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Chief of Naval Research Cuts Ribbon

A most definitive moment in the brief history of NORDA occurred September 7, 1984 when the Chief of Naval Research, RADM J.B. Mooney, Jr., cut the ceremonial ribbon, opening NORDA's Ocean Science Center at NSTL, Mississippi. Since its establishment there in 1976, NORDA's staff had been occupying portions of buildings and office trailers. In the photo are (l. to r.) Vic Tilley, building contractor; Jerry Hlass, Director of NASA/NSTL; Dr. Ralph Goodman, former NORDA Technical Director; RADM Mooney; CAPT G.T. Phelps, NORDA Commanding Officer at the time of the opening; Dr. James Andrews, current NORDA Technical Director; and CAPT Charles Darrell (USN-Ret.), NORDA's first Commanding Officer.

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About the Cover

This image, which shows sea surface temperature contrasts associated with a Gulf Stream meander and three major cold core rings, was acquired with the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA-7 polar orbiting satellite during a cold air outbreak in the spring of 1983. Contrasts in the image have been enhanced by scientists at the Naval Ocean Research and Development Activity (NORDA), using a two-dimensional, digital filter, developed by M. Lybanon, which results in a relief-like effect, with warmer areas being higher than colder areas. Though the correlation between sea surface temperature and topography is not one-to-one, the image is liberally used to depict the depressions and elevations associated with the cold core rings and Gulf Stream meander, respectively. The altimeter on board the U.S. Navy GEOSAT satellite will measure sea level along the illustrated groundtracks during a two year Exact Repeat Mission (GEOSAT ERM) scheduled to begin approximately 1½ years after launch this spring (1985).

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NAVSO P-510

Introduction

The Naval Ocean Research and Development Activity (NORDA) is a field activity of the Office of Naval Research. NORDA was established in March 1976, and located at the National Space Technology Laboratories (NSTL) near Bay St. Louis, Mississippi. This action was part of the plan to create a focus on Navy Oceanography at NSTL through the co-location of the newly created NORDA with the Commander, Naval Oceanography Command and the Naval Oceanographic Office.

Reporting to the Chief of Naval Research (CNR), NORDA is one of the Navy's three tech base laboratories (with the Naval Research Laboratory and the Navy Biosciences Laboratory), and has responsibility for Navy-wide leadership in oceanography, environmental ocean acoustics, and mapping, charting and geodesy. Approximately 30% of NORDA's in-house research effort is dedicated to basic research in the ocean sciences.

NORDA is a broad spectrum laboratory, covering the major oceanographic disciplines: geology and geophysics, physical and chemical oceanography, biological oceanography, ocean acoustics, ocean modeling and prediction, acoustic modeling and prediction, ocean engineering, and oceanographic remote sensing. In addition, NORDA carries out mission oriented research in the areas of Arctic oceanography and acoustics, and in mapping, charting and geodesy advanced survey and data base applications.

Early investment guided growth at NORDA, with concentrations in the areas of ocean modeling and ocean remote sensing. The results of these decisions are apparent today in the satellite receiving and image processing systems in place, and the large coordinated research program focusing remotely sensed, in situ and model data in programs such as the Regional Energetics Experiment (REX), discussed in this issue.

The papers in this issue of *Naval Research Reviews* are intended to convey the results of exciting research programs, to provide a sense of the development of NORDA over its first eight years, and to outline some of the capabilities which NORDA has developed for application.

James E. Andrews
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THE FNOC TOPS/TEOTS OCEAN THERMAL FORECAST/ ANALYSIS SYSTEM

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Introduction

Fleet Numerical Oceanography Center (FNOC) currently uses a northern hemisphere, upper-ocean, thermal anlysis/forecast system on an operational basis. This system consists of two major components. The first is an ocean forecast model developed at the Naval Ocean Research and Development Activity (NORDA), which is designated the Thermodynamic Ocean Prediction System (TOPS). The second is the TOPS Expanded Ocean Thermal Structure (TEOTS) analysis. The coupled system, TOPS/TEOTS, runs daily on the FNOC Northern Hemisphere, polar stereographic grid. This article provides a brief description of the system, its present capabilities, and its future development.

The Navy requires an operational capability to accurately represent the present and future state of the oceanic environment. This requirement stems from the impact of the environment on acoustic surveillance, nonacoustic anti-submarine warfare, search and rescue planning, the performance of weapons systems, and other aspects of modern naval operations. Because of its acoustic influence, upper-ocean thermal structure is a particularly important environmental parameter. FNOC, for example, uses their thermal analysis to provide input to the acoustic performance prediction models that are run for fleet users.

Prior to implementation of TOPS and the TOPS/TEOTS system, the upper-ocean thermal structure analysis at FNOC relied almost solely on extremely sparse expendable bathythermograph (XBT) and surface ship observations, with a fairly rapid reversion to climatology in data-sparse areas. Furthermore, no use was made of the knowledge of physical processes governing changes in the ocean thermal structure, for example, the response of the surface mixed layer to atmospheric forcing.

This situation is being improved in several ways. Satellite observations are greatly increasing the information available about the state of the ocean's surface. More sophisticated analysis techniques are being developed to make better use of the available data by explicitly taking into account the characteristic space and time scales of oceanic variability. And numerical ocean models are being developed that can provide a forecasting capability, prolong the usefulness of older observations in data sparse regions via hindcasting, and help deduce subsurface ocean structure from the much better observed surface fields and atmospheric forcing. TOPS represents the "first generation" of these ocean models.

Description of the TOPS/TEOTS System

The TOPS/TEOTS system consists of two components, an upper-ocean forecast model (TOPS) and an upper-ocean thermal analysis scheme (TEOTS). A brief summary of the system is provided here. For a more comprehensive description, see Clancy and Pollak.[1]

The TOPS ocean forecast model can be termed a synoptic, upper-ocean, mixed-layer model. The model describes the modification of the upper-ocean thermal and salinity structure due to wind mixing and surface buoyancy fluxes (heating, cooling, evaporation, and precipitation), and provides for advection due to wind-driven and climatological geostrophic currents. The model is initialized from the TEOTS analysis (see below) and is driven by surface wind stresses and heat and moisture fluxes produced by the Navy Operational Global Atmospheric Prediction System (NOGAPS), the Navy's global atmospheric prediction model.[2] Forecasts of up to 3 days can be made using NOGAPS air-sea fluxes for forcing.

TEOTS is a modified version of EOTS, the FNOC Expanded Ocean Thermal Structure analysis.[3] The EOTS analysis uses the FIB (fields by information blending) technique to map oceanic observations to a three-dimensional grid. In TEOTS, the previous TOPS forecast plus a slight adjustment toward climatology is used as the first-guess field for the next analysis. Updating information for the analysis is provided by ship, XBT, and satellite Sea Surface Temperature (SST) observations.

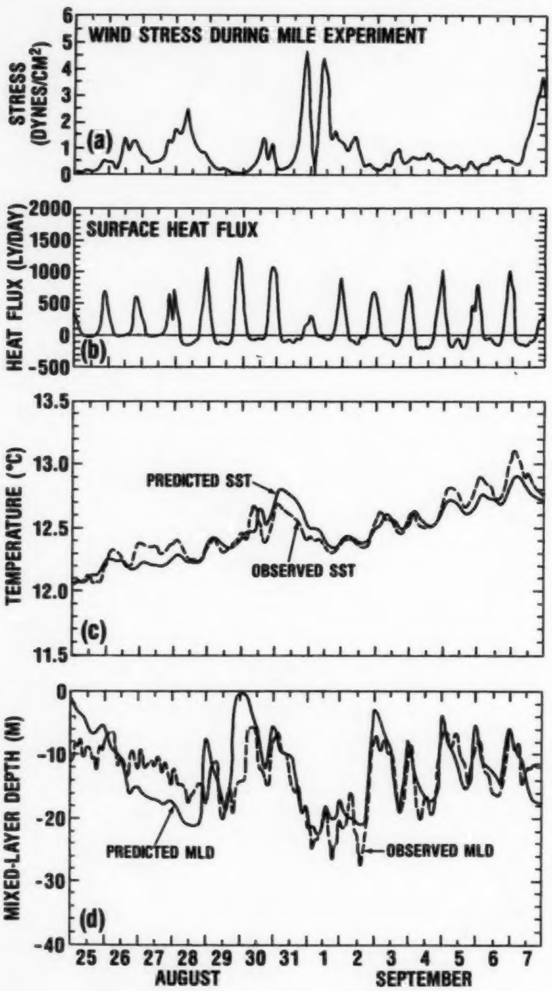
In summary, the TEOTS analysis provides initial conditions for the TOPS forecast; and the TOPS 24-hour forecast, in turn, provides first-guess field information for the following day's TEOTS analysis. TOPS/TEOTS thus operates in an analysis/forecast/analysis cycle similar to atmospheric prediction systems.[4] TEOTS keeps TOPS consistent with the daily observed thermal structure while TOPS helps fill in data-sparse areas of the analysis with thermal structure consistent with oceanic physics and atmospheric forcing.

The Mixed-Layer Model

The Mellor-Yamada Level 2 (MYL2) turbulence closure scheme is used in TOPS to parameterize vertical mixing in the mixed layer.[5,6] In the MYL2 model, the rate of vertical mixing is governed by eddy coefficients that depend on the local turbulent kinetic energy (TKE) and Richardson number. The TKE is calculated using a quasi-equilibrium form of the TKE equation in which shear production, buoyancy production, and dissipation are in local balance. In stable conditions, the mechanism for generating TKE is the shear instability of the Ekman current. The depth of mixing is determined by the depth where the shear instability is stabilized by the density stratification. In unstable conditions, TKE is also generated by density instabilities.

Figure 1

Mixed-layer simulation of data taken during MILE. (a) Wind stress, (b) surface heat flux, (c) observed and model-predicted SST, (d) observed and predicted MLD.



The MYL2 turbulence model has demonstrated predictive skill in several mixed-layer simulations. Mellor and Durbin tested the MYL2 turbulence model with data taken at Ocean Weather Station PAPA in the eastern North Pacific with good results.[6] Warn-Varnas, Dawson and Martin used the model to simulate observations made during the MILE (Mixed Layer Experiment) conducted near Station PAPA in August and September of 1977;[7] and Martin used the MYL2 model to simulate changes in the ocean recorded by a NOAA buoy during the passage of Hurricane Eloise across the Gulf of Mexico in September 1975.[8]

Figure 2

Mixed-layer simulation of buoy observations taken in the Gulf of Mexico during Hurricane Eloise. (a) Observed wind speed, (b) observed and model-predicted SST, (c) observed and model-predicted E-W and (d) N-S current at 50 m depth.

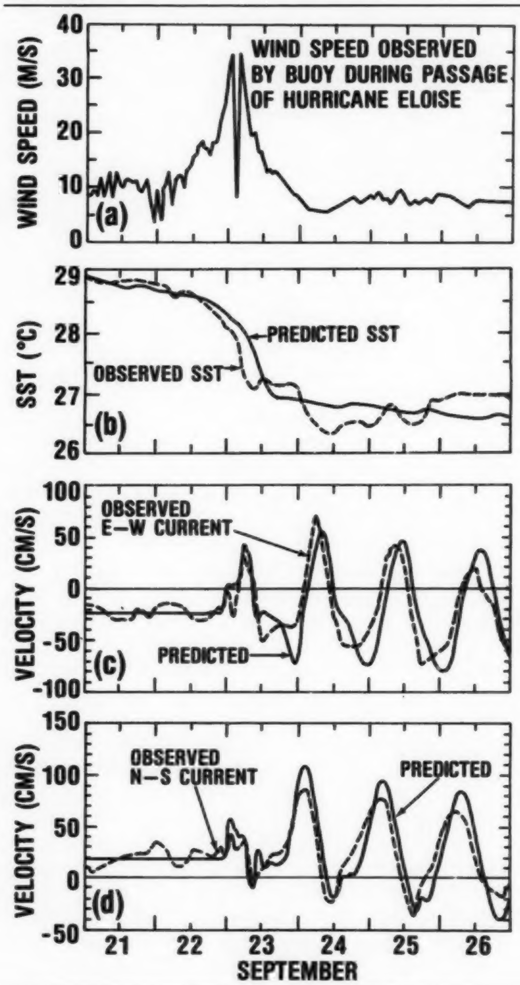
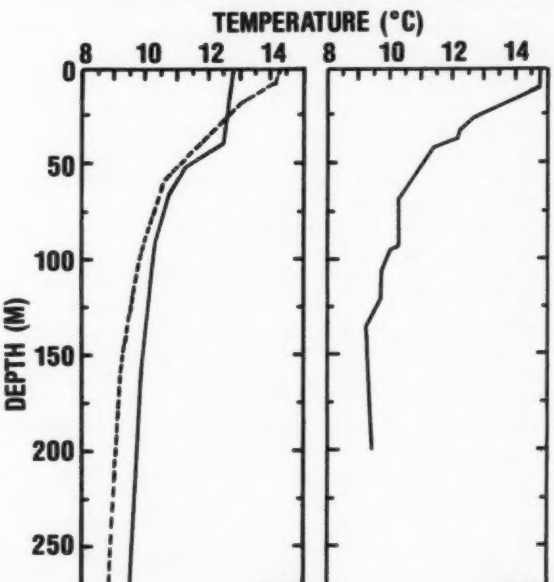


Figure 1 shows a comparison of observed and model-predicted SST and mixed-layer depth (MLD) from a simulation of the MILE data. The surface wind stress and heat flux calculated from the meteorological observations and used for forcing are also shown. The model closely simulates the steady, seasonal, surface warming that occurred late in the summer, modulated by a diurnal fluctuation of about 0.2°C caused by daytime solar heating and nighttime cooling. A slight decrease in the SST can be observed at the end of August caused by increased winds and cloudiness during the passage of a low pressure system. The MLD responds to the changing winds of the passing weather systems on the synoptic time scale, and there is also a diurnal fluctuation of the MLD produced by solar heating when the winds are light.

Figure 2 shows the wind speed observed by NOAA buoy EB-10 during Hurricane Eloise and a comparison of the response of the observed and model-predicted sea-surface temperature (SST) and near-surface current. The predicted SST shows the drop of over 2°C that occurred during the strongest winds on September 23. The predicted current shows the large inertial oscillation generated by the hurricane winds during the same period.

Figure 3

(a) Temperature profiles in the upper 300 m at the location of Ocean Station LIMA (56.9°N, 20.3°W) at 0000 GMT on 25 July 1984 from the FNOC climatology (solid line) and TOPS/TEOTS (dashed line). (b) Temperature profile from a bathythermograph observation at Station LIMA on the same day at 0900 GMT.



Examples of TOPS/TEOTS performance

TOPS improves the TEOTS analysis by providing additional information based on oceanic physics and atmospheric forcing. This improvement is illustrated by Figure 3a, which shows vertical temperature profiles from climatology and TOPS/TEOTS at the location of Ocean Station LIMA (56.9°N, 20.3°W) on 25 July 1984. Following a period of weak winds and unusually strong downward heat flux in this region, TOPS/TEOTS shows an anomalously warm, shallow, surface mixed layer. The bathythermograph observation from Station LIMA on the same date (shown in Figure 3b) confirms the presence of the anomalous layer. Note that this observation provides independent verification since it was not assimilated into TOPS/TEOTS prior to this comparison.

In addition to improving the analysis of ocean thermal structure, TOPS provides a real-time forecast capability. Figure 4, which shows a 72-hour TOPS forecast initialized at 0000 GMT 7 June 1984 at Ocean Station ROMEO (47.0°N, 17.0°W), illustrates this capability. During the first 24 hours of the forecast, the model predicted virtually no change in the thermal structure and exhibited a mixed layer to a depth of 30 m (Figure 4a). During the last 48 hours of the forecast, however, TOPS predicted near-surface warming and the formation of a transient thermocline at 5-m depth (Figure 4b).

The synoptic weather patterns during this period are of interest and are shown in Figure 5. At the beginning of the forecast, a low pressure system centered just west of the English Channel produced winds in excess of 15 knots and a daily-averaged net surface heat flux near zero at Station ROMEO (Figure 5a). Hence, the surface layer remained mixed to 30 m, and no warming or cooling resulted. During the last two days of the forecast, however, a high-pressure system moved into the northeastern Atlantic, producing winds of less than 10 knots and strong downward surface heat flux under clear skies at ROMEO (Figure 5b). These conditions caused the formation of the shallow thermocline in the TOPS forecast.

Finally, Figure 6 shows bathythermograph observations taken at Station ROMEO within a few hours of the beginning (Figure 6a) and end (Figure 6b) of the forecast. These observations are completely independent of the TOPS forecast and verify the formation of the shallow transient thermocline predicted by the model.

Figure 4

(a) Initial temperature profile from TOPS/TEOTS analysis (dashed line) for 0000 GMT 7 June 1984 at Ocean Station ROMEO (47.0°N, 17.0°W), and TOPS 24-hour forecast (solid line). (b) TOPS 48-hour (dashed line) and 72-hour (solid line) forecasts based on the same analysis.

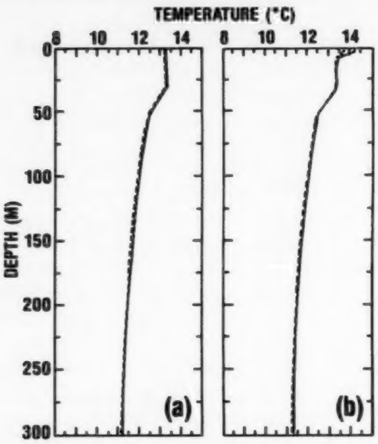


Figure 5

(a) Surface pressure from the FNOC analysis at 0000 GMT 7 June 1984. The contour interval is 4 mb. The position of Station ROMEO is indicated by the triangle. (b) Surface pressure analysis 3 days later at 0000 GMT 10 June 1984.

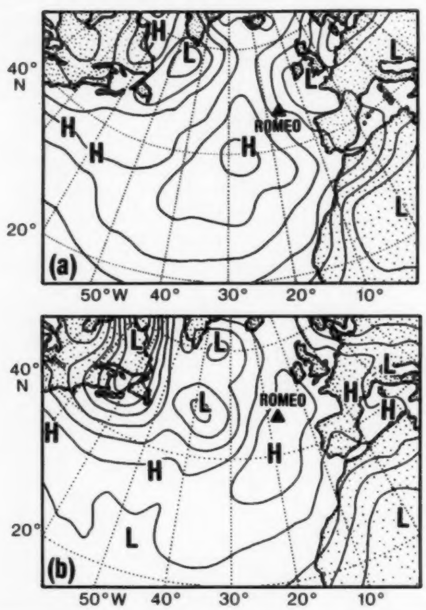
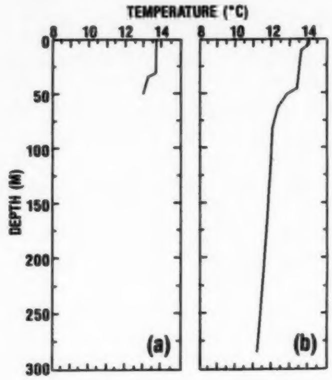


Figure 6

(a) Bathythermograph observation taken at Station ROMEO at 1000 GMT 7 June 1984. (b) Bathythermograph taken at ROMEO 3 days later at the same time of day.



Future Development of the TOPS/TEOTS System

At present, the primary area of TOPS/TEOTS requiring attention is the analysis scheme. The FIB methodology used by the TEOTS analysis employs a large number of weighting and tuning parameters whose relationships to the known statistics of instrumental accuracy and ocean thermal variability are unclear. Within the next year, the FIB technique will be replaced by the Gandin Optimum Interpolation (OI) technique.[9] This new analysis module, called the Optimum Thermal Interpolation System (OTIS), is currently under development at NORDA. The OI technique provides a rigorous mathematical framework for the objective analysis of information provided by a variety of observing systems and has been used to analyze ocean thermal structure by a number of researchers.[10,11,12,13,14]

Work is currently underway at NORDA to improve the atmospheric correction for the satellite infrared SSTs from the NOAA Advanced Very High Resolution Radiometer (AVHRR) onboard the TIROS-N series of polar-orbiting satellites. FNOC now uses up to 60,000 satellite, multichannel SSTs (MCSSTs) globally per day in their surface thermal analysis. The satellite SSTs provide much better coverage than ship data, though they are limited to cloud free areas. Their accuracy of 0.6°C is also better than the 1.5°C (typical) accuracy of ship data.[15]

Significant improvement in the specification of the surface winds required for TOPS will likely result in 1986 with the launch of the Special Sensor Microwave/Imager (SSM/I). This passive microwave instrument, mounted aboard a Defense Meteorological System Program (DMSP) spacebus, will retrieve global surface wind speeds twice per day with a resolution of 25 km and an accuracy of about 2 m/s. When combined (in 1990) with a scatterometer, surface wind data available for NOGAPS assimilation, and the resultant wind fields used to drive TOPS, will improve greatly. In addition, future satellite altimetry data will provide information on the surface current and on the subsurface thermal field.

