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13. ABSTRACT *(Maximum 200 words)*

The ocean circulation is known to be a central element in determining the present climate state and to be crucial in understanding how it might change in the future. However, our current understanding of the ocean is so primitive that forecasts of future climate states much be regarded as mainly speculative. Central to the problem is the very great difficulty of observing the state of the ocean today, and of determining whether it is changing to any significant extent.

The concept for Acoustic Thermometry of Ocean Climate being described by this document focuses on the critical role of the world's oceans in the process of global change. A research and engineering program to create a network of acoustic transmission paths represents the first step to measure long-term temperature change in the ocean (and hence by inference, atmospheric and climatic trends). This network can build on the results of The Heard Island Feasibility Test, of using very long-range underwater sound transmissions to measure oceanic temperature on basin scales. It involves a multi-year program to monitor the ocean on a global basis by installing a system of acoustic sources and receives at sites that provide adequate spatial sampling, and are technically, politically and logistically feasible.

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ACOUSTIC MONITORING OF GLOBAL OCEAN VARIABILITY

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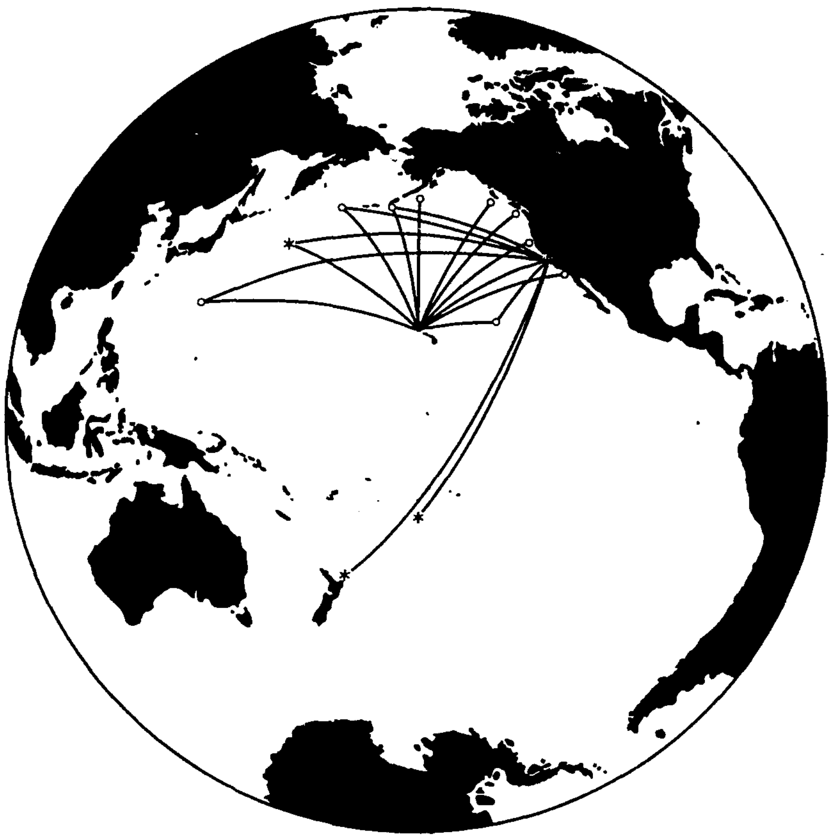

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I. INTRODUCTION

Despite more than 50 years of directed research and ocean measurements, the oceanographic community has yet to achieve an understanding of large scale ocean circulation processes adequate to form the basis for global predictive models. The speculative onset of global warming trends connected with the release of greenhouse gases makes the need for better predictive models critical. It is imperative to accurately characterize the global ocean's spatial and temporal response to the rising concentration of greenhouse gases.

There is a need for a program of ocean measurements to accompany the ongoing modeling effort. As yet there is no observational evidence for an oceanic greenhouse response. Nor is there adequate observational evidence for estimating the large-scale ambient variability against which the greenhouse effect (if any) has to be detected. We have to rely on model estimates for **both** the greenhouse signal and the ambient background noise.

It is widely accepted that the oceans play a pivotal role in moderating or otherwise affecting global weather changes connected with long-term warming. The oceans are the dominant reservoir for heat storage, and an important sink for carbon dioxide. There is a specific need to improve predictive global circulation models (GCMs) by assimilating ocean temperature measurements, satellite altimetry and other synoptic data spanning appropriate oceanic scales.

The program has two objectives: first, is to make a preliminary design of a network for mapping global warming with adequate spatial resolution that is derived from Global Climate Models (GCMs); second, is to put in place a demonstration system for acoustic monitoring in the Pacific Ocean that can provide information on gyre and basin scale ambient variability, and in a time frame of 24-30 months, can acquire the data needed to start the iterative process for empirical assimilation into GCM models. These objectives will also serve to provide a source of important, or in some cases unique data for a wide range of activities in general oceanography.

At 1 km depth we expect the greenhouse-induced warming to be of the order of $0.004^{o}C/yr.$ in the 1990s. By comparison there is a variability of $1^{o}C$ rms arising mostly from mesoscale eddies, typically of 100 km scale lengths. Detection of such a small, long-term trend in the presence of this mesoscale 'noise' would, in principal, take centuries. If, on the other hand, one could measure an average temperature over a range scale of 10 Mm (megameter), then the mesoscale noise is spatially averaged (20 dB reduction in noise intensity) and the situation is much more favorable.

Nevertheless, questions remain about the poorly understood gyre and basin scale variability and these questions must be resolved before the long-term detection performance and the complexity of a global transmission network can be established. Preliminary modeling results suggest that the oceanic greenhouse signal has the same gyre and basin scale as the ambient variability, but that the structure is different. In summary, we require an observational scheme that can resolve gyre and basin scale processes, but that suppresses mesoscale variability by spatial averaging.

Acoustic thermometry can do just that. The speed of sound is a sensitive function of temperature (5 m/s per ^{o}C) and the Sound Fixing and Ranging (SOFAR) wave guide permits the long-range transmissions for the required spatial averaging. The sound channel axis (typically 1 km) is somewhat deeper than one would like, but one expects (as will be shown) that some of the higher trapped acoustic modes will sample the ocean well above the SOFAR axis.

A network of sources and receivers which monitors acoustic travel times is needed. Can this be done with sufficient precision to detect the expected warming trend of 0.004^{o}C/year? This trend translates to a decrease in travel time by 1-2s in 10 years over a 10 Mm path. For the past 15 years acoustic tomography groups have made acoustic transmissions in the SOFAR channel to form path-integrated, or spatially averaged estimates of ocean temperature. Acoustic signal processing techniques have yielded a precision of 1 ms at 1 Mm ranges. A reasonable extrapolation to 10 Mm yields a precision of 10 to 50 ms, which is adequate. The problem is not precision, but the detection of the greenhouse signal over the background of ambient gyre and basin scale variability.

The extension of tomography techniques to global paths up to 16 Mm was made successfully in the Heard Island Feasibility Test, conducted in early 1991 -- acoustic signal-to-noise ratios exceeding 40 dB were obtained and stable arrivals (acoustic time-fronts) were observed. Specifically, it was demonstrated in the HIFT that coded low-frequency acoustic signals could be recorded at high signal levels at distances up to 16 Mm, thus forming the basis for using acoustic transmissions as an integrating, or averaging, temperature measurement

However, HIFT was limited to a duration of just a few days and required a moving source; so long-term variability could not be characterized. As the necessary first step toward a long-term monitoring effort, a demonstration program is needed which involves fixed source to fixed receiver transmissions for more than one year. These transmissions will span both global (~10 Mm) paths, and gyre resolving (~5 Mm) paths, thereby addressing the issues of global path stability, and gyre and basin scale long-term variability. Either of these issues may present important obstacles to the objective of empirically characterizing global ocean greenhouse trends within a monitoring program spanning a decade.

The purpose of the engineering and measurement program is therefore twofold:

> (1) *To demonstrate the extension of integrated temperature estimation to spatial scales spanning gyre, basin and trans-global paths (of the order of 10 megameters) and temporal scales spanning several seasons, and hence demonstrate the principles underlying an affordable network for measuring global ocean temperature change in a way that optimally detects the effect of greenhouse warming.*

(2) *To establish the baseline for an affordable long-term network using the minimum necessary number of paths, a reliable ocean hardware suite, and a design for data assimilation and analysis. The network is designed to foster international participation, both in connection with its operation and for the distribution and analysis of the data.*

II. OVERVIEW

When the Heard Island Feasibility Test was conducted in 1991, one moving acoustic source (actually a vertical array of sources), and a limited number of fixed receivers were used, as shown in Figure 1. The object of the feasibility test was to determine whether the signals could be transmitted and received with adequate signal-to-noise ratios and path coherence over ranges long enough to make oceanic temperature measurements by acoustic means practical. A single source and a handful of receivers sufficed because the unique location of Heard Island allowed acoustic propagation through most of the world's oceans. The small size of the experimental team meant that only two Naval Facilities (NAVFACs) and one Missile Impact Location site (MILS) were instrumented. International participation was on a voluntary basis and most of the nine participating countries deployed only single receivers.

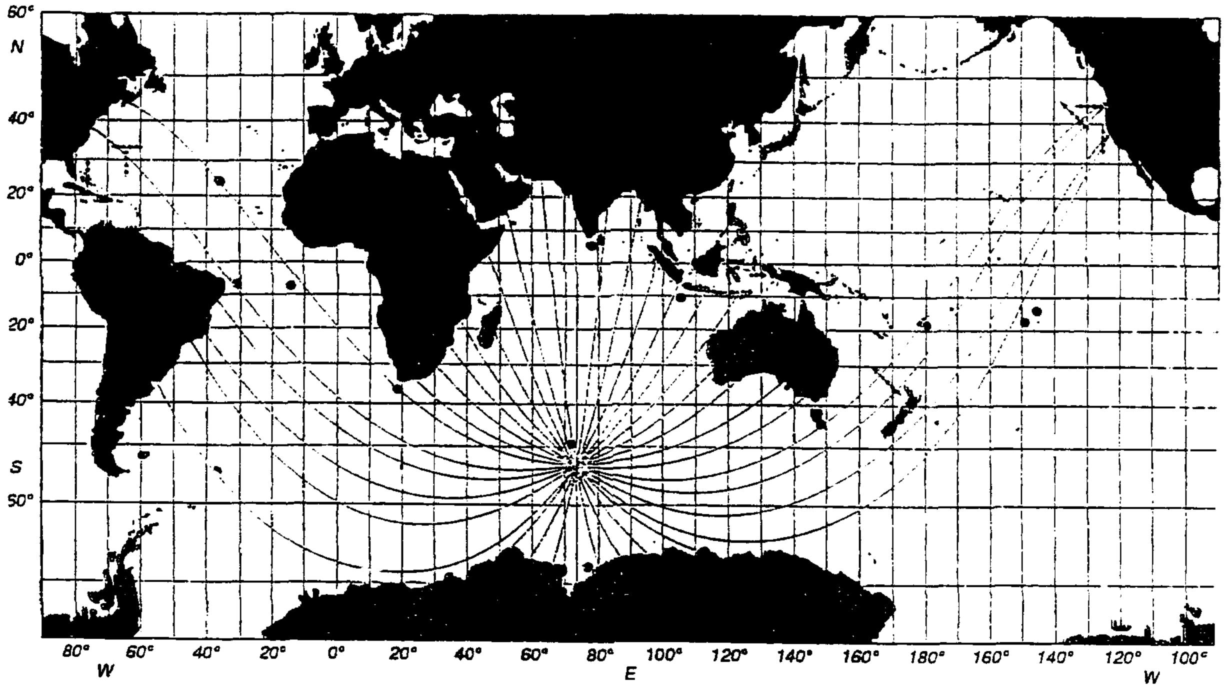


FIGURE 1. Axially refracted geodesics drawn every 10° from the source location at Heard Island. Receiver sites are shown. Horizontal lines represent horizontal arrays off the American west coast and off Bermuda. Vertical lines designate vertical arrays off Monterey and Bermuda. Lines with arrows designate a Canadian towed array off British Columbia and a New Zealand towed array. The Japanese occupied a station near Fiji island. The Australians occupied three stations, one near Christmas Island in the Indian Ocean, one off Tasmania and a third at Mawson Station, Antarctica. There was a French receiver east of Kerguelen Island, an Indian receiver off Gao, and a station by the University of Cape Town. NOAA recorded axial receivers at Ascension Island. A USSR acoustic vessel recorded at 25°N in the North Atlantic.

