Acoustical Technology for the Study of Marine Organisms

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LONG-TERM GOAL

The long-term goal of our research is to improve our ability to observe the ocean's plants, animals and their physical and chemical environment at the critical scales which control how they live, reproduce and die.

OBJECTIVES

Chronic undersampling of the marine environment, including both biological and physical components, has been and remains a major block to understanding how marine ecosystems function and how they respond to changes, whether natural or anthropogenic. Consequently, data-based models that accurately predict local variations in the abundance of plant and animal life in the sea are rare or do not exist at all. Such models would be invaluable in predicting variables such as acoustical and optical scattering in areas of tactical interest to the Navy. Our research directly addresses the root of this problem by attempting to advance acoustical technology as an aid in measuring spatio-temporal distributions of a variety of marine organisms in relation to the physio-chemical ocean environment.

APPROACH

Our research has multiple focus areas which are currently addressing: 1) advancing high-resolution multi-frequency acoustical technology for detecting and observing small zooplankton, micronekton and fish in time and space; 2) the development of a new multi-frequency, multi-static measurement concept, including some fundamental theoretical approaches to aid in remote detection and classification -- with the ultimate long-range objective of remote identification of small organisms in the sea; and, 3) support of other principal investigators in the use of our acoustical zooplankton sensors to carry out several science programs -- in the immediate past, most notably the critical scales program focused on thin layers.

***High-resolution (time and space) multi-frequency acoustical technology*:** Over the last five years, for shallow water environments, we have improved the space-time resolution of *in-situ* observations of small zooplankton by nearly **3 orders of magnitude** (Holliday, et al 1999; Holliday 1999). Multi-frequency acoustics is now a proven tool for studying the distributions and dynamics of zooplankton

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and micronekton distributions (e.g., Medwin and Clay 1998, Roman, et. al, [accepted], MacLennan and Simmonds 1992). These improvements have paralleled successful efforts by other scientists working to detect and resolve small-scale structures in phytoplankton, temperature, salinity and turbulence during the last decade. We now routinely observe important biological structures in zooplankton at length and time scales for which conventional sampling methods produce badly aliased data. *Much of this structure has been almost completely missed in the past due to the limitations of conventional sampling technology.* We anticipate that further improvements in our ability to observe small-scale distributions along with measurements of relevant ocean physics and chemistry at comparable scales will eventually lead us to a better understanding of what drives the dynamics of larger assemblages and populations.

Multi-frequency, multi-static measurements**:** To date, most investigators making measurements of scattering from biological organisms in the sea have focused on *backscattering*. We are now beginning to examine the possibility that information can be extracted from scattering at many angles with respect to the incident sound beam. We are extending our successful multi-frequency backscattering methods to include measurement of scattering into the 3-D space around an animal. Our work on this new approach is just beginning, but we have fabricated instrumentation that allows us to automate the measurement process. We anticipate that our measurements may point to the need for fundamental changes in conventional approaches to mathematical modeling of scattering from aquatic animals, at the same time providing information that can be used to formulate and then validate physics-based scattering models. A combination of advances in multi-static, multi-frequency measurement technology and modeling may eventually lead to *in situ* extraction of not only size, but also the shape, orientation, and physical properties of marine organisms, all of which are embedded in the details of the 3-D scattering of sound by an object. Measurement of these descriptors would be an important step towards remote acoustic classification and identification.

Biophysical interactions at critical scales**:** During the summer and fall of 1998 we participated in a multi-investigator program in a small, shallow fjord at East Sound, WA. As a key part of this field experiment, we used a number of high resolution, high frequency acoustical instruments to examine the zooplankton response to optically detected phytoplankton layers (~10 cm thickness). Data from these sensors were also used to direct conventional sampling devices (pumps and siphons) to those layers in order to examine their constituent parts. We are currently analyzing data and preparing publications jointly with our co-PIs that are based on the data we collected during these experiments.

WORK COMPLETED

We are continuing to improve the resolution of our multi-frequency TAPS technology. Our current focus is on the mechanics of increasing the rates at which we can sample to intervals of less than one minute. We have completed processing for our data from all of the sensors we deployed in the 1998 East Sound field work with the "thin layers" group. These data have been distributed to all of the particpants and selected results presented at several scientific meetings. We have participated in several data synthesis meetings of the thin layers group and continue to provide data to various PIs in this group for use in papers that are in various stages of preparation. A small, but descriptive sample of our data have been included in the thin layers section of the ***Critical Scales*** web page listed in the header above.