The testing of mixed-layer models at NORDA, which involves a number of mixed-layer models and a variety of data sets, will result in the incorporation of improved mixing parameterizations in TOPS. The testing and comparison of models in different regions and different conditions helps establish the particular advantages and deficiencies of the models, and the changes needed to improve their efficiency or predictive skill. Mixed-layer-model testing has also included the investigation of other parameterizations important to modeling the upper ocean. For example, seasonal mixed-layer simulations at Ocean Stations NOVEMBER and PAPA have shown that regional differences in seawater turbidity significantly affect the development of the seasonal thermocline, and can be responsible for an error in a long-term hindcast of the summer SST of several degrees.[16]

The increased accuracy and availability of satellite data will upgrade the skill of the regional TOPS/TEOTS and TOPS/OTIS systems currently under development at NORDA. The regional forecast/analysis models will have horizontal resolution from 20 to 60 km and will cover areas of significant Navy interest, including the Eastern and Western Mediterranean, and the Gulf Stream and Kuroshio regions.

The increased horizontal resolution associated with the application of regional TOPS/TEOTS and TOPS/OTIS systems introduces the problem of accounting for advection due to dynamic mesoscale features such as Gulf Stream meanders and mesoscale eddies. This problem is being addressed with the ongoing NORDA development of global and regional hydrodynamic models of sufficient horizontal resolution for proper treatment of dynamic mesoscale features.[17] These models, initialized and updated by satellite altimetry data, will provide the geostrophic advection currents for TOPS as well as information on the location and evolution of mesoscale fronts and eddies.

Acknowledgments

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Profiles in Science

Dr. Ralph R. Goodman, NORDA's first Technical Director, has held positions of scientific leadership within the ONR community for over fifteen years. Dr. Goodman served as NORDA's Technical Director from its founding until August 1981. Since Dr. Goodman was responsible for both the recruiting of NORDA's initial staff and the establishing of its scientific programs, he has left an indelible mark. Dr. Goodman is presently the Director of the SACLANT (Supreme Allied Command-Atlantic) Anti-Submarine Warfare Research Centre at La Spezia, Italy.

Prior to his duty at NORDA, Dr. Goodman was the first Associate Director of Research for Oceanology at the Naval Research Laboratory (NRL) in Washington, D.C., a position he held for eight years. He was responsible for establishing scientific programs in underwater acoustics, ocean science and ocean technology, as well as the Navy's Underwater Sound Reference Laboratory. At NRL he was Chief Scientist on two large multi-laboratory ocean operations in the Atlantic Ocean. During this time at NRL, he was invited to give a series of lectures in physical acoustics at the Enrico Fermi School of Physics at Lake Como, Italy.

Dr. Goodman began his early scientific career at the Naval Electronics Laboratory (now Naval Ocean Systems Center) in San Diego, California in 1958. In 1959, he joined the staff of Colorado State University, becoming the Acting Chairman of the Physics Department in 1968. As an ONR contractor, his personal research interests included theoretical solid state physics, theoretical and experimental scattering phenomena, and long range underwater acoustic transmission. While at Colorado State, he was elected to membership on the Committee on Undersea Warfare, National Academy of Sciences, and was a visiting lecturer at Pennsylvania State University on underwater acoustics.

Dr. Goodman is a member of the American Physical Society, the American Geophysical Union, and is a fellow of the Acoustical Society of America. He has been awarded the Navy Distinguished Civilian Service Award.

Experimental Acoustics Reasearch at NORDA

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Naval Ocean Research and Development Activity

Introduction

The effective utilization of our Navy assets has played a major role in keeping our country free. With time, these assets have become more sophisticated and more capable of exploiting the ocean environment to achieve advantages not otherwise possible. This ability has particularly enhanced our use of sonar systems used to detect submarines. A good working knowledge of the acoustic propagation characteristics of the ocean is important to effectively utilizing the sonar system, while accurate, detailed knowledge is vital for designing new systems that are "tuned" to exploit the acoustic environment. The degree to which these objectives can be accomplished, in a large part, depends upon the success of our research and how well the results are communicated to those who must use them.

When NORDA was founded in 1976, its charter included the responsibility for conducting research of the ocean acoustic environment. Supporting an active experimental acoustics measurement program is one way NORDA is satisfying that responsibility.

This article discusses the development of NORDA's experimental acoustics research program. A historical perspective and examples of past measurement programs are given. Some of the major current programs and where they are likely to lead in the future follow.

Background

Experimental measurements are important to a research program because they are the vitally required validation tests, linking theory to reality. Theoretical investigations are necessary and must provide the foundation for a meaningful measurement program, but theories gain credence only after being tested by measurements. Hence, a significant purpose of any experimental acoustics measurement program is to test and varify acoustic propagation theories and to support the development and validation of models that contain those theories. This sometimes requires the accumulation of data bases that have sufficient depth to characterize with confidence the influential critical phenomena. These data bases can also be the foundations for empirical models. Some acoustic phenomena are still beyond our understanding and capability to express theoretically. For these phenomena, empirical models are the only viable approach. Furthermore, experimental acoustics measurements are often the only way to test some new systems concepts. The degree to which the concept has potential for improving sonar performance may depend on how well the system configuration, utilization, and signal processing have been "tuned" to the acoustic environment. This potential can be determined only by performing the appropriate measurements.

NORDA has recognized that ocean acoustic measurements are necessary and vital to a healthy acoustics research program and has always supported an active measurement program. At first, the program was severely limited in scope because of NORDA's relatively small research staff. Since environmental acoustics research is both interesting and important, NORDA has been able to attract seasoned researchers. Additional growth has been achieved by hiring highly motivated, new professionals and by developing their skills. NORDA now has a well-balanced staff of researchers who are devoted to increasing the Navy's effectiveness through a better understanding of the acoustic environment.

The experimental acoustics measurement program at NORDA is conducted by the Ocean Acoustics Division and is supported with measurement assets at sea by the Ocean Technology Division. A theoretical foundation and numerical modeling support are provided by the Numerical Modeling Division.

Two branches in the Ocean Acoustics Division conduct acoustic measurements, and one provides environmental support to the other two. One acoustic measurement branch focuses on the frequency range above about 2 or 3 kHz, and the other focuses on the frequency range below. This division of acoustic research according to frequency range is natural because the phenomena and mechanisms that influence the acoustic propagation and the ambient noise are different in these two frequency regimes. Furthermore, the objectives and uses of the sonar systems that operate in these two regimes are different. For example, acoustic mines and homing torpedoes operate at frequencies above several kilohertz while passive sonars operate at frequencies below a kilohertz. The former two are relatively small, short-range systems, while the latter are much larger in physical size and provide long-range coverage.

Past Measurement Programs

Much of the early experimental acoustic research by NORDA was through participation in multilaboratory measurement programs with NORDA, for the most part, playing only minor roles. In the past, a major role would have required more researchers than NORDA could provide. Instead, NORDA concentrated on a few areas in which its contributions could be ones of quality that could significantly impact on our knowledge of the acoustic environment. Table I lists the objectives, the approximate geographic locations, and the corresponding year for acoustic measurements by the Ocean Acoustics Division, beginning from 1976 when NORDA was founded, until 1984. Three current programs are not listed but will be discussed later as examples of the multidisciplinary research that is more typical of NORDA's present and future experimental acoustics research.

Each project listed in Table I addressed an important objective but did not require a multidisciplinary approach. One project was the utilization of the vertical line array (VLA) for antisubmarine warfare (ASW) and the high resolution signal processing of the corresponding data (the 82-83 project). The emphasis of this project was on estimating source position through precise measurement of the vertical arrival structure of the acoustic energy received from the source. This precise measurement, combined with knowledge of the acoustic propagation, permits the accurate determination of the source position in the water mass. However, poor angular resolution and inaccurate or incomplete knowledge of the acoustic propagation result in errors in estimates of the position. NORDA has made significant contributions here by applying high-resolution beamforming techniques and by improving acoustic propagation models.

This project's major contribution has been to demonstrate that high resolution beamforming techniques can separate closely spaced arrivals, something conventional beamforming is unable to do. Without this capability, accurate source positioning would not be possible.

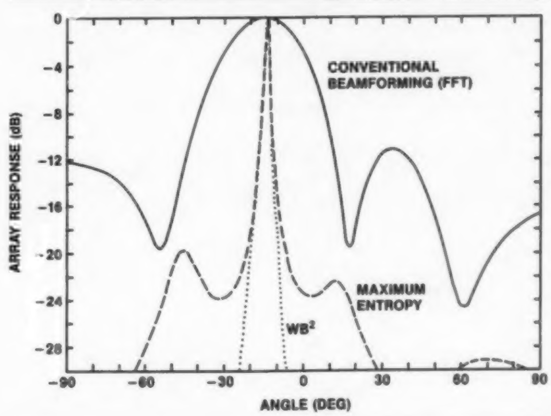
Table I
Past Experimental Acoustic Research at NORDA

Year	Location	Objective
76	Gulf of Alaska	Oil rig drilling noise
	Bering Sea	Ambient noise & acoustic propagation
77	N. E. Pacific	Ambient noise & sonar performance
	Gibraltar & Caribbean	High-frequency volume reverberation
78	Washington Coast	Bottom interaction & vertical array performance
	W. Mediterranean	Spatial variability of ambient noise & frontal effects
	Delaware Coast	Volume reverberation
79	N. W. Atlantic	Noise from shipping
	Cariaco Trench	Volume reverberation
	Bermuda	Whale false targets
80	N. E. Atlantic	Spatial coherence of bottom interaction
	Gulf of Mexico	Volume reverberation
80–81	C. Mediterranean	Topographic noise stripping
	S. Atlantic	Ambient noise spatial variability
81–83	NORDA (Lab)	High frequency fluctuations
82	C. & E. Mediterranean	Ambient noise statistics, spatial variability & topographic noise stripping
	Rhode Island Coast	High-frequency surface scattering
	California Coast	High-frequency bottom scattering
82–83	N. E. Pacific	Signal vertical arrival structure & high-resolution processing sonar performance
83	Florida	Volume reverberation geographic variability
83–84	Baltic Sea	Ambient noise temporal and spatial variability

The results in Figure 1 illustrate the gains made possible by high-resolution beamforming[1]. The source of data was an acoustic experiment in which sound was transmitted from an acoustic source and received by a horizontal line array. These data were then processed by a conventional (FFT) beamformer[2] (solid curve) and two different high-resolution beamformers: the maximum entropy method[3] (MEM-dashed curve) and the Wagstaff-Berrou broadband method[4] (WB^2-dotted curve). These results, which are typical, indicate that the high-resolution beamformers provide narrower beamwidths, by about an order of magnitude, and more background noise suppression than conventional beamformers. Both characteristics are important measures of system performance and enhance detection and tracking functions. The response patterns in Figure 1, clearly show that the arrivals can be identified and located better by high-resolution beamforming than by conventional beamforming, thus permitting position estimates to be made with greater confidence. Furthermore, such results indicate that high-resolution beamforming makes it possible for short arrays to achieve performance similar to arrays many times larger. This capability is important in many applications where size is a constraint (i.e., a vertical array in shallow water) or where a system might contain many arrays, but costs must be minimized by limiting the number of sensors per array.

Figure 1

Typical results for a conventional (FTT – solid curve) beamformer and two high – resolution beamformers (maximum entropy method – dashed curve; Wagstaff-Berrou Broadband method (WB^2) – dotted curve).



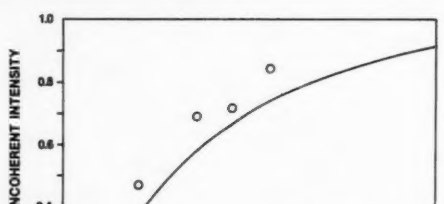
Not all acoustic measurements conducted by NORDA researchers have been in the field. Some have been performed in the laboratory with specially designed equipment. One advantage of working in high-frequency acoustics is that the wave-lengths are relatively small, and most phenomena that affect acoustic propagation scale according to the wavelength. For example, at 150 Hz the wavelength is about 10 m and at 15 kHz it is about 0.1 m. Hence, characteristic dimensions at 15 kHz are 100 times smaller than at 150 Hz. This permits some high-frequency acoustic research to be conducted in model tanks, while nearly all research at the lower frequencies must be conducted in the ocean.

An example of a laboratory-conducted measurement is the experimental verification of the Wenzel theory[5] of acoustic fluctuations[6]. The Wenzel theory states that the forward volume scattering in a randomly inhomogeneous medium causes the temporally incoherent portion of a signal to increase with both range and frequency, asymptotically approaching a saturation value. Many advanced sonar processing algorithms require high coherence in the received signal. Therefore, the phenomena by which acoustic energy is transferred from a coherent wave field into an incoherent field must be understood before the performance of such advanced processing techniques can be accurately predicted and optimized for the wide variety of possible operating environments.

To test the Wenzel theory, signals transmitted from a source (S) in a large water tank were scattered from inhomogeneities in the microstructure caused by a heating element (H) near the bottom or a cooling element near the surface. (see insert of Figure 2). R denotes the receiving element; the cooling element is not shown. The results in this figure correspond to the Wenzel theory (curve) and the experimental measurements (circles) of the normalized intensity of the incoherent portion of the received signal (a measure of the fluctuations) versus normalized propagation range. Within the range of the experimental measurement, the data show good agreement with the theory and provide evidence that the fluctuations do not continue to increase linearly. Additional measurements will be conducted in the ocean to determine the types of environments, frequency ranges, and propagation ranges over which the assumptions implicit in the Wenzel theory are valid.

Figure 2

Experimental verification of the Wenzel theory of saturation for sound propagation in a random medium. Theory – curve; experimental data – circles.



Present Measurement Programs

Most of the simple questions in underwater acoustics have already been answered and, in many cases, the resulting payoffs have been great. To once again reap large payoffs, multidisciplinary investigations are required to identify and understand the characteristics and features of the acoustic environment, which can be exploited to enhance the design of future systems and in the utilization of present systems. NORDA has reached the maturity level to reap such payoffs and is now at the forefront of acoustic research. Acoustics measurements, acoustic modeling, oceanography, marine biology, geology, and geophysics are all present in one organization; combined with the spirit of cooperation that exists at NORDA, it is now as natural to field multidisciplinary research teams to investigate the most complex issues the acoustic environment poses as it was in the past to field a small research team to address one simple issue.

A number of ongoing programs illustrate the complex nature and the wide scope of the research that is presently done within a single project; three are discussed here.

Very Low-Frequency Acoustic Propagation

The Very Low-Frequency (VLF) Acoustic Propagation Project is a good example of a multidisciplinary investigation of very low frequency acoustic propagation in shallow water. The objective is to quantify potential gains in shallow-water submarine detection achievable by exploiting the radiated acoustic energy in the VLF band (from 5 to 20 Hz).

The energy in this band propagates in the water column and within the bottom. As the water depth becomes shallower the waterborne energy arriving from deep water decreases and, eventually, the only sound that is propagating has a substantial component within the sediment. Ocean bottom seismometers (OBS) will be used to sense the acoustic waves in the sediment, and hydrophones will be used to sense the waterborne acoustic waves. The signal-to-noise ration (S/N) measured by the seismometers will be compared to the S/N measured by the hydrophones. Additional data to be acquired with a vertical hydrophone array will be used to determine the energy distribution within the water column. Knowledge of the bottom geophysics will be required to understand and extrapolate the results to other areas and conditions.

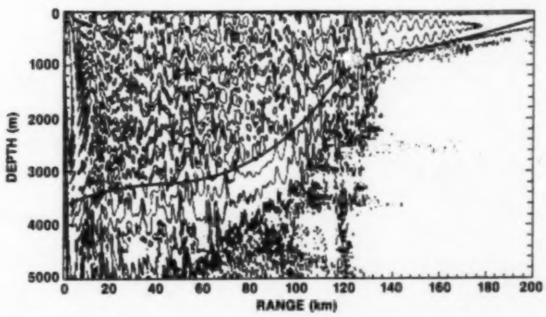
Since acoustic propagation within the ocean bottom is a critical element of the VLF project, the geologists and geophysicists at NORDA are equal partners with the acousticians in this project. The first measurement exercise will also be a cooperative effort with scientists of the United States Geological Survey (USGS). This cooperation will strengthen both research efforts.

Preliminary geophysical measurements of the subbottom structure made by the USGS off Cape Fear, North Carolina, provided the required parameters for the initial acoustic modeling study. These preliminary measurements also form the basis for a more thorough investigation of the bottom geophysics that will be conducted later in conjunction with the acoustic measurement.

Figure 3 illustrates an acoustic modeling product that utilized inputs from the preliminary geophysics investigations at the measurement site. This plot is for sound at 5 Hz traveling from deep water (from the left side) into shallow water where OBSs and the hydrophone array will be located. Depth is on the vertical axis and range is on the horizontal axis. The heavy line represents the bottom profile. The source is at 100 m in the deep water. The curves in the water column and in the sediment are contour lines of equal sound intensity. The high density in the deep water is indicative of favorable propagation. The "thinning out" in the water column as the bottom depth becomes shallower and the extension of the contour lines into the bottom indicate that the acoustic energy is being progressively coupled into the bottom. In very shallow water the acoustic energy ceases to propagate in the water and is only found propagating in the bottom.

Figure 3

Sound intensity contours at 5 H for the Cape Fear, N.C., VLF measurement area. The source is at 100 m depth in the deep water at the extreme left side. The solid line is the bottom profile.



Acoustic measurements can be designed with the aid of these and other quantitative predictions to test the efficiency of the sound coupling into the sediment and how well it propagates in the bottom and in the water column. This knowledge can then be used to verify theories and validate models that can be used to estimate sonar system performance in similar environments. The models can in turn be utilized to aid in designing surveillance systems to exploit this unique acoustic environment so that an enhanced ASW capability is achieved.

The first experiment, which will be conducted by the VLF project, is in the geologically well known area off Cape Fear, North Carolina. A follow-up experiment is planned off the Washington Coast, where the subbottom structure is much more complex. The insight and knowledge gained in the previous experiment will be invaluable to understanding and interpreting the results obtained in the geologically complex Washington area.

Effects of Shallow-Water Geological Processes or High-Frequency Acoustic Scattering

Acoustic sensor arrays utilize the spatial separation among the sensors to achieve directivity that is proportional, in wavelengths, to the array aperture. Since the wavelength decreases with increasing frequency, it is possible to have a highly directional array on a relatively small weapon system, such as a homing torpedo. A torpedo uses this directivity to transmit and receive acoustic signals in a narrow cone centered near the horizontal, where a target is likely to be. Signals returned from angles far from the horizontal are discriminated against to avoid masking the target signals by signals scattered and reflected from the surface and bottom.

This approach works well in deep water, but in shallow water the submarine is sufficiently close to both the surface and the bottom so that the directivity pattern cannot effectively discriminate against the scattered signals. The scattering and attenuation of the returning signals from the bottom can greatly affect the torpedo performance. Presently, too little is known about these effects, their causes, and the relevant environmental parameters to develop reliable environmental acoustic models that can be used to predict weapon systems' performance in shallow water.

At high frequencies, acoustic bottom penetration of a few meters or less is expected. Furthermore, because of the relatively small wavelength, the roughness of the bottom interface and the near bottom interface composition will be important. Determining the acoustic effects of bottom interaction requires that biological and geological investigations be conducted in conjunction with the acoustic measurements. Only be such a multidisciplinary approach will it be possible to identify the relevant parameters and determine the causes. Without this, only an empirical model could be developed, and it would be unlikely that the model could be used to extrapolate to other areas, conditions, and frequencies.

The first stage in this measurement program was to acquire the measurement instrumentation. Two towers were required, one to support a transmitting and receiving array and the other to support a receiving array. Signals beamed at the bottom from the transmitting array would be scattered from the bottom and received by both receiving arrays. Separation between the towers and tilt angles of the arrays had to be variable and easily controlled. Such instrumentation could also be used to study scattering from the sea surface and high-frequency, direct-path fluctuations.

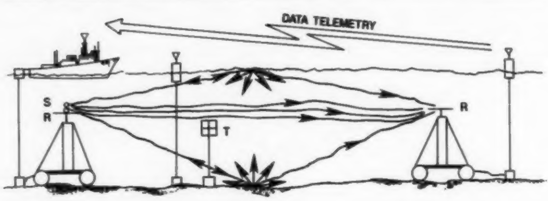
The solution, a novel one, was to construct the towers with catamaran bases that could be easily towed to the measurement site. The bases would then be flooded and the towers gently sink to a stable upright position on the bottom with the arrays already in place. After completing measurements the central towers are purged of water by high-pressure air stored in containers on each tower. The towers slowly rise to the surface where the bases are purged of water by high-pressure air from the towship. The towers are then towed away. On shore the towers are easily disassembled and shipped by flat-bed truck.

Figure 4 illustrates the towers and the experiment setup. The tower on the left side supports transmitting (S) and receiving (R) arrays. The right tower supports a receiving (R) array. A temperature microstructure measurement system (T) monitors the microstructure of the water while data links transmit the measured data to a nearby ship, where the data and the progress of the experiment can be monitored. The lines with arrowheads denote the propagating signals, which are scattered and reflected from the boundaries and inhomogeneities in the water. Supporting measurements to characterize the bottom, some of which are performed by divers, are not depicted in this figure, but are nonetheless vital to completely understanding and interpreting the results.