The situation is different for a global monitoring objective. Results from the best of today's analytical and numerical coupled ocean-atmosphere dynamical models make it clear that transglobal coverage of the oceans is necessary. To obtain required spatial sampling some ocean basins should be more heavily instrumented than others. For example, most of the heat that finds its way into the interior of the oceans does so in high latitude regions like the North Pacific, Greenland and Norwegian Seas in the north and the Southern Ocean in the south. An efficient monitoring network will sample these areas relatively more densely than some mid-latitude ocean basins.

Based on preliminary studies of GCM-based network design, no more than 100 paths are needed to resolve or over-resolve the greenhouse Empirical Orthogonal Functions (EOFs) from ambient variability. This network would require no more than 6-8 sources and 35-40 receivers for long-term global coverage. The design could be less complex once the data from the needed studies are compared with GCM model runs. More detailed characteristics of a concept for a global network are given in the next section.

It is necessary to not only address and resolve the ocean variability questions, and begin the process of GCM assimilation with synoptic data, but also to build the operating prototype of a long-term monitoring network of sources and receivers in the Pacific Ocean. The time required to achieve detection of the greenhouse signal is not yet well defined, neither is the complexity of the network required to make the initial detection. The program will determine these parameters and iteratively define the minimum required network configuration.

ATOC's approach is built on the results to date of the HIFT data interpretation process and on the international cooperation and collaboration achieved to date. A network of sources and receivers strategically placed to ensonify gyre, basin and global scale paths in the Pacific (4 to 10 Mm path lengths) is needed. To avoid the issues connected with path identification and re-identification already raised by the HIFT data, one approach is to track discrete path arrivals using highly time resolving acoustic signals, and to emphasize near-SOFAR axis paths. ATOC should use deep sources and receivers mounted on continental and island slopes; and, wherever possible, cable to shore processing sites. In the process of procuring sources and receivers, the program will develop and test the technology necessary for long-term monitoring, and will have the core of a long-term Pacific basin network already installed and operating in support of the long-term monitoring effort.

Figure 2 shows a preliminary network of sources and receivers for the Pacific. The plotted paths (great circles) closely resemble the actual acoustic paths. This network is proposed for the demonstration phase, but can also form the core

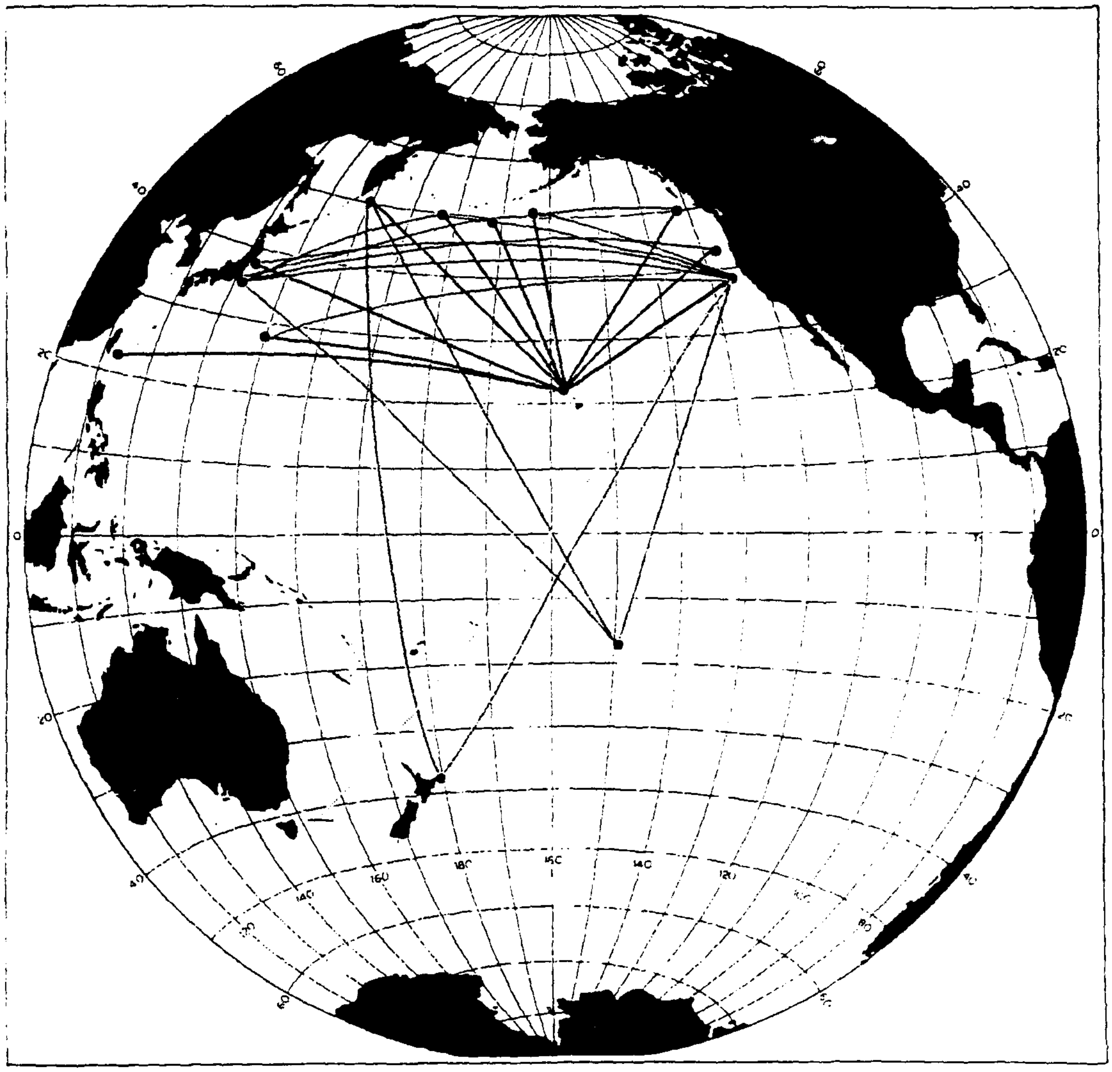


FIGURE 2. The proposed ATOC demonstration network locates HLF-6 sources (red and blue) on deep sites at Kauai and Point Sur to ensonify 5 and 10 Mm paths and an Australian relocatable array. Additional source sites near Japan and Kamchatka that may be made possible by cooperative arrangements are shown in green. Acoustic paths to foreign receiver sites and fictive Navy receiving arrays (NAVFACs) are shown.

of a long-term Pacific basin network. This network would make maximum use of logistically practical sites and take advantage of the international partnership already established by the HIFT effort. Sources and receivers are near the SOFAR-axis with short cable runs to shore-monitoring sites. The deep source sites and reduced projector power levels will avoid, to the maximum feasible extent, interference with marine mammal populations by generating near-surface acoustic levels significantly less than typical ship radiated noise.

International collaborators are essential to the conduct of the Pacific demonstration program -- Australia, New Zealand, Taiwan, Japan, Russia, France and Canada -- in the data collection, site monitoring, technology development and data analysis. While developing this collaboration, in concert with the design iteration for a global network, arrangements will be worked out for projector and receiver sites strategically located around the Atlantic and Indian Oceans -- in Asia, South Africa, Europe and South America -- whose scientific and logistical coordination efforts will be vital to extending the network to the global ocean for long term monitoring.

Characteristics of a Global Network

At this time there is not an adequate basis for the specific design of a global network; such a design is to be developed in the demonstration program. Nevertheless, its basic characteristics can be outlined by the following points:

- Acoustic path coverage needs to be provided in ocean regions where GCM models indicate strong greenhouse signals compared to ambient variability.

- Both source and receiver sites should be stationary to aid in the identification and long-term tracking of discrete acoustic time-fronts on an inter-seasonal basis.

- Acoustic sources should avoid shallow sites and polar waters so that interference with marine mammals is minimized. Conversely, temperate ocean sites on steep slopes near the SOFAR axis should be selected where possible in order to optimize the received acoustic signal-to-noise ratios (SNRs) and thereby reduce the required source power level. At near-SOFAR axis depths, sound levels in the 200 m depth zone above the sources should be 20 dB lower than the radiated source (spectrum) level of typical merchant ships.

- Acoustic paths should not cross the polar convergences in either hemisphere, to avoid frontal variability and strong mode-mode coupling in the polar to temperate transitions.

- Site selection should also be strongly keyed to affordable logistics for maintenance and communications, and easy access by international partners who are participating in the program and using its data. This implies generally that fixed sites with nearby shoreline access are heavily favored over mid-ocean, moored or drifting sites.

• The network design should maximize the number of receivers that have clear acoustic paths to each source (optimum source site geometry), and the number of sources that have clear acoustic paths to each receiver (optimum receiver site geometry).

• Given the international scope of the proposed program, the processed data should be archived and made available to both project participants and the general oceanographic community in a timely fashion. Hence, a data center architecture capable of supporting open access by qualified investigators world-wide will be needed.

These specifications can be met in principle, with a modest engineering and installation program that involves cooperation with scientific, government and industrial groups having access to the necessary ocean sites. The long-term monitoring effort should be conducted in a partnership with these groups.

Rationale for the Demonstration Network & Supporting Development

The rationale for the structure of the program -- including the investigation and further development of GCM models, data assimilation into the models, the global network strategy, propagation physics and the supporting technology development-- is specific and can be stated as follows:

• The approach is to emphasize the empirical determination of ocean climate over the measurement of ocean "weather", i.e., to focus resources on global scale measurements needed to improve global climate models ultimately to the point that they will become useful predictors. This method for earliest detection of the global greenhouse signal is fundamentally model-based -- we will make those measurements needed to unmask the greenhouse EOF(s) as a first priority. There is another way of saying this -- global arrays have to be gyre and basin scale resolving (the climate scales) and mesoscale suppressing (the ocean weather scale).