Although the principal emphasis of our work has involved the processing of our data from the East Sound thin layers experiment, we have continued our efforts to exploit azimuthal dependencies in scattering from zooplankters. We have further developed software and hardware needed to measure the azimuthal and spectral dependence of scattering from millimeter-size (small crustacean-sized) targets.

RESULTS

As an initial test of our multi-static measurement system we have measured the bi-static broadband scattering from a spherical target made from RTV 615, a material that can be molded into a wide variety of shapes and which, more importantly, for which the process of curing results in consistent material properties. Data were collected at 5° intervals of azimuth from 20° (near backscattering) to 160° (near forward scattering) and converted to target strength in dB (Fig. 1).

The most interesting feature of this data set is the "ridge and bump" structure in *ka*-angle space. The term "ka" is the product of the acoustic wavenumber (*k*, proportional to frequency) and the radius of the sphere (*a*). This is the type of pattern that, when described in *ka*-space from multi-frequency measurements alone, allows us to estimate the size of a scatterer from its backscattering spectrum with a MAPS or a TAPS. By adding measurements over a wide range of bi-static angles, a surface representing the target reflectivity in *ka*-angle space has been generated. Much more information about the target is embedded in this presentation than would be present in the backscattering measurements alone (e.g., one cut along the back axis of the surface displayed in Fig. 1). We sometimes refer to the detailed structure in such an acoustic signature as "character". It is easy to see that considerable "character" is present in the details of the 3-D surface of Fig. 1. This "character" is actually the result of constructive and destructive interfering echoes that originate with both internal and external parts of the scatterer. The biophysical characteristics, e.g., the size, shape, internal structures, and physical properties that we hope to eventually extract with an "inverse" calculation are embedded in these patterns. The challenge is to extract and identify them. Understanding the process of echo formation and developing the necessary technology to do so is the main subject of our multi-static, multi-frequency research thrust.

We formulated a relatively simple bi-static model for multi-frequency, multi-static scattering from a sphere, using the measured properties of coupons of the same material used to fabricate the target for which data are provided in Fig. 1. The major features in the model results were also clearly evident in the measurements. While some of the details remain to be examined and explained, the qualitative agreement between experiment and theory is reassuring and leads us to believe we are on the right track. The essential message in both the scattering data and the model results is that there is much more "character" revealed in the pattern of scattering when measured in *ka*-angle space than when examined in just the multi-frequency (*ka*) dimension.

