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PROCEEDINGS OF THE AUSTRALASIAN WORKSHOP ON THE USE OF UNDERWATER ACOUSTICS IN BIOLOGICAL OCEANOGRAPHY, FEBRUARY 1979

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Abstract

The proceedings of a workshop held in February 1979 by Australian and New Zealand acoustic researchers are presented. They include a review article on the present state of the science of underwater acoustics, abstracts of presented papers, and recommendations adopted by the workshop participants.

CONTENTS

After this initial research an intensive survey was made throughout the known range of the jack mackerel of the south-eastern continental shelf waters from mid-September 1977 to late January 1978. The surveyed area had been stratified into ten regions, the majority of which were surveyed twice and some three times to span the spawning period of the jack mackerel. The considerable amount of biological and acoustic data resulting from these cruises is now being analysed. As with most large projects of this nature, some questions were answered but many more posed by the completion of the field work. It was with this background that the workshop was organised.

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INTRODUCTION

A workshop on the use of underwater acoustics in biological oceanography, with the emphasis on fisheries research, was held in February 1979 at the CSIRO Division of Fisheries and Oceanography in Cronulla. The principal objectives of the workshop were to review the state of the art of this branch of acoustics and the work of CSIRO in fisheries acoustics and to recommend future courses such acoustics research might take within the constraints imposed by the Division's resources.

Scientists from New Zealand and Australia were invited to present papers on their research and to participate in subsequent discussions. Professor A.C. Kibblewhite was specially invited to present a paper discussing the role that underwater acoustics has played in physical and biological oceanography and its potential use in the future. His paper is published in full in this report.

BACKGROUND TO THE WORKSHOP

Research scientists of the CSIRO, Division of Fisheries and Oceanography have used underwater acoustics (echosounders) in fisheries research since the early 1950's. Blackburn (1956) acoustically detected heteropods in Bass Strait surface waters and Blackburn and Downie (1955) used echosounders to study pilchards in waters off New South Wales. Early observations were almost entirely qualitative in nature. Rapson (1953) estimated the quantity of pilchards between Albany and Esperance in the Great Australian Bight using data from echograms and fishing trials.

Overseas, during the 1950's and 1960's, there was an increasing use of underwater acoustics as a quantitative tool in fisheries research with the ultimate objective of estimation of fish stock biomass.

Echosounders were also of considerable value as tools to study aspects of fish and zooplankton behaviour. Such work was not actively pursued in Australia until the late 1960's when sonar surveys were carried out in waters off Tasmania to estimate the seasonal variation in abundance of pelagic fish, especially jack mackerel *(Trachurus declivis)* (Wolfe 1970, 1971, 1976). Several years later echosounder surveys were made in waters off New South Wales in order to locate and study pelagic and demersal fish (Gorman and Graham 1977).

In 1974 Dr K. Radway Allen, then Chief of the Division, initiated a programme of pelagic and demersal fish research that was to involve the use of quantitative acoustics to estimate fish abundance. For this programme the research ship *FRV Courageous*, a stern trawler, was commissioned in September 1975 and a computerised echo counting and integrating system (Shotton and Dowd 1975; Castle 1977; Zeglinski and Jain 1978) was subsequently installed on the ship in late 1976.

Between November 1975 and August 1977 a series of research cruises was conducted in waters off south-east Australia to carry out preliminary acoustic and biological work for the later quantitative acoustic survey.

This preliminary research enabled the selection of a suitable target species, jack mackerel. This species was believed to be present in these waters in commercial quantities (Butcher 1967) and similar species are widely harvested overseas. Prior to our work little was known of the life history or behaviour of this fish. (Fraser and Hynd 1967).

SUMMARY OF THE WORKSHOP ACTIVITIES

During the first day of the meeting, participants presented papers concerning their current research in fisheries acoustics. The papers can be broadly categorised as those using single directional-transducers and narrow-bandwidth high frequency acoustics, and those using acoustic volume reverberation methods.

Use of directional transducers and high frequency signals

Two papers were presented on CSIRO's Division of Fisheries and Oceanography experience with a computer based echo-integrating system used to study pelagic fish in Australian waters. Mr D. Owens described this system in detail and discussed its advantages and disadvantages. This system was acquired during a developmental stage and problems were encountered in its operation and the subsequent analysis of recorded data. Based on our experience with this equipment a system has been designed for our purposes. The broad concepts of this instrument were also discussed by Mr Owens. Mr M. Castle presented preliminary results of acoustic surveys made using the computer based echo integrator. He discussed the data analysis techniques and possible sources of bias and variance in a stock size estimate.

Mr C. Francis and Mr R. Coombs presented papers relating to the status of fisheries acoustics in New Zealand. Mr Francis outlined the development of their acoustic tools from the early stages of echogram analysis to the present micro-processor based data collection systems. The merits of such a micro-processor system, currently in use in New Zealand, were also outlined. Mr Coombs discussed the rationale for the development of such systems and presented details of the software and hardware design.

Dr S. Brandt discussed the use of quantitative acoustic techniques to study the distributional ecology of fish. Such knowledge can be used to design acoustic stock assessment programmes and help to identify the targets that cannot be directly identified. His research on the alewife *(Alosa pseudoharengus)* of Lake Michigan and the response of fish to thermal structure in the western Atlantic was cited.

Acoustic volume reverberation techniques

Dr M. Hall spoke of his research on acoustic volume reverberation and its relationship to scattering of sound by nekton and plankton in the deep ocean. The effects of diel and geographic variation were also discussed. Mr I. Dunstan reviewed the subject of acoustic volume reverberation from the biologist's viewpoint and outlined plans for increasing knowledge about the biological component of sound scattering in waters around Australia.

Also presented was an account by Dr J. Penrose of his research into the use of acoustic techniques in the Australian prawn fishery; penaeid prawns are a major component of the fishing industry and an important export. Dr Penrose also presented the results of his research on the target strength of penaeid prawns.

The business of the first day was concluded with Professor A.C. Kibblewhite's paper, "Acoustical Oceanography", a review of the state of the science and its prospects for the future.

The second day of the meeting was devoted to two discussion sessions (Appendix 1). The first session was informal, providing a forum for each person to discuss their present involvement in fisheries acoustics and where they believed there were areas that merited further attention.

The second discussion session was formal and structured with the objective of providing guidelines for future work. Nine recommendations were formulated as a result of the meeting. These recommendations form part of this report.

The review paper "Acoustical Oceanography" and abstracts of other papers presented are reprinted here. Further information in regard to any of the papers can be obtained from the author concerned.

RECOMMENDATIONS ARISING FROM THE FORMAL SESSION

1. Quasi-synoptic surveys of the jack mackerel in south-east Australian waters have provided maps of fish distribution. While allowing for the lack of knowledge of this unexploited stock and the seasonal distribution of the stock, the significance of this mapping should be established by conducting repeat surveys.

   It is recommended that repeat surveys be conducted on this resource even if on a reduced scale and only working on aggregations of fish. Ideally, such repeat surveys should use the original echosouncer system, but supplemented with an advanced unit such as a multi-beam transducer system or sidescan sonar. Such surveys should incorporate any data-logging and recording instrumentation shown desirable by past experience.

2. Without certain basic knowledge of the behaviour and distributional ecology of a species an efficient acoustic survey cannot be designed.

   Therefore it is recommended that any stock assessment of little studied species be preceded by combined acoustic and biological research to determine the parameters necessary for the adequate design of an acoustic stock estimation survey.

3. There was a trend during the 1970's towards providing a real-time output of 'fish density' information on board during research cruises. Often the models used in these analyses were inappropriate to the determination of absolute fish density in many of the wide range of distributions of fish likely to be encountered.

   It is recognised that, except in in a few situations, the determination of absolute fish density in real-time is not likely to be feasible. However, the preliminary analysis of data on board to indicate the relative distribution of fish density can be essential for optimising cruise plans at sea, especially when one is conducting behavioural studies.

   It is therefore recommended that:

   (a) the basic need is for the retention of data that are essential for a variety of more sophisticated analyses on more powerful shore based computers, and

   (b) that provision be made for the preliminary analyses of such data on board during a research cruise. This latter capability should enable one to apply the most appropriate model for the situation under study.

4. In the past much acoustic research has been constrained by the performance of the analysis and data-logging system should be preceded by a design study that involves the examination of:

   (a) the performance of existing echo-sounder systems with the aim of establishing the influence and limitations of each component part of such systems, and

   (b) the objectives of the acoustic research programme, which determine the nature of the data to be collected.

5. It is acknowledged that there is a considerable literature on the target strengths of fish, butvery little on marine invertebrates. It is also evident that there is considerable variability in most sets of data.

It is recommended that:

(a) further studies of fish target strength, in the Australian context, should be confined to *in situ* methods, preferably using the dual-beam transducer techniques or the Peterson, Clay, Brandt method; and,

(b) such target strength studies be made on dominant plankters such as salps and invertebrate resources such as squid and euphausiids. A combination of laboratory and field studies are appropriate for the invertebrates.

6. Existing underwater acoustic technology, in terms of gathering data and the signal processing of those data, is little used in fisheries research. In consideration of directions for future research in the Australian region it is agreed that the full use of existing underwater acoustic technology has not been explored sufficiently.

It is recommended that future research be mindful of the possible applications of existing technology in respect of, for example:

(a) dual-beam transducers and more complex arrays,

(b) side-scan sonar,

(c) the resonance methods that have successfully been used on pelagic fish,

(d) the use of other than discrete high frequency sound sources, by the use of several frequencies, employing not only the conventional higher frequencies but also frequencies as low as a few KiloHertz,

(e) the side-ways looking sonar methods that have been used on pelagic fish that school in the upper water column,

(f) the effects of acoustic and electrical noise on signal quality, and signal processing methods that can be employed to minimise the effects of such contamination.

7. An indirect target strength estimate method is available for the study of monospecific fish populations which are poisson distributed. However, such situations are not common in commercial fisheries where multi-species and varying modal size distributions are common.

It is therefore recommended that the effects of target distribution and departure from uni-modal size distribution on the indirect target strength method should be studies using mathematical simulation techniques.

8. Demersal species form a large proportion of the Australian fish catch. A high percentage of these fish stocks occur within a few metres of the seabed. Fish so close to the seabed often pose special problems in detection by acoustic means.

It is recommended that the existing acoustic methods of locating fish close to the seabed be evaluated with a view to improving their capability for detection and identification.

9. It is recommended that, in view of the wealth of oceanographic data that can be provided by acoustics measurements, consideration be given to the use of acoustics as a sensing technique in future physical oceanographic experiments.

APPLICATION OF ACOUSTICS TO THE STUDY OF FISH BEHAVIOUR AN EXAMPLE FROM LAKE MICHIGAN

S. B. Brandt

One of the major problems with acoustic techniques is the inability to directly identify targets. There is a need for detailed information on distributional ecology of target species. Characteristic distributional patterns of fishes cannot only be used as clues to target identity but can also aid in the design of a sampling strategy that encompasses a representative segment of the population. Additionally, information on distributional ecology will help to define better the functional role of the species in the ecosystem. An example of a program to estimate alewife *(Alosa pseudoharengus)* abundance in Lake Michigan illustrates these points.

A versatile simultaneous echo counting (pulse height analysis) and echo squared integration system was developed to measure densities of pelagic fish. In the field, data are collected with a high resolution Simrad EK-120 echosounder. The transducer for this echosounder is housed within a hydrodynamically stable 1.2m V-fin 'fish' and towed alongside the research vessel. The fish provides for a smoothly riding platform; an elastic shock absorber prevents roll of the ship from being transmitted to the towed body. The acoustic system is visually monitored by a chart recorder and an oscilloscope. Analog acoustic data are recorded on magnetic tape. The portable nature of this assembly allows its use on various ships of opportunity.

