would be important, as they tend to retain phytoplankton cells in a part of the water column that is well lit by sunlight for longer periods than would be the case if phytoplankton sinking rates were not modified by the buoyancy of such small bubbles.

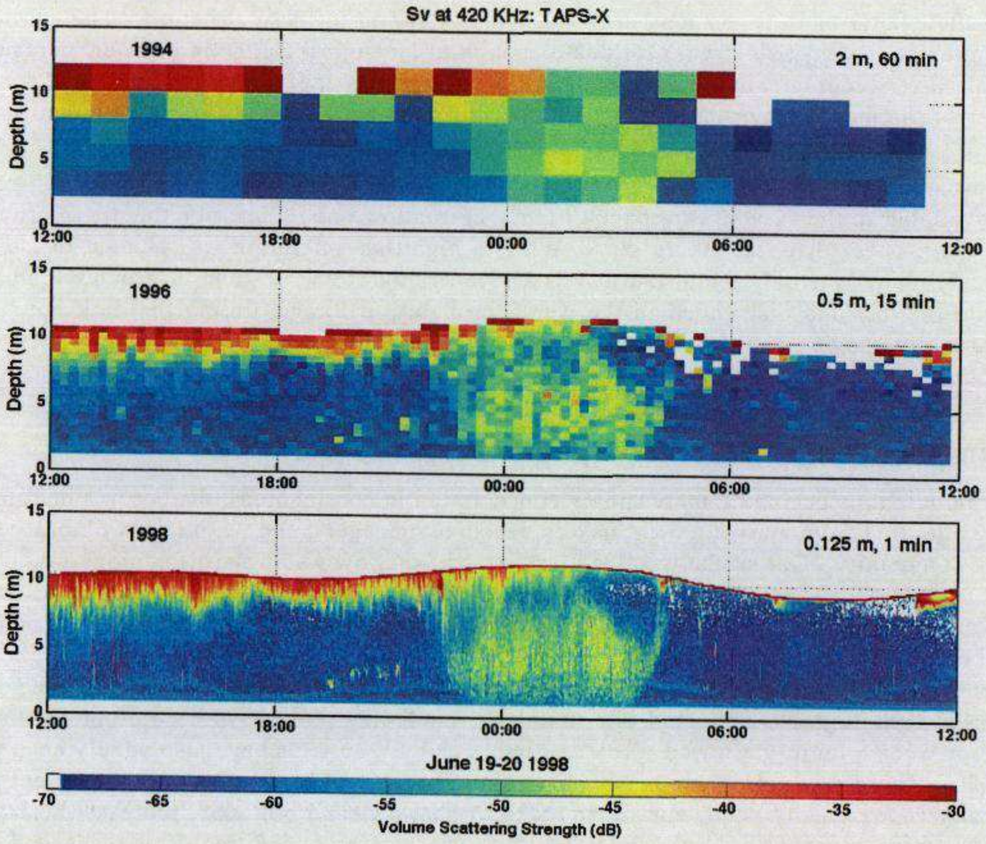

Figure 1. A one day, one frequency (420 kHz) record from a TAPS acoustical zooplankton sensor moored at a depth of 10 m on the 20 m contour in the northern reaches of East Sound, Orcas Is., WA USA. The three panels illustrate the change of nearly three orders of magnitude in temporal and spatial resolution achieved in zooplankton acoustics between 1994 and 1998. See the text for a detailed interpretation of the patterns in the bottom panel.

The days are long in June at this latitude, with sunset occurring at 20:15 PST and sunrise at 04:08 PST. An inverse migration of organisms is evident in the bottom panel of the acoustic record. Careful observation of the record reveals a "patch" of intense scattering near the surface immediately before and immediately after the migration, a pattern that was also present in the data from the companion moorings. A multi-frequency inversion [21, 22] was used to estimate the size of the organisms that migrated from the surface to feed at night and then returned to the surface to spend the day. When bubbles did not completely dominate the scattering, we were able to make size estimates for the migrators. Sizes were consistent with those of *Psuedocalanus spp.*, which occurred in net tows and pump samples collected at and just below the sea's surface. *Psuedocalanus spp.* is a genus of small crustaceans that is known to exhibit a reverse migration behavior in studies conducted in a similar small fjord in southern Puget Sound [23, 24].