This project started in FY-83, progressed through the equipment testing stage, and has completed the first major scattering experiment off Panama City, Florida, in 30 m water depth. This first site was carefully chosen to serve as a benchmark for future sites, which will have much more complex characteristics. The results are expected to have a major impact on the design of high frequency systems for shallow water operation.

Figure 4

Typical experiment setup for studying the effects of shallow-water geological processes on high-frequency acoustic scattering. Two catamaran base towers with transmitting (S) and receiving arrays (R), temperature microstructure measuring system (T), and the telemetry data links are depicted.



Arctic Acoustics

A final example of the multidisciplinary investigations that typify experimental acoustics at NORDA is the Arctic Acoustics Program.

There has recently been an increased awareness that the Arctic region could play an important role in the future distribution of strategic forces, particularly submarines under the ice. When submarines are at sea, there is a requirement to operate sonar systems for navigation and ASW, as well as to understand the influences, limitations, and constraints imposed by the environment. When sonar performance is degraded by the environment, that degradation should be minimized by exploiting our knowledge of the environment and, perhaps, by designing new sonar systems that are especially "tuned" to the environment.

The ice cover makes a significant difference in the oceanography, the acoustic propagation, and the ambient noise of the region, as compared to more temperate ice-free regions. The surface is no longer an acoustic pressure release boundary when covered by ice. Therefore, acoustic propagation models for ice-free waters are not valid for the ice-covered regions. With ice cover, there is no wind stress on the sea surface to form mixed layers or wind-driven current, but sometimes low-salinity surface layers of cold water are caused by melting ice. Furthermore, the thermal stresses in the ice due to temperature changes cause high level impulsive noises that sometimes dominate the ambient; at other times, the shielding effects of the ice quiets the ambient noise to levels far below that ever measured in ice-free oceans. The Arctic is a unique environment and poses new problems for ASW and, hence, for acoustic measurements as well.

NORDA has assembled a multidisciplinary team of researchers to investigate Arctic acoustics and the influential environmental factors. Expertise is required in Arctic oceanography, ice properties and movement, personnel survival (researchers must survive), underwater acoustics, signal processing (sonar system performance), acoustic modeling (theoretical acoustics), and ocean engineering (equipment and instrumentation).

The most common technique for conducting acoustic measurements is to utilize a ship as the research platform, with the acoustic sensors and a data link to the ship nearby. Data acquisition and processing equipment on board is similar to a laboratory ashore. With the exceptions of the annoying motion of the ship and the inconvenience of cramped quarters and being away from home, being in the laboratory ashore is similar to being aboard the ship. Conditions at an ice camp, however, are different. The first concern must always be the survival of the field team. Potential hazards include storms; extreme cold; separation and rifting of the ice, which could destroy an entire tent camp; and hungry polar bears. During a storm, it is possible to become lost just by going from one shelter to another. Conventional lubricants can freeze, making equipment, that functioned perfectly on shipboard or ashore not work at all on the ice. The amount of time a human can spend outside working in the harsh environment and the total amount of available daylight severely limit the quantity and quality of work that can be performed. These and numerous other factors combine to increase the difficulty of performing measurements and acquiring useful data.

Summary

NORDA is a newcomer among the Navy Laboratories. From its beginning, NORDA has supported an active experimental acoustics program. Our first measurement efforts were modest and addressed fairly simple objectives. As NORDA matured as a research organization, it became more capable of fielding mutidisciplinary research teams to investigate complex acoustic problems. It is in these multidisciplinary research efforts that significant gains in knowledge can still be achieved, and NORDA has begun to contribute substantially to the field of acoustics research.

Acknowledgment

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The REX and the U.S. Navy GEOSAT

Jim L. Mitchell, Zachariah R. Hallock, J. Dana Thompson, Naval Ocean Research and Development Activity

Introduction

Developing a suitable satellite system for the global observation of the world's oceans is rapidly becoming a major thrust within the oceanographic research and development communities. Much of this effort within the U.S. Navy is appropriately focused upon mission planning for the Navy Remote Ocean Sensing System (N-ROSS), scheduled for launch in 1990. A major focal point for interim activity, however, is the U.S. Navy GEOSAT, launched in March, 1985, and the associated NW Atlantic Regional Energetics Experiment (REX).

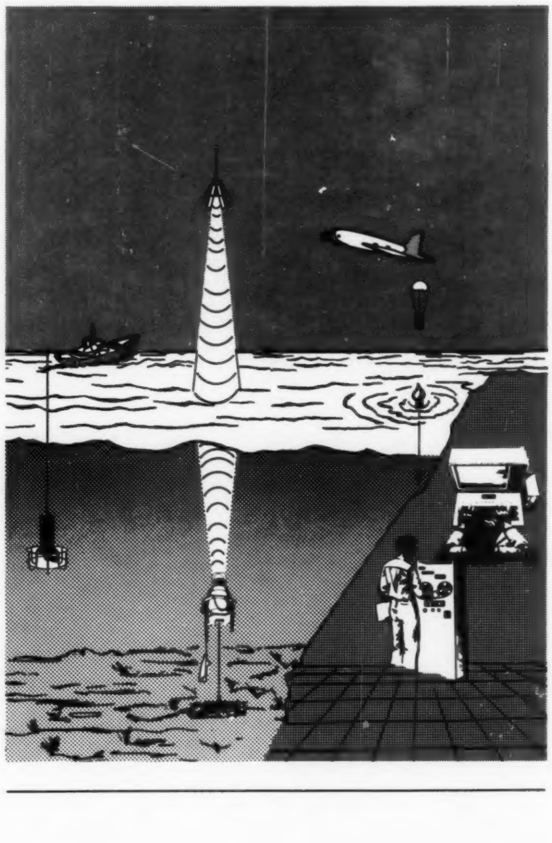
This paper presents an overview of the research objectives and specific plans for the multidisciplinary NW Atlantic REX. Ocean topography in the Gulf Stream/NW Atlantic region, as collected by the U.S. Navy GEOSAT (described below in *U.S. Navy GEOSAT: The Missions*), plays a major role in these REX plans. The REX represents the first concurrent application of several developing oceanographic techniques. The goal is to increase the fundamental, process-oriented knowledge of the dynamics and energetics of the Gulf Stream and associated rings. Thus, the program is ambitious, both with regard to the technologies employed and to the fundamental physics studied. The section, *Scientific Objectives of the REX*, provides an initial discussion of the fundamental oceanic processes to be studied during the NW Atlantic REX. The major experiment (see Figure 1) centers around the analysis of:

- Topographic data from the U.S. Navy GEOSAT;
- Long time series of sea surface and thermocline fluctuations collected via arrays of Inverted Echo Sounders with Pressure Gauges (IES/PG);
- Extensive Airborne Expendable Bathythermograph (AXBT) surveys using new equipment capable of measurement to depths of greater than 700 meters;
- Regional, eddy-resolving numerical model results (using much of the above data as model input and as a means of refining model dynamics).

These developing technologies are described in more detail in later sections.

Figure 1

Artist's concept of the NW Atlantic Regional Energetics Experiment (REX). The major components of the REX are sea surface topography provided by the U.S. Navy GEOSAT, field data collected from bottom-moored Inverted Echo Sounders with Pressure Gauges (IES/PG) and regional AXBT surveys, and extensive regional numerical modeling studies.



Scientific Objectives of the REX

Understanding the dynamics of the oceanic mesoscale is inseparably linked to a technical ability to observe and numerically simulate mesoscale circulation. Holland, Harrison, and Semtner provide an excellent review of the major scientific questions presently being addressed via eddy-resolving numerical simulation.[1] Interestingly, the context of much of their discussion is the same as that for the REX: regional mesoscale energetics. Also in common with the REX are several major questions:

- What processes account for the presence of mesoscale variability?
- Do mesoscale phenomena play a fundamental role in the character of the time-mean circulation?
- Can the effects of mesoscale circulation be parameterized in terms of mean field quantities?

In addition to these questions, meaningful future work clearly must address the impact of the sparsely measured barotropic (depth-independent) mode of the ocean circulation and the interaction of the circulation with bathymetry. Ongoing numerical modeling studies being performed at the Naval Ocean Research and Development Activity (NORDA) indicate that the introduction of the barotropic mode into regional Gulf Stream models leads to a decrease in the spatial and temporal scales of rings and meanders and to the occurrence of Gulf Stream bifurcation phenomena.[2]

Further, the subsequent indirect (i.e., the seamounts do not physically penetrate into the upper layer in these simulations) interaction of the circulation with the strong bathymetry of the New England Seamount Chain enhances the frequency of ring generation somewhat to the west of the seamounts and induces a persistent meander in the mean Gulf Stream path over the seamount chain.

Observational evidence suggests that these differences in the space/time scales of the stream fluctuations are maintained far downstream (eastward) from the seamounts themselves.[3] In fact, a valid question for the REX is: does a "Gulf Stream" (i.e., a coherent jet) exist downstream from the New England Seamounts? Of course, the relative order of the bathymetry's interaction with the circulation depends largely on the relative strength of the barotropic mode of the circulation. Other fundamental scientific questions to be addressed by the REX are:

- What are the pertinent space/time scales of Gulf Stream fluctuations in the region of the New England Seamount Chain?
- What is the relative importance of the barotropic and low-order baroclinic (depth-dependent) modes in governing the circulation within the REX region?
- How is mesoscale vertical structure influenced by interaction with bathymetry?
- What are typical energy partitions within the REX region? For example, what are the relative amounts of stored Available Potential Energy (APE) and released kinetic energy?

A major anticipated difficulty in using GEOSAT measured sea level in the REX region will be the removal of seamount geoidal effects. This is particularly a problem, since warm core rings tend to be quasi-stationary in the seamount region as a result of topographic (i.e., bathymetric) trapping.[3] On the other hand, numercial models of the circulation in the Gulf of Mexico successfully assimilate synthesized altimetry even when a considerable geoid error is included as part of the synthesized data.[4] In the NW Atlantic, the best available gravimetric geoids will be used to alleviate at least some of this potential problem.

Comparisons between the REX data and model results will represent a major local extension of the initial comparisons made by Schmitz and Holland.[5] Additionally, the unique ability of the REX-collected IES/PG data (see *REX Field Program* section below) and altimeter topographic residuals (see section *U.S. Navy GEOSAT*, below) to respond to barotropic fluctuations, as well as to the low-order baroclinic fluctuations, makes prospects for these REX data particularly exciting. The REX represents a logical next step, following MODE and POLYMODE, in the study of the oceanic mesoscale in a high variability ocean region.

U.S. Navy GEOSAT: The Missions

As implied by the acronym GEOSAT (GEOdesy SATellite), the primary mission for this satellite is improvement of the marine geoid. During the initial 18-month period after post-launch calibration and checkout, the U.S. Navy GEOSAT will collect precise measurements of the range from the satellite to the surface of the ocean via K_u-band radar. Coupled with an independent measure of the satellite's position relative to the global TRANET system of radiometric tracking stations, a measure of sea level relative to the earth's center of mass may be recovered with an absolute accuracy of approximately one meter radially. Refer to Tapley, Born, and Parke for a thorough discussion of satellite altimetry techniques.[6]

The primary geodetic mission data will be used to satisfy the operational needs of U.S. military inertial and strategic navigation systems. Therefore, raw range measurements collected during this 18-month period will be classified. The basic approach taken to satisfy the satellite's geodetic objectives is to place GEOSAT initially in an orbit whose groundtracks fill in the spatial gaps left in the SEASAT coverage by that satellite's early demise. As high spatial resolution is desired for these geodetic objectives, GEOSAT will initially lay down a tightly spaced global mesh of groundtracks, no two of which will completely overlap or repeat. The major oceanographic objective for GEOSAT is to use the altimeter for observing the oceanic mesoscale and the resulting sea surface topography (defined herein as that component of sea level arising from geostrophically balanced ocean currents). Of course, a nonrepeating pattern of groundtracks does not generally allow for the unambiguous separation of the geoidal and topographhic components of measured sea level, except in those limited regions where extremely precise gravimetric geoids have been measured.

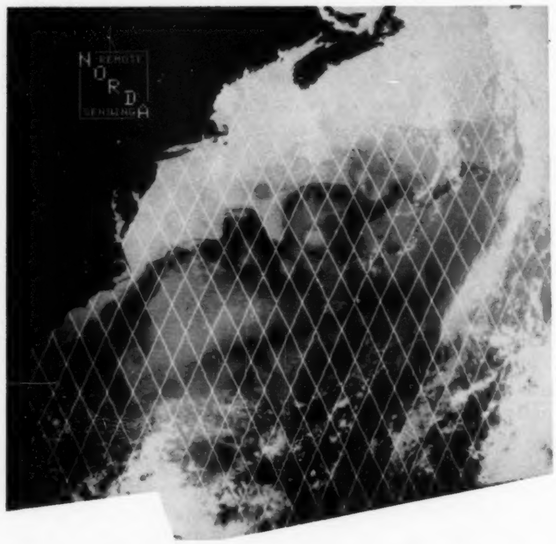
Thus, in the oceanographic research community, potential users of the topographic data collected during this initial 18-month mission are faced with a number of logistical (i.e., raw range measurements are classified) and technical (i.e., initial orbit is nonrepeating) restrictions.

In 1981, mesoscale oceanography was formally recognized as the secondary objective of the overall GEOSAT mission. To adequately accomplish this secondary objective, Mitchell proposed the extended oceanographic or GEOSAT-Exact Repeat Mission (GEOSAT-ERM).[7] During the two-year GEOSAT-ERM, which will begin at the end of the nominal 18-month geodetic mission, GEOSAT's orbit will be slightly modified to place the satellite in a so-called collinear or exact repeat orbit. Possible repeat periods run a gamut from 3 days to much longer periods. Repeat periods between 10 and 40 days are the most appropriate for quasi-synoptic recovery of the topographic signal associated with the oceanic mesoscale (see section *REX Numerical Modeling*, below). A 17-day repeat period has been selected from among these many possible collinear orbits. As well as providing nearly optimal sampling for mesoscale oceanographic studies, this particular choice of exact repeat orbits may allow declassification of all GEOSAT-ERM range data, which greatly increases their research utility. From this particular 17-day exact repeat orbit, the GEOSAT-ERM will not provide for significant geoid recovery beyond that already possible using unclassified SEASAT data because GEOSAT-ERM tracks would almost exactly overlay earlier SEASAT tracks. Thus, this particular orbit is specifically designed to alleviate any national security issues with regard to range data collected during the GEOSAT-ERM. Figure 2 illustrates the pattern of GEOSAT-ERM groundtracks laid down in the REX region during a 17-day period. The 17-day exact repeat orbit provides a global grid of 244 orbits; tracks are equally spaced 164 km at the equator. Data collected from the global grid of GEOSAT-ERM groundtracks will prove invaluable for fundamental studies of global mesoscale variability. These data will also provide a wealth of the space-time scale correlation statistics necessary for the development of objective data assimilation schemes to be eventualy employed in the operational use of N-ROSS collected altimetry. During a single 17-day period, these data will in essence provide the equivalent of 75 years of ship draft data.[8]

Additionally, GEOSAT will return measurements of both significant waveheight ($H_{1/3}$) and nadir wind speed magnitude. As with SEASAT, the measured $H_{1/3}$ values will be based upon the slope (in time) of the early return or "leading edge" of the reflected radar pulse. Inference of wind speed magnitude will be based upon the attenuation of the radar pulse by the ocean surface as measured in the observed backscattered power. However, this paper and the REX it describes will concentrate on the oceanographic use of the topographic range data.

Figure 2

Pattern of groundtracks in the NW Atlantic along which sea surface topographic fluctuations will be measured during the GEOSAT-ERM. During this two-year mission, global sea surface topographic fluctuations will be collected in a 17-day repeat cycle (i.e., every 17th day the satellite will overfly a given groundtrack). The background sea surface temperature mosaic is from recent NOAA polar orbiter IR images and provides a spatial scale for comparison with the GEOSAT-ERM groundtrack spacing.



U.S. Navy GEOSAT: Data Flow and Hardware

GEOSAT is being built and operated in orbit by the Applied Physics Laboratory (APL) of the Johns Hopkins University under contract to the Office of Naval Research. Launch support is being provided by the U.S. Air Force Space Division. Data will be routinely stored on board the satellite and dumped approximately twice per day when GEOSAT is in view of the single command and playback groundstation at the APL Satellite Control Facility. Within several hours of data receipt at APL, a quick-look version of the satellite's Sensor Data Record (SDR) will be transmitted from the APL groundstation to NORDA at the National Space Technology Laboratories (NSTL), Mississippi. At NORDA, these data will be subjected to initial scrutiny by research oceanographers. The quick-look data will be used in a developmental program (the GEOSAT Ocean Applications Program or GOAP) sponsored by the Oceanographer of the Navy to produce near real-time analyses of ocean mesoscale topographies in a NW Atlantic test site (which coincides with the REX region seen in Figure 3). Refer to Lybanon for a more complete description of GOAP.[9] As part of this developmental program, geophysically valid wind and waveheight measurements will be transmitted in near real-time from NORDA to the Fleet Numerical Oceanography Center (FNOC) in Monterey, California. These quick-look data will provide the basic research REX experimenters with timely information on the specific locations of mesoscale structures in the REX area. This information will be particularly useful in the targeting of P-3 AXBT surveys (see section *REX Field Program,* below).

On a longer time scale (i.e., one month or so post-realtime), precise orbital ephemerides, based upon Doppler TRANET radiometric tracking data, will be computed by the Naval Surface Weapons Center (NSWC) at Dahlgren, Virginia, and subsequently used to produce a Geophysical Data Record (GDR). This GDR will be used to satisfy both the primary mission geodetic objectives and the research oceanographic objectives, as well as to provide non-realtime corrections and checks on the quick-look, developmental GOAP data.

The GEOSAT hardware configuration consists of a single frequency (13.5 GHz) radar altimeter mounted on an improved GEOS-C bus (see Figure 4). The GEOSAT altimeter subsystem is a significantly modified version of the SEASAT altimeter. Three major modifications were made to SEASAT altimeter measurement strategy:

1. Factor of 2 wider gate window for tracking.
2. Diminished time lag for Automatic Gain Control (AGC) resets.
3. Enhanced instrument range and range rate digitization.

These modifications result in a lower instrumental noise floor (±2 cm precision in GEOSAT range vs. ±3.5 cm precision in an analogous SEASAT data stream) and an improved ability for the GEOSAT altimeter to track over ice and land. A major modification on SEASAT design has been the use of a long-lived low power traveling wave tube amplifier (TWTA) on GEOSAT. This alteration results in long predicted lifetimes (i.e., several years) for the GEOSAT altimeter subsystem. In fact, use of this low-power TWTA makes plans for the two-year GEOSAT-ERM feasible.

However, not all of the differences between GEOSAT and SEASAT design are entirely desirable from an oceanographic point of view. Some GEOSAT limitations and their related impacts are:

Lack of a boresighted radiometer for water vapor concentration measurements with GEOSAT

Isolated instances of water vapor pathlength errors as large as 40 cm may be observed, although every attempt will be made to use precise water vapor pathlength corrections. These corrections should be available from the Special Sensor Microwave Imager (SSM/I) scheduled to fly on board a Defense Meteorological Satellite Program (DMSP) satellite slated for launch in 1986. These corrections, albeit not always concurrent with altimeter overflights, should be avail-

Figure 3

The NW Atlantic REX region with contoured bathymetry. NORDA arrays of IES/PG's will be located in regions 2 and 3, far downstream of the recent University of Rhode Island (URI) array in region 1. The mean axis of the Gulf Stream (dashed) is from Halliwell and Mooers (reference 13). The domain in which GEOSAT topography will be available during the initial 18-month geodetic mission is outlined.

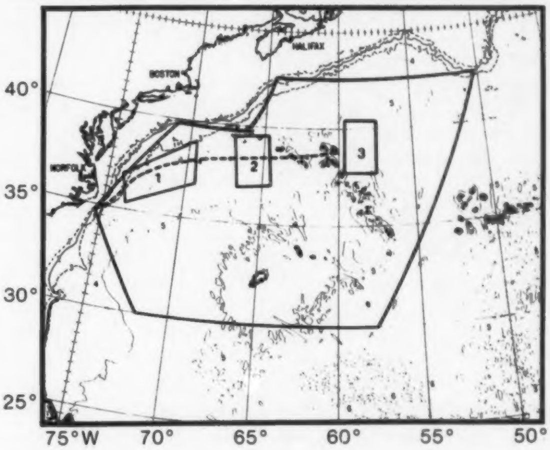
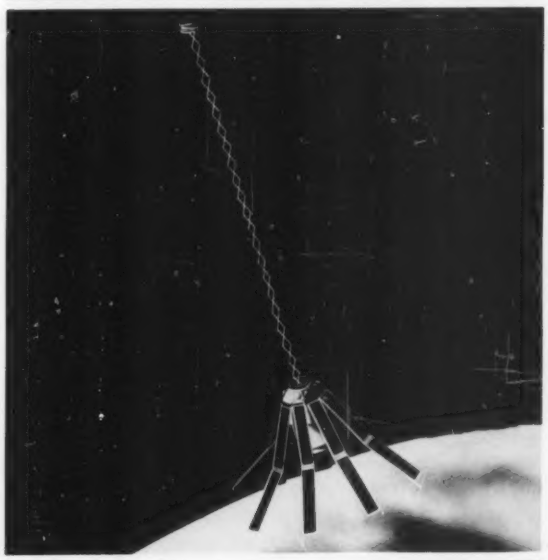


Figure 4

Artist's concept of the flight-configured U.S. Navy GEOSAT. Attitude stabilization is provided via the extended boom on the modified GEOS-C bus. The one-meter diameter altimeter antenna dish is located underneath the spacecraft.



able throughout the GEOSAT-ERM time frame. Long wavelength (10^3 km or greater) pathlength corrections, based upon atmospheric model output, will be made throughout both GEOSAT missions and will be included as part of the GEOSAT GDR.