Analog tapes are analysed in the laboratory by a Data craft 6024/5 computer. Analyses occur in real time. Output includes a measure of mean echo squared integration and number of target counts for each contiguous 1m depth interval for every two minutes along a transect. Since the acoustic signal processing system is software determined, great flexibility is realised. Computer 'echograms', contours, and three dimensional plots of fish distribution are also provided.

An application of this system and a 200 kHz echosounder to Lake Michigan showed that adult alewives and *Mysis relicta* simultaneously migrated off the bottom to the base of the thermocline at night. Adult alewives fed on *Mysis* exclusively at night. A bimodal distribution of acoustic targets suggested that Young of the Year (YOY) and adult alewives were thermally segregated with YOY concentrated in the epilimnian. This distribution was confirmed by an intensive trawling study near a frontal zone at the intersection of the bottom with the thermocline.

Thus behavioural observations of fishes helped to explain distribution of acoustic scattering. Thermal distribution of other major species in Lake Michigan were also precisely related to temperature and different species dominated trawl catches at different temperatures. A comparitive study in a much more complex system - the Western Atlantic at the edge of the Gulf Stream - demonstrated that these fish species and communities were also very responsive to thermal structure. It was suggested that temperature and other habitat assessments to specific species or communities of fishes.

A REVIEW OF THE ACOUSTIC SURVEY OF JACK MACKEREL AND METHODS OF DATA ANALYSIS

M. J. Castle

Biological and acoustic surveys were conducted on the jack mackerel *Trachurus declivis* Jenyns) stock from 1976 to 1978 in south east Australian waters. Prior to these surveys little was known of the life history of this unexploited stock. In the latter part of 1977 a quantitative acoustic was carried out on the stock throughout its known range in the south eastern waters.

The objectives of the acoustic phase of the study were to estimate the biomass of the jack mackerel resource and to add to the knowledge of the behaviour of this species. Discussed in this paper are those aspects of the behaviour of jack mackerel, that influence the design of the survey, such as its seasonal migration and diel vertical migration, and those that became apparent during the quantitative survey and which are likely to result in biases in the stock estimate.

During the quantitative survey a Simrad EK50 echosounder was used in conjunction with the Computerised Echo Integrating System developed by R.G. Dowd, of the Marine Ecology Laboratory, Bedford Institute of Oceanography.

The analysis of the digitised acoustic data from the echosounder is complicated by the presence of several species of fish in the survey area and the frequent occurrence of scattering layers due to zooplankton. A method of data analysis is described that involves the qualitative analysis of the echograms and the merging of these data with the appropriate digitised data. In this way the judgement of the echogram analyst in identifying the species causing the echo observed can be combined with the quantitative nature of the digitised data. The analysis software being designed enables one to edit the data and select from the assemblage of data only the echoes from the species of interest, within the limits of accuracy of the echogram analyst.

THE DOWD FISH COUNTING AND INTEGRATING SYSTEM

D. Owens

Since the early sixties the Bedford Institute of Oceanography, Canada, has been developing acoustic stock assessment systems for use in fisheries research. CSIRO purchased one of these systems at the 1975/76 stage of development. The computerised system included a counting programme for large, dispersed groundfish with swimbladders and an integrating programme for use on schooling pelagic fish.

The CSIRO System is based on a 50 kHz Simrad scientific echosounder with a towed transducer, a Honeywell 316 computer with a data acquisition system and a nine-track magnetic tape drive. All the software had been developed by Honeywell, Canada, to specification by the Bedford Institute. The integration programme was at a very early stage of development when it was acquired.

To set either the integrator of counter systems running, the operator must input such values as the estimated target strength of the observed fish, sonar calibration values, transducer directivity information, and other factors influenced by ambient conditions such as the speed of sound.

Both programmes record echo return data on magnetic tape in a manner that reflects its sampling mode: the counter assumes an 0.6 mS return echo from a discrete target (transmits 0.4 mS) and samples the envelope of the return echo 0.3 mS after detection of a target. The analog-to-digital converter value is recorded on magnetic tape and sampling is continued every 0.3 mS while the return echo persists: the integrator records the voltage squared level of the envelope for each 0.1 mS over the sampling period for each transmission.

The programmes also provide a print-out report of the calculated biomass density, using the Dowd-MacNeil model in real time, as a numerical indicator to the operator.

Practical difficulties in using the system are reviewed concerning accurate measurements of the acoustic parameters the system requires. The system complexity requires the operator to have a knowledge of fish species identification from echograms, besides the specialised operating procedure to obtain any meaningful information in the printed reports.

Overall accuracy of the system for an absolute assessment of stock could possibly be as good as one more accurate (e.g. three to four times accuracy).

Both the absolute and relative assessments are likely to involve biases due to biological factors and survey design consideration.

AN ECHO-RECORDING SYSTEM

R. F. Coombs

Pressure on New Zealand's inshore fish stocks has increased steadily over recent years and to this has been added a rapidly expanding deep water fishery exploited for the most part by foreign fishing vessels. This has generated on the one hand a need for detailed information on population structures of heavily exploited stocks and on the other, rapid assessments of the potential yields of largely unknown stocks. A system is described here that meets both these needs by using echo-soundings to provide data complementary and supplementary to that produced by more traditional methods.

Echo information from a Simrad 120 kHz scientific echo-sounder is digitised and recorded on an eight track digital magnetic tape recorder for subsequent computer analysis. Echoes appearing at the echo-sounder are monitored and if they exceed a pre-set threshold level the depth of the echo is determined and a sequence of samples defining the envelope shape taken. The echoes are digitised using a 10 bit analog-to-digital converter and recorded together with the depth and codes determining when transmissions took place and echoes occurred. The system is controlled partly by means of hard-wired logic and partly by a microprocessor; the main function of the latter is to provide a large buffer store (8 K bytes).

The main design aim is to preserve as much of the information available from the echo-sounder as practical to allow maximum choice of subsequent methods of analysis.

PRELIMINARY ASSESSMENT OF AN ECHO-RECORDING SYSTEM

C. Francis

The echo-recording system used by the Fisheries Research Division (N.Z.M.A.F.)* is evaluated as an aid for fisheries scientists and managers in investigations of stock assessment and fish behaviour.

This system is a part of the third phase of the application of echosounders to fisheries science. The first phase involved the manual processing of echograms and the direct observations of fish echoes on oscilloscopes. That phase was characterised by simplicity of analysis, loss of information, and tedium of processing. In the second phase, special purpose electronic hardware was built to analyse echo data in real time. This resulted in a gain of information and sophistication of analysis at the cost of a severe loss of flexibility. When the advantages to be gained from being able to analyse the same data in several ways were realised, the third phase was entered, that of recording echoes for later computer processing. This allowed a further gain in information and more sophistication and flexibility in dealing with it.

The great detail with which echoes are recorded by the present system enables a closer analysis than is possible where only peak values of echoes are recorded. Two examples of this are (a) the increased precision with which fish and bottom echoes may be separated, and (b) the possibility of distinguishing echoes from different targets solely by the shape of their echo envelopes.

While this system allows for standard biomass estimates by means of echo-counting or integrating (or any combination thereof), its greatest strength may be in more subtle studies of fish echo structures and the differences in patterns of echoes generated by different species of fish or by the same species under different conditions.

* New Zealand Ministry of Agriculture and Fisheries

VOLUME REVERBERATION AND BIOLOGICAL MATERIAL IN THE OCEAN

Marshall Hall

The results of surveys of volume reverberation in deep ocean areas around Australia, using explosions as sound sources, are compared with estimates of organic productivity. Reverberation and productivity in the Coral Sea are both significantly less than their average values in the Tasman Sea or Indian Ocean.

In tropical latitudes, volume reverberation at frequencies near 4 kHz increases markedly over the sunset period as the marine organisms, including the mesopelagic fish with gas-filled swimbladders, rise towards the surface. At higher latitudes, this diurnal variation is less pronounced.

During a recent survey in the Southern Ocean, specimens of plankton in the upper 100m were collected in conjunction with measurements of volume reverberation over sunset. The two parameters increased by similar proportions at about the same time.

The reverberation spectrum from a Deep Scattering Layer usually has a resonance frequency from which the average size fish in the layer can be estimated. Examples of results of this type of observation are discussed.

SOUND SCATTERING BY MARINE ORGANISMS IN AUSTRALIAN WATERS

Ian C. Dunstan

Scattering of acoustical energy by inhomogeneities within the water column, or volume reverberation, generally occurs within discrete layers within a water mass, called Deep Scattering Layers, and is a major source of interference to underwater sonar systems.

The reverberation profiles, particularly at frequencies between 0.5 to 20 kHz, are dominated by the resonance backscattering from gas-filled structures in marine organisms, primarily the swim-bladders of mesopelagic fish. Gas-filled floats of siphonophores may also be significant and at higher frequencies scattering from fish tissue and planktonic organisms will be observed.

Information on the identity and acoustic properties of sound-scattering organisms within the Australian region is sparse. The Marine Environment Group of the Materials Research Laboratories intend to undertake a program of biological sampling and experimentation:

(i) to identify the biological entities responsible for sonar interference,

(ii) to investigate the geographic and temporal variations in composition and density of Deep Scattering Layers, and

(iii) to evaluate the acoustic properties of midwater faunal communities.

Such information will allow a greater understanding of acoustic propagation in Australian waters, and aid acoustic engineers to maximise the performance of underwater sonar systems.

ACOUSTIC RESEARCH IN RELATION TO THE AUSTRALIAN PRAWNING INDUSTRY

J. Penrose

Marine acoustics research at the Western Australian Institute of Technology has been directed recently to an analysis of the scattering mechanisms involved in the formation of echo signals from biota, midwater layering and the sea bottom. Much of this work has been funded from the Fishing Industry Research Trust Account as part of a programme of research into the use of acoustical techniques in the prawning industry. Such techniques are hampered by problems associated with detection efficiency, near bottom resolution, resolution from other species and beam coverage. A twin sounder and alarm system has been developed to increase beam coverage and aid chart monitoring in the banana prawn fishery in the Gulf of Carpentaria.

As part of the prawn research programme, a series of target strength measurements have been made on penaeid prawns of length 16 $\pm$ 2 cm and over the frequency range 50 kHz to 1200 kHz. The average target strength in the dorsal plane is -50 $\pm$ 5 dB re 1 metre and is sensibly constant over the whole range of frequencies studied. This constancy of target strength with frequency is essentially in accordance with the results from a compilation of target strengths for fish presented as empirical relationships linking fish target strength with body length. These relationships are shown to give useful agreement with experimental values for a range of organisms, including some plankton.

A number of aspects of the distribution of echo amplitudes to be expected from a penaeid prawn in field sounding conditions have been modelled using Monte Carlo computational methods. The results indicate the conditions under which a single target may be detected and are presently being used to assess the effect of variations in target size and distribution on in-field sounder calibration techniques.

ACOUSTICAL OCEANOGRAPHY

A. C. Kibblewhite

Because of the electrical properties of seawater, electromagnetic radiation is severely attenuated in the oceans. Accordingly, when the requirement for underwater navigation, communication and detection. Sound was found to perform with promising efficiency and the science of underwater acoustics was born.