• Long path spatial averaging is essential to the architecture of an affordable global monitoring network. Our architecture opts for reliability and long-term operability of a relatively few network nodes (sources and receivers), at the minimum cost per node commensurate with these objectives, over a sampling strategy to generate a large number of nodes which make relatively local measurements.

• The benefits of maximizing spatial averaging are very high. Mesoscale eddy "noise" has already been demonstrated to be suppressible and the HIFT data show that 10-15 Mm paths can be linked by highly time-resolving signals with modest source power and receiver complexity.

• With new insights derived from the HIFT acoustic arrival structures, there is a strong preference for long-term fixed path geometries, i.e., permanently installed, bottom mounted sources and receivers. We can then work with small time-of-arrival trends in discrete arrivals within complex arrival structures without the problem of re-identifying specific paths over spans of time and space.

- ATOC should avoid the various limits imposed on the HIFT scenario. First, the limitation to just a few days of transmission prevented the analysis for long-term path stability. Second, the problems associated with a moving source scenario: the propagation effects of changing bottom topography near the moving source, the oceanic effects of changing the propagation path structure over time and the problems of determining and tracking source and receiver locations. Third, problems associated with source depth limitations, the polar transition, and polar frontal effects. A plan to conduct transmissions over a seasonal cycle will permit a direct and vital check by a comparison of the measured acoustic travel time changes with those computed from oceanographic measurements.

- ATOC should limit technology development requirements and risks for sources and receivers, and the network control and data management system by making maximum use of existing technologies already developed for related applications, namely, U.S. Navy developed sources, Navy and commercial undersea electronics developments for receiving arrays and data telemetry, open-architecture scientific data-base management software, hardware and networking from the seismic community, and new, lower cost ocean installation techniques and systems from recent commercial submarine telecommunications developments.

Reliance on fixed transmission paths for the ATOC network is best illustrated by a typical HIFT processed signal (Figure 3), which shows the matched-filter processed arrival structures from a single (MILS) hydrophone at Ascension Island, 9.2 Mm from the HIFT source. The signal period is about 22.3 sec. The figure begins exactly 90 minutes after the start of the transmission and shows 12 minutes before the signal arrival, 60 min. of signal and 12 min. after the signal; roughly 32 periods, 161 periods and 32 periods respectively. Each period yields an analysis of the arrival structure over that 22.3 sec. The carrier was removed from the reception and used to estimate the received signal quality -- about 25 dB compared to the noise in a 1 Hz band, implying that the 22.3 sec signal quality would be 39 dB for this transmission if there were only one arrival. At the top of the figure, the signal magnitude structure (on a dB color scale) is shown as a function of time for relative path delays extending over 1 period, using 1 period of coherent processing. This figure illustrates well the rich multipath structure after more than 9 Mm of propagation. The upper 10 dB most energetic arrivals (red to yellow) span about 8 sec in delay space, with perhaps 5 to 8 arrivals per second, right at the edge of HIFT's resolution. The duration of individual path arrivals is clearly seen to be of the order of 10 to 20 minutes in this figure, corresponding to path-length changes of about 2 km extent. The ship was moving at 3.51 kts relative doppler during this transmission sequence. After coherent phase removal of this doppler, the combined phase (color encoded)

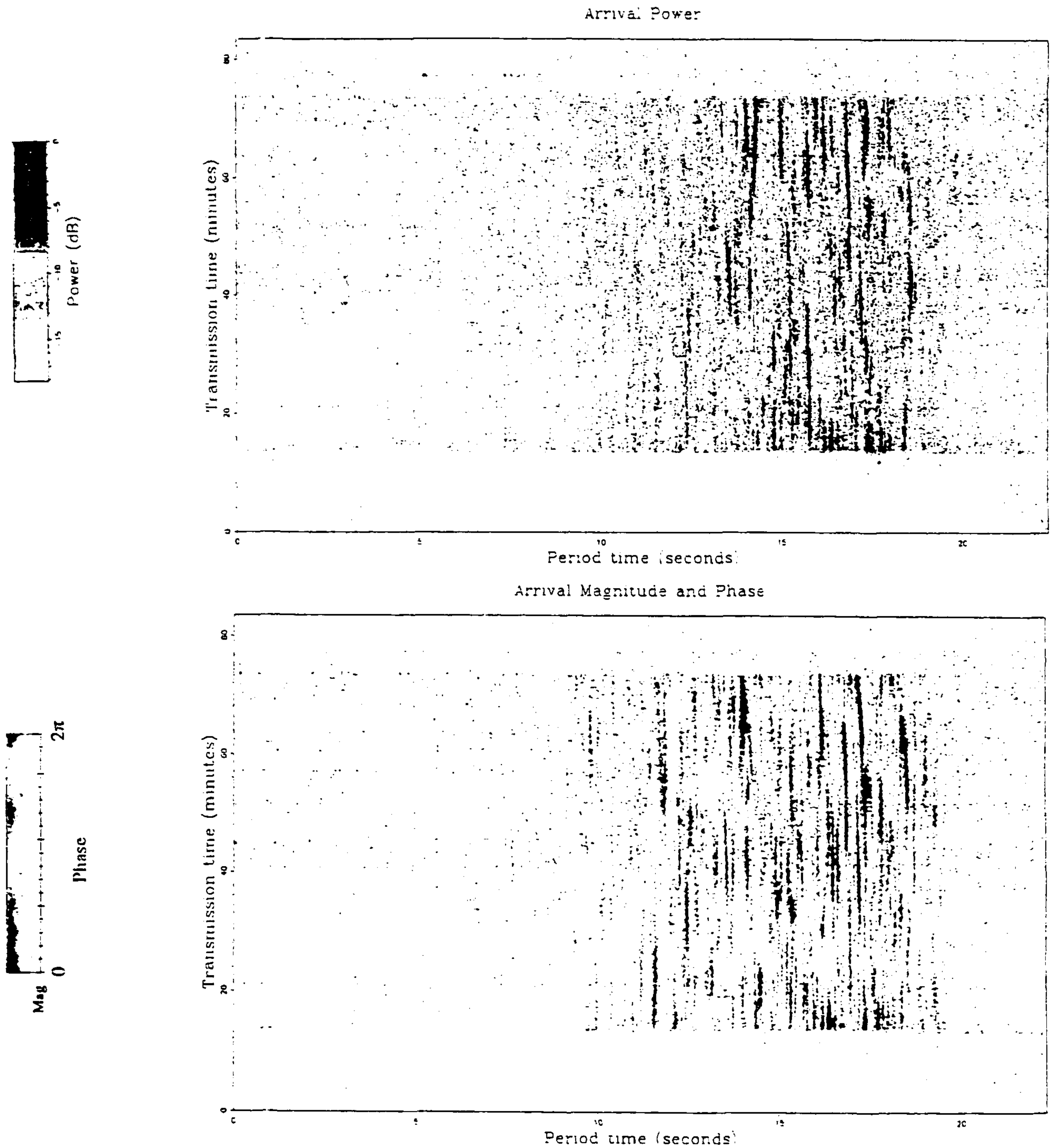


FIGURE 3. Ascension Island acoustic arrival structure from a typical 60 minute HIFT transmission. Amplitude is color coded in top figure. Phase is color coded in the bottom figure, with amplitude graded by intensity.

and amplitude (intensity) is shown at the bottom for the same transmission. This signal pattern shows exceptional phase stability for each discrete path during individual periods of high SNR. Signal phase is a more sensitive indicator of edge-overlapped arrivals than is amplitude, and indicate that frequently there are arrivals perhaps 50-100 msec center-to-center in the most intense 4 seconds of arrivals (spanning 14-18 sec arrival delay). ATOC is specifying a 20 Hz signal bandwidth vs. HIFT's 11.3 Hz to obtain the necessary resolution.

These results suggest that with fixed source and receiver geometry (non-translating propagation paths) ATOC should be able to observe non-fading discrete paths, and maintain time tags on discrete paths over inter-seasonal spans of time despite their large extents. But, the record also shows that the problem of identifying specific paths will be significant, even if geometries are fixed.

The above elements comprise an underlying strategy for a global ocean climate monitoring network. They in turn generate specific objectives for a demonstration network and supporting studies.

The most general and highest priority objective is to demonstrate that an affordable international network can be constructed and operated that is capable of detecting and characterizing the actual oceanic greenhouse signal.

To do this, the program should:

- Develop and prove new hardware/software designs for sources, receivers, data telemetry, networking and management.

- Establish ocean installation techniques that are highly reliable, cost efficient and can be used worldwide by international partners.

- Iterate the design to achieve the minimum impact on the ocean environment, particularly to avoid disturbing marine mammal populations (we will conduct experiments to investigate behavior patterns of these animals in the vicinity of source locations).

- Finally, to address the scientific obstacles to these objectives early in the program, continue collaboration with GCM developers, and conduct the studies necessary to resolve questions about gyre and basin ambient processes and long path propagation which could affect the design of the network.

III. DESCRIPTION OF PROGRAM

GLOBAL CLIMATE MODELS

Collaboration with ongoing efforts towards global coupled atmosphere-ocean models is an essential component of ATOC, and was initiated prior to HIFT. The goals are:

(i) *To detect the greenhouse "signal" over and above the "noise" of ambient ocean variability.* The essential consideration here is that even after a century of ocean exploration, variability on gyre and basin scales (scales of principal concern here) are not sufficiently known to provide the observational background for the detection problem. We need to go to the modelers for both the signal and the ambient variability structure, as speculative as model results may be.

(ii) *Given the structure of signal and noise as provided by the models, to design an adequate and affordable acoustic network.*

(iii) *To provide for early assimilation of the acoustic measurements into the modeling efforts.*

(iv) *To consider the special situation in the Arctic.*

(v) *To contribute to our understanding of large-scale ocean variability.*

Global Network

The ocean is a turbulent fluid in which one anticipates natural variability on all space and time scales. Distinguishing a greenhouse warming trend from natural variability is the central goal of the observing program. In the absence of any global empirical evidence, one needs to go to models for guidance. We have selected the coupled atmosphere-ocean models of MPI-Hamburg and GFDL-Princeton to provide such guidance. The initial procedure will be to represent ambient model variability using time-variable Empirical Orthogonal Functions. Preliminary computations indicate that a dozen EOFs can account for most of the model ambient variance.

Similarly, the greenhouse-induced model perturbation can be represented by just one or two EOFs. It is then a matter of applying detection theory to ask whether n years of data can resolve the EOFs with probability p, given a certain observational strategy. The models have many shortcomings, however, and considerable caution is required in determining which results are robust.

For an initial observational strategy, we will adopt a network of sources and receivers on the basis of availability of coastal recording sites, closeness to shore of the sound channel, and preliminary model estimates of the geographic distribution of greenhouse signal and ambient variability.

The next step is to do the "forward problem" of producing time series of travel time against clocktime from the model ocean. These synthetic time series provide the basis for solving the detection problem, and for suggesting a more efficient (and preferably smaller) network. The results of this work will go well beyond separating greenhouse and ambient variability and will also provide a basis for a model of global ambient variability to be tested against field observations in years to come.