Lack of an active thruster-controlled attitude adjust system (i.e., the GEOS and GEOSAT configurations are gravity gradient stabilized)

Error in both range and wind speed magnitude could result from any inaccuracy in knowledge of GEOSAT's attitude or nadir pointing angle. To overcome this potential problem, a scheme has been devised for estimating attitude based upon an analysis of the late or "trailing edge" return of the reflected radar pulse. Corrections based upon the estimated attitude will be applied to both range and wind speed magnitude as part of the ground data system processing. Following application of this correction scheme, it is anticipated that the residual error in range due to off-nadir attitudes will be no larger than 2 cm (1σ) for waveheights ($H_{1/3}$) of 16 m (residual error decreases with diminishing $H_{1/3}$). The corresponding residual error in the Automatic Gain Control (AGC), which responds to backscattered power of the pulse is about 0.1 dB. This results in an approximate 0.7 m/sec (1σ) error in wind speed magnitude at wind speeds near 20 m/sec.[10] The residual error diminishes with decreasing wind speeds. Thus, significant errors in range and wind speed magnitude are not anticipated, despite the lack of an active attitude adjustment system.

Lack of a laser retroreflector for range calibration independent of the nominal TRANET VHF and UHF radiometric tracking

Initial orbital ephermerides based upon TRANET tracking will allow for radially locating the satellite at approximately the one-meter level of accuracy (this absolute accuracy is not to be confused with the relative point-to-point precision of the range measurement). This accuracy level is adequate for many (though by no means all) oceanographic objectives. In particular, this accuracy is more than adequate for most mesoscale oceanographic studies. Note that the order one-meter error in absolute accuracy will be due to residual orbit determination error on very long wavelengths (i.e., of the order of the orbital circumference). The nominal one-meter orbit determination accuracy planned for GEOSAT represents a substantial improvement over the present accuracy of the SEASAT ephermides.

The major contribution of GEOSAT and, more particularly, the GEOSAT-ERM to the REX will be to provide oceanographic topography (computed as residual sea level after removal of the geoid and a tidal model) on rapid (quasi-synoptic) and broad (regional) scales. These data will be used in studies of the mesoscale dynamics and energetics of the REX region (see section *Scientific Objectives of the REX*, above). During the geodetic portion of the GEOSAT mission, topography in the REX region will be obtained by differencing classified GEOSAT measured sea level with existing classified gravimetric geoids of the region. The subsequent residuals or ocean topography will be unclassified and subsequently of much utility to the research community. Numerous studies have amply demonstrated the utility of satellite altimetry for recovery of mesoscale topography.[11] Major shortcomings faced in the use of SEASAT altimeter data were the short mission duration and a SEASAT mission strategy that never placed the satellite in an orbit capable of adequately resolving (both spatially and temporally) mesoscale topography in the cross-track direction. Data collected during the GEOSAT-ERM will overcome some of these SEASAT limitations. The satellite observed topography will be compared with in situ data collected from arrays of bottom-moored inverted echo sounders and extensive P-3 AXBT surveys as described in the following section.

REX Field Program

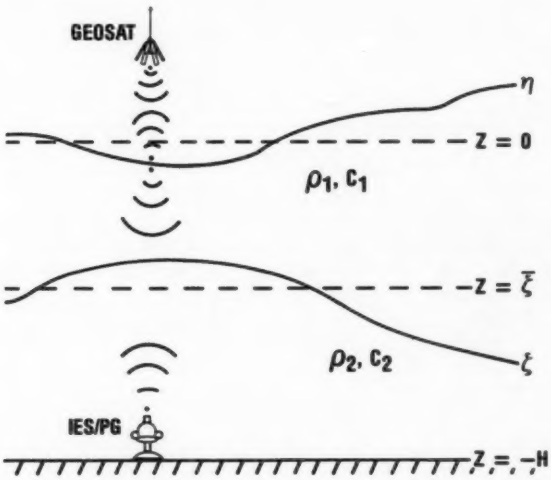
Field activities for the REX will focus on collecting and analyzing data from regional P-3 AXBT surveys and from two arrays of bottom-moored IES/PG's deployed slightly up and downstream of the New England Seamount Chain.[12] Figure 3 depicts the deployment of the moored instrumentation along the mean axis of the Gulf Stream.[13]

A major objective of the regional AXBT surveys, originating from Patuxent River, Maryland, will be to provide a regional, quasi-synoptic measure of the temperature structure associated with mesoscale features in the REX area. Extensive use will be made of the new Sippican deep AXBTs (Model ANSSQ-36 modified), which are capable of measuring to depths of at least 700 m. Use of these deeper instruments will greatly increase the utility of the AXBT data for studies of the APE distribution within the REX region. Intercomparison of sea level as measured from GEOSAT with the dynamic (baroclinic) topography based upon a vertical integration of these AXBT data (and reasonably assumed temperature-salinity relations) may allow for an assessment of the relative roles played by the barotropic and baroclinic modes of the circulation (see discussion in Section *Scientific Objectives of the REX*, above). Quasi-synoptic coverage of the REX region is possible using a single P-3 aircraft in 4 to 5 full flight days. Typical switchback patterns over the Gulf Stream frontal area, as well as individually targeted star-pattern surveys over specific mesoscale features, will be performed.

Actual deployment patterns for the moored instrumentation within the two regions shown in Figure 3 will allow for the collection of both cross-stream and local along-stream correlative records of fluctuations in acoustic roundtrip travel time (τ') and bottom pressure (p'). As discussed in Watts and Wimbush and Hallock these records may be interpreted in terms of fluctuations in main thermocline depth and free surface topography based upon a knowledge (or climatological assumption) of the appropriate temperature-salinity characteristics of the region.[14, 15] Figure 5 depicts a simplified two-layer ocean geometry for the single point intercomparison of IES/PG records and the overflying altimeter. Note that while the IES/PG has the ability to collect a long duration time series of barotropic and lowest order baroclinic fluctuations at fixed points in the ocean, the altimeter has the unique ability to provide rapid (quasi-synoptic) regional monitoring of the free surface fluctuations due to the sum of the barotropic and low order baroclinic components. Intercomparison of these data may lead to an ability to extrapolate lower order vertical structure information over the fairly broad REX region.

Figure 5

Schematic of the intercomparison between the overflying GEOSAT altimeter and bottom-moored IES/PG. Equations express the relationships used to derive fluctuations in main thermocline depth (ζ') and sea surface topography (η') from the measured time series of acoustic roundtrip travel time fluctuations (τ') and pressure fluctuations (p'). The coefficients A, B, C, and D depend upon the regional temperature-salinity characteristics. In the first equation, A is generally much larger than B (i.e., acoustic travel time fluctuations are dominated by thermocline fluctuations). In the second equation, both C and D may be of the same order (i.e., both barotropic and low order baroclinic modes may be equally important in governing topographic fluctuations).



$$\zeta' = A\tau' + Bp'$$

$$\eta' = C\tau' + Dp'$$

REX Numerical Modelling

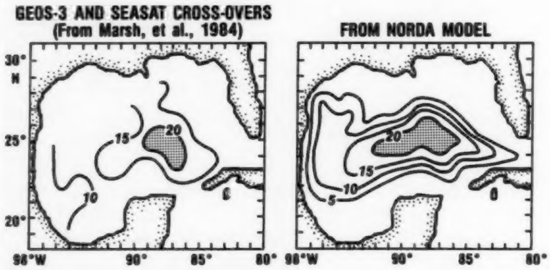
Perhaps the major limitation on the use of any satellite-collected oceanographic data is the inability (for the most part) of the satellite sensor to penetrate the ocean surface.[16] Clearly, what is needed is either a means of direct observational augmentation (e.g., hydrography, current meters, deep AXBT surveys) or an indirect means of inferring the internal density field associated with the ocean circulation based upon the surface observation alone.

At present, the most promising indirect approach seems to be the concurrent application of satellite altimetry and regional, eddy-resolving numerical models of the ocean circulation. In fact, the collection of sea surface topography via satellite altimeters and the subsequent assimilation of this topography into eddy-resolving numerical models promises to provide the cornerstone of any future global ocean monitoring and prediction system.[17] The methodologies of both satellite altimetry and eddy-resolving numerical modeling appear to be rapidly maturing and are closely convergent over the time scale of the coming decade. Ocean dynamical modeling at NORDA has concentrated on the use of low vertical mode, eddy-resolving primitive equation models (i.e., based upon mass and momentum conservation rather than direct vorticity constraints) in regional situations. Dynamical models have now become sufficiently realistic for some ocean regions that their results can be compared directly with altimetric data.[18] Figure 6 compares topographic variability from GEOS-3 and SEASAT crossovers[19] in the Gulf of Mexico with that observed in a two-layer model of the Gulf.[4] The major advantage of experiments within a bounded region is the relative ease of specifying lateral boundary conditions as opposed to the difficulty with which these conditions must be prescribed in open ocean domains (e.g., the NW Atlantic REX region).[20] Over the past year, numerous numerical experiments have been performed using the Hurlburt-Thompson models for the circulation of the Gulf of Mexico and simulated altimeter data. The latter is provided by sampling the model surface topography along "groundtracks" that represent realistic possibilities for future satellite altimeters. These studies by Kindle have been instrumental in selecting an appropriate range of repeat periods to consider the GEOSAT-ERM.[21] Perhaps the most encouraging interim result of these ongoing experiments is the demonstration by Hurlburt[22] and Thompson[4] that the exclusive use of sea-surface topography (as would be collected by the altimeter alone) is quite often adequate for initializing multi-layer, eddy-resolving models. These models also provide the diagnostic tool necessary to extrapolate the surface topography observed by the altimeter into an indirect measure of the deep pressure field (i.e., the lower fields in these 2- and 3-layer models). Hence, the satellite altimeter appears to have great utility for both prognostic and diagnostic studies with regional, eddy-resolving numerical models.

Finally, as noted in Born, Lame, and Mitchell[23] and again by Mitchell (1983),[7] the single satellite altimeter, flying in a collinear or exact repeat orbit, faces an unavoidable tradeoff between the spatial and temporal scales that can be simultaneously sampled (refer to Figure 2). The longer the repeat period of the collinear orbit, the tighter the spacing of resulting groundtracks (i.e., a more enhanced spatial resolution results). Similarly, an increased temporal resolution (faster repeat period) results in an unavoidable decrease in the crosstrack spatial resolution. The modeling studies of Kindle indicate the applicability of the regional, eddy-resolving numerical model as a tool for alleviating this sampling dilemma.[21] It appears that in some regions the model may be used to provide either an enhanced temporal or spatial resolution to the altimeter data set alone, possibly alleviating the unavoidable inadequacy of sampling with the single altimeter. While the open boundaries of the NW Atlantic REX region will admittedly be a problem, initial studies by Hurlburt and Thompson suggest that realistic eddy-resolving models of the circulation of the Gulf Stream from Cape Hatteras out beyond the New England Seamounts are possible.[2] As a parallel effort to the NW Atlantic REX described in this paper, GEOSAT-ERM data will be used in diagnostic and prognostic studies of the bounded circulation in the Gulf of Mexico. Hence, the long-range objectives of the REX are not limited to only that section of the Gulf Stream as seen in Figure 3, but include the Loop Current far upstream of the initial NW Atlantic REX area.

Figure 6

Comparison of the Gulf of Mexico altimetric sea surface variability (reference 19) and surface variability as observed in numerical simulations (reference 4). Both the rms magnitude of the fluctuations and the geographic location of maximum variability are in excellent agreement. Additionally, the altimeter results suggest the same westward extension as seen in the model results. This westward extension is a result of the quasi-periodic shedding of eddies from the Loop Current and their subsequent westward propagation.



REX Schedule and Milestones

The U.S. Navy GEOSAT was launched in March 1985. An initial REX IES/PG deployment cruise is scheduled on the USNS BARTLETT for May-June 1985. During 1985, three major sets of P-3 AXBT surveys are planned from Patuxent River, Maryland. As already noted, numerical experiments using synthesized altimeter data are already ongoing at NORDA and are now a major emphasis of the NORDA Ocean Forecasting Program. Actual data from the U.S. Navy GEOSAT will be available for comparative and diagnostic studies in conjunction with numerical model results during 1985. Eventually, assimilation of data from the GEOSAT altimeter into several regional circulation models (e.g., Gulf Stream and Gulf of Mexico models) is planned.

As a result of the greatly increased oceanographic utility of GEOSAT topographhic data during the GEOSAT-ERM, the NW Atlantic REX will be directly augmented by academic researchers supported under a special Contracts Research Program (ONR/CRP) research option to begin in 1986 with a focus on western boundary current dynamics and ocean prediction. Additionally, the global utility of the GEOSAT-ERM for mesoscale studies will enhance other programs, including the ONR Southern Oceans Program, the Minerals Management Service Gulf of Mexico Program (which has been extended to better overlap with the GEOSAT-ERM), and the NOAA Tropical Oceans-Global Atmosphere (TOGA) Program.

Acknowledgment

The NW Atlantic Regional Energetics Experiment described in this paper is sponsored by the Naval Ocean Research and Development Activity (NORDA) of the Office of Naval Research. The Navy GEOSAT Mission which will produce the altimeter data has been developed under the management of Mr. R. G. Joiner of the Office of Naval Research.

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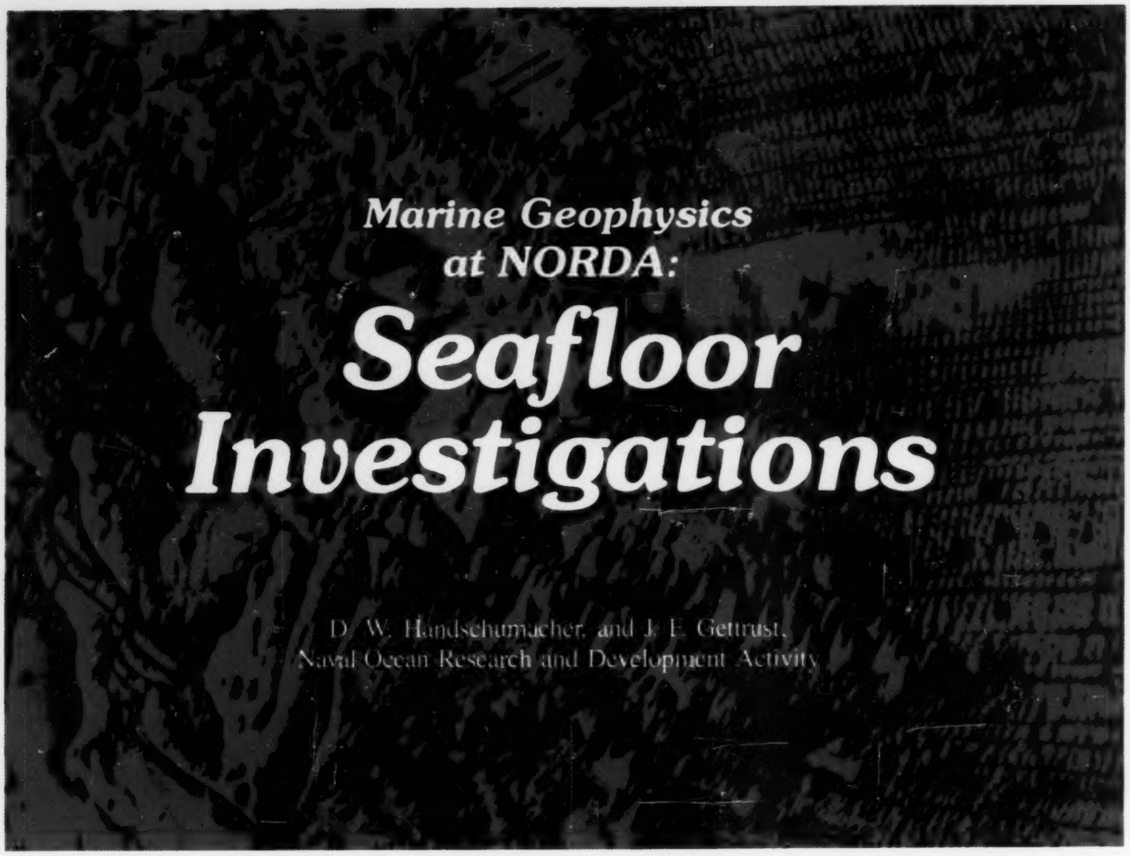

Marine Geophysics at NORDA: Seafloor Investigations

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Naval Ocean Research and Development Activity

Introduction

The marine geophysics program at the Naval Ocean Research and Development Activity (NORDA) focuses on geomagnetism, plate tectonics, and seismic research. These research efforts span the spectrum from developing a basic understanding of earth processes to support of advanced system development. Broadly stated, the research projects are directed towards providing the Navy with a better understanding of how the sea floor and sub-bottom affect sound propagation, as well as defining the source and spatial and temporal variability of potential fields, and the effects of these features on Navy systems and operations.

The development of a detailed understanding of the marine environment is of particular importance, considering that the Navy must deal with increasingly quieter targets in more complex environments. This problem is analogous to detecting ever smaller signals imbedded in a noise field. The solution is to improve our understanding of the noise. In this case, the noise generated by the earth (e.g., geomagnetic signals, earthquake swarms, etc.) and by the interaction of the signal with an unknown earth structure (e.g., compressional to shear wave conversions, sub-bottom seismic refractions, etc.) are significant components of the total noise field. By developing detailed, quantified models of the marine environment, NORDA scientists provide support for existing and future Fleet needs.

A historical perspective of marine geology and geophysics demonstrates how important understanding of basic earth processes can be to the Navy. Optimizing the performance of sonar and magnetic anomaly detection (MAD) systems developed or perfected during World War II for ASW purposes necessitated an improved understanding of the marine environment. As a result, after the end of World War II, the Office of Naval Research (ONR) supported marine geophysical research at a level that led to significant breakthroughs in our knowledge of the earth.[1]

This work led to the syllogism of plate tectonics, a model for tectonic processes that explains the gross structure of the ocean basins and continental margins.[2,3] One of the aspects most critical to the development of this model is the concept of seafloor spreading;[4,5,6] a concept that has allowed marine magnetic anomaly lineations to be related to the age of the oceanic crust. In this model, the anomaly lineations represent crustal isochrons produced by past polarity reversals of the earth's internal magnetic field, which were "frozen" into young oceanic crust as it cooled below the Curie temperature during the spreading process. The oceanic crust is, in this context, similar to a magnetic tape recording of the opening of the ocean basins. The plate tectonics model explains with elegant simplicity the origin of oceanic ridges (where new oceanic crust is generated), circum-Pacific earthquake activity (where oceanic crust is subducted into the earth's interior), the relative motion of the continents, and an extensive list of other kinematic and structural features. This model makes it possible to predict bottom topography, sediment type and structure and, thus, the gross distribution of geoacoustic properties of the sea floor in a systematic manner.

Geomagnetism/Plate Tectonics Program

In 1979, NORDA established a basic research program to further investigate the geology and geomagnetism of ocean basins within the framework of plate tectonic theory. The program's broad objectives address fundamental questions concerning the origin and nature of seafloor structure, magnetism, and tectonism (Figure 1). The research approach is empirical and predicated on field investigations involving airborne and shipborne deep-tow/surface-tow magnetic surveys. Airborne magnetic surveys are vital to the program; they provide the most cost-efficient method of study in remote regions where supporting ship operations is logistically and financially difficult.

One of the first areas identified for an intensive aeromagnetic survey was the western Pacific. Even a cursory examination of a world bathymetry map (Figure 2) reveals the anomalous complex structure of the sea floor in this region. Numerous deep basins are transected or bounded by oceanic rises, plateaus, troughs, and ridges. In addition, the region contains an anomalously large number of seamounts which occur in linear chains, amorphous groups, and isolated settings. Prior attempts to develop a coherent tectonic model for the evolution of these structures had been hampered by the presence of a regional magnetic "quiet zone" (Figure 1).

Figure 1

This figure schematically illustrates the empirical approach taken by NORDA's geomagnetism and plate tectonics program in addressing fundamental questions concerning seafloor structure, magnetism, and tectonism. Examples of research operations discussed in the text are presented and experiment sites located with respect to seafloor age.