While the essential physics governing sound propagation in pure water was understood, early experiments quickly revealed that other factors had to be taken into account when operating in the ocean. Additional attenuations were detected and explained in terms of the chemical properties of seawater, but more significantly an inconsistency in sonar performance was observed in the ocean environment. The explanation of this acoustic variability was ultimately traced to the inhomogeneity of the ocean.

Since these early experiments were carried out, our understanding of the complex relationship between the propagation of sound and the physical properties of the ocean has grown steadily and underwater sound is now used extensively. Apart from its well known role in naval systems, underwater sound has also been applied successfully in many branches of marine science; echosounding, reflection and refraction seismology, navigation, communication, seabed and fisheries reconnaissance come readily to mind as important examples of civilian utilization.

In recent years, acousticians have been concerned more and more with low frequency transmissions over very long distances in the ocean. These studies have revealed additional properties of the measured variability in the propagation of acoustic signals through the ocean volume. The observations suggest in fact that the statistics of the acoustic fluctuations can be used to monitor the temporal and spatial characteristics of the dynamical processes occurring in the sea. Acoustics is thus on the threshold of a new application in which it will provide information on ocean dynamics over wide enough areas and for sufficiently long periods of time to add significantly to our understanding of the physical and biological processes in the ocean.

ACOUSTICAL OCEANOGRAPHY

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Contents

1. EARLY HISTORY OF MARINE ACOUSTICS

The first application of underwater sound in naval problems was in a so called PASSIVE system in which the detection of submarines depended entirely on detecting the self noise of their engines and propellers and on determining the direction from which these sounds were coming.

This system of detection had obvious limitations and effort was soon directed towards the development of transducers with a directional capability, around which ACTIVE echo ranging systems could be developed. The first experiments with such systems were completed by the end of World War I.

From the outset naval acousticians experienced difficulty with large variations in echo intensity. Some of this variability appeared to be characterised by a diurnal cycle. The equipment worked more or less to specification in the morning, but would not produce any echoes from submarines from early afternoon on, except at very short range.

In seeking the explanation for this phenomenon an experiment was designed in which tests of the sonar equipment were combined with measurements of the properties of the water through which the sound was propagating. It was in this experiment that the oceanographer made his first contribution to marine acoustics.

It soon became apparent that the upper levels of the ocean were heated each day so that by early afternoon a layer up to several metres thick had developed that was 1 to 2°C warmer than the uniform layer of water beneath. Its development during the day coincided exactly with the deterioration of sonar detection ranges.

Oceanographers and acousticians did not take long to deduce that the warm layer caused sound entering it to refract downward; thus casting an acoustic shadow within which a submarine could sit with impunity. This experiment in 1937 was really the birth of the discipline now often called "ocean acoustics" or "acoustical oceanography" and the first clear indication of the complexity of the relationship between underwater sound and the ocean medium.

The years during and following World War II were directed towards trying to understand how the ocean alters sound passing through it. We now know that sound is refracted in a complex way by the medium, reflected and scattered by the sea surface, by the sea floor and by any inhomogeneities within the ocean itself. We understand the reasons for the existence of the SOFAR (Sound Fixing and Ranging (Urick 1967)) channel, predicted by Maurice Ewing (Ewing and Worzel 1948) on the basis of the known temperature-depth profile in the deep ocean, and the nature of convergence zone propagation in which the same refractive properties of the ocean are involved but in this case for a source and receiver that are both shallow (Hale 1961). A good summary of this early work in acoustics is given by Urick (1967).

Throughout all this development of marine acoustics the interaction between the acoustic and oceanographic communities was close. The two decades following World War II were particularly productive, and by the end of that time the cross effects observed in underwater acoustics were at least understood. Much credit for this achievement must go to the oceanographer.

The interaction getween the two groups brought in turn undoubted bonuses to the oceanographer, primarily through the wide application of ocean acoustics in echo sounding, sound ranging and seismic prospecting. Some examples follow.

Ocean Bathymetry

Echo sounding techniques were developed in several countries from as early as 1925, but surveying only became extensive after World War II. Very quickly however the major features of the ocean basins were established bringing attendant impact on such disciples as global oceanography and plate tectonics.

Geodetic Control Experiments

By ranging with a combination of simultaneously transmitted radio and underwater sound signals, the US Coast and Geodetic Survey experimented extensively to exploit the new science of underwater acoustics in a technique aimed at providing geodetic control between neighbouring land masses. The radio broadcast the instant that the sound was transmitted and the acoustic travel time, which gave the land mass separation, could be measured by noting the interval between the radio emission and the corresponding sound signal. An extensive series of acoustic/geodetic surveys were in general thwarted however by the apparent variability of the acoustic velocity in water.

Much of this variability was due to shallow water operation. The New Zealand participation in the CHASE V experiment had as one objective to test this acoustic/geodetic technique on a transoceanic path, using the greater stability of the SOFAR channel (Kibblewhite and Denham 1969).

Marine Geology

Around 1950 Cambridge University, the Scripps Instutition of Oceanography, Woods Hole and Columbia University began a series of world-circling seismic refraction measurements. These measurements marked the beginning of a new interest in the structure of the earth's crust beneath the oceans, and along with the general bathymetric surveys of the oceans, have played a major role in the development of the theories of modern global tectonics.

Deep sea reflection experiments (as distinct from refraction studies) led to the development of the Continuous Seismic Profiler (CSP) in the early 1960's. This technique was quickly combined with towed arrays of receivers and broad spectrum sources to provide a variety of seismic equipment that have since been used at sea in oil exploration and in more academic studies. Modern signal processing techniques have made this tool an extremely versatile one.

Over the past 20 years the phenomenon of sound transmission through marine sediments has become of great interest to many groups and acoustic mapping of the ocean floor a major part of marine acoustics. A recent publication edited by L.D. Hampton (1974) gives an idea of the status of this work.

Marine Biology

The early echo ranging sonars operated typically at frequencies around 20 kHz. (These frequencies are much higher than those applied in refraction studies (2-30 Hz) and in reflection seismics (15-1500 Hz). In operation these high frequency sonars often produced diffuse echoes from the body of the water. These echoes, which occurred in horizontal layers, were found at a depth of about 400 metres at noon, and were observed to migrate to the surface during twilight and early evening. At dawn they returned to their original depth to complete a daily cycle.

Subsequent work has shown this Deep Scattering Layer (DSL), as it came to be known, to be biological in origin and to be present in most deep water areas (Urick 1967).

The Deep Scattering Layer proved to be only one source of interference encountered with ACTIVE sonars. Scattering from other non-target reflectors was also observed, the general background signal being called "reverberation". Commercial fisheries have exploited this problem of the naval operator for many years and as we are aware it is this application of acoustics to marine biology which is the main reason for our meeting this week.

In the last 20 years there has been a renewed interest in PASSIVE sonars and the development of naval systems designed to detect the low frequency signals produced by ships and submarines. As such systems are impaired by other noises in the sea their development has led to an extensive study of the ambient noise in the ocean (Urick 1967). Certain contributions to ocean noise field have been traced to biologic origin. Interest in the field of bioacoustics has accordingly been keen since World War II, and the byproduct for marine biology has been impressive. Even the humble sea-egg has been shown to contribute to the background noise in the sea!

Acoustic Instrumentation

Ocean acoustics has also had an impact on oceanography in the field of remote sensing instrumentation. We will expand on this theme later.

This review, albeit incomplete, should have demonstrated the two way benefits which accrued from the close interaction of acousticians and oceanographers in the period during and immediately after World War II. It is surprising therefore that this close collaboration did not continue at the same level, particularly when it was generally accepted that sound propagation could develop into a primary tool for monitoring the ocean. However in the next ten years the oceanographic community servicing acoustics was restricted to small groups associated with each of the major defence research laboratories. The major oceanographic institutions turned their attention to other aspects of global oceanography.

Several factors were probably responsible for this change. Financial constraints were being applied universally, with a consequent reduction in the US Navy's allocation to basic research in marine sciences; there was a move away from ACTIVE to PASSIVE sonar systems, with a consequent change in the frequency and range scales being employed; and the instrumentation (acoustic, oceanographic and computing) required to service this move to low frequencies and long range operation was not immediately available.

In this period of separate development however oceanographers became increasingly aware of the variability of ocean parameters and the limitations of traditional synoptic surveys in describing the ocean environment. At the same time, as naval acousticians moved to lower frequencies in a search for longer detection ranges, they too were forced to recognise a wider range of space and time scales in the ocean than had concerned them with the earlier acoustic systems. It is therefore not surprising that the interests of both communities should converge once more and there has recently been a resurgence of acoustical oceanography.

It will be convenient to review the recent progress in acoustical oceanography under the heading of Physical Oceanography, Biological Oceanography and Marine Instrumentation, although obviously other headings would be equally appropriate. A recent publication by Clay and Medwin (1977) will provide a useful reference source.

2. PHYSICAL OCEANOGRAPHY - ACOUSTIC MEASUREMENT OF OCEAN DYNAMICS

Oceanographic studies of the past twenty years have highlighted the complexity of all oceanographic sea circulation patterns and our need to learn more about these before we can understand their true influence on the ocean environment. Techniques are now available to help in such studies but the oceanographers still suffers from constraints. For instance, while satellite maps are proving useful in monitoring surface water they do not provide any real insight about underlying structure. Again, while reliable deep sensing instruments of various sorts have been developed to provide this sub-surface data, probes such as moored current meters and CTD (productivity, temperature, depth) packages have inherent disadvantages. CTD probes for example can yield only a discrete sample of ocean conditions and only on a very broad sampling grid. The study of the time evolution of dynamic behaviour in the oceans requires a large number of lowerings and the prohibitive cost of shipping restricts our ability to exploit such units. Likewise while moored current meters can these days record for as long as a year, they are too expensive to be deployed in sufficient numbers to provide adequate coverage of large areas of the ocean.

In the past various acoustic programs have confirmed that sound transmission in the ocean exhibits several properties that can be measured and then related to ocean variables. By exploiting these relationships acoustics provides the possibility of measuring some of the temporal and spatial characteristics of ocean dynamics. The move in naval acoustics towards frequencies less than 1000 Hz has significantly extended the potential for such applications of acoustics to oceanography. Measurements of ocean dynamics can now be made over a sufficiently large area of the ocean for long enough periods of time to overcome many of the deficiencies of conventional techniques.

An examination of a few examples will emphasise the growing importance of this form of remote sensing in oceanography.

Acoustical Sensing of Small Scale Effects (1-10 cm).

Various techniques, such as hot wire anemometers, are used to measure very small scale turbulence in the ocean. The Russians have included acoustics techniques in their wide range of impressive turbulence instrumentation (Osmidov 1973). In this case the scale of the turbulence being investigated calls for high resolution. This is achieved by operating at very high sonic frequencies (MHz) to achieve the narrow beam widths and short pulse lengths required to sample the small oceanic volume of interest. In these systems doppler frequency shift acts as the acoustic property which is related to the ocean property (turbulence) under investigation.