Assimilation

None of these results will be any better than the modeling on which the calculations are based. ATOC should investigate those aspects of climate modeling to which the acoustic monitoring is particularly sensitive and try to evaluate the degree of confidence one can place in the results. Looking toward the time when actual large-scale acoustic measurements are available, several modeling strategies need to be pursued. Data can be employed with climate models in two superficially different ways.

In one method, the observations of change in the ocean can be compared to those predicted by the models and the resulting compatabilities and inconsistencies (one expects both) used to establish confidence in both models and observations, to permit their interpretation, and to guide modifications of the models and observational strategies.

Alternatively, one can produce a more direct combination, essentially by attempting to force the dynamical models to be consistent with the observations (sometimes known as "assimilation"), and to produce tests of consistency and reliability through formal error measures. A central advantage of the latter method is that it can employ not just acoustic measurements, but any or all other types of observations with a bearing on the problem of climate change. Assuming formal consistency can be demonstrated, one achieves a "best estimate" of the oceanic changes, along with an estimate of reliability.

Both these modeling strategies need to be pursued. As part of the second strategy, tools should be developed to use dynamical ocean models in direct conjunction with the measured acoustics. This work will involve both development of a new generation of ocean model, as well as procedures (there are many candidates) for direct combination of acoustic and other data with the model. A new generation model is proposed (based upon an existing regional model of Marshall's) because the known problems of the models already in existence are so great (the surface flux correction being only the most notorious example), as to suggest a serious effort should be directed at alternatives.

The use of large-scale acoustics for the study of climate change must take place in the context of (a) known oceanic physics and dynamics, and (b) the other observational programs intended to examine related aspects of the same problem. Descriptions of known physics are expressed mathematically in model form, of which the most sophisticated extant examples are the global circulation models. As part of the planning for the use of global acoustics, existing models at Hamburg, GFDL, and NPG/NCAR have been, or will be employed for ray tracing, and prediction of the nature of greenhouse warming and of the magnitudes of the background variability.

In tackling a problem whose time scale is decadal, one must anticipate that all the necessary elements of the program should come to maturity when they are required, and the modeling element is no different from the instrumental one. The investigators on this proposal need GCM's for a variety of purposes, including those already listed: for the acoustic property studies (e.g. determining ray trajectories), for predictions of the background physics and man-induced trends, for synthesis into one self-consistent picture of both the acoustic measurements and any other available measurements with bearing on the problem - e.g. altimetry (this latter activity is referred to by some as "assimilation").

The development of a new model will include an acoustic component as an integral part. There are several reasons for attempting construction of a new model. Most (but not all) of the GCM's used for oceanic climate studies are direct descendants of the GFDL model of Bryan and Cox (1968). As such, they share common codes and paramaterizations. The absence of a significant number of independently coded models is proving an increasing handicap in understanding the reliability of climate forecasts involving the ocean. We would propose furthermore, during the model development, to construct the acoustic capability (e.g. computation of sound speed and potential sound speed, and the diagnostic fields for acoustic computation) as an intrinsic part of the model, rather than something which has to be "bolted on" afterwards. Finally, as we have discussed at length elsewhere (e.g. Wunsch, 1990, Munk et al., 1992), the most effective way to use any kind of oceanographic data, but particularly given the integrating properties of acoustic signals, is to use it to constrain a model to the data, and use the model - as the summation of known physics - to compute the diagnostic quantities of interest (net warming, sea level rise, mass transport shifts, etc.)

This constraining process is known variously as "assimilation", "inversion", "optimization", etc., and several ways are known to do it. The most sophisticated such computations (e.g. Fukumori et al., 1992; Tziperman et al., 1992) have employed models which already existed (Fukumori et al., used the Haidvogel SPEM, Tziperman et al., used the Bryan-Cox model). If one knows the model is to be constructed with an adjoint (as in Tziperman et al.), or for which a transition matrix in a linearized sequential estimation process (Fukumori et al.), some of the appropriate computations can be built into the model at the outset (e.g. if the surface boundary conditions are to be controls in an adjoint (Pontryagin principle) formulation, the numerics will be somewhat different.) In the past several years, considerable experience has been obtained in the practical (as opposed to the 'simulations' which dominate the literature) application of such methods.

A new global ocean circulation model for the study of the ocean in climate and climate change and for ultimate use with the acoustic data is needed. It would represent a considerable departure from the Bryan and Cox (1968) hydrostatic primitive-equation model which has dominated ocean modeling over the past twenty years. The new model, based on more complete dynamics, would in principle be used to represent motions from the scale of convective plumes in the open-ocean (~1 km), to ocean currents of global scale. A prototype of the new model already exists and is described in Brugge, Jones and Marshall (1991). It is being used now to simulate acoustic paths from a tomographic array deployed by Professor Schott and his colleagues in the western Mediterranean this winter. A new generation of ocean model based on superior dynamics and numerical approximations is needed because many of the insights into how the ocean works are based on the results of integrations using numerical models which have a common ancestry in the - albeit highly successful - Bryan-Cox model based on the primitive equations.

A major difficulty of that model is inherent in the numerical algorithm on which it is based; the equation that expresses the condition of incompressibility - the continuity equation - is used to compute the vertical velocity. This procedure leads to loss of accuracy and a noisy vertical velocity field at the grid scale of the model. Adoption of such a scheme is necessary because of the strict imposition of the hydrostatic equation, which sets time-derivatives in the vertical momentum equations to zero. This neglect of a time derivative actually changes the nature of the equations - they cease to be hyperbolic and can become ill-posed (see the discussion by Browning, Holland, Kreiss and Worley, 1990), leading to numerical difficulties.

The model being developed at MIT is based on the incompressible Navier-Stokes equations in which the full (non-hydrostatic) prognostic equation for the vertical velocity is employed. The continuity equation is then interpreted more naturally as an equation for the horizontal divergence. The prognostic variables are the three components of velocity, potential temperature and salinity; the pressure field is diagnosed by inverting, at each time-step, a constant-coefficient, three-dimensional elliptic operator with appropriate boundary conditions.

The equation of state for density that closes the model is the polynomial of the International Standards Routines and accounts fully for salinity and compressibility effects. This model uses an Euler-backward time-integration scheme; this has worked exceptionally well in high-resolution ocean convection experiments. It also has the advantage that it reduces the relative amplitude of high temporal frequencies - see Matsuno (1966) - and so is an ideal device to damp spurious high-frequency noise generated by the assimilation of observed data.

A fully-operational prototype model of a rectangular, flat-bottomed ocean, has been developed and is being used for the study of open-ocean deep convection - see Jones and Marshall (1992). At sufficiently high resolution (~1 km) the model is capable of explicitly resolving rather than parametrising the convective process. Both haline convection and overturning due to surface heat loss are being modeled. Because the model is non-hydrostatic it can readily be employed from the very smallest convective scales up to global scales. On the scale of convective plumes, non-hydrostatic terms cannot be neglected, and very high resolution is required. On the scale of ocean gyres, such high horizontal resolutions are neither possible nor desirable, but because the model retains a prognostic equation for the vertical velocity, it will have superior numerics to conventional primitive-equation models which strictly impose hydrostatic balance.

In the specific context of large scale acoustics, there are several special considerations. The model would have a minimum of 10 levels, and ultimately many more, as required to resolve the main thermocline and major topographic features. Preliminary discussions with acoustic modelers suggests that 10 levels are adequate for the general propagation calculations. There are many other issues that would be dealt with along the way. For example, if propagation studies take place only within the adiabatic limit, one need not store the full acoustic fields, but only certain of their statistics.

The issue of climate trend detection via the combination of model and data is a central one. It is anticipated (as with the ongoing Hamburg/GFDL/ etc. work) that the global model would produce a realistic low frequency variability of the major oceanic gyres associated with the seasonal and interannual cycles of wind and thermodynamic coupling. True subduction of properties from a surface mixed-layer undergoing seasonal cycles would be reproduced in the model. We anticipate that the ten-twenty year ventilation time-scale of the ocean gyres would be a major element of natural low-frequency variability influencing all oceanographic data.

A major focus of model use would be the distinguishing such natural variability from that induced by an increasing atmospheric greenhouse. This "detection problem" is a non-trivial one, involving trend detection in the presence of red-noise processes, and would eventually become a central issue (there is an existing literature which would be explored, with the help of A. Baggeroer and other MIT signal extraction experts).

Programs such as the World Ocean Circulation Experiment (WOCE), the TOPEX/POSEIDON altimetric mission and other programs will be generating large amounts of data which one will wish to compare to, and combine with the acoustic measurements. With major support from these other programs, the model would ultimately be constrained to **all** the data available, not just the acoustic sets. The 'assimilation/inversion' methodologies alluded to above are quite general and do not limit to any particular type of data (although there are remaining issues of practicality in some cases, e.g. concerning computational load, 'colored noise' problems and the like) which need to be investigated.

Arctic Environment

The objective is to examine, through the use of coupled air-ice-water acoustic models and oceanographic data, the feasibility of monitoring long-term temperature changes in the Arctic ocean and changes to the Arctic ice cover.

There is general agreement that despite its relatively small size, the Arctic Ocean and adjacent seas exert a strong influence of the earth's climate. Deep water production in this region is a major driver of the global thermohaline circulation.

The ice-cover has an important effect on planetary albedo. Global models show increased *atmospheric* warming at high latitudes. But this is as far as the agreement goes. Manabe predicts a relatively small ocean response to atmospheric warming. Some models even postulate high latitude ocean cooling, increased precipitation in the form of snow, and a *thickening* of the ice cover. But a 15 year record of satellite ice cover shows no significant trend.

ATOC should study whether trans-polar acoustic transmissions could provide significant evidence for changes in temperature and ice cover. Here, as elsewhere, the integrating properties of the method provide basin averages, as required. A very preliminary estimate suggests a decrease in travel time of order 15 ms/year (1 cycle) might be taking place due to warming of near-surface waters by $0.01^{o}C/y$. Thinning the ice cover by 10 cm/y has a much smaller effect on travel time. It will be difficult to detect and interpret such small changes. But here we are aided by the fact that the variability associated with internal waves and mesoscale processes is one to two order of magnitude smaller in the Arctic ocean than in the temperate ocean!

The reflection from sea ice provides a further complexity. Comparison of the predictions by the full wave equation theory of Fricke with the spectral approach by Kuperman and Schmidt should be made. ATOC's objective should be to design a pilot experiment which takes these factors into account, and specifies source and receiver requirements, waveforms and signal processing. This effort will be greatly aided by measurements now planned for the same period under an ONR sponsored Ice Mechanics Accelerated Research Initiative.

PROPAGATION ISSUES

The ATOC requirement is to measure changes in travel time along a stable and identified path to a precision of at least 50 ms. There is a qualitative difference between propagation issues for 1 Mm and 10 Mm ranges. HIFT was designed to define these issues. With different models of propagation giving loss estimates differing by up to 60 dB, it was by no means certain that the long range measurements were feasible.

