INVERSE METHODS AND RESULTS FROM THE 1981 OCEAN ACOUSTIC TOMOGRAPHY EXPERIMENT

by

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ABSTRACT

Ocean acoustic tomography was proposed in 1978 by Munk and Wunsch as a possible technique for monitoring the evolution of temperature, density, and current fields over large regions. In 1981, the Ocean Tomography Group deployed four 224 Hz acoustic sources and five receivers in an array which fit within a box 300 km. on a side centered on 26°N, 70°W (southwest of Bermuda). The experiment was intended both to demonstrate the practicality of tomography as an observation tool and to extend the understanding of mesoscale evolution in the low-energy region far from the strong Gulf Stream recirculation.

The propagation of 224 Hz sound energy in the ocean can be described as a set of rays travelling from source to receiver, with each ray taking a different path through the ocean in a vertical plane connecting the source and receiver. The sources transmitted a phase-coded signal which was processed at the receiver to produce a pulse at the time of arrival of the signal. Rays can be distinguished by their different pulse travel times, and these travel times change in response to variations in sound speed and current in the ocean through which the rays passed.

In order to reconstruct the ocean variations from the observed travel time changes, it is necessary to specify models for both the variations and their effect on the travel times. The dependence of travel time on the oceanic sound speed and current fields can be calculated using ray paths traced by computer. The vertical structure of the sound speed and current fields in the ocean were modelled as a combination of Empirical Orthogonal Functions (EOFs) from MODE. The horizontal structure was continuous, but was constrained to have a gaussian covariance with a 100 km. e-folding scale. The resulting estimator closely resembles objective mapping as used in meteorology and physical oceanography. The tomographic system has at present only been used to estimate sound speed structure for comparison with the traditional measurements, especially the first two NOAA CTD surveys, but the method provides means for estimating density, temperature or velocity fields, and these will be produced in the future.

The sound speed estimates made using the tomographic system match the traditional measurements to within the associated error bars, and there are several possibilities for improving the signal to noise ratio of the data. Given high-precision data, tomographic systems can resolve ocean structures at small scales, such as in the Gulf Stream, or at large scales, over entire ocean basins. Work is in progress to evaluate the usefulness of tomography as an observation tool in these applications.

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CHAPTER 1

INTRODUCTION AND HISTORICAL SKETCH

1.1 INTRODUCTION

One of the principle difficulties plaguing physical oceanographers is the shortage of ocean data. The oceans are large, and the important processes have scales of tens to hundreds to thousands of kilometers (Richman, Wunsch, and Hogg (1977)). The two major means of observation are ship-borne measurement systems such as the Conductivity-Temperature-Depth probe (CTD) which records temperature (T) and salinity (S) as a function of depth during lowerings from a stationary ship, and moored instruments, such as current meters and temperature-pressure (T-P) recorders which are deployed along cables stretched between an anchor on the bottom and buoyant floats at or below the sea surface. CTD lowerings require upwards of 3 hours, but produce extremely detailed records permitting small-scale resolution of the vertical T and S structures. Moored instruments can sample rapidly in time, and their vertical resolution is only limited by the spacing between sensors, although usually no more than about 10 instruments are placed on a 5000 meter mooring. Each mooring or CTD cast samples at a single horizontal (x,y) location, so that area coverage is limited by the expense of moorings or by ship steaming time.

With the increasing sophistication of ocean models, the need for data has become much greater than during the early exploration period when the large-scale structures of the oceans were being defined. The early exploration cruises pictured the ocean as having steady, large-scale, surface current systems with a rapid decrease in strength with increasing depth. The deep ocean was thought to be nearly at rest, with a few very large, slow currents. Once the major current systems had been mapped, interest shifted from exploration to understanding the mechanisms which controlled the observed features. The more data oceanographers took, the more complicated the pictures became, and the simplicity of the large-scale steady currents was replaced by a complex of interacting and intermittent motions, no less varied than the weather in the atmosphere.