Acoustical Sensing in the Medium Range Scale (Metres to Kilometres)

We have already referred to the diurnal fluctuations in acoustic signal level that arise from the afternoon heating of the ocean. In addition to such diurnal variations, much more rapid fluctuations in signal level can be observed. These pulse to pulse variations were

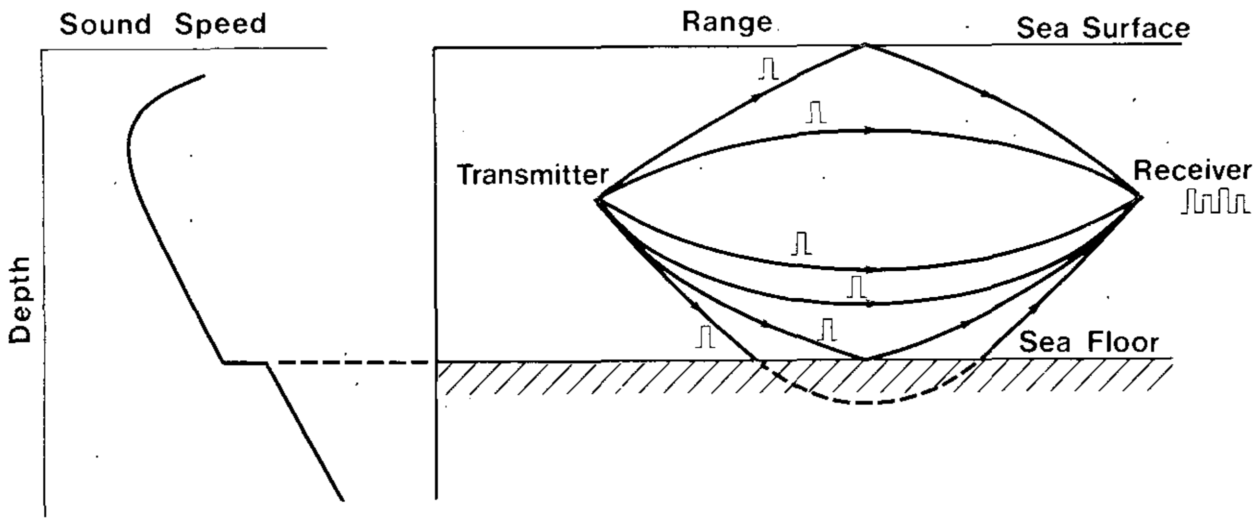

Fig. 1. Propogation of sound occurs along different paths within the ocean. The multigraph arrivals are observed at the receiver and the resulting signal is dependent upon the interference between them.

attributed to oceanic inhomogeneities of some sort and their identification and classification has been the subject of much research effort. One program in this field has been carried out by our Auckland group (Sagar 1973) and some of the most convincing evidence relating the fluctuations to temperature micro-structure was produced in a recent experiment (Rickard 1976). This experiment also confirmed the role of insolation in producing the micro-structure and indicated the possibility of using the acoustic fluctuations to measure the nature of the ocean inhomogeneities so produced.

Acoustical Probing of Large Scale Dynamical Phenomena (10-1000 km)

As the attenuation of sound in sea water is proportional to the square of the frequency, it was essential for naval acousticians to move to lower frequencies to obtain increased operational ranges. To get a feel for the relation between frequency and range we can note that in general geophysical studies propogation over distances of the order of 100 km implies sound frequencies below 1000 Hz and distances in excess of 1000 km frequencies less than 200Hz. However there are great technical difficulties in building the high level transducers necessary for the application of ACTIVE sonars at low frequencies. Attention has thus turned to PASSIVE systems aimed at exploiting the low frequency components produced in the noise spectrum of ships by their hull and propeller vibrations.

With the renewed interest in PASSIVE systems naval acousticans have accordingly spent much effort in the past 20 years in examining the behaviour of underwater sound at low frequencies and over long ranges. Numerous experiments have been carried out. Besides providing the basic acoustic data required some of these have again demonstrated the possibility of using acoustic monitoring to sense ocean dynamics, and in these cases over large temporal and range scales. A few examples will serve to demonstrate the potential of this form of remote sensing of oceanographic parameters.

i. Experiments with Pulsed Sources:

In a typical experiment sound is transmitted in short bursts between two suitably placed transducers (fig. 1).

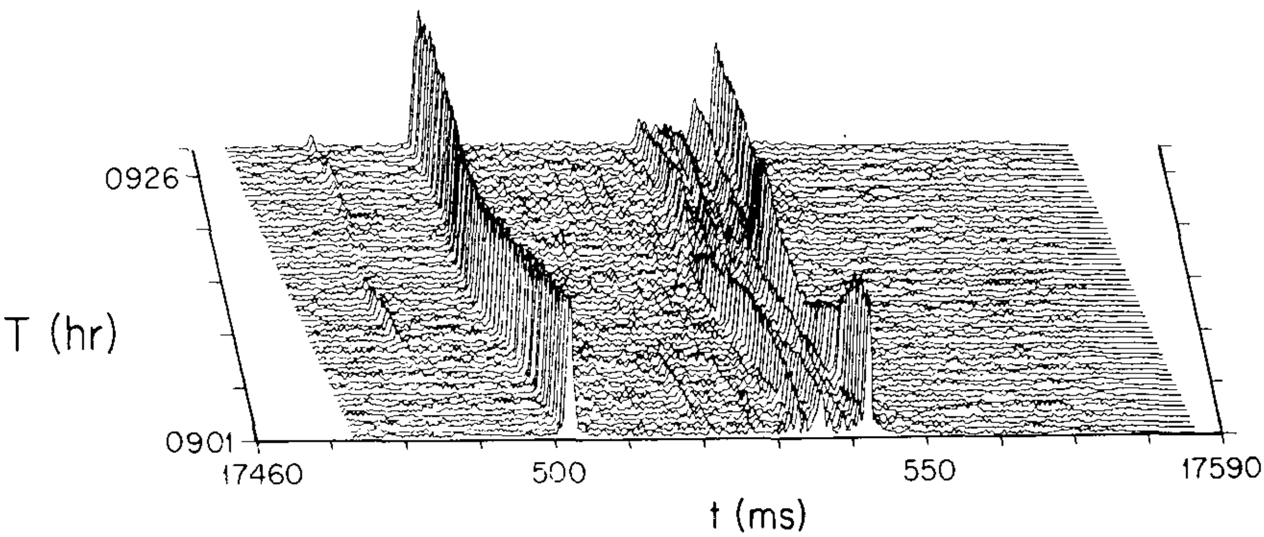

Fig. 2. Stacked returns for pulses emitted once per minute. Each return consists of a pulse at 17,500 ms and a pulse group at 17,530 ms. From Porter (1977).

This burst travels by various refracted and reflected paths and arrives at the receiver as a series of short pulses. The time taken by each pulse to reach the receiver depends primarily upon the temperature and current along the path. Each received pulse has travelled a different path and can thus be used to determine the average ocean properties along that path and the statistics of any fluctuations existing within it.

Variations in travel time will arise from fluctuations in ocean parameters such as temperature, salinity and current. Such variations are random but the structure of the received signal, which is determined by the interference of the many multipath arrivals received, will also vary in a related manner. With modern signal processing techniques the possibility exists of using the pulse structure to determine the properties of the ocean variables. An excellent example of temporal variations in pulse structure which can arise from multipath effects was obtained in a recent experiment carried out by the University of California (Porter 1977) fig. 2. A single narrow pulse is emitted from a projector. Two major pulse groups arrive at the receiver 17,500 milliseconds and 17.530 milliseconds later. One minute later another pulse is emitted. Its received pulse groups are aligned here in a three dimensional display where pulse emission time versus arrival time is plotted with pulse amplitude shown in the vertical plane. The return at 17,500 ms is a single pulse whose amplitude varies slowly over the 26 minutes of the record, in response to some slowly varying ocean parameter which influences sound transmission. The return at 17,530 ms consists of a group of pulses whose amplitude varies over the 26 minute interval. A computation of basic ray acoustics predicts only one pulse at 17,530 ms. The reception of many nearly simultaneous arrivals is the result of a complicated interaction between the sound and ocean variables along the path such as temperature, salinity and current. The possibility exists therefore of using the pulse structure to determine the properties of the ocean variables.

In this experiment the frequency used was around 2000 Hz and the separation of projector and receiver was of the order of 25 km. Other experiments of this type have been carried out (Ewart 1976), the frequencies and ranges involved being comparable, to explore relationships between the acoustic and oceanographic properties of the ocean environment.

ii. Experiments with Continuous Sources:

Experiments using continuous tones rather than pulses have also been carried out and these too show promise of application to ocean sensing (Steinberg and Birdsall 1966; Clark and Kronengold 1974; Steinberg *et al.* 1972). In a classic experiment over a 1250 km path between Eleuthera and Bermuda, Steinberg and Birdsall (1966) transmitted a continuous wave of 406 Hz and recorded its relative phase and intensity over a period of many months. On the results of this work Munk has shown that the fluctuations observed may be closely related to internal wave behaviour, and that the statistics of the acoustic fluctuations offer the possibility of measuring the spectral properties of this important form of oceanic dynamics (Dyson *et al.* 1975; Garrett and Munk 1975).

Woods Hole have recently extended this work with another study of the influence of internal waves on the phase and amplitude of low frequency sound (Porter 1977). Measurements have been performed using an acoustic range which consists of a sound source at the axis of the sound channel at a distance of 300-400 km from a receiving package (fig. 3). The measurement is sensitive to vertical motions in the thermocline, since the displacement of an isotherm produces a change in sound velocity. An acoustic wave passing through the internal wave region thus experiences a change in phase equivalent to a change in travel time, the actual phase difference being related to the displacement of the isotherm. Further, the rate of change of the displacement is a vertical current that can be estimated from the rate of change of phase. Vertical current spectra obtained by acoustic measurements compare very favourably with those determined by direct measurements of vertical currents. Both show that at frequencies above 1 cycle per hour the energy drops off rapidly in accordance with expectation since little internal wave energy exists for shorter periods (fig. 4).

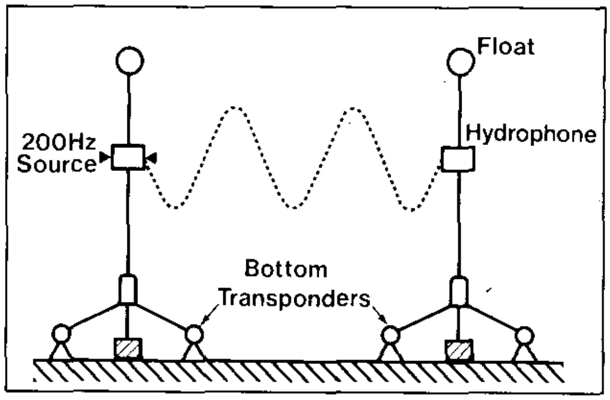

Fig. 3. The Woods Hole Oceanographic Institution mobile acoustic range. A mooring with a sound source is buoyed off the bottom. The source motion is tracked relative to two fixed beacons. The tracking receiver measures the change in position. The mooring 300 km away contains hydrophones for monitoring the 200 Hz source. A ray path is sketched. The position of the receiver is also tracked relative to the fixed acoustic beacons.

iii. Measurement of Ocean Currents

The mooring of systems of the type used in the Woods Hole experiment naturally move in direct response to ocean currents. The move of the moorings under the influence of such currents must be measured accurately