HIFT results were positive. The frequency signatures were very clear with S/N up to an astounding 40 dB. Signals were clearly received up to the maximum ranges of 16 Mm., as shown in Figure 4. The phase coherence of the processed signals was found to be up to 20 minutes at 10 Mm and one hour at 5 Mm. By any reasonable extrapolation of past experience in tomography we can expect travel time precisions of better than 50 ms, possibly 10 ms.

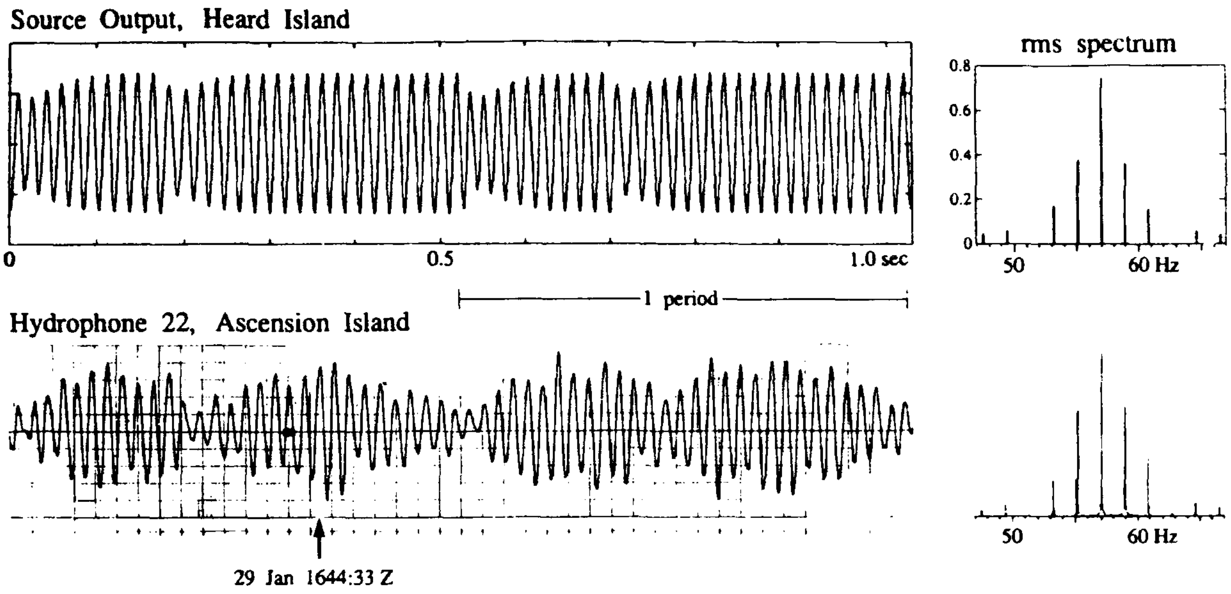


FIGURE 4. Ascension Island recorded signals from HIFT transmissions. A 43 dB SNR was recorded from a single hydrophone.

There were a number of surprises in HIFT. The expected path from Heard Island to the State of Washington was through the Tasman Sea. Even while the experiment was underway, a Canadian towed array gave an arrival direction 20^{o} to the left of the expected value, indicating as passage to the east (rather than the west) of New Zealand. This was later confirmed by the computed Heard Island launch angle. We have to be very careful in determining the horizontal path structure.

A second surprise had to do with the richness of the arrival structure. Despite expectations of just one or several modes to survive the very long ranges, the vertical array at Monterey gave at least six modes. The rich arrival structure at Christmas Islands (shown in Figure 5) is indicative of a multiple arrival propagation. This is both good and bad: good because if many stable arrivals can be identified, then one can learn about changes in the upper ocean as well as at axial depths, thus vastly improving the opportunity for detection; bad because it makes the identification and stability problems much more difficult.

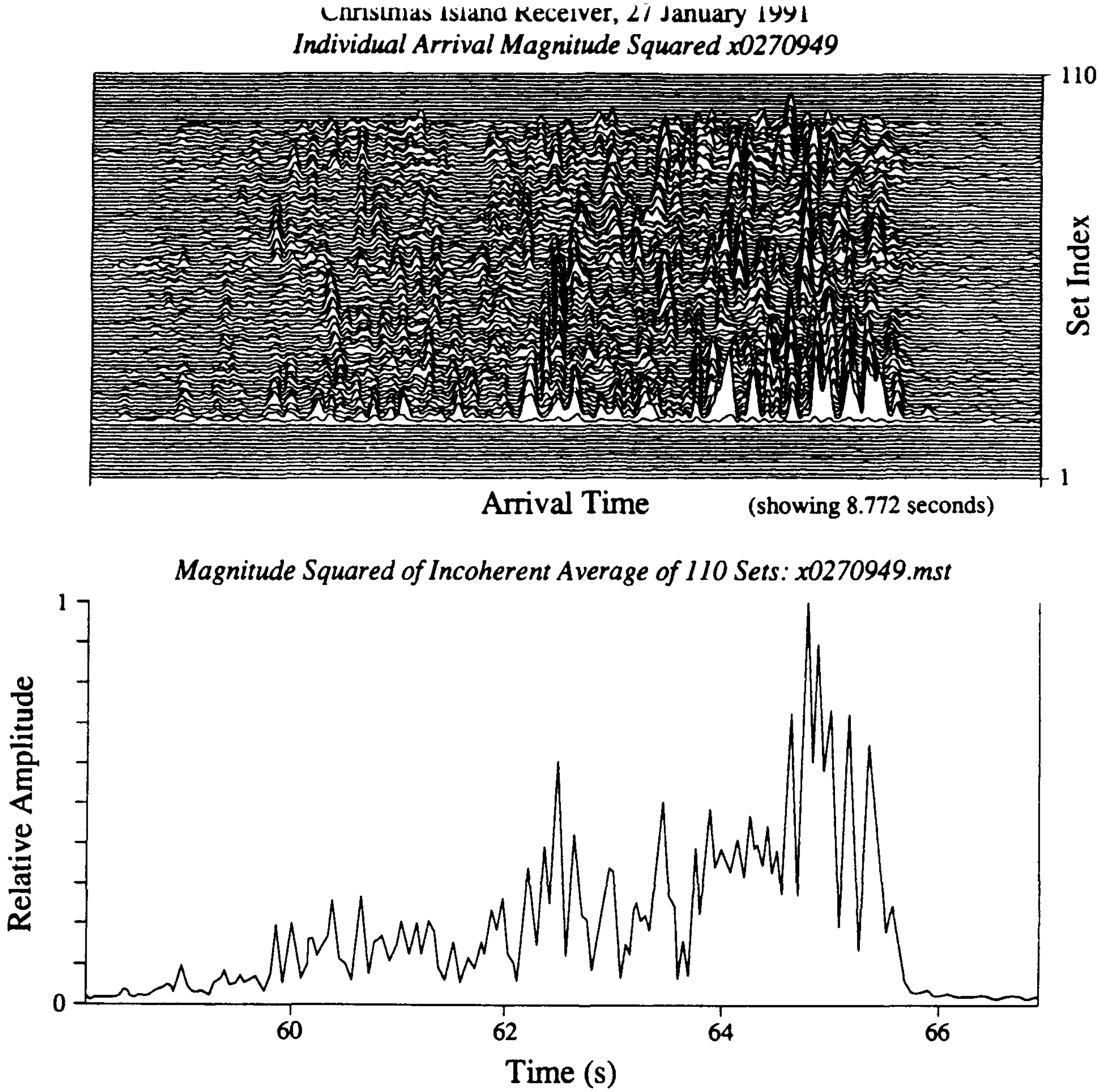


FIGURE 5. Christmas Island (~5 Mm) arrival structure showing complex arrival structures not anticipated for this path.

There were some fundamental restraints to the HIFT feasibility test.

(i) the HIFT source ship had to be underway into the wind during transmission so that the propagation at the end of the transmission hour was through a structurally different ocean than at the start. In the proposed program we shall have about a dozen fixed-to-fixed point transmissions.

(ii) HIFT was necessarily limited to a few days. The proposed program will yield information on seasonal changes. We will measure the seasonal changes by oceanographic sections along the path in winter and summer, and compare the oceanographic and computed changes.

(iii) The HIFT source was limited to 300m depth and thus a high-latitude source location. As a result the initial propagation along all HIFT paths was along a highly dispersive polar surface duct. The proposed transmissions are largely through a temperate ocean environment.

(iv) With the exception of Kerguelen and Mawson Station on Antarctica, the propagation passed through the Antarctic Convergence zone; this sharp transition zone is associated with mode coupling and other complexities. We propose to place all ATOC sources to the north of the Antarctic Convergence.

Future work should also place emphasis on understanding the HIFT rich arrival structure:

(1) Continue work on comparing measured and computed arrival structure. For that purpose we shall compare adiabatic and non-adiabatic codes, 2-D and 3-D PE codes, ray and mode codes.

(2) At ranges of order 10 Mm the problems of splitting paths into horizontal multi-path by mesoscale eddies and bathymetric features needs to be considered. This can be done in two ways: by applying Dashen's path integral method, and by constructing refracted geodesics through a Semtner eddy-resolving ocean model.

(3) Some recent work by Shang in Boulder suggests significant mode-mode coupling can occur under some circumstances. This important consideration will be pursued by theoretical calculations, and if necessary by some mid-range measurements with some other vertical/horizontal receiver array.

(4) Global tidal currents will modulate the received signal phase by several times 2π. ATOC should compute and correct for these tidal effects *a priori*, thus opening the way for interpreting the measured phases. In fact, the acoustic measurement of tidal currents is probably the best way of measuring open-sea tidal currents. The amplitudes are typically 1 cm/s, and moored current meters stall at these low velocities. Further, the horizontal and vertical averaging accomplished by the acoustic transmissions separates the baroclinic from barotropic tidal currents. This work can be done by Dr. David Cartwright, who has written the definitive account of open-sea barotropic tides based on satellite altimetry. It is expected that the tidal coefficients derived from the transmissions will significantly enhance co-tidal charts for the Pacific Ocean.

(5) Frequency dispersion may become a significant factor at very long ranges. Attempts to extract dispersion information from the HIFT data are underway and will continue.

The ATOC problem involves a fascinating and difficult interaction of parameters, among them source intensity, frequency and bandwidth, signal duration and duty cycle, and the dimension (vertical and horizontal) of the receiving arrays. A first-order choice has been done, but it is vital that the final specifications in this parameter space be done against the best possible understanding of the propagation physics.

INTERNATIONAL PARTICIPATION

The Heard Island experiment could not have been carried out without strong international cooperation among a number of individual investigators, institutes and foreign governments. Following HIFT, a joint effort by L. Brekhovskikh and the HIFT principals established a Scientific Committee on Ocean Research (SCOR) working group which held an organizational meeting in Vienna in August 1991. ATOC should expand the international network established during HIFT for the program, first to establish the Pacific demonstration network, secondly, to put in place the broader network that will be needed for global long-term monitoring, and lastly to foster an international network of scientific work with the data.