When moorings carrying current meters became available, much of the ocean kinetic energy was found to reside in "mesoscale" motions, with horizontal scales of order 100 km. (O(100 km.)), and time scales of O(50 days) (Richman, Wunsch, and Hogg, 1977). The dynamics of these motions are analogous to those of weather in the atmosphere. Oceanographers now face the same problems that meteorologists have been struggling with--obtaining adequate sampling in space and time to resolve the mesoscale motions, i.e. a "synoptic" data set.

Meteorological data systems now include satellites in a global network of pressure and radiosonde measurements, but the oceanographic observation systems have not kept pace. The oceans are opaque to electromagnetic radiation, so that satellite measurements cannot observe beyond the sea surface, and the open ocean is an extremely inhospitable environment for instruments, so that mechanically complicated systems present tremendous engineering difficulties. Munk and Wunsch suggested a solution to the data-acquisition problem (Munk and Wunsch, 1979) (called MW in the following) with a proposal to monitor the oceans using remote sensing by sound energy. They called the technique "Ocean Acoustic Tomography" because of its similarity to medical tomography (Swindell and Barrett (1977)) which uses X-rays transmitted along many paths through a patient to reconstruct a 2 or 3 dimensional picture of the region through which they passed. Low frequency sound transmitted from a source to a receiver moored at depth in the ocean propagates along distinct ray paths as well, and Munk and Wunsch proposed to use the travel times for pulses following different ray paths to infer the structure of the intervening ocean.

1.2 BRIEF HISTORY

The tomography proposal built on an existing body of work on ocean acoustics, bringing together a number of ideas and techniques which had been developed for other applications. The possibility of long-range transmission of low-frequency sound in the ocean had been known since the 1940's, and a scheme for locating downed fliers by triangulating on the sound from TNT charges had been proposed (Ewing and Worzel 1948). Porter, Spindel, and Jaffee (1973) developed a mooring tracking system which used the travel times of acoustic transmissions to monitor the motion of a mooring. By 1977, low-frequency sound transmissions were being used to track neutrally bouyant "SOFAR" floats over long distances (Webb (1977), Spindel, Porter, and Webb (1977), or see Baker (1981)). Steinberg and Birdsall (1966) transmitted continuous wave (CW) sound across the Florida straits using a 406 Hz sound source, and a later experiment transmitted CW sound over 1250 km. (Clark and Kronengold, 1974). The early transmission experiments were mounted to study the intensity of sound transmitted over long distances, while the phase structure was found to be very unstable, due in part to internal wave variations.

Sound speed in the ocean is most sensitive to temperature and pressure effects, and decreasing temperature with depth produces a decrease of sound speed with depth in the upper ocean (in most areas) while the increasing pressure eventually more than balances this effect, resulting in a sound speed minimum at about 1 km. depth in the North Atlantic. (Figure 1.1). The acoustic waveguide is called the SOFAR channel, which tends to refract sound energy toward the axis. This waveguide, coupled with the fact that mechanical absorbtion decreases with decreasing frequency, permits long-range sound transmissions using sources with finite energy. Sound transmitted from a source to a receiver can be described theoretically as a set of "rays" (by analogy with light rays in optics) each of which follows a different path (Figure 1.2). A single pulse leaving the transmitter will be received as a set of "image" pulses, one for each distinct ray (Figure 1.3). The travel time for a given pulse depends on the length of the path it took and the sound speed along that path. These travel times can be computed, given the path and the sound speed profile, by solving the so-called "forward problem". The solution of the forward problem describes the dependence of the pulse travel time along a particular path, Γ_i, on the sound speed field of the ocean, $C(\underline{x},t)$.