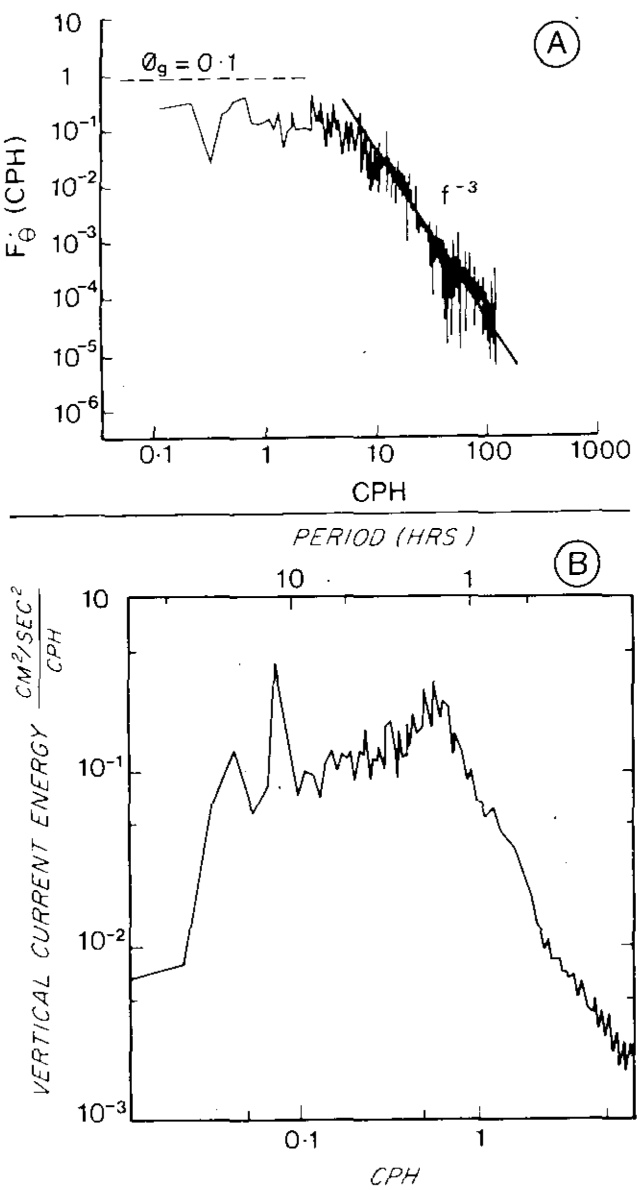

Fig. 4. Comparison of acoustic phase fluctuation spectrum (a) with that obtained directly by measurement of the vertical current (b); both fall off rapidly about 1 cycle per hour. From Porter (1977).

by acoustic tracking devices before the effects of internal waves can be resolved. The acoustically detected mooring movement gives a method of monitoring the currents involved. The displacement of two moorings 5 km apart located 3,700 metres above the sea floor, showed the dominant motion to be due to the demi-diurnal tide but other long term phenomena are also clearly present (Porter 1977, Fig. 12).

Another medium range experimental program which emphasises the sensitivity of acoustic sensing is one we are pursuing in Auckland. This involves a study of normal mode propogation in shallow water (Tindle *et al.* 1978). The normal mode structure has been shown to be very sensitive to variations in oceanographic parameters such as tidal amplitude and to the effect of current on the hydrophone mooring. In this study the true normal mode pattern was only clearly resolved when the effects of the array displacement were removed.

iv. Acoustics and Surface Wave Studies
(a) Side Band Generation:

In other studies, in this case with a moving continuous wave (CW) source, forward scattering from the ocean surface has produced side bands in the narrow band signals from the source, and a strong correlation between sideband spectral shape and the ocean surface gravity-wave spectrum has been observed (Williams 1973; Brown and Frisk 1974).

In a recent experiment Shooter and Mitchell (1976) studied signals from a moving CW source operating at 138 Hz and towed at 5 knots. The typical narrow band signal for zero sea state was modified by reflection from the rough sea surface (fig. 5). By narrow band spectral analysis of the signal received on hydrophones up to 400 km away they were able to show:

(1) Size lobes occurred at about 0.1 Hz from the carrier, and that this displacement corresponded to the frequency of the surface wave spectrum peak;

(2) The amplitude of the side lobe was sea state dependent;

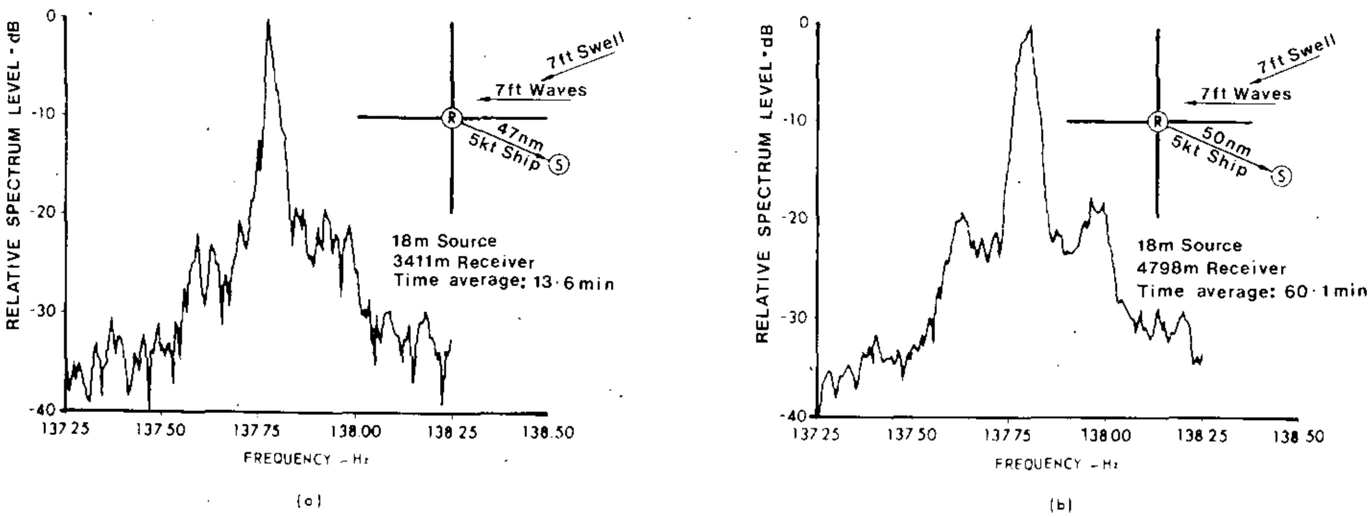

Fig. 5. Relative signal spectra from a narrow band CW source at range 47 nm and 50 nm for two different receivers. From Shooter and Mitchell (1976).

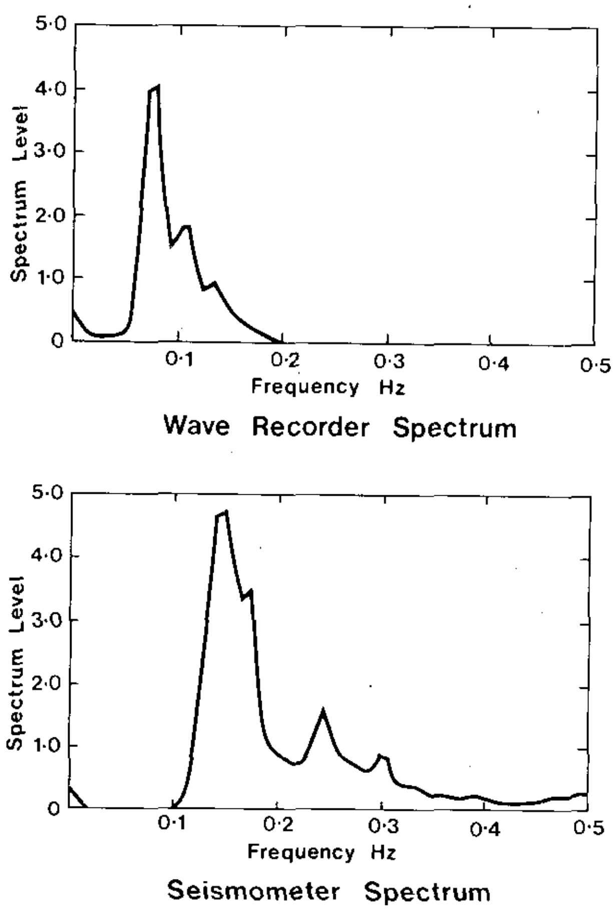

Fig. 6. A comparison of ocean wave spectra as measured by an off-shore wave recorder and an on-shore long period seismometer.

(3) An asymmetry in the side band structure could be related to the relative motion of the sound and wave/swell direction.

This procedure thus offers the possibility of studying ocean wave spectra at considerable distance and over an extended surface region.

(b) Observations of Ocean Microseisms:

In a completely different application of acoustics, ocean induced microseisms can be monitored ashore to provide information on ocean surface wave spectra. Figure 6 present data from an Auckland University experiment and compares spectra from a land based seismometer and a wave recorder off the coast. Note the two to one relationship in frequency and the similarity of the spectra.

Sound Attentuation in the Ocean

Another interesting application of ocean acoustics to oceanography has arisen from the study of sound attentuation in the oceans of the world.

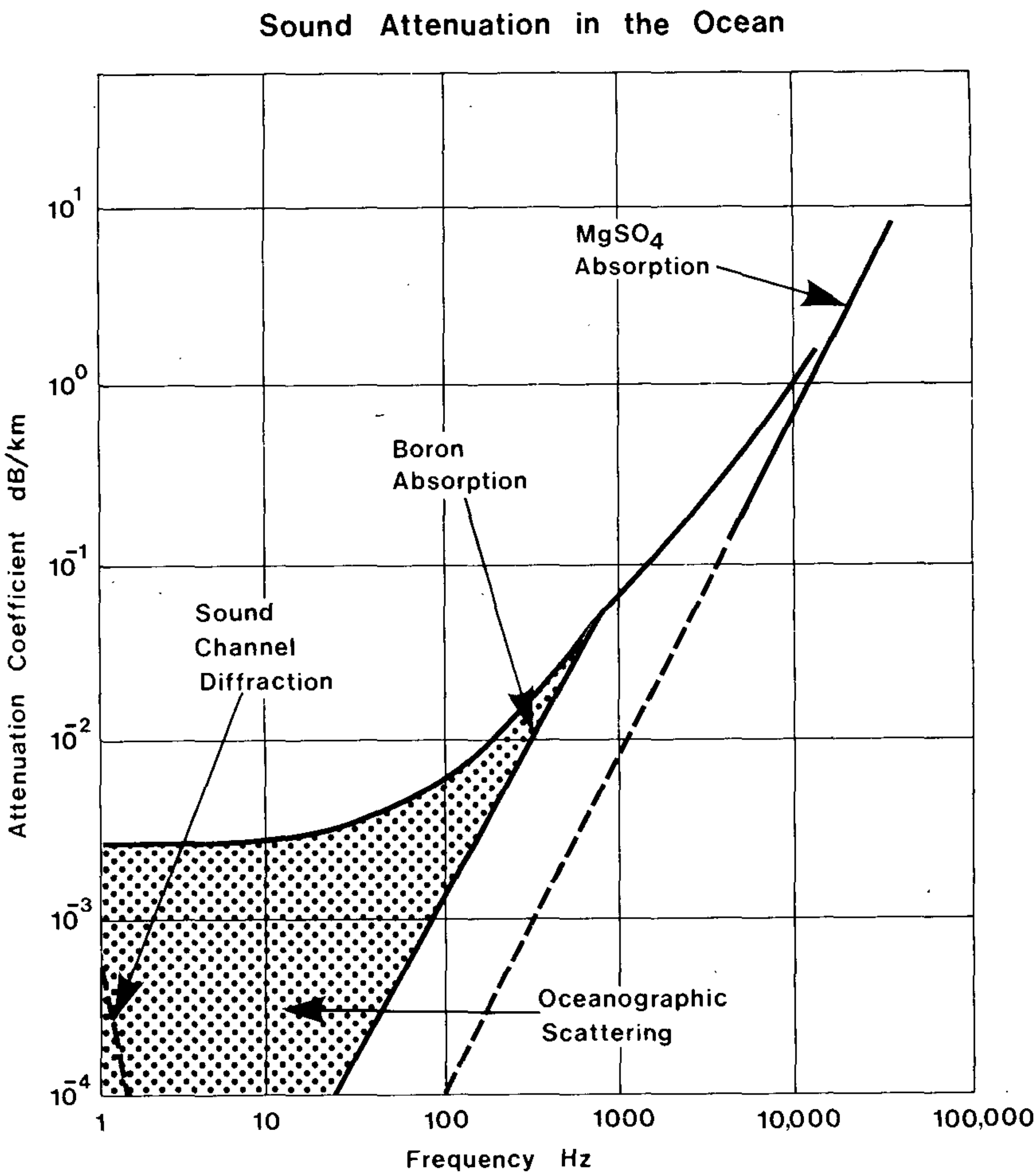

Fig. 7. Sound attenuation in the ocean.