A Pacific monitoring program specifically necessitates a strong international component. The basic task of acquiring data at foreign sites can only be seriously planned through co-operation with scientists and institutions in different countries, both because of the technical support required (such as ships-of-opportunity for instrument deployment) and also for very practical and political reasons. Moreover, the magnitude of the scientific problem necessitates broadening the participation to include as many scientists from around the world as are both interested and capable. A broad international perspective also demonstrates a general acceptance of the program in the world scientific community, thus providing added impetus to the work and added support in the search for continued funding.

For all these reasons it appears essential that a sustained effort be initiated to involve reputable and interested scientists from around the world. In the initial stages it will be necessary to actively seek participants from countries that lie in the path of the first planned transmissions. The proposed Pacific network will require the participation of Australian, New Zealand, French, and Canadian based scientific teams, and will benefit significantly from the participation of Japanese, Taiwanese, South African and Russian teams.

International Network System Engineering

The ATOC Pacific network shown in Figure 2 depends on successful liaison with the governments and institutes of New Zealand and France to operate stations and collect data from Tahiti and the New Zealand littoral. These paths are an essential part of an effort to resolve issues connected with inter-gyre and inter-seasonal variability.

Additional contacts have been made with the CSIST institute in Taiwan, the JAMSTEC Institute in Japan, the Acoustics Institute of the (Russian) Academy of Sciences and the Pacific Oceanographic Institute in Vladivostok. JAMESTEC has tentatively expressed an interest to install a source or receiving array on their east coast. The Russians propose to build an acoustic source capable of transmitting ATOC signal formats. If such a source can be built and proves affordable, it could be installed off the Kamchatka Peninsula, probably at or near the site of an existing installation. This node would provide a valuable addition to the network.

ACOUSTIC SYSTEM DESIGN

One baseline for the design of the acoustic system builds on technical findings derived from the HIFT acoustic transmission data. Despite the motion of the HIFT source, robust signal-to-noise ratios were obtained with a high degree of temporal coherence in discrete, short-term paths. This result confirms the basic approach to sample 10 Mm fixed transmission paths with the objective of resolving and tracking (in the long-term) the time-of-arrival of principal, discrete multiple acoustic arrivals from near-SOFAR axis paths. The obtained coherence and SNRs permit transmission bandwidths at a useful limit of source technology, of about a Q of 3 or 4 (~20 Hz at 70 Hz center frequency) while observed SNRs permit a design frequency of about 70 Hz (above which absorption becomes a problem for 10 Mm paths) and reduced source levels compared to HIFT of 195-200 dB re 1μPa (about 250-750 watts acoustic output). This signal specification generates a significant cost reduction over the HIFT baseline concept and permits consideration of affordable, cabled transmitter sites not requiring periodic, ship-based maintenance and causing minimal interference to marine mammal populations. The specified frequency also reduces the potentially deleterious effects of ambient internal waves which degrade discrete path coherence over long transmission paths.

Based on HIFT our proposed network design philosophy is to: (1) develop a thorough understanding (as outlined above) of the propagation physics governing the basin and trans-global paths comprising the proposed network; (2) specify highly time-resolving signals capable of extracting the maximum amount of travel time information from multiple paths sampling the intervening ocean water column (near-SOFAR and upper ocean); and (3) iteratively compare the obtained data with GCM predictions to better distinguish the low-frequency variability of oceanic gyres from the greenhouse signal. With this philosophy in mind, the issues pertinent to developing the parameters for the system are:

source power and signal duration

propagation losses

received coherent signal power

noise power at the receiver

temporal signal processing

spatial signal processing

processed output quality.

The essential result is that the signal consists of multi-period transmissions of a continuous signal whose modulation is controlled by a linear, maximal length, binary sequence. It will have a center frequency of 70 Hz, a Q of 4 (or 3 if possible), nominal bandwidth of 20 Hz, period of about 30 seconds, and transmission time of 20 minutes or longer.

During the course of the demonstration program, the signals will be transmitted at progressively lower duty cycles until a minimum duty cycle consistent with the desired measurement is established. For the beginning transmissions we propose to transmit signals as follows:

stage 1) every 4 hours every day

stage 2) every 4 hours every fourth day

These duty cycles will start at about 10%, spanning the first few months of transmission, during which the propagation characteristics of basin and 10 Mm scale paths will be determined. The subsequent period of seasonal trend characterization, of the order of 4% source duty cycles will extend for up to one year followed by a lower, long-term sampling cycle, characteristic of the minimum required for the long-term monitoring network.

Transmitted signal levels will need to be at least 195 and may be as high as 200 dB re 1μPa, leading to on the order of 30 dB estimated signal to noise ratios at 5 Mm in the Pacific and 10 Mm at New Zealand, although only 22 dB SNR at 10 Mm in the North Pacific. The table below illustrates the 10 Mm acoustic budget for New Zealand where low local ambient noise will permit operating at better than 30 dB SNR most of the time.

<u>Estimation At 10 Mm - 195 dB Source - 70 Hz</u>

Source Level	195 dB re 1μPa at 1m
Spreading Loss	130 dB
Attenuation Loss	3 dB (Pacific)
Received Level	62 dB re 1μPa per arrival
Noise Spectral Density	65 dB re 1μPa (New Zealand)
S_r/N_o	-3 dB
Time SP Gain	30.6 dB for ≈ 20 minutes
1 phone $(S/N)_{out}$	27.6 dB
Vert./Horiz. array gain	6-15 dB nominal for 31 phones
On Beam $(S/N)_{out}$	>30 dB nominal, per significant arrival

Implicit in this budget is a requirement to achieve array gain at the receiver and to coherently matched filter process the entire 20 minutes signal.

This selection of source power, signal and receiver configuration generates an engineering development requirement which is very modest compared to pre-HIFT estimates, and also limits the cost of qualifying reliable undersea hardware for a long-term observation program.

As outlined in the next sections, the technology development effort is low risk, with near-term sources based on currently available designs, and receivers based on existing mechanical and electronic telemetry designs. We will fabricate PC-based receiver signal processors for on-site beamforming and matched filter processing. These will in turn permit periodic transmission of highly compressed acoustic arrival time data to a central data management facility by use of ordinary digital telephone links. Receivers and transmitters should be designed to permit remote management of their functions so that the activities of the network can be managed from one or several central sites.

SOURCE DESIGN & DEVELOPMENT

The source characteristics required for the long distance transmissions of the global network are based not only on results of the HIFT, but also on approximately a decade of team experience in measuring acoustic travel times in the ocean accumulated during a dozen or more ocean acoustic tomography experiments. The essential specifications for long-term sources are:

Center Frequency -- 70 Hz

Bandwidth -- Q = 4 (20 Hz)

Source Level -- 195 - 200 dB re 1μPa @ 1m, for periods of 30 minutes, continuous

Operating Depth -- on the order of *800-1500*m

Operational On/Off Cycles -- 10,000 over 10 years

Efficiency -- reasonable input power requirements for driving 20 to 40 miles of cable (~10-20%)

Reliability -10 year deployed lifetime

Some relief in operational reliability can be specified for the demonstration program in order to limit costs and start the data collection process early in the effort. ATOC should conduct a procurement of an existing design for the near-term program, and a parallel, two year technology development and testing effort to ready source installations supporting the long-term monitoring network.

ATOC RECEIVERS

The receivers for the ATOC demonstration phase refer to both shore-based processors and undersea acoustic arrays. They have several objectives:

Establish the limits of how well paths can be resolved and tracked over seasonal cycles for signals which have propagated over 5-10 Mm;

Specify the simplest receiver design consistent with the goals of a world-wide, long-term ATOC network.

There is the long-term need to develop receivers for operations at worldwide sites. ATOC's development effort for the vertical and horizontal arrays will be used as the basis for these tailored designs. The overall objective will be reliability and low cost. Future receivers may consist of a single phone, horizontal arrays on the bottom, vertical arrays or some combination depending upon the demands of the acoustic propagation over a particular path.

Array Geometry

The geometry of the array is driven by several factors: array gains, angular resolution, and location in the water column. Modeling based upon the HIFT data suggests that 12-15 dB of array gain coupled with 30 dB of time-gain is sufficient to provide the 20 dB SNR that is required for a 20 msec path resolution. Gains for horizontal and vertical arrays differ, so they need to be discussed separately. A 30 element array operating against uncorrelated noise provides 15 dB of array gain. For a horizontal array this can be achieved by spacing the hydrophones at least a half wavelength apart, or in excess of 10 m for a 70 Hz center frequency, which implies an array at least 300 m long if SNR is the only issue. (If the noise field is directional and hence coherent over longer distances, higher array gains often can be obtained; however, some form of adaptive processing such as null placement is needed to exploit this.)

Gains for a vertical array are more difficult to determine. First, low frequency ambient noise is more correlated over vertical separations since much of the noise is ducted by the SOFAR channel with ray/mode angles of +/-15°, or 1/4 of the propagating wave numbers. The signal is also ducted in the same channel; consequently, one can space sensors at a two wavelength separation to sample adequately the vertical field. The array gain depends upon the noise distribution. If we use a ray model, a flat distribution leads to the noise at two wavelength separations being uncorrelated, so 15 dB of gain requires at least 30 sensors and a 1200 m array. More specific calculations for gain require either the vertical distribution of the noise using rays or the modal coherence matrix using modes. The array processing for vertical arrays lately has received a lot of attention in the context of matched field processing, so a significant literature exists which can be used by ATOC.

The second issue concerning the geometry is overall length of the array since it determines spatial resolution in both the vertical and horizontal dimensions. Most of the propagation uncertainties concern the ray/mode structure of the signal in the vertical. For 5+ Mm distances only those paths which are not subject to bathymetric blockage can be detected. The high angle, deep diving rays used in the past for ocean acoustic tomography can be resolved both temporally and spatially with a 1200 m vertical array which is needed to achieve 15 dB array gain. The low angle, axial signals which we believe will dominate the ATOC propagation are more difficult since they arrive at close time intervals which are beyond the resolution of the signal and their phase velocities, or equivalently their angular separation, are closer.

The axial signals are best represented in terms of modes, so the array processing requires combination of pulse compression and mode extraction. A 1600 m array centered on the SOFAR axis covers the vertical extent of the first 16 modes and we believe it should be adequate modal beamforming methods.

Any ATOC arrays would be placed near the SOFAR axis, which is nominally between 600 - 1000 m at mid latitudes. The vertical arrays must span the SOFAR channel. Near field bottom interaction can be a problem at either a source or a receiver since it complicates the vertical propagation by local bottom bounces or mode coupling. Consequently, the bottom of the vertical arrays should be moored a few hundred meters above. For most SOFAR channels this implies a mooring depth of at least 1.5 km. Figure 6 shows a conceptual installation.