As was the case for much of the time we occupied this fjord, a complex of thin, but relatively weak, scattering layers were present at several distinct depths during the afternoon of June 19 and the morning of June 20. One such layer was located near the moored TAPS sensor, ranging during the period of this record from about 1 m to 3 m in height above the 10 m deep transducer face. During this particular 24-hour period the thin layer structures maintained nearly a constant depth below the sea surface, roughly paralleling the tidally modulated record of scattering from the surface. At times these layers contained the majority of the entire water column's zooplankton biomass within a sub-meter thick structure. The location of these structures often coincided with, and temporally tracked, changes in the depth of one or more abiotic parameters that describe the local ocean physics, e.g., the thermocline, a region of shear, or the pycnocline. We also often found a correlation between the depths of these sub-meter scale zooplankton distributions and fluorescence, bioluminescence, optical scattering and absorption. At other times, however, zooplankton behavior appeared to dominate, resulting in deviations from coherence with passive biotic and abiotic tracers of local water mass boundaries, e.g., small scale, thinly layered distributions of prey organisms (microzooplankton and phytoplankton). The numerical density of organisms in these thin layers, the percentage of the total water column zooplankton biomass they often contained, their persistence and their horizontal dimensions draw deserved attention to these structures. Their probable impact on survival of organisms (e.g., fish larvae) fortunate enough to locate and forage in them encourages us to consider these very thin layers ecologically significant. Thus, we sometimes apply the phrase "critical scale structures" to these features of the marine environment. Additional information on the work in East Sound, that of our co-PIs, and on critical scale structures can be found at "http//:www.gso.uri.edu/criticalscales/".

It is important to note that the Langmuir-related bubble plumes were not sufficiently well resolved with the technology available in the "1994" (top panel, Figure 1) to allow one to describe the distribution or suggest any detail about the process that was taking place. While a nighttime migration was evident in the "1996" (middle panel, Figure 1), there was only a hint that it was a reverse migration, i.e., one in which the animals were at the surface during the day and distributed in the water, probably to forage, during the dark hours. The thin layer structures were not resolved in either time or space and could not have been observed and tracked as they moved vertically in the water column before 1998 (bottom panel, Figure 1).

3. Adapting acoustics to examine populations on the seafloor

With human populations becoming increasingly concentrated in coastal areas, the ocean's margins have begun to receive more attention from marine policy makers, resource managers, and, with the availability of funding, from the scientific community. One of the unsolved problems in shallow water marine ecology involves estimation of the biomass (numbers) of benthic animals. The traditional approach is taken from terrestrial ecology and often involves divers making observations as they swim along a line transect or taking a census within a predefined grid on the bottom. In environments where visibility allowed their use, traditional imaging optical methods have had a tremendous impact on our knowledge of life on and near the seabed. Since Edgerton's pioneering work with strobes [25], photographs collected in a time-lapse mode at a point have been often employed to study life on the seafloor when visibility allowed. Towed camera and TV systems have also widely been utilized to cover more area [26]. These methods have usually been most successful at relatively shallow depths and in waters where visibility is reasonably good, e.g., over rocky or shallow sand bottoms. In areas where visibility is poor these methods are problematic at best. Muddy bottoms where currents and tidal flow resuspend sediments, areas of high phytoplankton abundance in the water column, and deeper coastal environments where light penetration is poor, all offer serious sampling challenges for optical methods. In addition, many animals are buried during the day, with little or perhaps no surface expression. Making observations at night, when many organisms are actively foraging is often problematic as well, as the introduction of light will often modify behavior and distribution of the animals one wishes to study, a biological analogy of the Heisenberg principle in physics.

Adapting acoustical technology to map habitat and to enumerate, locate, and track benthic marine organisms over larger areas for longer periods may offer at least a partial solution to some of these sampling challenges.

While there are exceptions that require some knowledge of acoustic propagation and scattering, sound will often penetrate the assemblage of particles in the water column that limits the usefulness of optical methods. With proper experimental design, by carefully choosing operating geometries and acoustic frequencies, one can also sometimes "see" into the bottom with sound. While there are several relevant adaptations of methods originally developed for use in the water column, we will discuss only one here, high-frequency side scan sonar.