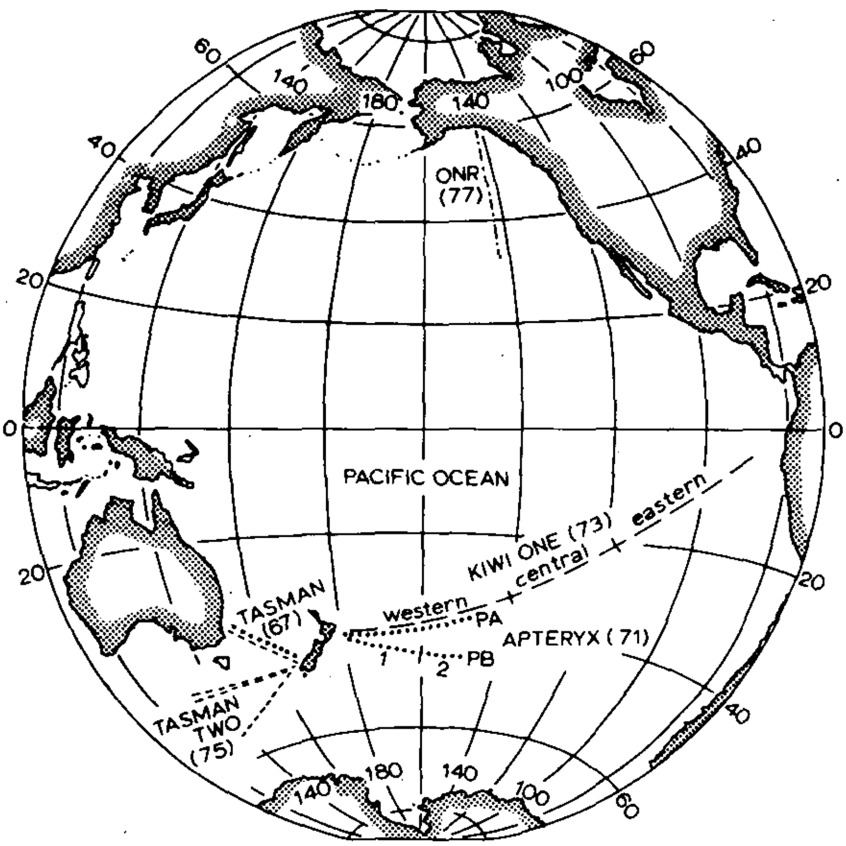

Fig. 8. Long range propagation experiments that have identified hydrological boundaries in the Pacific Ocean. From Kibblewhite and Browning (1978).

Since World War II it has been recognised that a magnesium sulphate relaxation reaction was the principal cause of sound absorption in sea water at high frequencies (> 100 KHz). As acousticians have become interested in lower and lower frequencies, it was found that other attenuation mechanisms exist (Schulkin and Marsh 1977; Mellen and Browning 1977; Thorp and Browning 1973). Specifically in the region below 10,000 Hz two chemical absorptions were discovered, one involving boron and the other magnesium carbonate, the relaxation process involving boron being the dominant of the two. At very low frequencies, below 200 Hz, it appears that scattering from oceanographic inhomogeneities is the principal agency causing attenuation (fig. 7).

In seeking to establish the dependence of attenuation on frequency the acoustician has revealed several effects of interest to the oceanographer.

i. The pH Dependence of the Relaxation Reactions.

Each of the three relaxation reactions involving magnesium sulphate, boron-boric acid and magnesium carbonate has a different temperature dependence. Further, the latter two are both buffering reactions and thus pH dependent; the greater the pH, the greater the sound absorption (Mellen and Browning 1977). This dependence on pH has provided the explanation for a reported regional variation in sound attenuation at frequencies

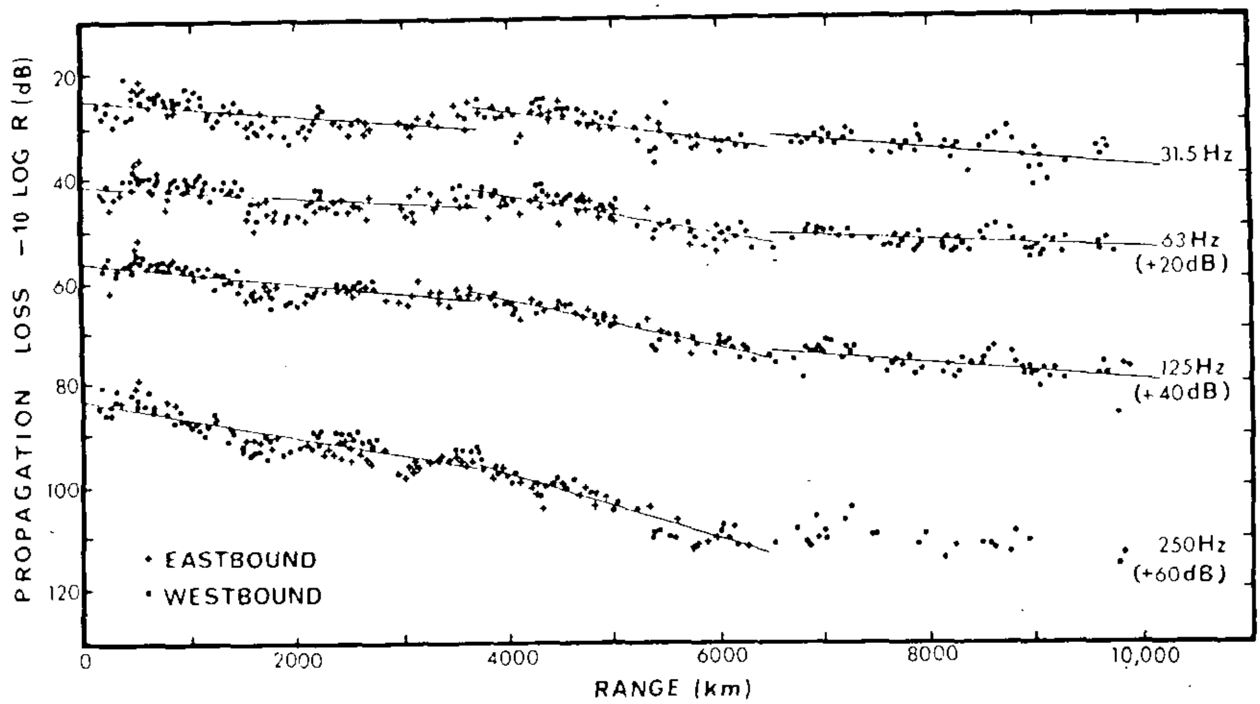

Fig. 9. Attenuation data from Project KIWI-ONE. From Kibblewhite and Browning (1978).

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below 10 kHz. For instance, the attenuation in the North Pacific was found to be only half that measured in the North Atlantic. Typical pH profiles revealed that a regional variation does occur. Acoustic attenuation measurements can thus provide a measure of average pH in an ocean region.

ii. Regional Variation of Attenuation below 200 Hz:

At very low frequencies - below 200 Hz - we enter a frequency independent attenuation regime. It has been hypothesised that the excess attenuation of this region is due to scattering from oceanographic inhomogeneities. Since attenuation is very low (0.001 dB/km), very long ranges in the ocean are required to obtain measurable changes in signal level and in many experiments trans-oceanic transmission paths have been used, many within the South Pacific Ocean (Kibblewhite and Browning 1978) (fig. 8).

Again the results have revealed a regional variation in attenuation and provided useful feedback to the oceanographer. For instance, in Project Kiwi One which covered a track across the entire South Pacific three distinct regions of attenuation were found, with the central region having the highest value (fig. 9). Similar measurements in other oceans have revealed similar features. These regions of different acoustic properties must have distinct oceanographic properties. One suggestion is that different internal wave regimes account for the changes in acoustic properties, and that the attenuation is a sensor of these regimes.

iii. Identification of Oceanographic Fronts:

More important to the oceanographer perhaps has been the power of the acoustic measurements to identify the position of major oceanic fronts.

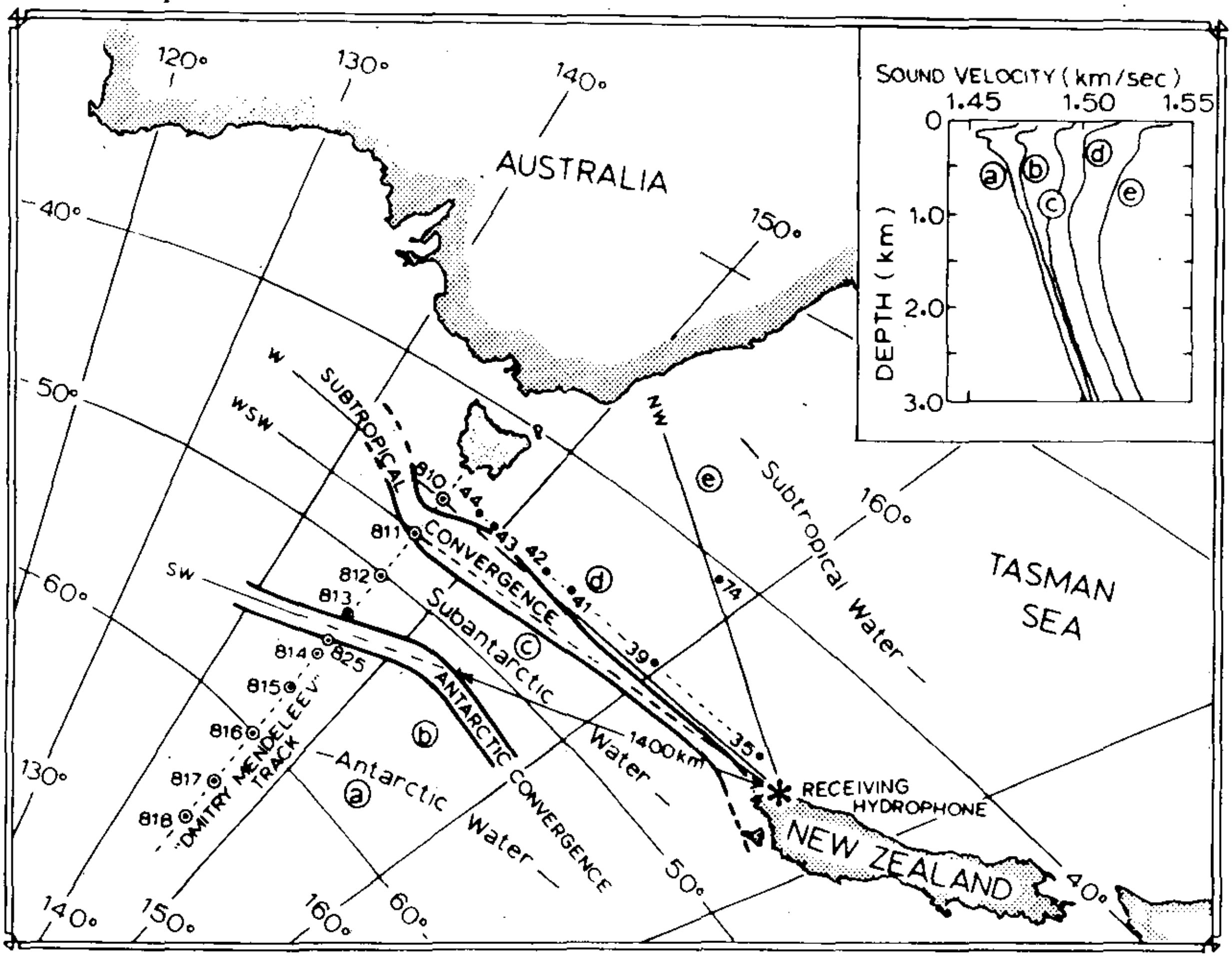

Fig. 10. Transmission paths for the experiment Project TASMAN-TWO. Paths designated as NW, SW etc pass through different water masses. From Kibblewhite and Browning (1978).