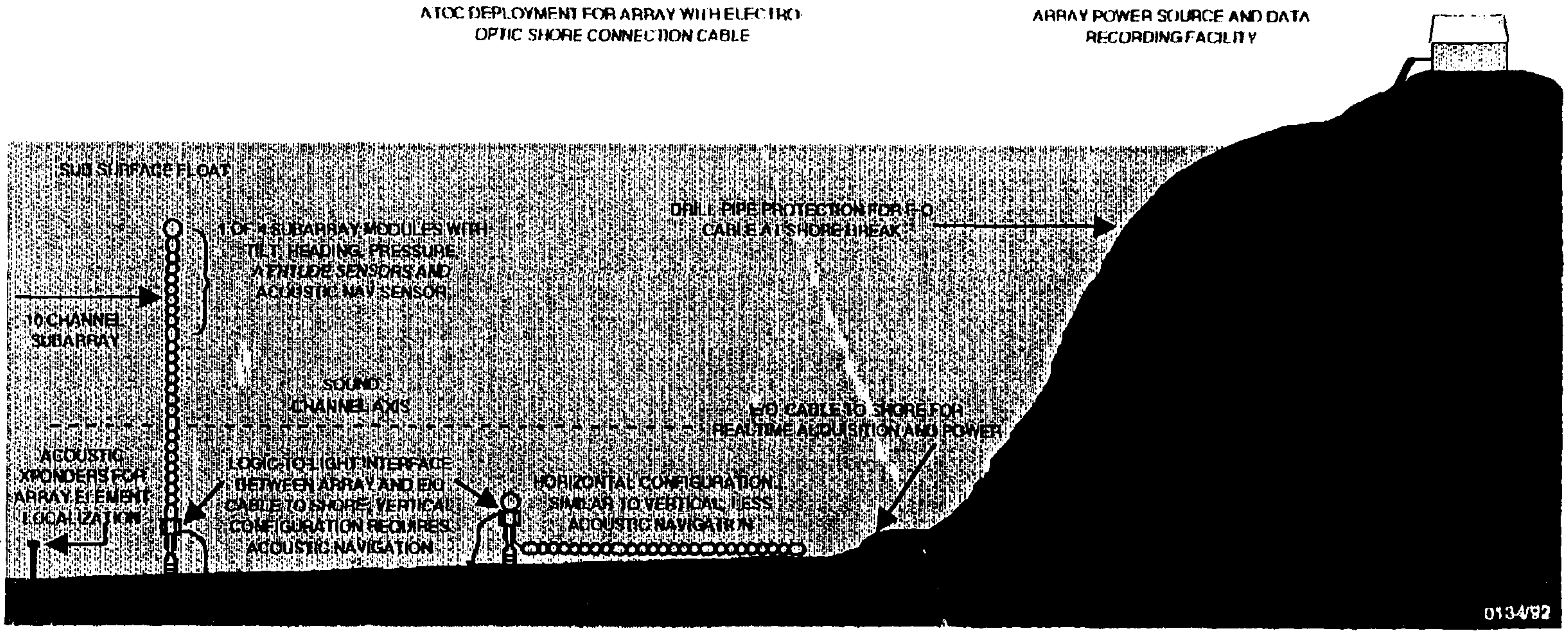
There are several options for the data transmitted:

- undersea cable to shore;
- acoustic/rf telemetry;
- autonomous recording which is retrieved periodically.

Undersea cable to shore

Cabling is done fairly routinely, but it can be expensive. The advantages are i) real time data availability ii) high data rates (the bandwidth of a fiber optical cable is not taxed by ATOC needs) iii) high reliability once it is installed. The cable must be rugged and it must be protected from fatigue and wear of the surf zone. The feasibility of cabling depends on the length of run, the offshore bathymetry, local fishing, and opportunities to cross the surf zone. There is also a need for permits in certain areas. It is a reasonably well known technology and this is the approach we

Figure 6.



Vertical/horizontal line array configurations to be developed for the ATOC program.

plan to use for both Point Sur and New Zealand once we do the reconnaissance to verify the quality of the received signals.

Acoustic/rf telemetry

Cabling may not be an option in some locations or we may wish to acquire some reconnaissance data from an array before committing to a cabled installation. In this configuration we use two moorings. One mooring is for the vertical/horizontal array upon which is attached an acoustic telemetry unit. A second mooring with a surface expression receives the acoustic data. A two mooring system is used because electrical connections for a cable attached to a surface buoy are prone to failure due to the continual wave stresses. Acoustic telemetry rates up to 20 kbit/s (2 kbyte/s) can now be achieved with very low error probabilities, ($<10^{-6}$). The duty cycle for the ATOC transmissions will be low, so the data rates for an ATOC array can be handled using modest buffering. The advances here will assisted by an ongoing DARPA program for acoustic telemetry. The rf link to shore exploits local area network technology and we are confident that installation up to 30 km offshore will operate reliably.

Autonomous recording

The third system for data acquisition is an autonomous mooring and builds upon the technology developed for ocean acoustic tomography. One of the important changing aspects of this is the ongoing advances in data storage technology with either high density Winchester disk drives or helical Exabyte tape recorders. Storage volumes of 20 gigabytes corresponding to over 100 hours of uncompressed data are easily achieved. The major disadvantage of the autonomous system is the need to retrieve the system to recover the data. In addition to the delay for this, there is the uncertainty about the successful operation of the system until recovery. Nevertheless, this technology is probably the most mature of the three approaches.

Long-Term ATOC Receivers

The receivers for a ten year ATOC program need to be reliable and cost effective. At the current time the information to specify their design is not available since we need to determine the array gain and resolution required of them. We can, however, indicate the important issues which will influence this.

- Location: The receivers must be located where there will be a strong climate signal. It is very desirable as well to locate them where logistical and local monitoring is available.

- Array gain: We should keep source levels as low as possible to reduce any potential impact on marine mammals and generally avoid all the environmental permitting issues required with very powerful sources. In addition, lower source levels lead to more reliable sources since they are not driven as hard. This reduction implies that the receivers must have higher gains against noise.

• Resolution: Tomography obtains its resolution in the vertical largely by temporal resolution of the paths. Perhaps this may be true at the 5 Mm+ distances for ATOC, more likely some form of spatial resolution will be required.

• Expenses: The cost of a receiver is comprised of many factors: At one extreme one can have an autonomous system which is periodically recovered. At the other is a full array which is cabled to shore. One must also consider the maintenance cost for deployments and repairs.

• Reliability: These systems must be reliable if they are to last for the decade planned for the ATOC program. Repair not only is expensive, but also compromises the data by interrupting the time series.

A choice of 195 dB transmission levels and deep locations in temperate ocean sites as the baseline limits zones of high level interference that might adversely affect local animal populations. This is illustrated in Figure 7 for a site north of the island of Kauai. The figure shows loss contours of 75 dB and greater for a source at 800 m depth. 75 dB loss corresponds to an acoustic level of 120 dB with a 195 dB source.

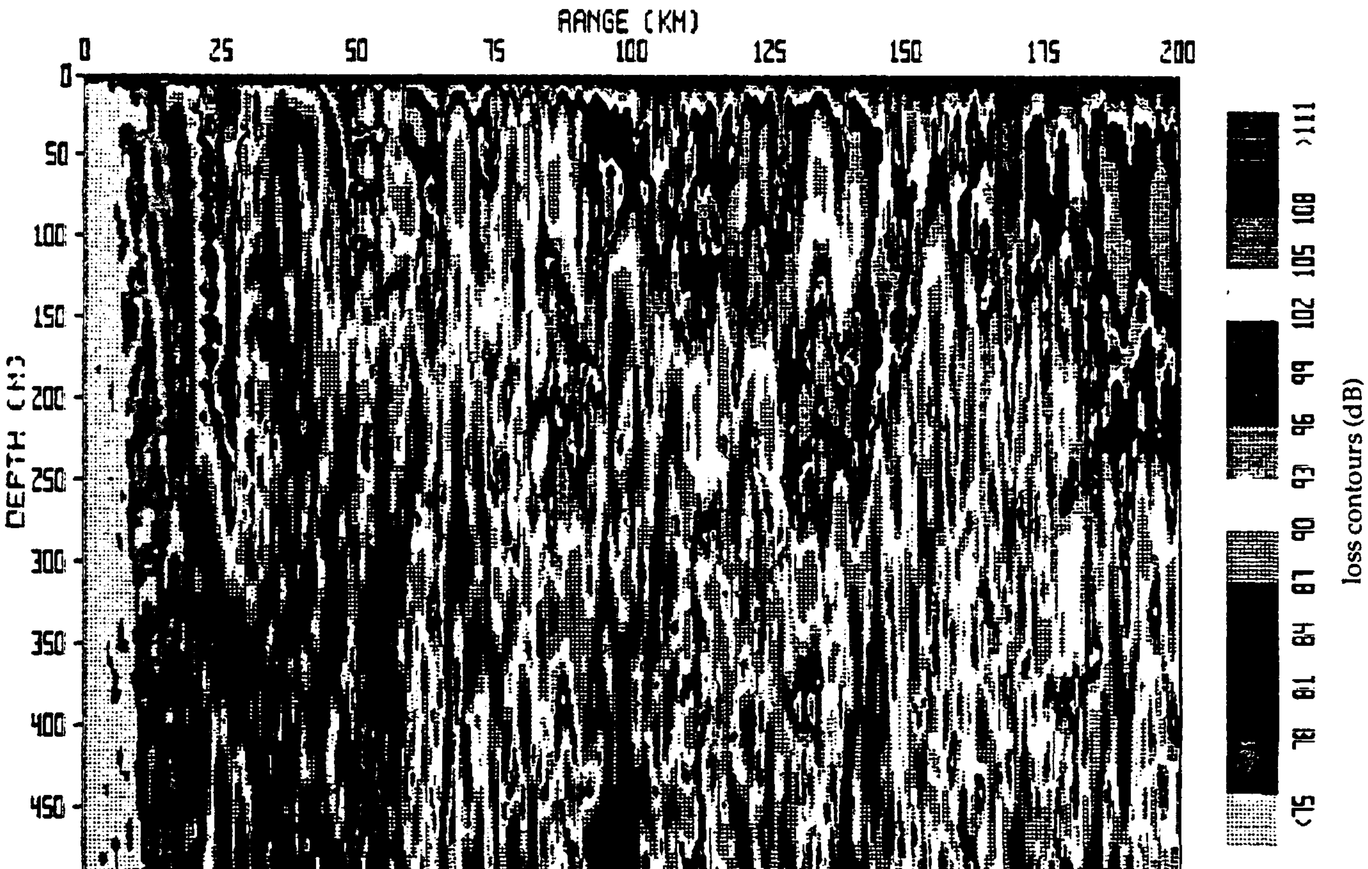


FIGURE 7. PE Propagation loss prediction for an 800m source depth off Kauai. Propagation is approximately uniform on all radials extending from 290° to 70° ref. north.

A 70 Hz acoustic source, cabled to shore, can be deployed on the bottom, near sound channel axis depth, to the north of Kauai at a site shown in Figure 8. This location has an excellent view toward the North Pacific and axial depth water is available near shore, thereby minimizing cable runs and providing a steep enough slope to reduce acoustic interaction with the bottom. This site is also attractive because the Navy operates a Pacific Missile Range (PMR) test facility on the western shore of Kauai and a number of sea cables are already terminated in this area, some of which may be available for ATOC usage.

Transmissions from this source will be received by a variety of existing receivers (refer back to Figure 2), providing a rich set of acoustic paths throughout the North Pacific. Instrumentation previously outlined will be installed at the appropriate Navy facilities to acquire this data, beamform and correlation process it for time-of-arrival statistics, store it and transmit portions of it automatically over telephone modems. The raw unprocessed data will be stored on 5 Gbyte 8 mm tapes at each site and forwarded.