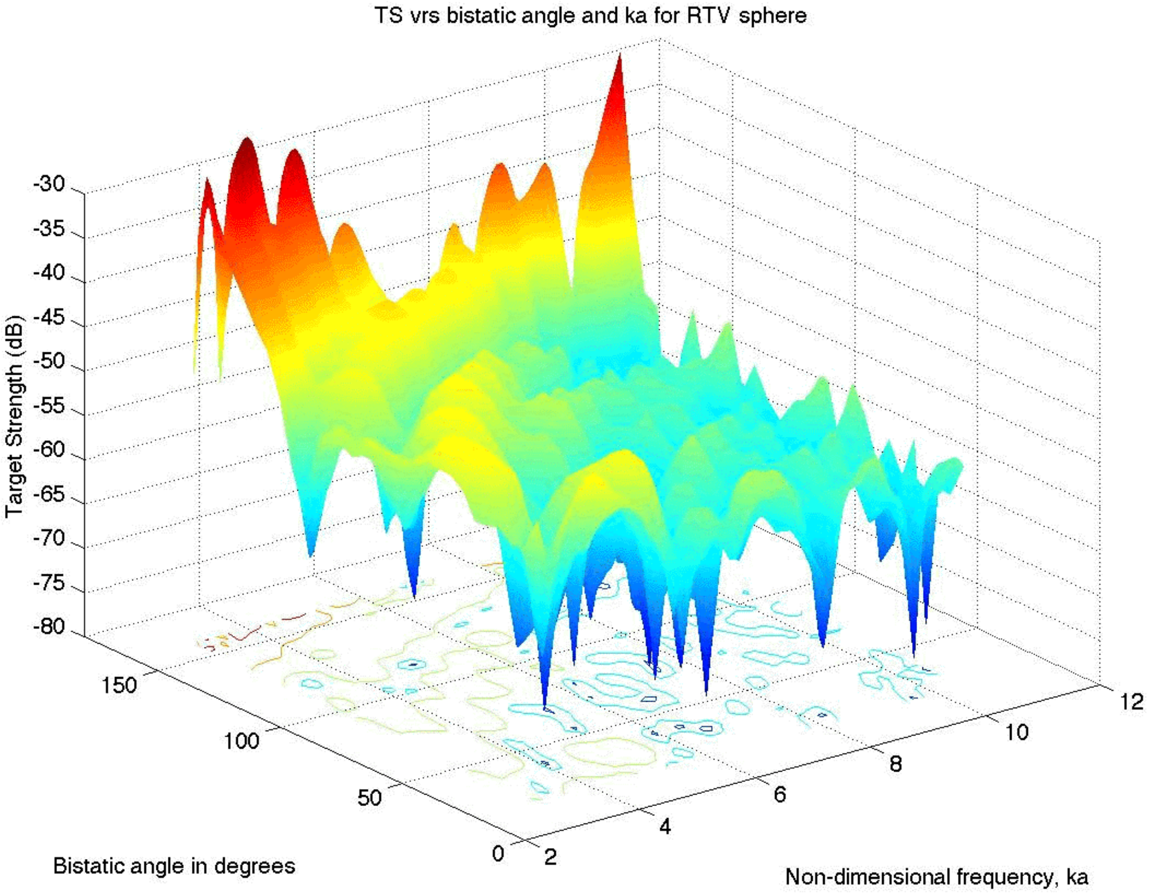

Figure 1: Multi-static scattering from a small RTV sphere. These preliminary data did not extend sufficiently low in frequency to adequately resolve the transition to Rayleigh scattering. That transition, for backscattering, would be near ka = 1.4.

The addition of arbitrary shapes for target organisms means the general problem will be four-dimensional. That is, for each aspect angle of the scatterer with respect to the source there is a complete 3-D map of bi-static scattering such as that shown in Fig. 1. It is not yet evident how to include this in an inversion scheme but the suggestion is clear that it may be possible to extract some measure of information on shape and orientation as well as an estimate of size and physical properties. The addition of shape to the problem will require addition of still another dimension to our bi-static, multi-frequency measurements. This suggests that in the general case it will be necessary to make measurements on a surface surrounding an elongate scatterer, as opposed to measurements on an arc around a spherical scatterer. It is also important to note that by using multiple receivers, the *ka*-angle space measurements described above could theoretically be made with the transmission of a single broadband "ping".

IMPACT/APPLICATION

Observation of aquatic animals in their natural environments remains a major challenge in both biological oceanography and limnology. Critical processes in feeding, reproduction, growth and predation in small zooplankton occur at scales from fractions of millimeters up to scales which match the ambits of individuals. It is very difficult to reproduce all essential features of the marine environment in the lab, where observation of small scale processes is more tractable than at sea. Therefore, there is continuing interest in improving our ability to observe and quantify *in situ* spatial and temporal changes in the distribution and abundance of zooplankton in relation to natural physical, chemical and other biological fields. Understanding the distributions of small scale structures, their patterns and the processes that lead to their formation and dissolution must preceed modeling and prediction of their occurrence and subsequent impacts on underwater visibility, water column optical properties and underwater acoustical scattering.

In addition to our science objectives, our research efforts are adding to a base of knowledge that impact the following areas with direct Naval relevance: 1) the performance of high-frequency sonars; 2) the performance of high-speed vehicles in the littoral; 3) the fine- and micro- scale vertical distribution of small crustaceans, including those that exhibit bioluminescence; 4) temporal variations in seabed roughness (impact on the scattering and penetration of sound into the seabed); 5) underwater visibility; and; 6) the performance of systems used for bottom mapping in shallow water.

TRANSITIONS

During the last decade, we have developed a variety of new multi-frequency acoustical technologies for use by fisheries scientists and biological oceanographers. Direct participation in such programs is intended to assure a transition of these technologies to a broad range of scientists working with zooplankton in marine and limnological ecosystems. We continue to build several TAPS each year for investigators who employ them independently in their own research (e.g., S. Smith at UM/RSMAS and P. Jumars at U. of ME).

RELATED PROJECTS

Using several TAPS, we, Peter Jumars (U. of ME), Jill Schmidt (U. of Washington) and David Thistle (FSU) recently studied the emergence of benthic animals from the seafloor for ONR in the Gulf of Mexico during the fall of 1999 (SAX-99). We have been leasing TAPS sensors to scientists at the University of Maryland (CEES) in support of the NSF-sponsored TIES research in the Chesapeake Bay. We are currently using TAPS to describe the distribution of lower trophic levels in the Mediteranean Sea to assist in determining whether anthropogenic noise may cause spatial redistribution of marine mammals. This ONR-sponsored project (SOLMR - Sound Oceanography and Living Marine Resources) is with scientists from SACLANTASWCTR, the U. of Pavia, WHOI, NMFS and ICRAM.

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