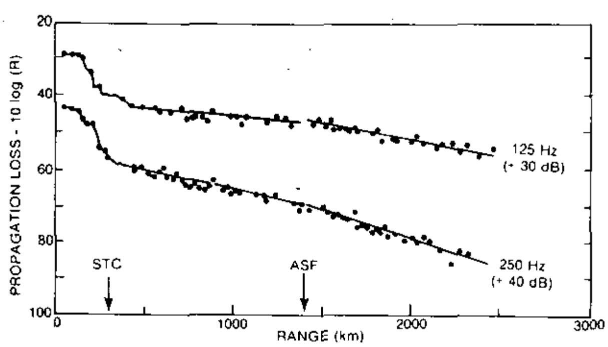

Fig. 11. Transmission data for path SW (TASMAN-TWO) indicate that changes in the acoustic properties occur at the intersection of the Subtropical Convergence (STC) and Australasian Subantarctic Front (ASF). From Kibblewhite and Browning (1978).

Recent measurements in the Southern Ocean have successfully identified the major oceanographic boundaries in this area (Kibblewhite and Browning (1978). The propagation paths (fig. 10) were chosen to sample the four distinct water masses to the south of New Zealand. The acoustic transmission data show significant acoustic changes occur at the boundaries between the water masses (fig. 11). The results of other experiments confirm the potential of long range acoustic transmissions to identify hydrological and bathymetric discontinuities in the deep ocean.

iv. Topographic Mapping

Low frequency sound also contributes to marine geology and geophysics (Kibblewhite 1974). An interesting example is provided by the acoustic mapping of large areas of unchartered ocean. This capability was demonstrated in the CHASE V experiment (Kibblewhite and Denham 1969). Unchartered sea mounts in the Pitcairn Island region were identified by reverberation signals received in New Zealand from an underwater explosion detonated off the west coast of the U.S.A. Indeed from a distance of nearly 5,500 km from the Tuamotu Ridge it was possible to resolve discrete features which were separated by distances of only 40 km and establish their absolute positions to an accuracy better than ± 20 km (Kibblewhite and Denham (1971).

Future Application of Acoustic Monitoring

It is clear that low frequency propagation studies may have some interesting applications in future efforts to increase our understanding of the chemical, physical, geological and biological characteristics of the ocean.

The scale of ocean eddies and other dynamic phenomena (200 km) makes acoustics an appropriate tool for their study. Australian and New Zealand experiments have already demonstrated this possibility (Nysen *et al.* 1978). Moored systems suitably deployed, capable of recording for up to six months, would provide effective acoustic sensors to study the behaviour of such mesoscale oceanic features. Mesoscale "eddies" are analogous to atmospheric storm systems and the application of acoustic methods offers one possible method of mapping ocean weather.

By reverting to explosive sources and low frequency acoustic techniques the possibility exists of monitoring oceanic fronts and the nature of oceanic turbulence on a global scale. The easy identification of such features could be of particular interest to the biological and physical oceanographer alike.

The use of SOFAR floats offers considerable hope for monitoring ocean currents in the deep ocean over very long time scales (Rossby *et al.* 1975). The floats are free floating aluminium tubes, adjusted to float at any prescribed depth. These devices emit pulses of sound which can be monitored by sensitive listening equipment distributed at widely scattered sites. In this way their movements can be tracked over large distances for many months.

As a specific test of the applicability of acoustics to ocean probing Walter Munk is developing a long base line acoustic current meter (Munk and Williams 1977). The instrument is designed to measure average current along a 50 km path by acoustic travel time observation. Sound travels faster with the current than against it so that two moored transmitter/receiver systems allow an unequivocal determination of current flow.

The sophistication of the instrument packages required and the status of the experimenter together point to the likely future of acoustic probes in extracting quantitative information on the properties of oceanic processes.

3. ACOUSTIC INSTRUMENTATION

A review of this sort would not be complete without reference to the wide application of acoustics in general marine activities. In one form or another acoustic systems have been used in applications such as the following:

Acoustic Fixing

The speed of sound in water is 200,000 times slower than that of electromagnetic radiation in air, so that time measurements can be 200,000 times less precise for the same fixing accuracy. Acoustic systems can give fixes to less than 1 metre when operating at high frequencies and short ranges and acoustics has found application in:

i. Acoustic navigation including Doppler based systems;

ii. The tracking and positioning of towed instruments;

iii. The dynamic positioning of ships - e.g. at tanker terminals;

iv. The finding and relocation of deep sea bore holes.

Sea-bed Reconnaissance using Side Scan Sonar

The use of side scan sonar virtually revolutionises bottom observations. Such a system provided distinct identification of bottom type and its variability. A survey of 500 metres side sweeps can in 8 hours map an area of 60 km^2. Such maps can be used to locate biological sampling sites, to survey for pipe and cable routes, to locate underwater objects, and to provide indications of bottom scouring and erosion.

Acoustic Bottom Drifters

In place of current meters, instrumented bottom drifters can be positioned and tracked by sonar with sufficient accuracy to infer bottom-water circulation caused by tidal and other storm effects.

Reflection and Refraction Seismology

Until recently reflection seismology has been restricted to determining the geometry of geologic formations. Recently acoustic techniques have been developed to provide sediment classification. Indications are that remote sensing will permit the determination of sediment physical properties, in appropriate cases, to depths of 1.000 metres.

Detection of Neutrinos

An interesting application of acoustics is contemplated in this fundamental project. In this case the aim is to detect the acoustic signals produced by neutrinos in an underwater range sited off Hawaii (Session 00 1978).

4. BIOLOGICAL ACOUSTICS

The potential application of acoustics in marine fisheries arose from two problems encountered by the naval acoustician and sonar operator. These were related to the background reverberation produced by diffuse scattering agencies within the ocean and the discrete echoes produced by reflectors in the ocean. The first effect increases the general background noise against which submarine echoes have to be detected, and thereby reduces the signal to noise ratio of the sonar system; the second produces a classification problem, and one which has intensified as weapon systems have become more sophisticated. It would be humiliating for the captain of any antisubmarine unit to expend antisubmarine missiles costing $100,000 against a school of fish!

Since these sources of interference were shown to be largely biological in origin, these difficulties for the sonar operator became the basis for improved performance in the fisheries industry. Acoustic techniques were accordingly applied to the study of fishing from as early as 1930.

The cooperation which developed between the physical oceanographer and the acoustician has not however been paralleled by comparable interaction between the acoustician and the marine biologist and little of the sonar technology available today has to date found application in marine fisheries.

Acoustics in a fisheries context is concerned with two main endeavours: (1) the location and capture of fish, and (2) the assessment of fish stock and the evaluation of fish as a resource.

Among other things, fishermen need to know where fish are, what their distribution is, what their migration patterns are and what type of fish are present and their abundance. These assessments are difficult to obtain by conventional trawling and it is these difficulties which have made remote acoustical sensing attractive.

In reviewing the application of acoustics to fisheries it will be instructive to compare the fishery and naval situations. In general the fishery problems are much more difficult (Clay and Medwin 1977; Chapters 5 and 7).

Sonar Detection by ACTIVE Systems

In any ACTIVE sonar, a short pulse of sound is transmitted. This sound travels outward from the projector, and is intercepted by any object insonified; part of the scattered sound is detected by the receiving element of the sonar system. There are two principal sources of variability in such a process.

First, the sound source has a beam pattern and the amplitude of the scattered sound depends upon the position of the body in the beam. For a mobile platform ship movement can produce significant beam movement and consequent ping to ping fluctuation in echo levels. In fisheries applications where high frequencies are employed this effect is intensified.

Second, the scattering process itself can result in considerable echo variability. Even in the case of the submarine where the target is rigid, of much greater dimensions than the wavelength of the insonifying radiation, and comparatively immobile, considerable ping to ping fluctuation can exist. With a biological target which is a much more complicated scattering object, and one subject to rapid movement, the variability in scattered sound is accordingly even more marked.

Another significant factor differentiates the naval and fisheries operation. The antisubmarine operator is usually dealing only with discrete targets. The fisherman is more commonly dealing with schools and aggregations of targets and has to contend with the complexity introduced by these multiple scatterers.

Add to these effects the pronounced variation in the attenuation which can occur in the oceans at the frequencies of interest to marine biology, and the marked variation in system self noise that occurs from unit to unit and time to time, and one can see that nearly every parameter in the sonar equation is to a large extent a variable quantity.

It is only recently that this situation appears to have been acknowledged. Fundamental measurement programs which should have preceded any extensive field application are only now receiving the attention they should have received, and this some 30-40 years after the first introduction of acoustics to biology.

It is now recognised that the successful and scientific application of acoustics to fisheries requires improved information on:

- the acoustic characteristics of individual fish;
- the acoustic properties of groups of fish;

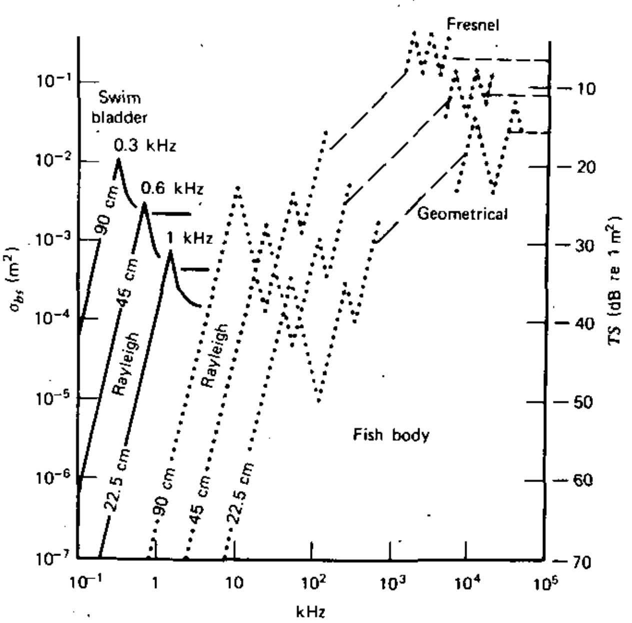

Fig. 12. The relationship between backscattering cross section (σ_{bs}), target strength (TS) and sound frequency for fish 22.5, 45 and 40 cm length. From Medwin and Clay (1977).