High resolution, high frequency side-scan sonar data were collected in a small, shallow, mud-filled fjord, West Sound, at Orcas Is, WA during the summer and fall of 1995. Orcas Island is located in the San Juan archipelago

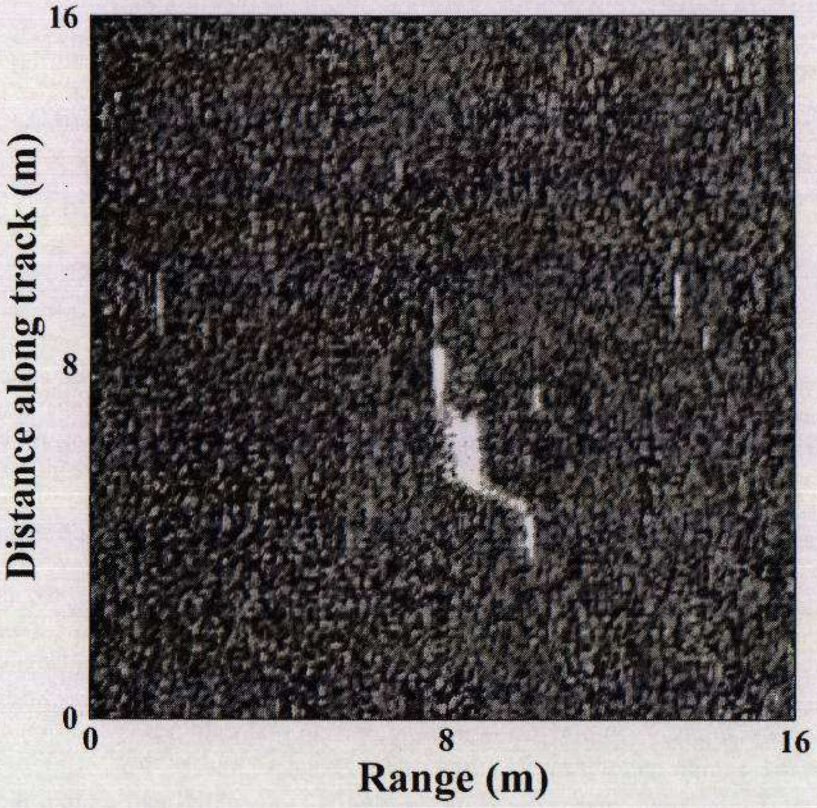

Figure 2. A sidescan image of twenty-three 6 cm diameter burrowing urchins after placement in a small "pile" a few hours earlier. The animals appear to be starting to disperse, leaving tracks in the mud. Careful study of the original image revealed several less distinct tracks, probably older ones that are being eroded by tidal current – driven sediment resuspension and the activity of other benthic animals.

of northern Puget Sound, near the Canadian border in the northwest United States. At the site of interest the bottom material was a fine, loosely consolidated glacial till or mud. The bottom topography was nearly flat and the depth was nominally 20 m. Tidal currents resuspend the fine sediments in West Sound on each cycle and the visibility for divers is usually very poor. An extensive data base resulted from the field work. The project was a joint research activity involving principal investigators from BAE SYSTEMS (at that time, Tracor), the Applied Physics Laboratory and the Department of Oceanography at the University of Washington (UW) and the Naval Research Laboratory (NRL) Stennis. Acoustical scattering from benthic organisms was extensively studied at several frequencies. Additional data and information regarding this project can be found at "http://www.aard.tracor.com".

With the assistance of our co-PIs from the University of Washington, Dr. Peter Jumars and Liko Self, we were able to perform a variety of bio-manipulations in West Sound. The bio-manipulations generally consisted of collecting locally available animals (e.g., burrowing urchins (*Brisaster latirons*), cockles, protobranch bivalves (*Acila*), thallasinid shrimp, sea cucumbers, crabs) and placing them in known places in order to see if they could be detected by a sidescan sonar with nominal center frequencies of 100 and 500 kHz. In this contribution we only discuss the results from the 100 kHz channel. The frequency content of the transmitted 100 kHz pulses actually ranged between 80 and 300 kHz, and although the spectrum of the transmitted signal was not "flat", this signal has a range resolution of about 3.5 cm. The exact spatial resolution in the dimension along the towpath of the sidescan "fish" depended on the towing speed (nominally 1 m/s) and the range scale in use. A Tracor Signal Processor (TSP) was used to process, record and display the raw (full bandwidth) data in real-time during the experiment and during playbacks for analyses done later in the laboratory. The TSP allows one to examine a specific target in detail during the experiment, to make precision measurements of a variety of the target's descriptive parameters, and to mark it digitally for easy retrieval and examination at a later time. The experimental protocol included a pass over each area where a biological manipulation was to be done, thereby allowing us to identify any structure present before we added animals to the seabed and to move the site elsewhere if there was too much "clutter" present at a particular location.