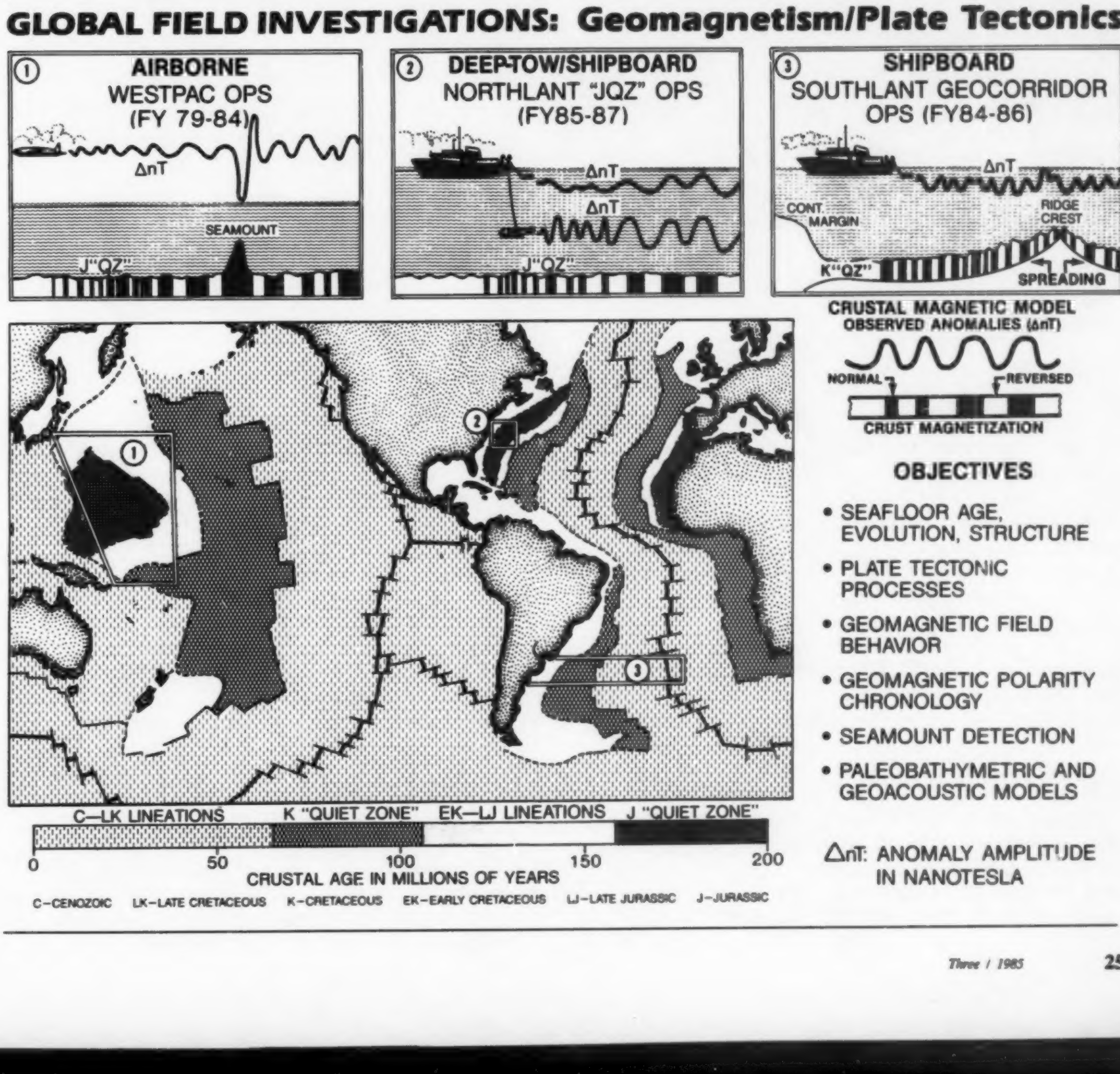
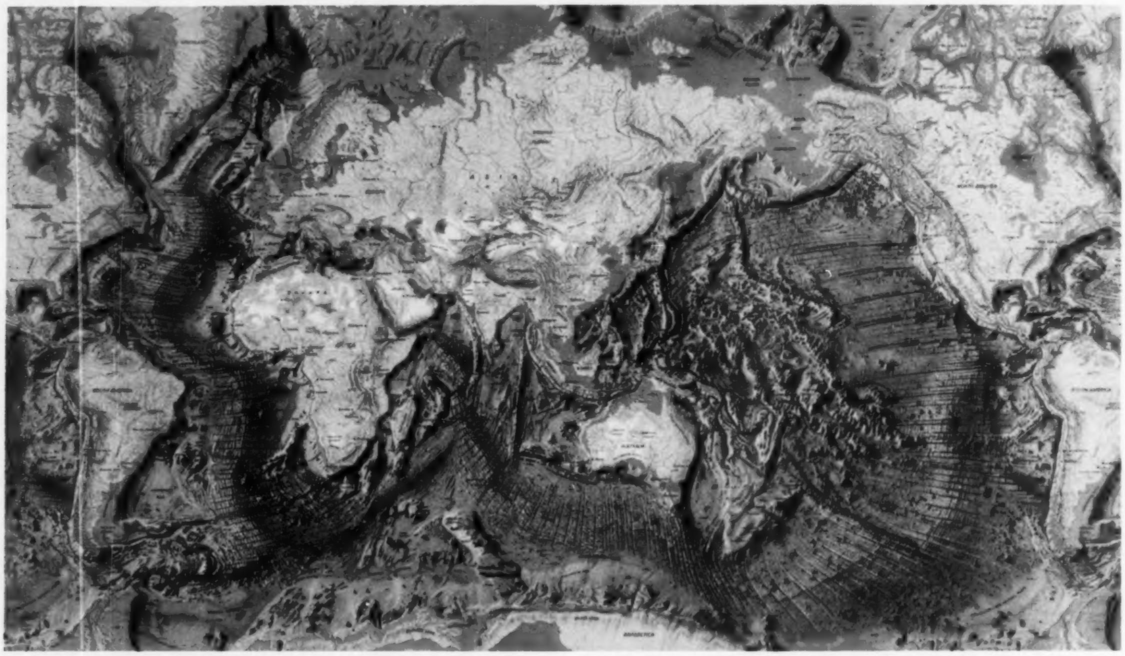


Figure 2

World bathymetry map compiled by Heezen and Tharp under ONR sponsorship.[19] *Note the anomalously complex structure of the western Pacific, which is located within or surrounding the Jurassic "quiet zone" (JQZ) identified in Figure 1.*



According to a widely accepted hypothesis,[7,8] the sea floor underlying this quiet zone and other quiet zones marginally located over coeval crust of the North Atlantic and Indian Ocean basins was formed during the mid to late Jurassic (approximately 150–180 million years ago) period of constant, i.e., nonreversing, geomagnetic field behavior. Interpreted as such, the Jurassic quiet zones (JQZs) represent blank sections in the marine magnetic record within which detailed study of the earliest spreading history of these oceans is precluded by the absence of crustal isochron control provided by magnetic reversal anomalies.

Shipboard and deep-tow magnetometer records, however, recently provided evidence that at least the youngest portions of the JQZs contain short wavelength reversal-type anomalies that could be related to seafloor spreading during a period of frequent reversals rather than a period of constant polarity.[9,10,11] This conclusion, if valid for older portions of the JQZs, would significantly impact not only tectonic studies of the JQZ regions, but also studies seeking to define the chronology and mechanism of the earth's magnetic field reversals. A primary goal of NORDA's WESTPAC aeromagnetic operations was to regionally test the frequent reversal model for the origin of the JQZs by determining whether or not seafloor spreading lineations can be resolved in these regions (Figure 1).

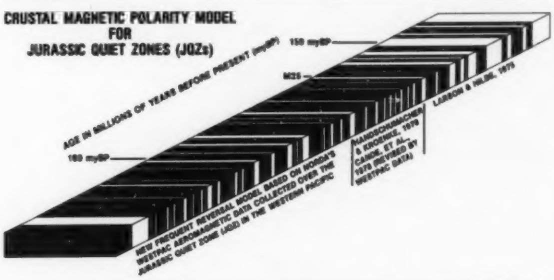
During WESTPAC OPS, NORDA collected over 100,000 nm of low-altitude (1000–2000 ft) aeromagnetic measurements in sparsely surveyed areas of the western Pacific aboard P-3 Orion aircraft. Much of this data set was collected during flight operations specifically targeted to search for linear anomalies in the JQZ.

The search was an unqualified success. A well-defined sequence of low-amplitude (10–50 nT), short wavelength (10–40 km) anomalies was identified in the JQZ east of the Mariana trench. Interpreted to be of the seafloor spreading variety, these magnetic anomalies have been used as the criteria for extending the geomagnetic reversal time scale backward in time to the earliest stages in the evolution of the Pacific, Atlantic, and Indian Oceans (Figure 3).

The success of the WESTPAC OPS provides incentive and precise criteria for re-examining the magnetic morphology of JQZs elsewhere. While the Pacific data are significant, a global correlation of the Pacific anomaly sequence would make the frequent reversal hypothesis for the origin of the JQZs more conclusive. In addition, if these anomalies are to be used for detailed tectonic studies, mapping programs must be initiated. It should be noted that the Pacific anomalies were mapped in a region where the crust is inferred to have formed at a relatively high spreading rate (>10 cm/yr). Crust formed at slower spreading rates will produce a less resolvable magnetic signature because individual polarity bands within the crust will be narrower. In the North Atlantic, for instance, model studies based on the predicted spreading rate of less than 3 cm/yr indicate that it will not be possible to resolve the predicted anomaly record in the JQZ with airborne or shipborne surface-tow magnetic surveys (Figure 4). However, the predicted anomaly pattern would be easily resolvable with a magnetometer towed at mid-depths (3000 m). For this reason, we plan to conduct a specialized deep-tow magnetometer operation off the east coast of the United States in FY 86 (NORTHLANT JQZ OPS, Figure 2). During this field operations we will test the frequent reversal model and determine the survey requirements for future regional JQZ mapping programs. If successful, this operation will show that detailed isochron information, critical to deciphering the initial rifting processes that produced the Atlantic ocean basin, exists and is resolvable in the JQZs.

Figure 3

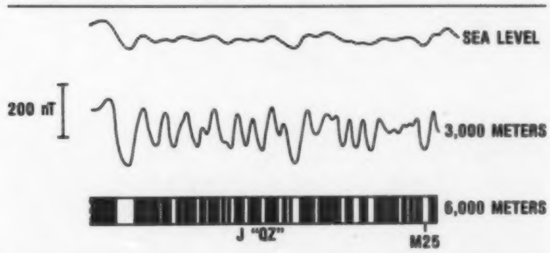
New crustal magnetic polarity model for the Jurassic quiet zones developed from magnetic lineations resolved in data from WESTPAC aeromagnetic survey operations. The model shows narrow banding of alternating polarity, which is attributed to seafloor spreading during a period of frequent reversals prior to anomaly M25 time. Age extrapolations were made using a constant spreading rate assumption and the time scale for post-M25 anomalies of Larson and Hilde.



The WESTPAC OPS also provided scientists with an opportunity to field test the use of aeromagnetic surveys to locate such uncharted bathymetric structures as seamounts (which produce a characteristic geomagnetic signal that can be resolved during low-altitude airborne magnetic surveys, Figure 1). This effort addressed the Navy's continuing requirement to detect and chart seamounts within its operational areas. In extreme cases, these seamounts can pose a hazard to surface or submarine navigation. More often, they represent significant environmental features that can adversely affect sensor/weapons systems. The introduction of deeper running submarines with increased operational ranges has expanded this requirement to large ocean areas where only reconnaissance grade bathymetry is available. One area of particular concern is the western Pacific. This region (Figure 2) contains an anomalously high number of randomly distributed seamounts. Outside localized areas that have been bathymetrically surveyed in detail, the probability of encountering uncharted seamounts or seamounts that shoal at depths less than those reported is considered to be high.

Figure 4

Predicted North Atlantic JQZ crustal magnetic polarity model based on Pacific data with synthetic anomaly profiles generated at sea level and at a depth of 3000 meters. These profiles demonstrate the requirement for deep-tow magnetometer operations to resolve the predicted JQZ anomalies in the North Atlantic JQZs.

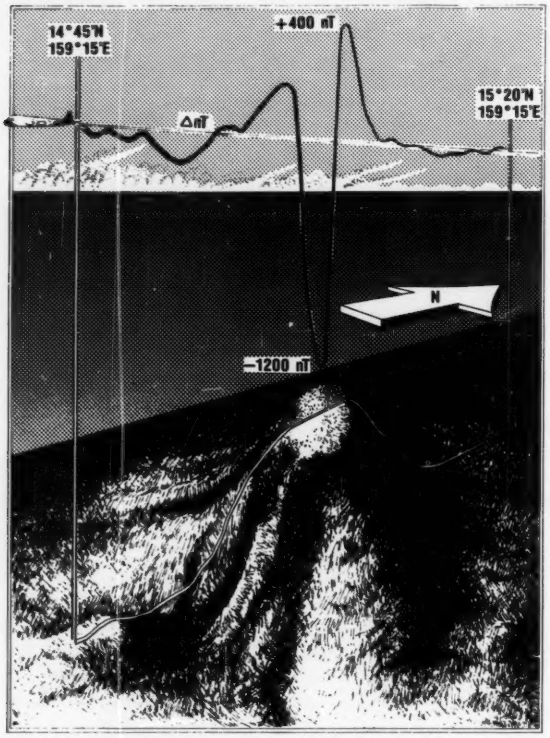


During WESTPAC OPS79, aeromagnetic survey data were used to predict the existence of three large, uncharted seamounts near Wake Island. Subsequent bathymetric surveys conducted by the Hawaii Institute of Geophysics (HIG) under NORDA/ONR sponsorship confirmed the aeromagnetic results. One seamount was found to rise over 4000 m above the surrounding sea floor and shoal at a depth of less than 1200 m (Figure 5). Subsequent flight operations were used to field test the potential application of aeromagnetic surveys to validate predicted sites of uncharted seamounts derived from SEASAT radar altimetry data. Although numerous sites were overflown, only one (Figure 6) yielded an apparent magnetic confirmation for the SEASAT prediction.

Although the western Pacific represents a region where the understanding of the gross structure, age, and evolution are still significant issues, these aspects of plate reconstruction are no longer a first-order issue in the South Atlantic. Initial rifting, defined by the "continental fit" of Africa and South America,[12] occurred about 130 million years ago.[13,14] NORDA scientists are using geomagnetic data from the South Atlantic (SOUTHLANT GEOCORRIDOR OPS, Figure 1) to address more detailed questions about the basin. The experimental design is to gather detailed geophysical data along the narrow corridor that extends from the eastern margin of South America to the axis of the mid-Atlantic ridge. Because the gross tectonic history of the Atlantic basins is well understood, it will be possible to take the detailed information from the geocorridor and extrapolate parameters of interest to the Navy to the whole South Atlantic basin. This particular project underscores the value of having developed global scale models (in this case, plate tectonics) to meet more direct Navy needs (e.g., obtaining estimates of geoacoustic parameters for the South Atlantic basin).

Figure 5

This figure graphically illustrates the detection of uncharted seamounts using areomagnetic observations. The large (1600 nT) magnetic anomaly shown in this figure was used to predict the existance of a large uncharted seamount near Wake Island. This prediction was confirmed by the Hawaii Institution of Geophysics (HIG) which ran bathymetric profiles over what is now known as SEASCAN seamount. An artist's conception of the seamount's bathymetry derived from the HIG data is shown.



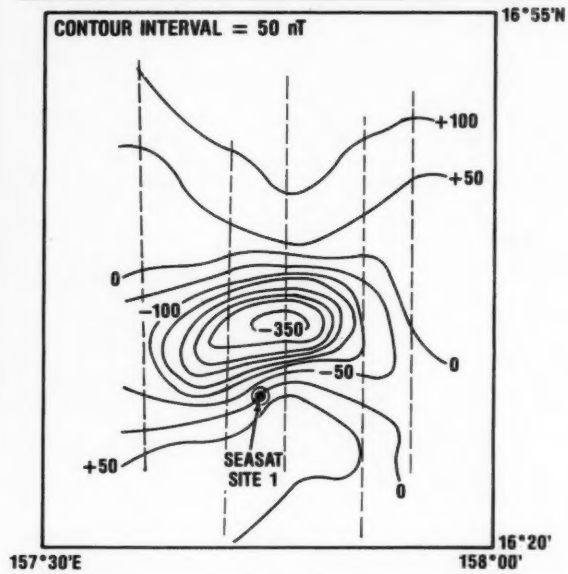
Seismology Program

The seismology program at NORDA complements the geomagnetic/plate tectonics effort by measuring geoacoustic properties in regions of Navy interest (Figure 7). The design and location of seismic experiments often is predicated on earth models derived from geomagnetic observations.

NORDA's seismic program is relatively young; the first major seismic refraction/reflection field program was conducted in 1979 when NORDA scientists participated in the Rivera Ocean Seismic Experiment (ROSE). This experiment was unique in that essentially every major marine geophysics group in the United States participated.[15] The goal of this project was to investigate the structure of young oceanic crust near the East Pacific Rise using the seismic refraction technique. More than 80 ocean bottom seismographs (OBSs) recorded both explosive "shots" fired from ships and earthquakes generated by the spreading of the oceanic crust. The indirect sampling of the evolving oceanic crust is of interest to the Navy because very low frequency (VLF) acoustic waves (roughly, 5–30 Hz) may become important to ASW surveillance, and acoustic signals at these low frequencies interact with the oceanic crust. Interpretations made of the crustal structure and seismicity in this area show that the oceanic crust structure is heterogeneous, that seismic (acoustic) velocity anisotropy in the upper mantle (which underlies the crust) is nil, and that measurable changes in the seismic velocities occur within the crust over the age range from 0.5 to 4.5 million years. The first analyses of ROSE data can be found in a special *Journal of Geophysical Research* (Vol. 87, B10, 1982).[15]

Figure 6

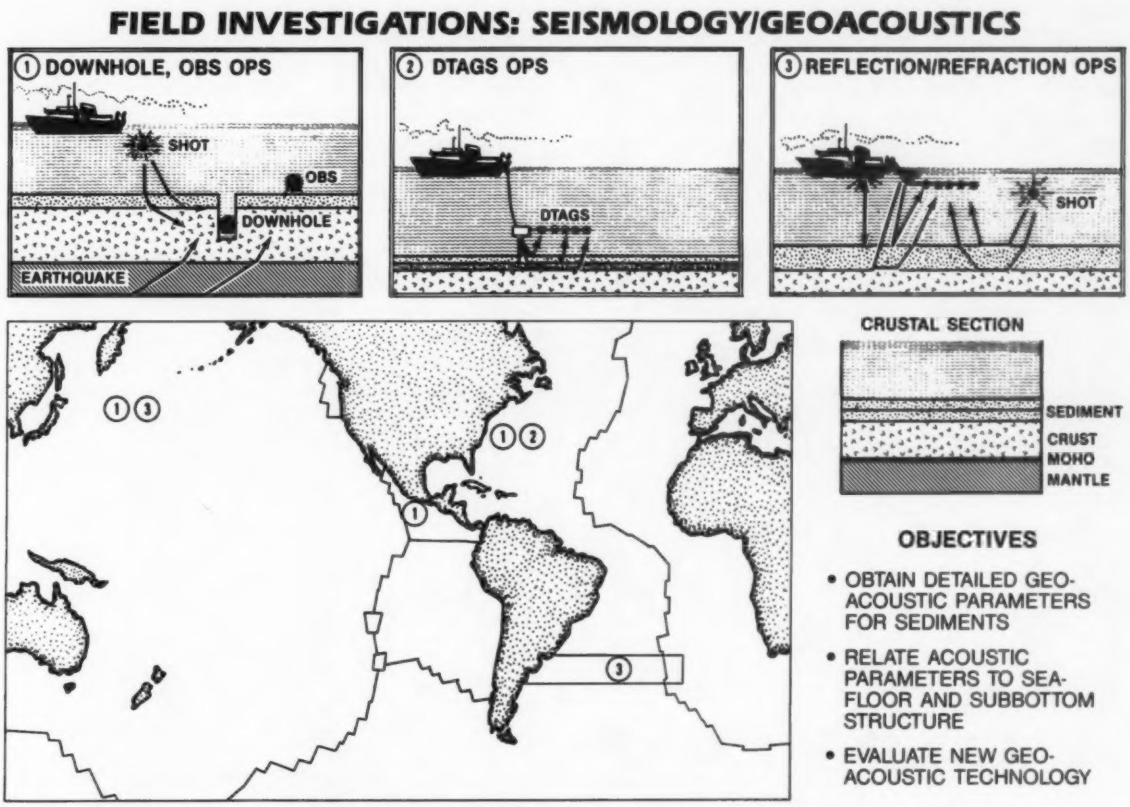
WESTPAC aeromagnetic contour map (flight tracks dashed lines), which provides independent confirmation of a SEASAT radar altimetry predicted site for an uncharted seamount.