In addition to reception by the (horizontal) Navy arrays, three vertical/horizontal receiving arrays will be fabricated and deployed. The first two will be permanent, cabled systems near NE New Zealand and Point Sur, CA, to allow long-term studies; the third will be a semi-autonomous recording system for use in reconnaissance deployments.

After installing the Hawaii source and NAVFAC receivers, a second 70 Hz source can be installed near Point Sur, CA. This source will allow reception of signals at approximate 10 Mm ranges (trans-Pacific), and would allow ensonification of the western and southern Pacific ocean, and reception by New Zealand's fixed array and by Australian towed arrays.

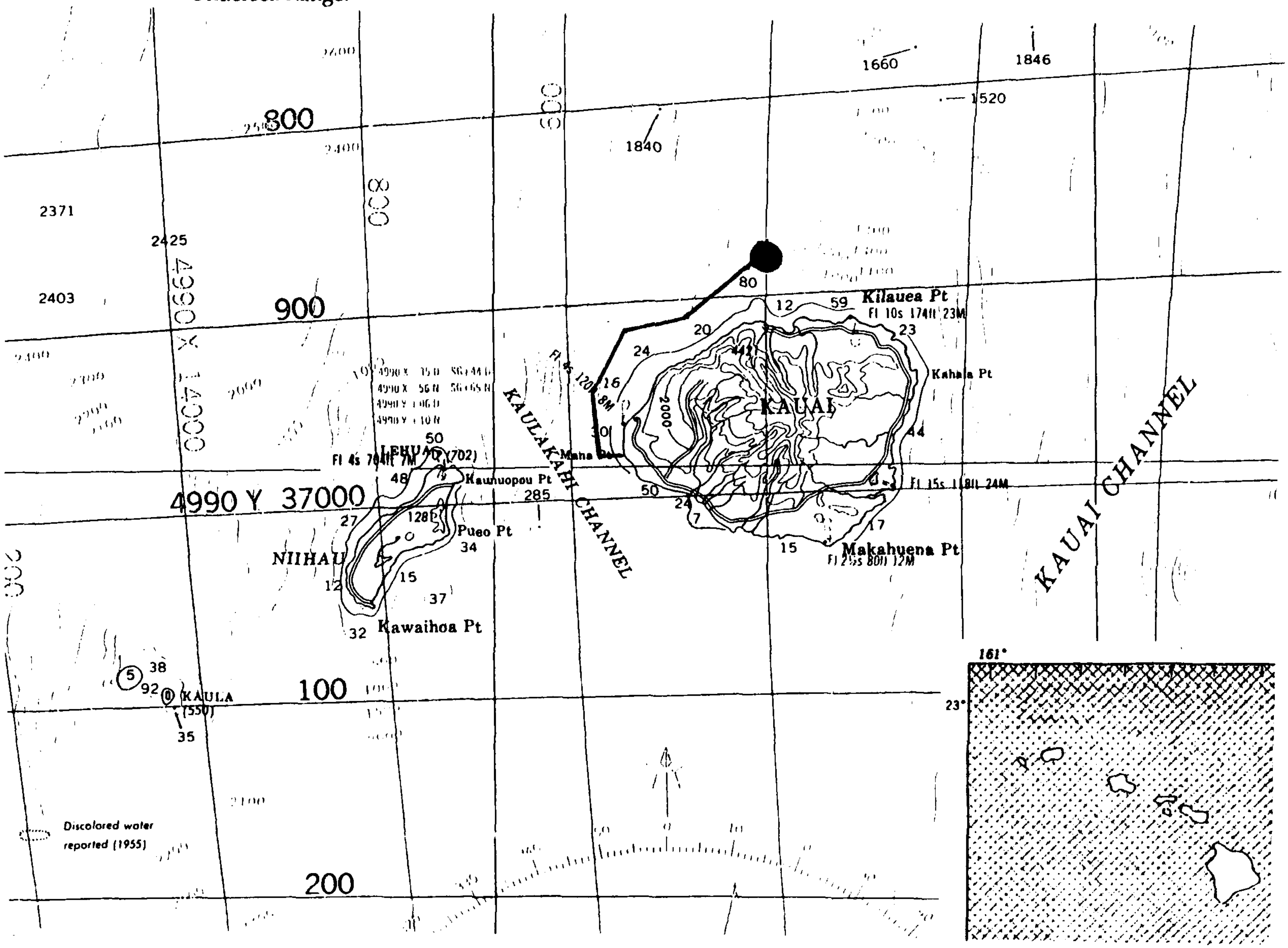
An important part of the field program would consist of oceanographic measurements to validate acoustic results., i.e., several CTD/XBT sections along selected transmission paths. The Point Sur to New Zealand path is particularly interesting for this purpose. Another aspect of the field program will be the conduct of appropriate marine mammal observations and surveys if such requirements are imposed by the cognizant permitting agencies. Significant part of the field program will involve testing of prototype acoustic sources at shore facilities such as the U.S. Navy Acoustic Test Facility, Lake Seneca, NY, where source level, bandwidth, pulse response, efficiency, heating and other acoustic and mechanical characteristics can be determined, and at sea, where operation at full ocean depth under actual operating conditions can be assessed.

STUDIES OF EFFECTS ON MARINE MAMMALS

Because noise disturbance is increasing in the ocean worldwide, future assessments of the impact of industrial, military, and recreational activities will require better methods for predicting cumulative, long-term impact of noise on marine mammals. The ATOC program provides a unique opportunity to study the impact

Figure 8

The proposed HLF-6 source site at Kauai is 800 m depth adjacent to a steep slope. The source cable terminates at an existing junction box at the sea-shore interface for the U.S. Navy Barking Sands Undersea Range.



of low-frequency noise that is unrelated to other human disturbances on the most vulnerable species, baleen whales and deep-diving odontocetes.

The short-term behavioral responses of marine mammals, particularly mysticetes, to broad-band, low-frequency, man-made noise have been studied repeatedly (see review in Richardson 1991), but little effort has been expended to study low-frequency narrow-band (tonal) noise, such as the ATOC transmissions. Unlike industrial noise, this narrow-band noise is intense within one perceptual critical band, but does not raise overall sound levels by a large factor. Therefore, while initial responses to narrow-band noise may be predicted by previous studies, long-term habituated responses may not be.

Mysticetes have been the object of most studies because they probably hear well at low frequencies, because they often breed and feed in areas with high levels of man-made noise, and because many species are endangered. However, none of the work has documented medium to long-term effects on reproduction, habitat use, or longevity, nor have they measured the extent to which these species can habituate to noise, how long the adjustment takes, the maximum exposure that they can tolerate, what stimulus features are most disturbing, or what effects the noise may have in conjunction with other disturbances, principally vessel traffic.

Based on short-term exposures of naive or relatively naive individuals, mysticetes consistently avoid relatively low levels of broad-band, man-made noise (10-30 dB above ambient). Most authors have interpreted these results as evidence that mysticetes consistently avoid areas where they are exposed to noise above a signal-to-noise threshold of 10-30 dB, and they have speculated that masking of biologically important signals is the major reason for this sensitivity. Other marine mammals, such as pinnipeds and sea otters, and large terrestrial mammals habituate readily; so, it is logical to suggest that cetaceans might habituate as well. However, the definition of "harassment" as given by the Marine Mammal Protection Act presumes that a marine mammal that does not change its behavior in the presence of noise is unaffected, whereas one that does has been harassed and possibly compromised. In essence, this is a model of effect that has never been tested.

To test the model, critical experiments are needed to determine 1) how well free-ranging marine mammals can habituate to noise, 2) how effectively narrow-band, low-frequency signals mask biologically-important signals in natural contexts, and 3) whether subtle, long-term effects can be detected in habituated individuals. The purpose of the proposed program is to conduct critical experiments on habituation and masking in several crucial species near the planned source sites. If the ATOC program is continued, as planned, over the long-term (ca. 10 years), these experiments would be followed by a long-term monitoring program to insure that any subtle effects of ATOC transmissions could be detected over the long-term.

The humpback whale (*Megaptera novaeangliae*) is one of the species of choice for behavioral experiments associated with ATOC transmissions. It is an endangered species found near most or all of the proposed transmission sites worldwide. It produces some calls at low frequency that may be masked. Off Hawaii, it engages in the activities that would, in principle, be most vulnerable to disturbance, i.e. migration, courtship, breeding, and calf-rearing. Because it is found in many areas where it is likely to be exposed to uncontrolled low-frequency anthropogenic noise, it is important to develop good models to predict noise impact over the long- term. Thus, in addition to the obvious long-term benefits of measuring global warming, the ATOC transmissions will provide a unique opportunity to collect data that will greatly improve existing models of noise impact on the humpback whale.

DATA MANAGEMENT

ATOC will collect large volumes of data from a widely distributed network of sensors. These data will be analyzed by routine procedures (these will generate standard data analysis products) and they will also provide a rich resource for research. Project investigators and others will conduct a wide variety of data studies, and the results of many of these studies will be maintained in the project data base. Productivity in the observational sciences depends, to a great extent, on the quality and accessibility of data. To support this access, ATOC should make it easy to store and retrieve raw data, standard data products and research data products (the latter two are types of meta-data) from a data center over computer-to-computer network links. Furthermore, the means should be developed to maintain a complete audit trail that allows reconstruction and review of all related scientific data and data analysis procedures.

Data Archiving

All sensor data should be maintained in an archive. Routine analysis products which are those results obtained from standard, operational analysis of the data will be maintained in the archive. Researchers will use the data in the archive through the use of the data management software. This establishes the need to capture the appropriate research results and maintain them in the archive.

Data Access and Utilization

The DMS should offer convenient access to the data for all authorized users. Specified data sets will be distributed routinely to a designated distribution list. The system will be accessed over a mixture of public and private internet connections. Thus, it serves as a communications hub connecting all project participants. The DMS will receive data from remote data recording nodes and other sources. A methodology for efficient analysis of scientific data and a wealth of software developed at the Center for Seismic Studies can be installed within the DMS, and be interfaced to ATOC codes.

Record-keeping and Quality Assurance

An auditable quality assurance program is necessary to ensure the integrity and consistency of all significant data. This quality control should be provided by the DMS software and operational procedures. The DMS will maintain a log allowing reconstruction of the system configuration and mode of operation at any time during the experiment. Thus, the DMS archives will include descriptions of the time history of the sensor configurations, source locations, coded signals, etc. in order to support "system" configuration management. Records of key data processing operations, input data sets and processing results should be maintained at all times.

IV. PROJECT MANAGEMENT

The proposed ATOC project involves foreign and domestic researchers and institutions in a three sided initiative:

(1) climate and propagation model development,

(2) ocean and shore systems hardware engineering development; and

(3) oceanographic data analysis and interpretation.

An ATOC project management structure has been developed to plan and execute the project. It has several aspects: (1) builds upon the established network of senior investigators and international partnerships in the HIFT, (2) provides the organizational infrastructure to integrate the proposed tasks to be executed by a number of research institutions, (3) establishes mechanisms to coordinate international participation in the project, and (4) provides a single management point of contact for the program.

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