FIGURE 1.1 AVERAGED SOUND SPEED PROFILE FOR N. ATLANTIC SOUTHWEST OF BERMUDA

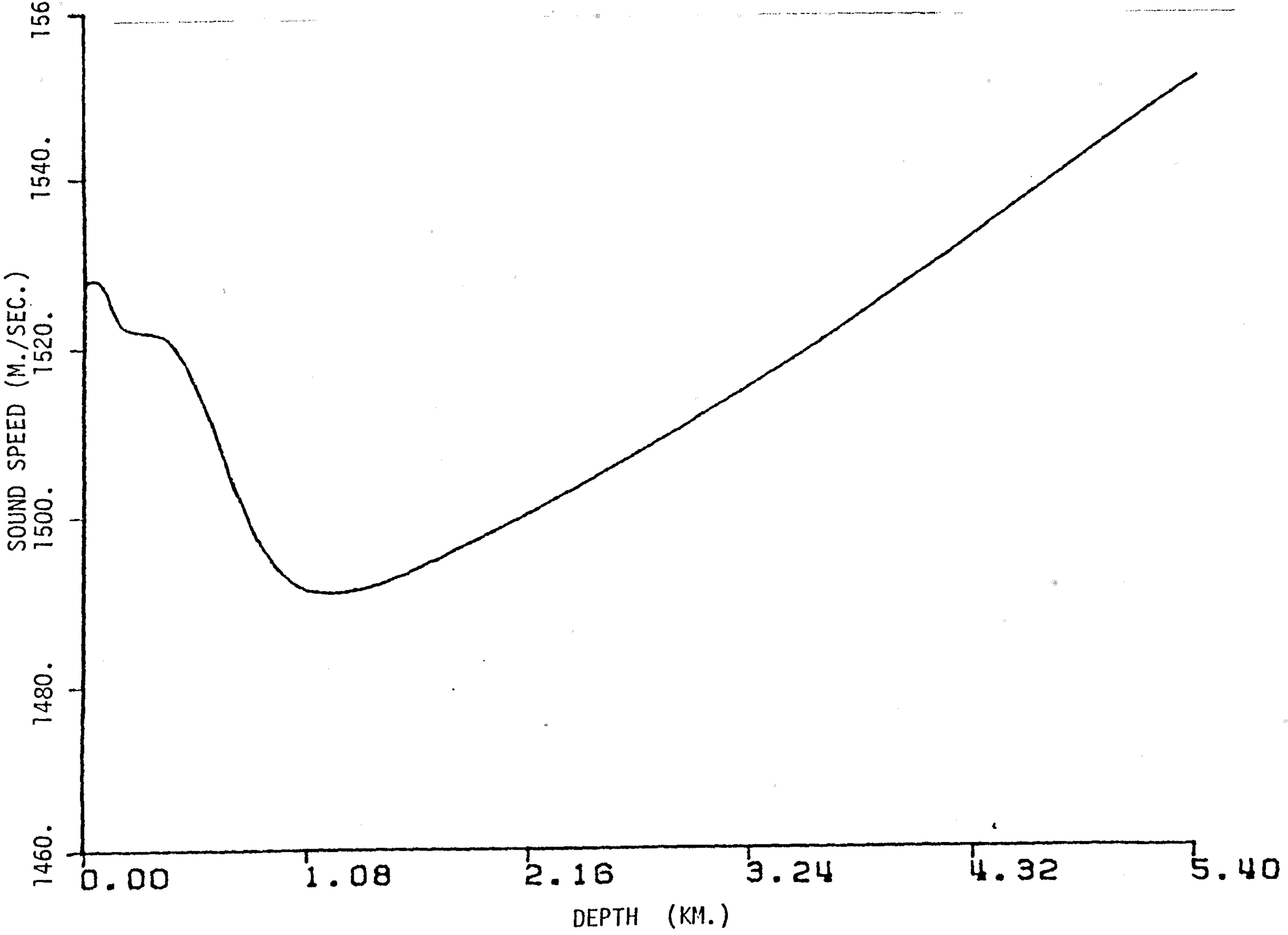


FIGURE 1.2 TWO NUMERICALLY TRACED ACOUSTIC RAY PATHS FOR THE PROFILE SHOWN AS FIGURE 1.1