NORDA seismologists also played a role in evaluating subbottom borehole seismic systems (Figure 7). The thrust of this program was to evaluate marine borehole instruments as sensors to verify compliance with future test ban treaties and for ASW surveillance. In 1982, the HIG borehole instrument was deployed off the Kamchatka Peninsula. Scientists from HIG, Oregon State University, and NORDA deployed OBSs in that area, and "shot" seismic profiles to the borehole instrument and the OBSs. These data have been used to compare the performance of the various sensor systems. Preliminary results from this experiment suggest that the signal-to-noise ratio (SNR) of the borehole instruments may

Figure 7

This figure schematically illustrates the research efforts and regions in which NORDA's seismologists have conducted field projects. The ocean bottom seismograph (OBS), borehole seismic, and deep-towed multichannel seismic systems are emphasized in the text.



be significantly better (>20 dB in certain frequency bands) than those found for conventional OBSs and bottom-mounted hydrophones. This improved SNR could impact the design of future ASW systems.

In a similar experiment carried out in the South Pacific, the marine Seismic System (MSS) borehole instrument, which was funded by the Defense Advanced Research Project Agency, produced similar results. The efficient transmission of 5–20 Hz seismic energy within the oceanic crust,[16,17] coupled with the lower noise figures found during these experiments, suggests that borehole instruments may have Navy applications. As a consequence, additional testing of marine borehole seismic systems in various marine environments is being planned.

The structure of the oceanic crust beneath the deep oceans may be of long-range interest to the Navy; however, bottom and subbottom acoustic wave interaction is of considerably greater importance in shallow water (the continental shelf regions, for example). NORDA is currently carrying out a VLF acoustic/seismic special focus project in which the energy partitioning between the water column and solid earth is being studied. The first field program under the VLF project will be conducted in June 1985 on the continental shelf offshore from Cape Fear, North Carolina (Figure 8). Acousticians and seismologists from NORDA will measure the acoustic signal and noise distribution within the water column, compare the SNR of solid earth path and pure water path signals, and relate these observations to the subbottom structure. One unique aspect of this experiment is that both impulsive and continuous wave (CW) acoustic sources will be used and both conventional acoustic and seismic sensors will be deployed. The acousticians' vertical hydrophone array will allow the scientists to study the acoustic field within the water column in detail. The seismologists' OBSs will allow them to compare the relative performance of geophones, which are sensitive to vertical or horizontal ground velocity, with each other and with bottom mounted hydrophones.

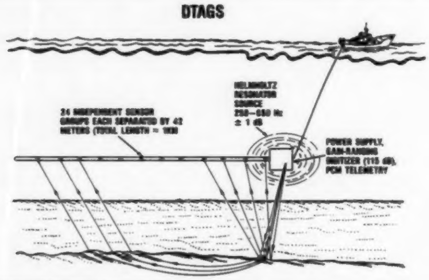
By combining the expertise of acousticians and seismologists in a single experiment, the propagation characteristics of VLF acoustic signals can be related to earth structure within a passive continental margin; this relationship makes it possible to better predict geoacoustic properties in similar geologic environments.

Figure 8

A schematic presentation of the Cape Fear experiment, which will be carried out in June 1985. Acousticians from NORDA Code 240 will deploy the vertical hydrophone array shown in this figure. Seismologists from NORDA will deploy the OBSs in various configurations. Both impulsive and CW acoustic sources will be used to study the geoacoustic properties of the region.

Figure 9

This figure presents the general configuration of NORDA's Deep Towed Array Geophysical System (DTAGS). Note that the acoustic source and multichannel hydrostreamer are towed close (500 m) to the bottom at full ocean depths. The deep tow configuration limits towing speeds to approximately 1.5 knots; however, the increased resolution that results from this geometry improves our sampling of the deep-sea sediments by an order of magnitude.

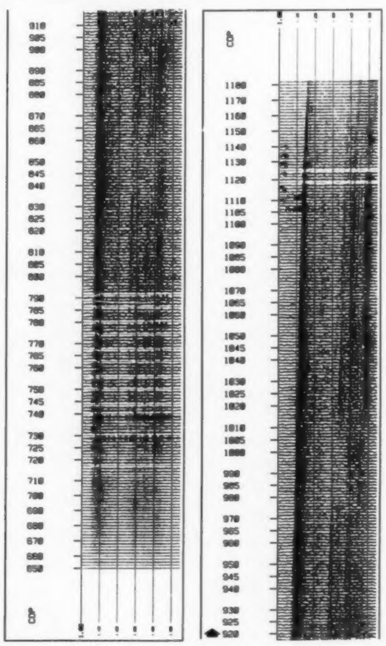


Another focus of NORDA's seismology program is the Deep Towed Array Geophysical System (DTAGS), which was developed by engineers in NORDA's Ocean Technology Division. NORDA geophysicists are taking the lead in applying this system to Navy environmental problems. DTAGS is a multichannel seismic system similar to those used with great success in petroleum exploration.[18] The primary difference between DTAGS and conventional multichannel seismic systems is that the DTAGS source and receiving array (Figure 9) can be towed at full ocean depths. This deep-tow configuration allows NORDA scientists to investigate the structure of deep-water marine sediments in significantly greater detail than has previously been possible. Estimates of the acoustic impedance and attenuation of the sea floor and subbottom at midrange (300–600 Hz) frequencies and the spatial variability of these properties will significantly improve the accuracy and predictive power of the Navy's geoacoustic models.

Engineering field tests of DTAGS were completed in September 1984. During this field exercise, seismic profiles were taken south of Bermuda; these profiles are the first "geophysics" data collected with DTAGS. Data from this cruise have been used to make a preliminary seismic section

Figure 10

A common depth point (CDP) stack of DTAGS data taken south of Bermuda during September 1984. This seismic section was produced by Digicon Corporation for NORDA as a benchmark evaluating their DISCO multichannel seismic analysis system.



of the sediment structure in 4900 m of water south of Bermuda (Figure 10). These data were taken with the DTAGS source and hydrostreamer deployed approximately 500 m above the sea floor. A swept frequency (250–650 Hz) signal 125 msec in duration was used. The deconvolved signals are shown in Figure 10 as a cross section of deep oceanic sediments along a short section of one profile. With a complete 24-channel seismic data set taken at 16 m intervals along the profile, it will be possible for the first time to obtain excellent in situ compressional velocity estimates in the upper several hundred meters of sediments at true ocean depths. The dense sampling capability of DTAGS also will make it possible to develop a viable statistical model for the spatial variability of sediment properties in that environment.

Summary

Both the geomagnetism/plate tectonics and seismology/geoacoustics programs at NORDA emphasize the measurement of environmental properties of interest to the Navy. The programs complement ongoing research efforts in academia, other government laboratories, and other NORDA Divisions. This aspect of the research program is well documented by the cooperative research efforts discussed in earlier sections of this paper. The emphasis of cooperative research efforts is in recognizing that a multidisciplinary approach to marine studies will enhance our ability to study the complex marine environment. NORDA geophysicists can take advantage of the breadth of the scientific research program at NORDA (e.g., image processing, oceanography, numerical analysis) to refine earth models to the degree required to meet current and potential Navy needs.

Acknowledgments

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MODELS OF SOUND PROPAGATION IN THE OCEAN

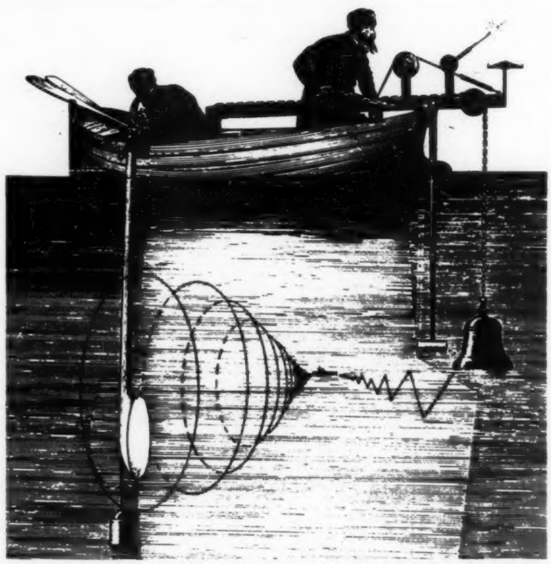
W. A. Kuperman, Naval Ocean Research and Development Activity

The physics of sound propagation in the ocean is of current interest because of environmental as well as military considerations. Its origins date back centuries; for example, Leonardo da Vinci noted that sound travels to great distances in the sea, and he even anticipated the passive-sonar fundamental consideration of avoiding self-noise by suggesting that the listener " . . . cause your ship to stop . . ."[1] before deploying a listening tube through the air water interface. This listening tube was improved on by Colladen[2] who, on Lake Geneva in 1827 employed a trumpet-like device as an underwater sound receiver together with a submerged bell to, in essence, assemble an active-sonar system (see figure 1) with which he measured the speed of sound to an accuracy of about two tenths of one percent. In addition, "Colladen marvelled that so little energy at the source could be transmitted so great a distance through the water medium and could still be detected by the trumpet receiver." It is still believed that only sound will propagate man-made signals to great distances in the sea.

The development of the theory of acoustics theory has followed a different historical path than optics/electromagnetic theory[3]. While there had been a long running battle in optics between ray and wave theory, acoustics originally developed with wave and vibration concepts as far back as ancient Greek times. Thus, for example, musical sound is the result of air motion generated by a vibrating musical instrument. This sound is propagated in an analogous manner to water surface waves which propagate disturbances (signals) but not matter long distances. The bending of sound around corners is then easily understood in the context of diffraction in the water surface *wave* analogy. In acoustics, the ray picture evolved as a mathematical approximation to wave theory[3]. In underwater acoustics, in which the medium is inhomogeneous and bounded by complicated interfaces, ray theory has historically proved to be an indispensable tool for understanding and studying sound propagation. However, with the advent of computers and the recent developments of numerical physics, sound propagation in the ocean can now be studied and quantitatively described in greater and greater detail with the more exact wave theory.

Figure 1

The experiment to measure the speed of sound was performed by Colladen and Sturm[2]. They were actually in two boats ten miles apart using a light source and a stop watch to perform the time of propagation measurement. This figure is a composite of their two sketches of separate source and receiving boats put together to indicate the fundamental components of a sonar system. The source and listening device is shown here detecting a hypothetical submarine in Lake Geneva. The fundamental acoustic phenomena that would be of interest for this scenario are the same as they are today: propagation characteristics, noise, scattering and acoustic target properties.



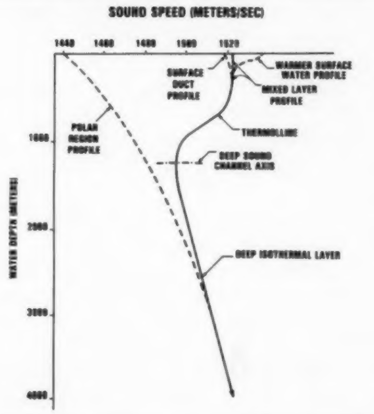
In this paper, we present a brief overview of computer modeling of sound propagation in the ocean. We will begin by describing the ocean acoustic environment, and we follow with a discussion on the different types of propagation models. We then conclude with a description of the thrust of the Naval Ocean Research and Development Activity (NORDA) program in basic research modeling of sound propagation in the ocean.

The Ocean Acoustic Environment

In underwater acoustics, the speed of sound plays the same role as the index of refraction does in optics. The sound speed in the ocean is an increasing function of temperature, salinity and pressure. Seasonal and diurnal changes effect these oceanographic parameters in the upper ocean. In addition, all of these parameters are a function of geography. Figure 2 illustrates a typical set of ocean sound speed profiles illustrating greatest variability near the surface as a function of season and time of day. In a warmer season (or warmer part of the day), the temperature increases near the ocean surface, and hence the sound speed increases with decreasing depth.

Figure 2

Generic ocean sound speed profiles.



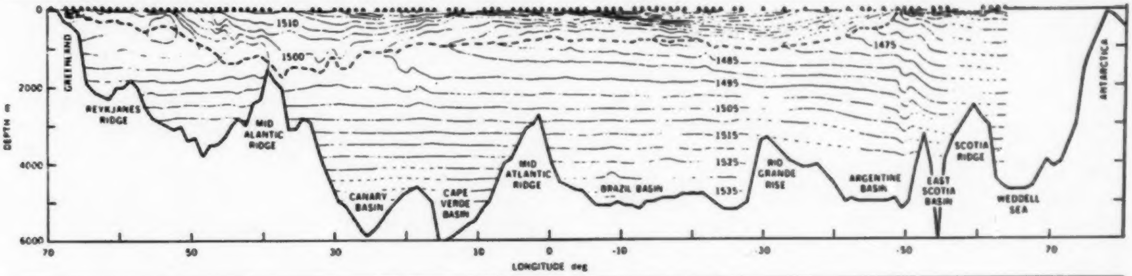
In nonpolar regions, the oceanographic properties of the water near the surface result from mixing activity originating from the air-sea interface. This near surface "mixed layer" has a constant temperature (except in calm, warm surface conditions where the situation is as described above). Hence, we can in this mixed layer have near isothermal conditions; or under certain temperature and pressure gradient conditions, actually have a sound speed profile which increases with depth near the surface. This is the "surface duct" region, and its existence depends on the near surface oceanographic conditions. Note, the more agitated the upper layer is the deeper the mixed layer, and the less likely there will be any departure from the mixed layer part of the profile depicted in Figure 2. Hence, an atmospheric storm passing over a region where a surface duct exists is likely to mix the surface waters and cause the duct to change.

Below the mixed layer is the thermocline where the temperature decreases with depth and hence the sound speed also decreases with depth. Below the thermocline, the temperature is constant (about 4°C—a thermodynamic property of salt water at high pressure) and the sound speed increases because of increasing pressure. Therefore, between the deep isothermal region and the mixed layer, we must have a minimum sound speed which is referred to as the axis of the deep sound channel. However, in polar regions, the water is coldest near the surface and hence the minimum sound speed is at the ocean/air (or ice) surface as indicated in Figure 2. In continental shelf regions[4] (shallow water) with water depths of the order of a few hundred meters, only the upper region of the sound speed profile in Figure 2, which is dependent on season and time of day, affects sound propagation in the water column.

Figure 3 is a contour display of the sound speed structure of the North and South Atlantic along the 30.50°W meridian[5] with the deep sound channel indicated by the heavy dashed line. Note the geographic (and climatic) variability of the upper ocean sound speed structure and the stability of this structure in the deep isothermal layer. For example, as explained above, the axis of the deep sound channel becomes shallower toward both poles, eventually going to the surface.

Figure 3

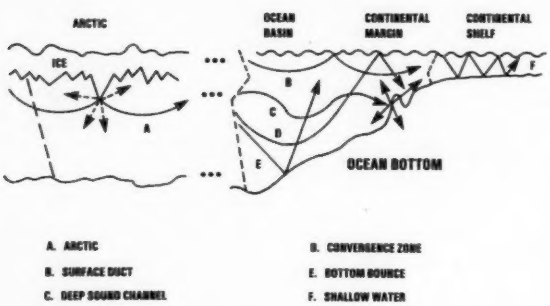
Sound speed contours[5] taken from the North and South Atlantic along the 30.50°W meridian. Dashed line indicates axis of deep sound channel. Courtesy C. Clay and H. Medwin, Accoustical Oceanography. (Clay, C.S. and H. Medwin, Acoustical Oceanography, *John Wiley and Sons, New York (1977).*



If we combine the above description of the ocean environment with a very simplified statement of Snell's Law of Refraction: sound bends locally toward regions of low sound speed (or sound is "trapped" in regions of low sound speed), a basic picture of sound propagation in the ocean naturally emerges. Figure 4 is a schematic that represents six essentially different paths of sound propagation in the ocean supported by the generic profiles in Figure 2. The dashed lines are sound speed profiles and the paths are determined by Snell's Law. Thus, in the Arctic and in a surface duct, sound is refracted toward the surface, and therefore there is a sound channel near the surface. The axis of the deep sound channel is at the minimum of the sound speed profile. This duct is bounded above (the lower boundary of the surface duct mixed layer) by the onset of the thermocline which is a region of internal wave activity and hence high variability. Sound trapped in the deep sound channel does not interact with either the ocean surface or bottom and therefore does not suffer losses associated with these boundaries; the deep sound channel supports long distance propagation of distances of thousands of kilometers. A very important type of sound propagation in the ocean is convergence zone propagation which is a spatially periodic phenomenon of refocusing near the ocean surface due to upward refraction in the deep ocean. Typical distances between the zones of high intensity are from 35–65 kilometers, the actual distance depending on the local sound speed profile. The bottom bounce path which interacts with the surface and ocean bottom is also a periodic phenomenon with a shorter cycle distance than convergence zone propagation and a shorter distance of propagation because of losses when sound is reflected from the ocean bottom. The right-hand side of Figure 4 depicts propagation in a shallow water region such as a continental shelf. Here sound is channeled in a waveguide bounded above by the ocean surface and below by the ocean bottom.

Figure 4

Schematic representation of various types of sound propagation in the ocean.



The modeling of sound propagation in the ocean is further complicated because the environment varies laterally ("range dependent") and all environmental effects on sound propagation are dependent on acoustic frequency in a rather complicated way which often makes the ray type schematic of Figure 4 misleading, particularly at low frequencies. Finally, a quantitative understanding of the acoustic loss mechanisms in the ocean is required for modeling sound propagation in the ocean. These losses are, aside from geometric spreading: volume attenuation loss, bottom loss, and surface and bottom scattering loss.

Volume attenuation increases with increasing frequency. Returning to Figure 4, the loss associated with path C, deep-sound channel propagation, will in general be volume attenuation because this path does not involve interaction with the boundaries. Since there is very little attenuation at low frequency, deep-sound-channel propagation has been observed to distances of many thousands of kilometers. Another volume effect is scattering due to volume inhomogeneities such as fish or internal waves. For example, we mentioned that the deep sound channel is bounded above by a region of internal wave activity which can be modeled statistically[6] and hence at higher frequencies we will get scattering out of the channel, possibly into the surface duct and hence loss in the channel. Similarly, this internal wave region is the lower boundary for surface duct propagation and permits scattering out of the duct. Returning to Figure 4, a source exciting surface duct propagation would not be detected below the duct, but now the addition of internal wave scattering permits "leakage" out of duct to the "shadow" region. This type of volume scattering also leads to fluctuations.[6]

When sound interacts with the ocean bottom, the structure of the ocean bottom becomes important. [Figure 5a] depicts a simple bottom loss curve with zero dB loss indicating perfect reflection; a 6 dB loss is an amplitude factor of one half and a 12 dB loss is a one fourth, etc. For a "non-lossy" bottom we still get severe loss above a certain critical angle (with respect to the horizontal) which results in loss in the water column due to transmission into the bottom. However, for the "lossy" (more realistic) bottom we never get perfect reflection even though the curves look similar. Path E in Figure 4, the bottom-bounce path, often involves paths which correspond to angles near or above the critical angle; therefore after a few bounces, the sound level will be highly attenuated. On the other hand, for shallow angles many more bounces are possible; hence, in shallow water (path F in Figure 4) most of the energy that propagates is close to the horizontal. In fact, as shown in Figure 6, there exists a small core where energy propagates long distances (Θ_c is typically 10°–20°). Energy outside the cone is referred to as the near field and is rapidly lost into the bottom whereas the propagating field in the cone is referred to as the "normal mode" field because there will be a set of angles which correspond to discrete paths which constructively interfere, essentially making up the normal (natural) modes of the shallow water environment.* Very often the ocean bottom is more complicated than that described by the frequency independent reflection curve of Figure 5a. A more realistic bottom limited ocean environment is shown in Figure 7, where the bottom is more accurately modeled by a sediment overlying a harder basement. For this layer structure the reflectivity will be a complicated function of frequency and incoming grazing angle with respect to horizontal. Figure 5b displays some model results of loss contours of such a layered bottom; The more familiar loss versus grazing angle curve such as depicted in Figure 5a is obtained from a vertical cut through the loss contours. For example, at low frequencies, Figure 5b indicates a critical angle of about 18° whereas at high frequencies we do not see a critical angle.

Finally, there is surface and bottom scattering as loss and fluctuation mechanisms. The ocean surface and bottom are rough which attentuates the mean acoustic field. Again, this attenuation increases with increasing frequency. Because the ocean surface moves, it will also generate acoustic fluctuations. Bottom roughness can also generate fluctuations when the sound source and/or receiver is moving The effect of roughness also depends upon the sound speed profile which determines the degree of interaction of sound with the rough surface.

Figure 5

(a) Bottom reflection loss vs grazing angle. (b) Contours of bottom reflection loss vs grazing angle and frequency.