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the correct specifications of acoustic systems applied specifically to fisheries operations.

(a) Acoustic Characteristics of Individual Fish:

Individual fish scatter incident sound rather than reflect it specularly. Incident sound is thus a complex function of the orientation of the fish relative to the direction of the sound beam (aspect-angle).

Further, as fish scatter sound by virtue of the acoustic impedance presented by their tissue, bony structure and gas bladders, the radiation pattern of individual fish is exceedingly complex, and becomes increasingly so at higher frequencies.

The gas bladder (where it exists) provides the most striking contrast of all, particularly when the bladder dimensions are critically related to the wavelength of the incident sound. For most fish of interest this resonance effect lies in the range of 1-2000 Hz but being depth dependent there is no unique resonant frequency for a given fish. Overall the acoustical characteristics of fish are far from simple.

The effectiveness of a fish as a sonar target is characterised by a parameter known as the TARGET STRENGTH. It is a major complication of fisheries acoustics however that the "target strength" is extremely variable, depending upon the orientation of the fish relative to the sound source and receiver, the acoustic frequency and the species involved. Figure 12 emphasises the complexity of the relationship between target strength, frequency and target size. Not surprisingly one of the main problems in fisheries acoustics lies in determining the target strengths of different fish. Some of the great variability of target strength with azimuth can be offset by statistical averaging over many fish with differing orientations but this is only practical because many species of commercial interest conveniently operate only in groups of their own kind. In general however target strength remains a fundamental parameter about which insufficient is known.

(b) Group Characteristics:

While the acoustic properties of individual fish are complicated they can be deduced from models based on their physiology and behaviour.

At sea, however, we are often concerned with aggregations, the characteristics of which must be expressed in terms of statistical rather than deterministic models.

The acoustic effects of groups of fish are determined by the fish density involved. At low densities, the echoes from individual fish are small enough in number that they do not overlap and each can be counted to obtain an estimate of fish density provided the sonar system has the appropriate properties. At intermediate densities echoes from individual fish can overlap and they cannot be counted individually. The acoustic response now involves one of scattering from a relevant volume defined by the range and pulse length, rather than from an individual target. The assessment of fish numbers in this situation requires a different technique. The most common procedure currently applied is the so called "energy method" (Clay and Medwin 1977). At very high densities the target characteristic will change again and be very dependent on the wave length of the insonifying radiation. From an assessment standpoint therefore knowledge of the acoustic characteristics of groups is essential to reliable resource evaluation.

State of the Science and Future Trends

The major advantages of acoustic techniques in fisheries research have been and remain the capability of sampling large ocean areas, the continuity of the sampling (so as to provide a measure of patchiness) and the minimal interference with the environment. At the moment however the science appears to be inhibited by certain deficiencies. In examining the state of the science we can look at the areas of detection and location, classification and assessment.

i. *Detection and Location Capability:*

As in many other areas of human endeavour acoustic technology involves compromises. Early sonar operated at around 20 kHz because this provided an acceptable compromise between range and resolution. At these frequencies detection ranges of a few thousand yards could be realised with transducer dimensions that could give a beam width of about 10 degrees. Operation at lower frequencies, which would allow longer detection ranges, was constrained primarily by engineering problems related to transducer dimensions and the size of surface vessels. A move to 5 kHz for instance implies a wavelength of 0.3 m and transducer dimensions of about 3 m for reasonable bearing discrimination. It is not surprising therefore that most ACTIVE sonar operate at frequencies above 1 kHz.

For fisheries sonar the move to low frequencies has not generally been appropriate for several reasons. First while the resonant frequency of swim bladders is typically 1-2 kHz, the target strengths and dimensions of the fish body call rather for high frequency sonars. Secondly the large transducers required for reasonable bearing and location discrimination at low frequencies would not be suitable for any but the largest of fishing boats. Thirdly for fish stock assessment and actual fishing operations the requirements of high range and bearing resolution call for narrow beam widths and short pulse lengths, both of which dictate the use of high frequencies and the acceptance of the shorter detection ranges these imply.

While the current detection capability in fisheries acoustics is reasonably effective there is no doubt that improvements could be achieved by exploiting the more sophisticated systems employed in naval applications. Naval systems in use today are very good at finding fish - so good in fact that one of the major problems facing the naval sonar engineer is that of "classification" - the discrimination of submarine and non-submarine targets. While the fisheries biologist is not going to get a

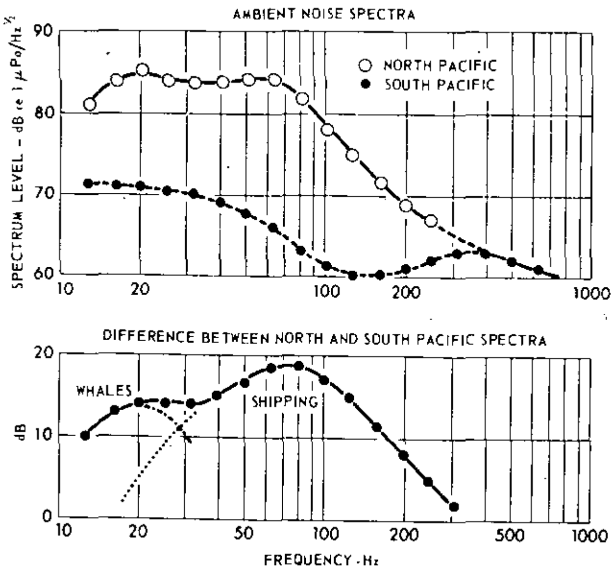

Fig. 13. A comparison of North and South Pacific ambient noise spectra. From Kibblewhite *et al.* (1976).

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computer printout with the name of the fish on it, it is true that existing technology could not help him immeasurably if the investment funds were available to acquire available systems and data processing facilities. Modern multibeam, high resolution equipment used in mine hunting and echo sounding (Clay and Medwin 1977; Chapter 8) should for example be ideally suited to fish hunting. As another example non-linear acoustic technology offers the opportunity of achieving a multiple frequency system which combines the narrow beam width of high frequency sonar (with effectively no side lobe problems)with the longer ranges obtained with the low difference frequency (Clay and Medwin 1977; fig. 5.4.2). Such systems are now coming into operation.

Obviously the cost of such sophisticated technology and the security blanket surrounding them are inhibiting factors, but improved communication between acousticians and fisheries biologists would at least be instructive in making the latter aware of what is available. In the course of preparing this paper for instance it struck me as questionable national policy that our New Zealand Defence Scientific Establishment has no brief which permits active participation in fisheries acoustics problems in New Zealand. I suspect the same is true in Australia.

I have of course been referring to ACTIVE systems. As was mentioned earlier much defence research effort in the past 20 years has been directed towards exploiting the low frequency propagation properties of the ocean in PASSIVE systems. For completeness we should note that ambient noise studies associated with these investigations have revealed many facts of interest to the marine biologist. For instance, the deep water low frequency ambient noise spectrum often displays a component at 20 Hz which has its origin in whale activity (Kibblewhite *et al.* 1976) (fig. 13). The signals influencing these spectra come from animals many hundreds of kilometres away. With systems currently available these animals could be located and tracked acoustically over long ranges.

ii. Classification:

Species identification remains an elusive ambition of fisheries biologists. Whether acoustic techniques alone will provide this capability remains to be seen but increased knowledge of target characteristics (as a function of species, size, depth, frequency, etc) is certainly basic to achieving this goal. It is likely however that identification at sea will always depend on ancilliary classification clues, but again only sophisticated acoustic systems are likely to provide these. Typical supplementary parameters of value are:

(a) Target depth;
(b) Target size and structure;
(c) Target speed and movement pattern.

In addition, environmental parameters will give additional clues important to identification. Correlations with chemical and physical observations will thus also be important to the development of fisheries management and again in this respect the role of acoustics must be acknowledged.

In target classification the fisheries biologist has a much more difficult task than his naval equivalent who can plan experiments at sea with cooperative targets. Difficult as equivalent *in situ* measurements will be, they remain essential to the development of fisheries acoustics.

iii. Acoustic Scattering from High Density Schools:

Present stock assessment methods depend heavily on assumptions of linear relationships between scattering and the number of individuals in the group. These relationships undoubtedly fall down at high packing densities. More information is clearly required on the scattering effects in medium and high density schools, to permit more confidence to be placed on quantitative evaluations. Again only high resolution, multibeam scanning systems have much chance of providing this information; but systems do already exist. The experiments required to test current theories are urgently needed. It is pleasing that some of these fundamental measurements are now taking place in various areas (Session JJ 1978).

iv. Acoustic Transponders and Telemetry Systems:

Finally, acoustic technology can be applied with advantage in ancillary roles such as monitoring actual trawl behaviour. With the need to correlate acoustic measurements with actual sampling, the advantages of extending the use of transponder technology to sampling systems is obvious.

Further, as transponders get smaller it will become possible to use telemetry devices to study the behaviour of various species through tagging programmes.

5. SUMMARY

In summary we can say that acoustics has a very impressive record in many branches of marine science. This review has touched only briefly on its present and future roles in physical oceanography and marine biology but has demonstrated that it has and will continue to make an important contribution to these branches of the subject.

The contribution is however likely to be greater in physical oceanography than in fisheries if only because naval requirements will continue to provide funding for acoustical oceanography at the levels needed for adequate progress. If experiments presently being planned by Munk and others do prove successful, additional funding from other major agencies are likely to give further impetus to large scale ocean monitoring.

The problems in fisheries on the other hand are such that the same spectacular successes are not likely to be achieved within the resources available, even though we have seen evidence of real advances in this seminar. It seems important therefore to be very selective in allocating resources to problem areas. It is, I am sure, one of the hopes of those planning this workshop that we will address this issue.

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APPENDIX I

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APPENDIX 11

Workshop Programme

Monday, 12 February 1979

Time	Speaker	
0945 - 1010	Dr G. I. Murphy	Introduction to the Workshop
1010 - 1015	Mr M. J. Castle	Introduction of the speakers
1040 - 1110	Mr R. Coombs	An Echo-Recording System
1110 - 1135	Mr C. Francis	Preliminary assessment of an Echo-Recording System
1135 - 1200	Dr S. B. Brandt	Application of Acoustics to the Study of Fish Behaviour; an Example from Lake Michigan
1200 - 1230	Mr D. Owens	The Dowd Fish Counting and Integrating System
1400 - 1425	Mr J. J. Castle	A Review of the Acoustic Survey of Jack Mackerel and Methods of Data Analysis
1425 - 1455	Dr J. Penrose	Acoustic Research in Relation to the Australian Prawning Industry
1520 - 1545	Dr M. Hall	Volume Reverberation and Biological Material in the Ocean
1545 - 1600	Mr I. Dunstan	Sound Scattering by Marine Organisms in Australian Waters
1600 - 1700	Prof. A.C. Kibblewhite	Acoustical Oceanography
1700 - 1705	Mr D. Rochford	Conclusion

Tuesday, 13 February 1979

0900 - 1000	Tour of electronics workshop
1020 - 1230	Informal discussion amongst the participants
1400 - 1630	Formal discussions amongst the participants (Chair: Mr J. Maclean)

Wednesday, 14 Februsry 1979

0900 - 1230	Concluding informal discussions

ACKNOWLEDGEMENTS

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