A single pass of a side scan sonar being towed at a nominal height of 7 m revealed the presence of twenty-three 6 cm diameter burrowing urchins that had been placed in a small area (< 1 m^2) on the mud bottom a few hours earlier (Figure 2). During this pass the combination of operating parameters (beam width, range scale, towfish speed, etc.) combined to provide a range resolution of 7 cm along the beam pointing direction and 10 cm along the towfish track. The range to the target was 34 m. The "pile" of urchins is clearly visible and the spatial pattern of the record suggests that the animals had begun to disperse. Two, or perhaps more, animals appear to have separated from the original distribution and their tracks are terminated with discrete echoes. The burrowing urchin, a deposit feeder, moves quite slowly through the mud.

4. Conclusions

Acoustical oceanography is easily distinguished from its older sibling, underwater acoustics, by the emphasis placed on the "inverse problem". Increasingly, the marine science community, including fisheries scientists and biological oceanographers, are joining with physicists and engineers to apply the tools of underwater acoustics to measurements of what lives in the water column. Successes with the estimation of fish biomass and distribution and with large and small scale plankton distributions have encouraged those interested in habitat and life on and in the seabed to look for acoustical tools to help solve some of the outstanding sampling problems associated with benthic ecology.

Finally, we offer a few opinions about probable future developments in bioacoustics. We would however, like to stress a relevant conclusion attributed to Yogi Berra, a practical American philosopher of the late 20th century, who noted that "Prediction is hard, ... especially when it is about the future." Thus, while we will allude to future directions in research, we are willing to admit that at best our guesses only apply to developments during the next decade or two. It is virtually certain that the most important technological developments of thirty to fifty years hence, and beyond, are completely unpredictable based on what we now know.

Even with this caveat, it seems relatively safe to suggest that: 1) the spatial and temporal resolution of acoustical systems will continue to improve; 2) the complexity and capabilities of acoustic systems for use in studying marine life will increase at the "high-tech" end, while; 3) the systems currently available will become more widely used, and the cost of acquisition, maintenance and deployment will decrease. Major progress can be anticipated in remote acoustic identification, with detailed definitions of morphology and physical properties among the early advances towards this goal. Species identification will probably first be accomplished in fisheries acoustics, and will likely be greatly benefited by advances now anticipated as a result of using 3-D acoustics to learn about species specific behavior. In plankton acoustics, better knowledge of plankton behavior will also play a role, but increasing use of multi-frequency and multi-static acoustics, in combination with innovative deployment methods, will provide access to additional independent measurements of acoustical parameters that will lead to much improved classification, if not outright identification. Nesting sensors of different kinds, e.g., optics and acoustics, to gain information at different spatial and temporal scales will continue. True synergistic applications of optical measurements and acoustical measurements at small to medium scales, e.g., tracking multiple individuals *in situ* while observing their bioluminescence, wake, optical image and acoustic reflectivity simultaneously to measure and synthesize the different signatures should also be possible.

New applications of acoustical tools we now have, and the development of undiscovered ones for use in describing benthic habitats, will rapidly advance. Current acoustical tools for habitat mapping are largely empirical and rely heavily on statistics for discrimination of different habitat types. Definition of the underlying physics of seabed reflectivity and scattering from the animals and structures that occur there will follow current empirical observations and should substantially improve accuracy in the remote mapping of habitats.

Perhaps, however, the largest gains in the near term will come from new and innovative modes of employment, and access to a diverse group of platforms for advanced sensors. It is likely that ROVs, AUVs, and drifters will soon employ sophisticated acoustical sensors to access environments that are difficult to study with ships (e.g., the deep seabed or under ice habitats). The costs of data processing for long-term ocean observatories, moorings and arrays of drifters may well result in pressures for new, smart sensors to be used *in lieu* of the traditional collection, processing and archiving of "bodies". In summary, there appear to be ample opportunities for the next generation of technologists, with acousticians playing a leading role.

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