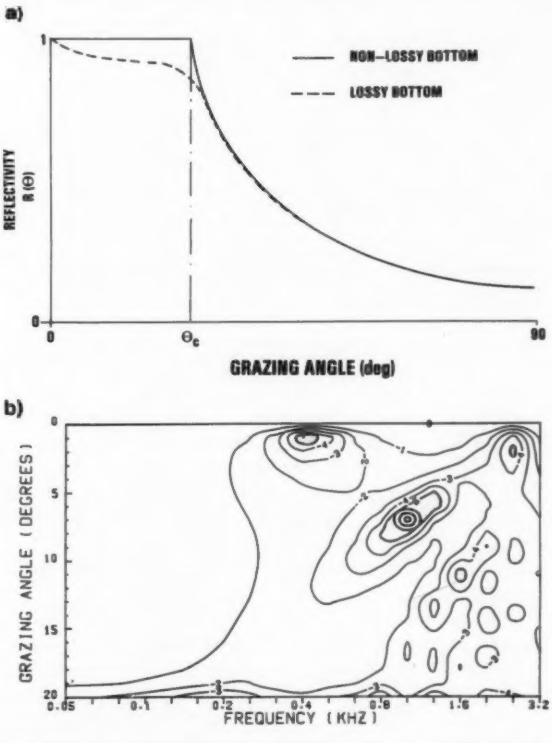


Figure 6

Ocean waveguide propagation. a) Long distance propagation occurs within a cone of $2\theta_c$. For angles greater than the critical angle, θ_c, acoustic energy is partially transmitted into the ocean bottom at each bounce resulting in severe decay of the acoustic field with range in the water column. b) Same as a) but with non-isovelocity water column showing refraction. Even below critical angle, higher angle paths have greater loss ber bounce as shown in Figure 5a.

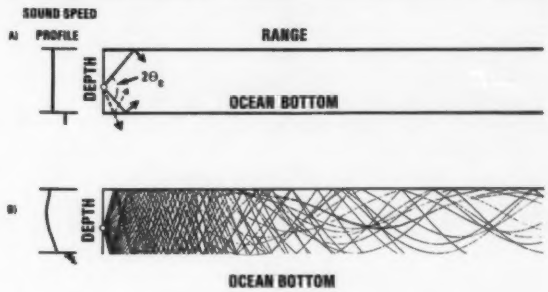
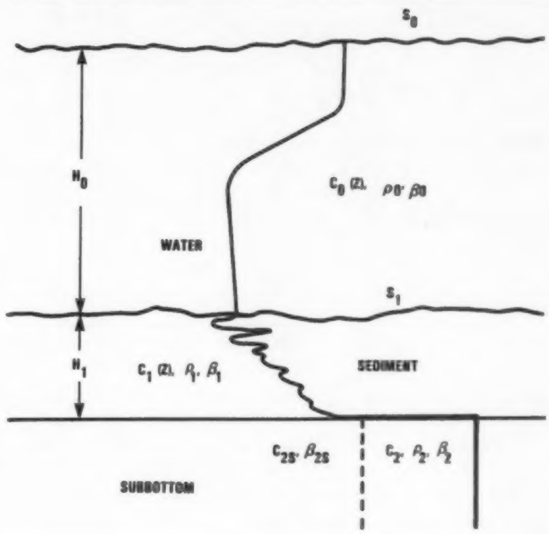


Figure 7

Realistic environmental input to ocean acoustic models. The rock subbottom is treated as a visco-elastic material which also supports shear wave propagation as indicated by subscript "S;" "C" refers to sound speed; ρ refers to density; β refers to attenuation.



Acoustic Models

Sound propagation in the ocean is mathematically described by the wave equation, a partial differential equation, and boundary conditions appropriate to the ocean environment. We will refer to a computer implementation of the solution of the wave equation as an underwater acoustic model. There are four essentially different and widely used models to describe acoustic propagation in the sea. Our goal at this point is to describe these models along with the physical assumptions that go with them, their advantages and limitations, and when possible, any correspondence between them. The models are: the ray theory model (RT), the fast field program (FFP), the normal mode model (NM) and the parabolic equation model (PE). All of the models considered here permit, to some degree, the ocean environment to vary with depth such as the change in sound speed with depth as shown in Figure 2. If the model also permits horizontal environmental changes such as a sloping ocean bottom or a change in the vertical sound speed structure as a function of horizontal position, the model is called "range dependent," otherwise, it is referred to as a range independent model (which therefore describes propagation in a "horizontally stratified" medium).

Ray theory in its simplest form is just an application of Snell's Law. The medium is divided into layers and Snell's Law is applied at each interface. A continuous limit can be taken by allowing the layers to become arbitrarily small, and we end up in a differential form of Snell Law (the "eikonal" equation) which when solved yields rays which represent the paths of energy flow, and these rays are perpendicular to the wave-front of the propagating acoustic energy. The actual intensity of the acoustic field is related to the density of these rays; that is, the denser the distribution of rays, the more intense the acoustic field is in that region. Formally, we obtain ray theory from the wave equation by asymptotically solving it in the infinite frequency limit and assuming the medium varies slowly in space with respect to acoustic wavelength. For most ocean acoustic applications, this latter restriction is acceptable, however, the infinite frequency approximation excludes wave effects such as diffraction. Such an effect would be the frequency dependent ability of a duct to trap energy. For example, there is a low frequency "cut-off" of propagation in surface duct. This cut-off is a wave theory effect and is not included in infinite frequency ray theory.

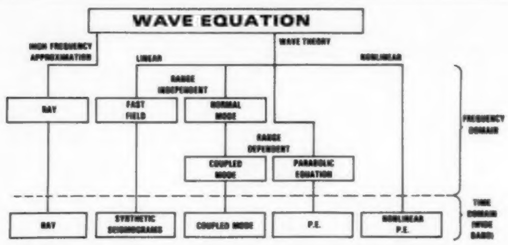
The advantages of ray theory are that the computations are rapid, and extendable to range dependent problems, and that ray traces give a very physical picture of the acoustic paths. The disadvantage is that ray-theory does not include diffraction and other wave effects. This shortcoming also prevents ray theory from adequately describing significant bottom interaction and low-frequency ducted propagation. Finite frequency corrections to ray theory are such that the complexity of the additional numerics begins to approach wave theory solutions.

Figure 8 schematically represents solution techniques for the wave equation increasing with complexity and sophistication of the physics, environment and numerical methods increasing from the upper left-hand corner (ray theory) to the lower right-hand corner (nonlinear PE). We now discuss the wave theory type solutions for finite frequencies which increase in computational time with increasing frequency

The fast field solution (FFP) [8, 9, 10] is a direct numerical integration of the range-independent wave equation. The "fast" refers to the utilization of a fast Fourier transform (FFT) for numerical integration over the independent variable associated with horizontal range. Hence, this model is only applicable to a horizontally stratified ocean. The advantages of the FFP are that it includes the nearfield (the region outside the cone $2\Theta c$ in Figure 6) and can describe propagation in or bounded by elastic media such as hard ocean bottoms or ice. Its disadvantage is that the procedure is not easily automated and is therefore essentially a research tool rather than a production model.

Figure 8

Hierarchy of computer implemented solutions of the wave equation.



The other range-independent wave model is the normal mode solution of the wave equation. This alternative to the direct numerical solution, the above mentioned FFP, actually appeared first, [7, 11] being more dependent on analytic rather than computational mathematics. The normal mode procedure is essentially the same in underwater acoustics as it is found in general waveguide problems in acoustics or electromagnetics or stationary state problems of quantum mechanics. The normal mode method involves expanding the solution in terms of normal modes in the vertical (stationary waves) and cylindrically spreading waves in the horizontal. For an ocean environment described in the previous section, this solution is the far field depicted in Figure 6 within the cone $2\Theta c$. For most underwater acoustic calculations, it is the far field that is of greatest interest. The normal mode method can handle the same type of environment as the FFP; however, propagation in elastic media poses additional severe computational problems. The advantages of the normal mode method is that it is easily automated and can be extended in an approximate way to range dependent environments through numeric procedures, though they then become rather cumbersome. Its main disadvantage is that it does not include the near field.

The parabolic equation (PE) [12, 13, 14] is an approximation of the wave equation in which the environment can vary both in range and depth. It is a wave solution including some diffraction phenomena (as opposd to ray theory). The PE model does not include backscattering and only accurately computes the acoustics for propagation in a direction within a small cone about a reference direction, usually the horizontal; this is referred to as the "narrow angle approximation." As mentioned earlier this limitation is not serious. The PE model's main advantage is that it is a range-dependent wave model. The procedure used for solving the PE is a range-stepping algorithm. The main disadvantage of this model is that calculation time goes up with increasing range, increasing environmental complexity, and with the square of frequency. In addition, its extension to include propagation in elastic media is not obvious at this time.

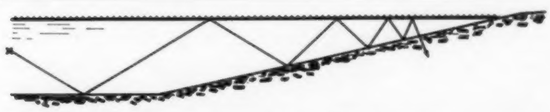
Some Recent Advances in Modeling at NORDA

Normal Mode

As mentioned in the last section, the standard normal mode theory does not include the near field (the "continuum") which corresponds to paths outside the $2\Theta_c$ cone of Figure 6. These are the paths that decay rapidly because of radiation away from the water column into the ocean bottom. Thus, for example, consider the problem of sound propagating up-slope as depicted in Figure 9. As the paths become steeper, their angles eventually exceed the critical angle (Θ_c) and sound (in the ray picture) is refracted into the ocean bottom. This phenomenon has recently been quantitatively predicted using the parabolic equation. [17] Standard normal mode theory cannot handle this problem for two reasons: the range dependence and the radiation into the bottom, the latter sometimes being referred to as coupling into the continuum.

Figure 9

Ray picture of up-slope propagation. Rays become steeper and eventually their angles with respect to the bottom interface exceed the critical angle resulting in transmission into the bottom and "cut-off" of acoustic propagation in the water column.

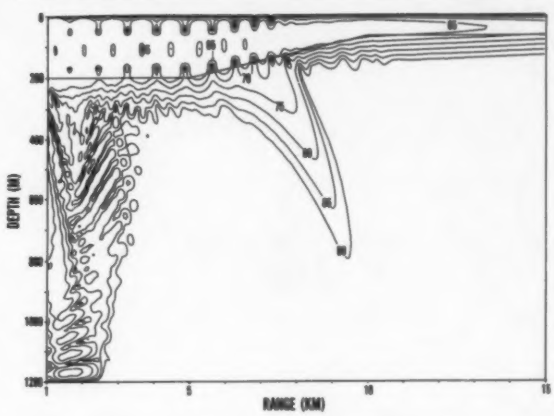


However, recently a range dependent coupled normal mode theory and computer model have been developed [15, 16] which include the two phenomena mentioned above. An example of an upslope coupled mode calculation is shown in Figure 10 where the sound field originates from the left and eventually radiates into the bottom corresponding to the schematic of Figure 9. This is in agreement with previous approximate calculations, [17] but this is in essence a direct numerical solution of the wave equation rather than a numerical solution of the approximate parabolic equation.

An exact solution of the wave equation in an irregular waveguide must also include backscattering as is the case for this coupled mode model. Consider the (ocean) waveguide shown in Figure 11 bounded below by a flat bottom and the same waveguide with a patch of roughness on the bottom. Note the energy scattered out of the water column into the ocean bottom and hence scattering is a loss mechanism for sound in the water column. The three transmission loss curves in Figure 11c indicate the relative effect of the roughness. The importance of the ability to include backscatter in this calculation is that for the first time we will be able to study boundary backscattered reverberation for abitrary environments in the lower frequency regime which requires the use of wave theory.

Figure 10

Contour of the acoustic field from couple mode (wave theory) calculation of up-slope propagation. Contour loss levels are in dB.

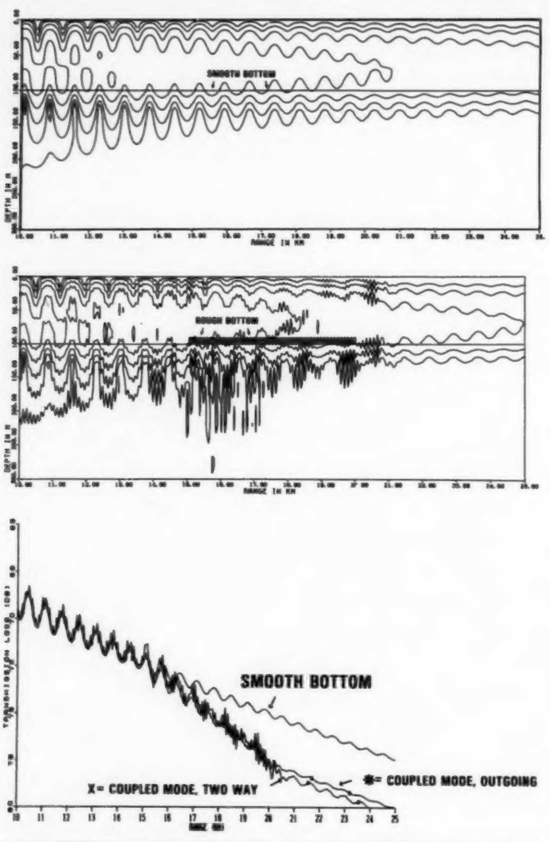


Parabolic Equation

The standard Parabolic Equation (PE) is intrinsically a narrow angle approximation. As originally introduced, the numerical solution of the PE employed the so called "split step" Fast Fourier Transform marching algorithm. Since then, finite difference and finite element [14, 18] methods have been developed to solve the PE, and with the introduction of these methods the PE technique has been extended to describe wide angle propagation. [18] That is, the standard PE is valid to about $\pm$ 20° about the horizontal, whereas the addition of the wide angle technique extends this region to about $\pm$ 40°. Not only is the result more accurate at steeper angles; but the computation for smaller angles is more accurate, in particular the calculation of phase which is an important factor when studying beamforming over extended apertures. Thus, for example, Figure 12 shows transmission loss calculations, the exact solution of the wave equation indicated as the FFP result. The acoustic field is the sum of contribution of the existing multipaths (or modes) for this ocean problem and the location of the nulls and the structure of the interference pattern is very sensitive to the phases of these multipaths. Note at the major null at 7 km range the wide angle finite element and finite difference methods agree with the exact solution of the wave equation giving us confidence that these methods can simulate complex acoustic fields with sufficient accuracy for studying such problems as large aperture array performance.

Figure 11

Contour of acoustic field in shallow water ocean waveguide. a) with smooth bottom. b) with 5 km patch of rough bottom. c) transmission loss for smooth bottom and rough bottom with and without backscattering included for case b.

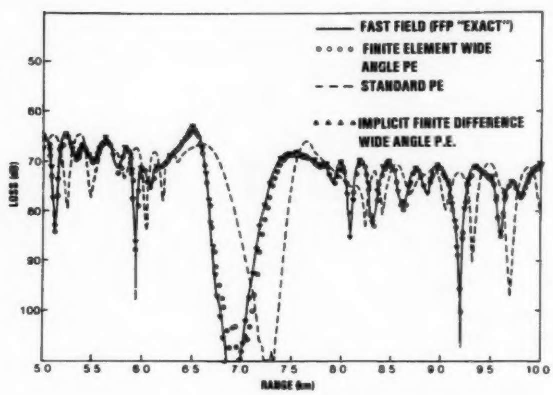


Object in an Ocean Waveguide

When studying propagation in the ocean where the acoustic wavelength is approximately within an order of magnitude or so of the vertical dimension of the ocean, we must treat the ocean as a wave theory. This is the case for low frequency deep water propagation as well as propagation in shallow water (continental shelf regions). In particular, in shallow water a submerged object is also likely to have dimensions approximately within an order of magnitude of the vertical extent of the water column. Until recently, the theoretical and numerical study of the scattering of sound off an object has been limited to ideally shaped objects such as spherical or near spherical objects, infinitely long cylinders, etc., which are in free space; that is, they are not located near a boundary, or in an acoustically inhomogeneous medium, for example, where the sound speed profile varies in space. A new method[19] has been developed to study scattering from elongated objects (a submarine might have typically an aspect ratio, length/diameter, of, say, 15), and research is proceeding in extending this technique to where the object is in a waveguide.

Figure 12

Transmission loss example for wide angle PE computation demonstrating its increased phase accuracy over standard PE.



An example of the scattering from an elongated object in free space is shown in Figure 13. These types of calculations have not been practical until now because of the unstable numerics associated with the manipulation of large matrices whose elements span large orders of magnitudes. This recently developed technique [19] uses the geometry of the object to appropriately decompose the incident field and then preselect the most important components which will dominate in transitioning to the scattered field. In addition, an active research program is presently underway to apply this method to the waveguide problem illustrated in Figure 14, where the real complication is that the object can be thought of as an inclusion in the ocean environment.

Nonlinear and Wideband Modeling

The wave theory models discussed up to this point have involved solutions implemented in the frequency domain. That is, they are solutions to the wave equation for a single frequency continuous wave. Pulse or wideband propagation can be obtained by Fourier synthesis of the individual solutions over the frequency spectrum of the signal under study; this imposes severe sampling restrictions. Up until now, the more difficult alternative to this procedure has been the direct solution of the time domain wave equation. A method to efficiently implement this latter procedure has emerged from a research program concerning shock wave propagation in the ocean, which, because it is a nonlinear problem does not permit Fourier synthesis procedures in a straight forward manner.

Figure 13

Scattering from a rigid spheroid with length/diameter ratio of 15, length 150 m and frequency 192 Hz.

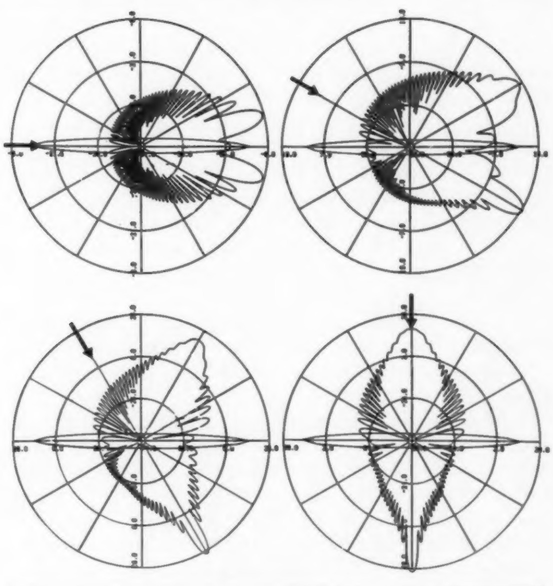
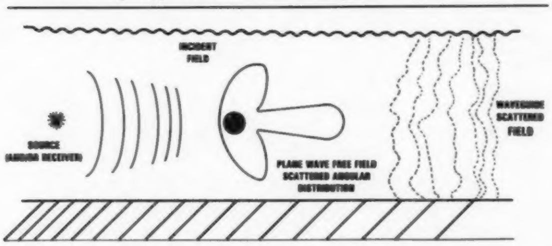


Figure 14

Geometry of scattering of object in waveguide. The lower the frequency and/or the larger the object relative to the depth of the waveguide or the closer the object to a boundary of the waveguide, the greater the departure of the nature of the scattered field from the free field case schematically depicted about the object.



The evolution of a propagating shock wave depends on its previous spacetime history and hence its description requires solving a wave equation in the time domain. A nonlinear time domain wave equation, the nonlinear progressive wave equation (NPE), has been derived [20] from the basic equations of hydrodynamics to describe shock wave propagation in a refracting ocean (Figure 4). Because the nature of a shock wave is such that it has a sharp leading edge, new numerical Methods had to be developed [21] to carefully track this mathematical discontinuity where physically the dissipation of the shock is occurring due to the increase in entropy resulting from the generation of turbulence as the shock propagates. When the nonlinear term is omitted, the NPE equation reduces to a time domain version of the parabolic equation discussed earlier but now we have a numerical method to directly solve this time domain equation without resorting to Fourier methods and the associated sampling problems.

The original shock problem was to study propagation of a shock wave through a caustic (a focal region) as depicted in Figure 15. Previously, much of shock propagation had been approximated using empirically corrected ray theory since the history of the propagation can be followed along rays. At a caustic, rays converge and the solution blows up. Hence the empirical approximation used could only make nonlinear corrections before and after the caustic and had to assume nothing special happened in the caustic region. However, the caustic is a region of high intensity and hence is the region of greatest nonlinearity. The newly developed wave theory contains no such artificial infinities, and hence the nonlinear shock wave can be tracked right through a caustic. Consider the problem shown in Figure 16 where a "N wave" is incident on a caustic. The classical linear solution is that an unattenuated "U wave" emerges from the caustic (that is, there is only a phase change in the frequency domain components of the pulse). Using the NPE with and without the nonlinear term, we compute the results for this problem as shown in Figure 17. In the linear case, we see the N wave going to the unattenuated U wave within the numerical resolution of the computation. The contour of the linear acoustic field also shows the expected symmetry of the field on both sides of the caustic. The results are radically different in the nonlinear case. The N wave transforms to a dispersed and dissipated U wave because of the increased generation of turbulence in the high intensity region of the caustic and the contour shows that the field is asymmetric. That is, the shock does not follow the linear ray path of Figure 16. The high intensity shock wave actually disturbs the medium modifying the local sound speed structure causing the shock wave to "self refract." This means, for example, that focusing of acoustic waves in the ocean such as convergence zone propagation will be different for shock waves than for the linear waves descriptive of sonar acoustics.

Summary

We have presented an overview of computer modeling of sound propagation in the ocean emphasizing those areas of

Figure 15

Ray theory does not even permit an empirical description of nonlinear phenomena in the vicinity of a caustic, a region of high-intensity.