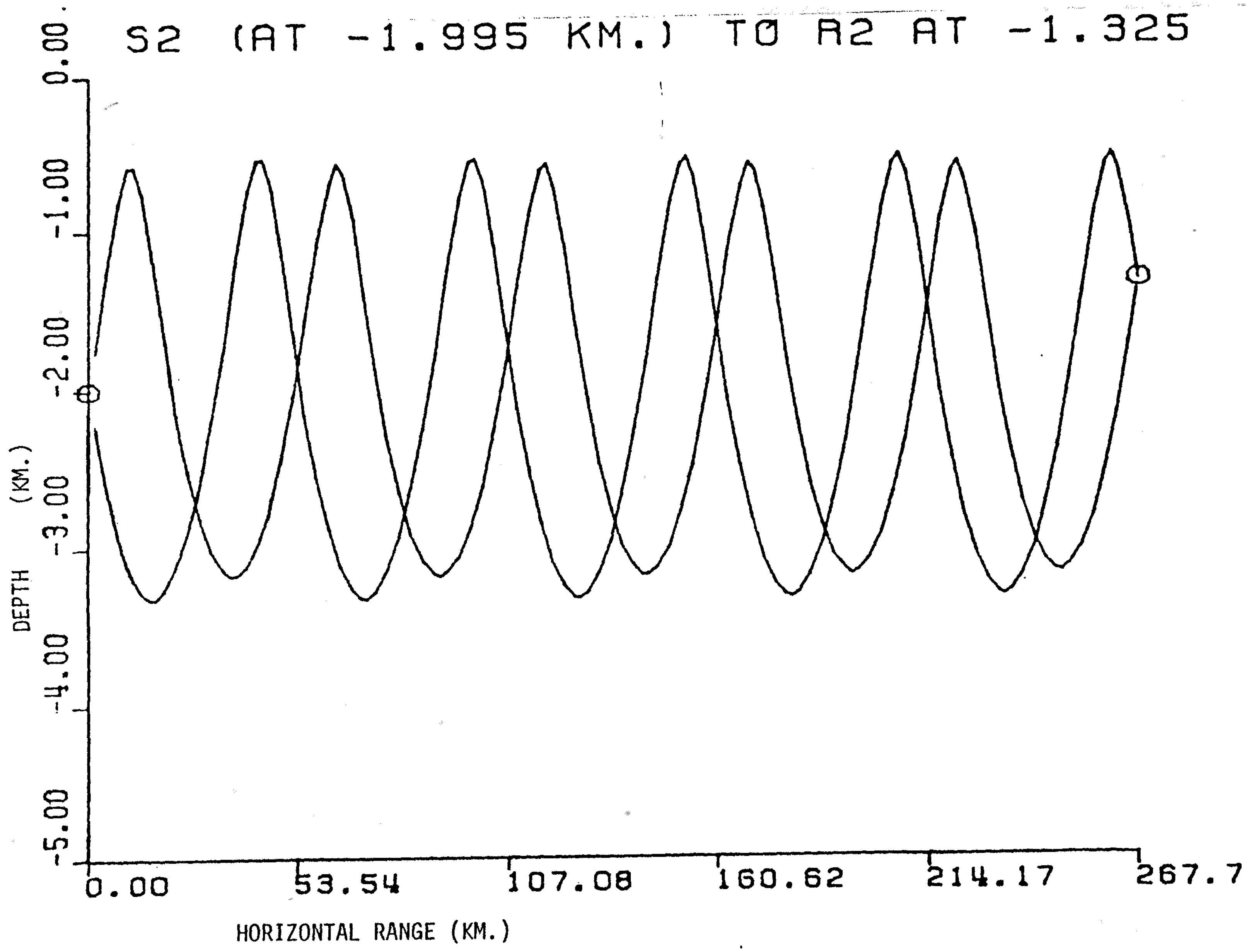
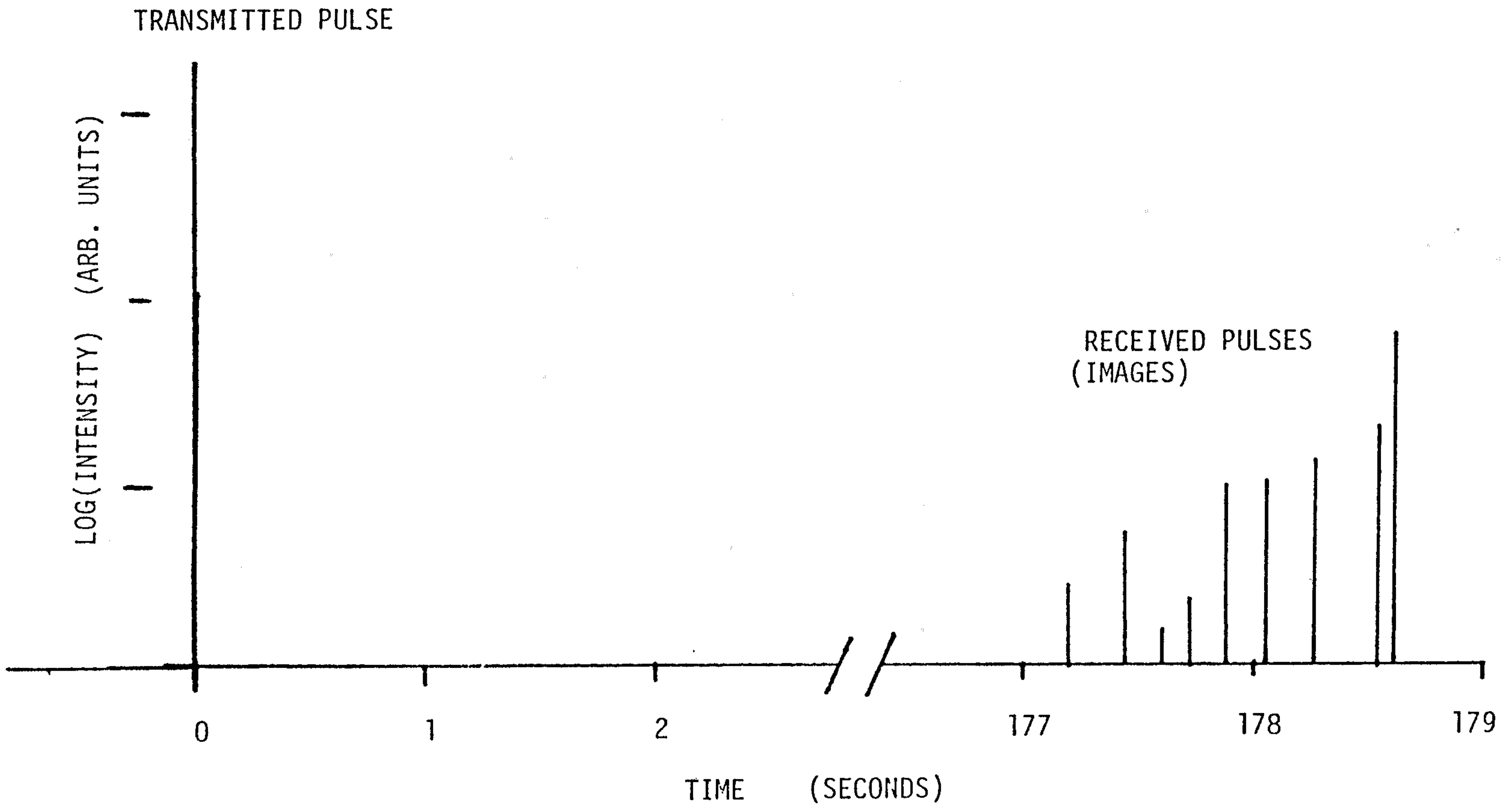