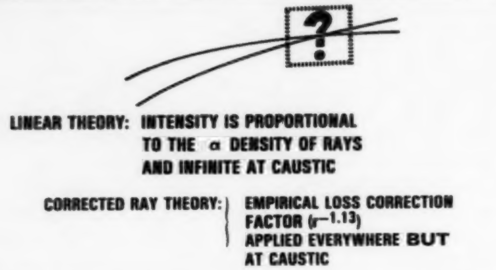


Figure 16

"N wave" nonlinear shock incident on a caustic resulting from sound speed profile c(z). Linear theory predicts emergence of unattenuated "U wave." ("N" and "U" refer to shape of pulse.)

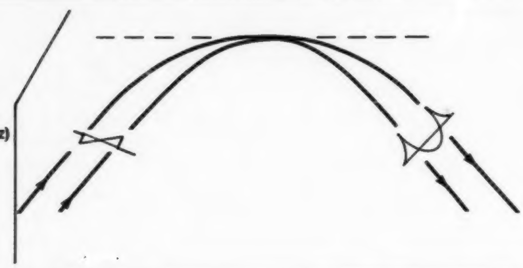
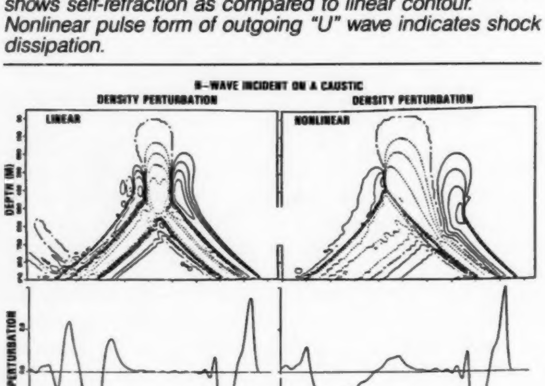


Figure 17

N wave incident on caustic. Asymmetric nonlinear contour shows self-refraction as compared to linear contour. Nonlinear pulse form of outgoing "U" wave indicates shock dissipation.



basic research where NORDA's modeling efforts have been concentrated. This computationally intensive research effort requires a combination of state-of-the art computer technology and the usage and development of modern numerical physics techniques. Together these two resources permit us to venture into areas of research which were virtually impenetrable six years ago.

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*By "near field" we mean the waveguide near field which falls off more rapidly than the propagating, normal mode field, which we refer to in this paper as the "far field."

Biographies of Authors Contributing to this Issue.

Paul J. Martin, a research oceanographer in NORDA's Ocean Hydrodynamics/Thermodynamics Branch, participated in the initial development of the presently operational northern hemisphere TOPS. His primary area of oceanographic interest is the effect of atmospheric forcing, mixing, and advection on upper-ocean density and currents.

John M. Harding, also a research oceanographer in NORDA's Ocean Hydrodynamics/Thermodynamics Branch, participated in the development of advective regional TOPS. His current interests include real-time, upper-ocean, thermal analysis and prediction especially for regional domains under strong advective influence.

Jeffrey D. Hawkins, a research oceanographer in NORDA's Remote Sensing Branch, is actively involved in the assimilation of satellite derived geophysical parameters into Navy operational ocean models. His present work centers on efforts concerning satellite retrievals of multichannel sea surface temperatures, sea ice edge, concentration and age, as well as the wind forcing possible from a scatterometer sensor.

R. Michael Clancy, a NORDA Alumnus, is a supervisory oceanographer and Head of the Ocean Models Branch at FNOC. His current interests and responsibilities include real-time analysis/prediction of ocean thermal structure, currents, waves, and sea-ice conditions. Mr. Clancy led the initial development effort on the northern hemisphere and regional Mediterranean TOPS.

Dr. Ronald A. Wagstaff, Head of the Array Effects Branch at NORDA, has conducted experimental research in underwater acoustics for about 15 years. His principle interests are the measurement, analysis, and modeling of undersea ambient noise.

Dr. Jim L. Mitchell is lead principal investigator for the basic research program in satellite altimetry at NORDA. He received his PhD in aerospace engineering from the University of Southern California. Other research interests include the laboratory simulation of ocean circulation, and planetary atmospheric dynamics.

Dr. Zachariah R. Hallock is principal investigator for the physical oceanography component of NORDA's Special Focus Program "Ocean Dynamics from Altimetry." He received his M.S. and PhD degrees in physical oceanography from the Rosenstiel School of Marine and Atmospheric Science of the University of Miami. His research interests include frontal and mezoscale ocean variability and associated observational techniques.

J. Dana Thompson is principal investigator for the numerical modeling component of NORDA's research in satellite altimetry. He received his Ph.D. in Meteorology from Florida State University. His recent research has focused on the dynamics of the Gulf Stream System, use of remotely-sensed data in ocean monitoring and prediction, and the thermodynamics of the upper ocean.

Dr. David W. Handschumacher is a senior research geophysicist in NORDA's Marine Geophysics Branch. His interests focus on plate tectonic and geomagnetism research in remote areas of the world's oceans.

Dr. Joseph F. Gettrust is the Head of the Marine Geophysics Branch at NORDA. His research interests include seismic studies of continental margins and oceanic crust, and numerical modeling of seismic wave propagation.

Dr. William Kuperman was a research ocean physicist for the Naval Research Laboratory for ten years. Afterwards he spent five years at the NATO SACLANTCEN Laboratory in La Spezia, Italy where he founded the Environmental Modeling Group. He returned to the United States where he headed the Numerical Modeling Division at the Naval Ocean Research and Development Activity. Presently he heads a project studying shock propagation in the ocean.

The Future of Ocean Science at NORDA

Simply stated, the mission of the Naval Ocean Research and Development Activity (NORDA) is to understand the ocean and its effects on Navy systems and operations. Within the last year, the Secretary of the Navy and the Chief of Naval Operations have emphasized the importance of this understanding to both the employment of our naval forces and the Navy's role as a smart buyer of systems during the acquisition process. Today, therefore, is a challenging and very exciting time to be charting the future of NORDA, a relatively young laboratory within the Navy community.

NORDA's future thrusts will combine the strengths we have developed during our first decade with the leadership role assigned to us by the Chief of Naval Research (CNR) in the areas of Ocean Science, Environmental Acoustics, and Mapping Charting and Geodesy (MC&G). In general, our functions will include environmental characterization and studies, systems support and application, development of environmental data bases, ocean environmental acoustics, development of basic ocean and acoustic models, development of measurement system techniques, environmental studies for system performance, application of remote sensing techniques to all areas of Ocean Science, and mapping charting and geodesy. Within the context of the above functions, the "environment" consists of the world's oceans, the air-ocean interface, and the ocean bottom and sub-bottom.

NORDA will place major emphasis on the rapid and continuing development of our capabilities in the areas of remote sensing, ocean modeling, acoustics, and MC&G, as well as the provision of "ocean environmental threat" assessments to weapon systems procurement managers during all phases of the acquisition process. In the areas of ocean modeling and MC&G, we will stress remote sensing of ocean and near-shore parameters, particularly those collected by satellite systems, using our state-of-the-art remote sensing, image and pattern analysis, and remote work processing facilities. We plan to improve our ability to accurately model the world ocean processes, based on limited data availability. The Navy needs the product of our capability to assimilate this data, predict operating environments, and fill gaps in remote sensing observations. Delivery of this product in the form of accurate ocean forecasts is our goal. Our expectation is that perhaps, within a decade, we will have developed the capability to provide this information on a global basis to the operating forces in near real-time.

In the area of ocean acoustics, we will emphasize acoustic model formulation, underwater acoustic experimentation, and ocean technology development. From our present basis of a comprehensive set of two dimensional acoustic models, we will expand to fully three dimensional models with strong acoustic-boundary interactions, and will provide impacts on system design and performance assessments, asset allocation strategies and environmental exploitation in tactical engagements. Our program will increasingly address the harsh acoustic environments of shallow water, bottom-limited areas, and the Arctic, and will cover the full range of frequencies for both passive and active sonar issues and environmental-acoustic (EVA) support for surveillance, sonar, and weapon systems. We will explore the EVA threat and exploitability for new and sophisticated beamforming, detection, localization, and multiple target classification techniques. Our associated ocean technology efforts will focus on more effective techniques of measuring the acoustic fields using newly developed and inexpensive multi-dimensional research management systems.

Finally, while continuing to build on existing strengths and programs in the areas of basic research and exploratory development, NORDA will emphasize the most promising initiatives both from within the laboratory and out-of-house to affect transition to advanced development R&D programs. Moreover, as a Navy laboratory, when we are faced with choosing among projects, we will continue to place our emphasis on relevance to future Navy needs. In doing this, we must delicately balance the need for continuing our technology base research programs to develop the ideas and science that will carry the Navy into the twenty-first century, with the ability to respond to the more immediate fleet requirements.

Captain Roger P. Onorati, USN
Commanding Officer
Naval Ocean Research and Development Activity

Research Notes

Fouling and Corrosion

It is well recognized that surfaces exposed to the marine environments are subject to fouling and corrosion processes. Traditionally, fouling and corrosion processes were addressed as independent problems; however, in recent years, this trend seems to have been reversed. The change in attitude has been the result of empirical observations and changes in the conceptual approach to marine deterioration. The problem that has remained is the determination of the mechanisms whereby microorganisms accelerate corrosion and a quantification of their impact. A multiple electrode, chemostat-corrosion vessel has been developed by Drs. Brenda Little, Naval Ocean Research and Development Activity and S. M. Gerchakov, University of Miami which provides this capability.

Polarization techniques have previously been used for measuring corrosion rates in aqueous environments. These methods assume that the metal is uniformly corroding by a Wagner-Traud type mechanism, whereby the anodic and cathodic processes occur with equal probability on all parts of the corroding surface. The patchy nature of bacterial colonization of surfaces suggests that uniform corrosion may not be the case when organisms are intimately associated with a corroding surface.

The newly-designed system consists of two chemostats biologically separated, but electrolytically continuous. Each compartment contains a test electrode of known surface area, a Luggin capillary for a reference electrode connection and a Pt counter electrode. Provisions are made for bubbling desired gases through each of the compartments and for flow of "feed" solutions. Data acquisition is controlled by a microcomputer using a potentiostat which is operated as a zero resistance ammeter.

Identical metal surfaces are placed in the individual compartments containing identical aqueous environments. The two metals are connected externally to a zero resistance ammeter allowing a separation of the anodic and cathodic components of the corroding metal. Under these circumstances, no galvanic current should flow between the specimens while both undergo uniform corrosion. When bacteria are introduced into one of the compartments and the other compartment remains sterile, a galvanic current is observed. The direction of the current indicates the nature of mediation (anodic and cathodic), and the current magnitude indicates the extent of that mediation.

The effect of a themophilic filamentous bacterium and that of a mesophilic marine pseudomonad on the corrosion of nickel and copper, respectively, have been examined using this approach. In both cases, the specimen in the bacterial compartment became the anode of the galvanic couple. The magnitudes of the currents were 3.8 $\mu A/cm^2$ for nickel, and 1.0 $\mu A/cm^2$ for copper. Three mechanisms have been evaluated individually in abiotic simulations that mimic microbial activities: (1) the creation of differential aeration cells, (2) the production of acidic metabolites and (3) the entrapment of heavy metals. When one compartment was depleted of oxygen, the specimen in that compartment became the anode of the galvanic couple in both the nickel and copper cases, and the current had a similar magnitude to the corresponding biotic experiments. This result suggests that these bacteria, due to their respiration activity, have created differential aeration cells responsible for their effect on corrosion.

(Brenda Little, NORDA)

Ocean Measurement Sensors

For almost any energy transferred from a ship or submarine, which can be considered a signal, there is a naturally occurring phenomenon or noise which masks it. The precision of acoustic predictions is limited by the knowledge of the oceanographic structure over the transmission path. Non-acoustic signal detections are limited by a knowledge of the noise field on which the signals are imposed. Thus, the Navy's intrinsic interests in upper ocean environmental conditions are evolving into ever finer scale resolution. The energy region of primary interest is near the current limit of measurement capability for both scalar and vector quantities. To define these fine and microscale fluctuations scientists need instruments which can measure the spatial and temporal variations of phenomena on vertical scales of meters to centimeters and resolve time scales of minutes to seconds.

These new requirements are being addressed under the sponsorship of the Ocean Measurements Sensors project of NORDA. Most of the project's development effort is expended in modification of promising systems initiated for basic research, with a small portion dedicated to developing new approaches. Expendable probes are one category of instruments on which a lot of recent attention has been focused. Expendables, required for rapid broad area samples, can provide quasi-snyoptic areal surveys. Recent developments include two entirely new instruments and two modifications. A dependable and accurate expendable current profiler (XCP) has just recently became commercially available. It provides a vertical profile of horizontal currents from the which the vertical shear can be calculated with a resolution of 1cm/sec. to a depth of about 1 kilometer. The development of an expendable dissipation probe (XDP) offers the unique ability to study the generation, decay and spreading of velocity turbulence in the ocean. An aircraft launched version of the sound velocity probe (AXSV) has been designed to measure sound speed in areas where salinity is the dominating factor. The Navy standard aircraft launched expendable bathythermograph (AXBT) has been modified to provide more accurate temperature resolution to much greater depths. New technologies combined with existing sensors make it feasible to envision a multi-sensor probe which can characterize the ocean's physical properties with each drop.

Many instrument systems mounted on or hard wired to ships (tow chains, profilers, etc.) suffer data contamination from surface induced wave motions and wind drift. As a result, contours obtained from CTD yo-yos are more properly inferred as spatial rather than temporal variations in the internal wave field. Another problem stems from mismatches in the dynamic response of co-located sensors. This makes the data difficult if not impossible to interpret. An advanced free-fall microstructure profiler (AMP) has been designed, constructed and tested that alleviates these problems. This instrument provides rapid and repetitive vertical profiles of both vector and scalar microstructure properties for display in near real time.

Various tow bodies and chains, required for large spatial coverage, are being redesigned to reduce or eliminate surface coupled motions. Techniques are being devised to utilize small aperture tow systems in conjunction with expendable profilers for two dimensional surveys. Small aperture instruments allow for close sensor spacing and fine scale resolution without requiring large dedicated computer systems and special ships to tow them. Body mounted sensors are being designed to improve existing sensing techniques and to develop new ones such as vorticity sensors or bathyphotometers.

Future instruments should carry combinations of sensors with matched dynamic response characteristics and use standard calibration techniques. Prior knowledge of the requirements should allow researchers to develop on board real time processing algorithms. This reduces the need for large data banks and enables the scientist to leave the ship with a processed data report in hand. Thus, the underlaying philosophy of the Ocean Measurement Sensors project is to encourage the development of complete data systems rather than just sensors. Hopefully, this philosophy will reduce the task of collecting the large amounts of synoptic data needed to construct predictive models from the realm of the impossible to that of just difficult.

(Kenneth M. Ferer, NORDA)

Ocean Finestructure is the Focus of Continuing Investigation

Several programs within Navy and private laboratories are concentrating on finestructure, defined as variability in the ocean of temperature, salinity, velocity, and other parameters having scales ranging from a few meters to centimeters or less. Interest in such features arises from the fact that they are the signature of processes which greatly enhance vertical mixing and have implications for such diverse topics as maintenance of the thermocline, biological productivity, and sound propagation.

Two mechanisms are believed to be responsible for most naturally occurring finestructure. The first operates whenever the vertical current shear becomes large enough to overcome the local density stratification, resulting in a small burst of turbulence. The shear may arise from any source, such as that associated with boundary currents, fronts or the periphery of the large, isolated eddies which are found in some areas. Another source of shear, which may be particularly important because of its applicability nearly everywhere in the world ocean, is the chance superposition of internal waves. Recent evidence has linked turbulent patches with the presence of inertial period oscillations, predicted by theory to modify higher frequency waves in such a way that their combined effect will initiate a turbulent overturning event.

The second mechanism involves a thermodynamic instability arising when temperature and salinity both either increase or decrease with depth. The latter case is especially interesting since it is the more vigorous of the two and conditions for it exist over large areas of the ocean. In this case, vertical columns of water having diameters of order one centimeter with alternating upward and downward interior flows are known to form. Under favorable conditions, these columns, known as salt fingers, can lead by a mechanism still not fully understood to two types of horizontal layers which form alternately with depth; one type is thin (1 meter) with high vertical gradient, the other is relatively thick (10 meters) with nearly zero vertical gradient. Staircase structures of this type, so called because of the traces they create in the displays of standard oceanographic instruments, have been observed at least intermittently in many areas of the ocean and have been correlated with the existence of salt fingers in a few cases. Salt fingers are also known to play an important role in the evolution of intrusions, where one water mass becomes interleaved with another.

Observing finestructure of either type presents a severe challenge to the oceanographer, because of its small scale and its intermittency in both space and time. However, gradual improvements have been made in sensors for temperature, conductivity and velocity having the necessary sensitivity and high-frequency response. New deployment methods have been devised where such sensors are installed in a variety of lowered, dropped, towed, or hull-mounted configurations. With the combination of new instruments and their wider deployment, it should be possible in the next decade to routinely distinguish between the two types of finestructure, and perhaps to quantify the role played by each.

(Henry Perkins, NORDA)

Hydrothermal Vent Type Biological Communities at the Base of the Florida Escarpment

Scientists aboard the deep diving submersible *Alvin* discovered dense biological communities apparently associated with seeps along the base of the Florida Escarpment near 26°02′N and 84°55′W. The communities consist principally of mussels and tube worms, with smaller numbers of clams, gastropods, limpets, holothurians, brittle stars, anemones, shrimp, and fish. In addition, patches of a flocculent white material, assumed to be bacterial mats, are associated with these communities. These organisms resemble taxa that characterize hydrothermal vent communities along the East Pacific and Galapagos Rises.

The close association of these communities to dark gray and black sediments containing pore waters with concentrations of H_2S and NH_4+ greater than seawater and of SO_4^{-2} less than seawater suggest that the communities are based on chemosynthetic bacteria as are the hydrothermal vent communities found in the eastern Pacific. However, elevated salinities (≈50%) in the pore waters of these black sediments and the lack of a significant elevation of bottom water temperatures, or of shimmering water, indicates that reduced inorganic compounds necessary for chemosynthesis are brought to the base of the Florida Escarpment by dense saline brines seeping from the adjacent Florida Platform, rather than by hydrothermal circulation.

The distribution of black, sulfurous sediments in fan-shaped patches, which narrow upslope into shallow gullies cut into the base of the escarpment, suggests a drainage pattern generated by these dense brines as they seep from the heads of the gullies and flow downslope.

(Ray Freeman-Lynde, NORDA)

Remote Work Processing Facility

The extraction of cartographic, military, and naval feature information from a wide variety of source imagery is a continuing requirement for the Defense Mapping Agency (DMA) and the military services, including the Navy. An active area of current research is the development of automatic and computer-aided interactive feature extraction techniques. The Remote Work Processing Facility (RWPF), with sites at the DMA production centers and the service laboratories, including the Naval Ocean Research and Development Activity (NORDA), is an integrated hardware-software computer system which serves as a testbed for research into automated feature extraction. The system is undergoing an upgrade modification for completion in August 1985 at the DMA Centers.

NORDA is currently configuring an image processing, feature extraction system which will be hardware and software compatible with the DMA upgraded RWPF. The NORDA system consists of a VAX/780 host computer with a Gould DeAnza IP8500 image processing system with high resolution, 1024 × 1024 image memory boards. Ancillary equipment includes an array processor, high density tape drive, laser graphic printer/plotter, video film recorder, table digitizer and Grinnell GMR275 color display system. Additional hardware to be delivered in FY85 consists of a second IP8500 image processing work station with an optical stereo viewing system to allow for full stereo processing and a Symbolics 3670 LISP minicomputer for enhanced symbolic and artificial intelligence capabilities.

The primary reason for common hardware at the various RWPF sites is to facilitate the use of common software and to allow for easy communications among researchers. The RWPF system uses the UNIX operating system (Berkeley bsd 4.2) and supports LISP and C high level languages. (The Digital Equipment Corporation's VMS operating system is also available.) A large set of integrated software has been developed for the RWPF for feature extraction and general image processing. The basis of the software is the Automated Feature Extraction System (AFES) which consists of a large number of image processing primitives (e.g. edge detectors, statistical classifiers, filters, and multi-band processors) which can be readily linked together to perform specific operator controlled functions. Software is also available for image restoration and manipulation, symbolic matching for automated stereo compilation, automated symbolic change detection, and stereo cross-correlation. An interactive aid for knowledge engineering is available to help construct knowledge bases for expert system programs. In addition to the common software developed for DMA, the RWPF is configured to be compatible with the Defense Advanced Research Projects Agency (DARPA) Image Understanding Testbed. The availability of software and common hardware results in a system in which new research ideas can be quickly implemented and tested.

The NORDA RWPF will operate in a research and development environment and will provide a useful facility for research in automatic feature extraction. The system will be able to support research in various ocean science areas. Furthermore, the availability of scientists at NORDA with expertise in a wide range of ocean science fields will allow for the rapid development of feature extraction and image processing techniques.

(Charles Walker, NORDA)

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