FIGURE 1.3 SCHEMATIC OF TRANSMITTED PULSE AND RECEIVED PULSE "IMAGES" REPRESENTING THE ARRIVALS OF PULSES WHICH TRAVELLED ALONG DIFFERENT RAY PATH. THE RECEIVED PULSE IMAGES ARE CALLED "MULTIPATH ARRIVALS".



The earliest experiments were mounted to gain information on how sound propagated in the ocean. Once the theory describing ocean acoustics ("the forward problem") was understood and verified, investigators began to consider the "inverse problem"--observing propagation and inferring ocean structure. LaCasce and Beckerle (1975) suggested (vaguely) that pulse transmissions might be used to "monitor the periodicities of Rossby waves", on the basis of a simple explosion-monitoring experiment southwest of Bermuda. Porter and Spindel, in 1977, proposed a specific way to monitor eddies using transmissions of 220 Hz pulses, based on their already considerable experience.

Munk and Worcester (1976) had also suggested that oceanographic information might be obtained from acoustic moorings, while an experiment by Peter Worcester (1977), along with Munk and Birdsall, tested the practicality of acoustic measurements of current over relatively short range. Worcester transmitted sound between transceivers suspended from two ships 25 km. apart, and used differences in pulse travel times between reciprocal ray paths to infer current velocity averaged along the ray paths, but encountered problems, such as untracked source and receiver motion. The currents produced arrival time shifts on the order of milliseconds, while the drifting and heaving ships introduced travel time changes two orders of magnitude larger. The experiment used 2 kHz sources to achieve enough bandwidth to transmit pulses, so that it would have been difficult to work at longer range, and the "inverse problem" of unscrambling the averaging along ray paths had not been attacked.

Hugo Bezdek put Worcester, Munk, and Birdsall in touch with Spindel and Porter, as a result of their experience with mooring tracking, and the common interest of observing the ocean acoustically. Spindel and Munk went to sea together in 1978 to deploy the 2 kHz sources on a mooring with tracking. Spindel also deployed the first source that sent coded signals at 220 Hz--using signal processing techniques to make long-range pulse arrival time measurements possible. The success of this add-on test by Spindel was the real beginning of the recognition that long-range acoustic ocean monitoring was truly possible.

If the travel times for pulses following different paths can be reliably distinguished, then slice reconstruction, as in medical tomography, should be possible, although the medical algorithms are not applicable, due to the complicated geometry and incomplete sampling. Theoretical calculations for the North Atlantic (MW) predicted that many different rays should be resolvable, providing a potentially large amount of information, but it was not known whether the paths or the pulse arrival patterns would be stable enough to reliably observe any shifts in travel time along a particular path.

On the basis of Fermat's principle (that sound propagates along paths which extremize the travel time for a given sound speed field) and a careful analysis of internal wave effects, MW predicted that the paths should be stable, so that changes due to the evolution of the ocean mesoscale would be resolvable.

The need to determine pulse arrival times requires a narrow pulse, and therefore a wide bandwidth of the transmitted signal. This is not a problem if explosives are used as the source, but is difficult for a low-frequency, low-power self-contained source such as would be needed on a long-duration mooring. The early low-frequency acoustic transmissions were CW, as mentioned above, as phases (travel times) were regarded as too unstable to be resolved, particularly given the limited bandwidths. The 270 Hz sources developed by Doug Webb for the SOFAR float program (Webb, 1977), were modified to send CW signals at 220 Hz (Spindel, Porter, and Webb, 1977). Later, digital signal processing techniques made possible by burgeoning computer technology were employed to send wider band, coded signals at 220 Hz (Spindel 1979) and 224 Hz (Spindel 1980). The source that Spindel deployed in 1978 which showed that accurate long-range arrival times were attainable in principle was of this type. The sources were derived from the SOFAR float program, but were modified to be part of a mooring and were larger and heavier than the original sources on the floats.

The 224 Hz sources used in the 1981 Tomography experiment use piezoelectric transducers to drive 4 large resonant tubes, resembling organ pipes, for efficient coupling to the water, and have bandwidths of 20 Hz. They transmitted a phase-coded digital signal which was phase-matched filtered (Birdsall, 1976) at the receiver to produce coherence peaks at lags where the received signal closely matched a stored replica of the transmitted signal. These peaks can be thought of as representing the arrivals of short packets of energy from the source, simulating ray arrivals from a broadband explosive pulse. The travel times for these "pseudo pulses" can be measured accurately enough to discriminate between different multipath arrivals. It thus became possible to test the conjecture that the arrivals would be stable enough to use as data in an ocean observation program.

Two tests were mounted, one over a 900 km. path near Bermuda (Spiesberger, Spindel, and Metzger, 1980), and another over 300 km. paths (Spindel and Speisberger, 1981). Both experiments confirmed MW's predictions, in fact surpassing their expectations, showing clearly resolvable paths which shifted in response to oceanic changes while preserving a stable pattern of arrival times. It was also learned that variations in arrival time for the final cutoff of a set of acoustic pulses from underwater explosions had been observed in the early 1960's (Hamilton, 1977).

Given the stability and resolvability of several different paths, consider the "inverse problem" of converting observed shifts in travel time for the different rays into maps of sound speed changes in the intervening ocean. In medical tomography, the X-rays pass directly through the patient and are transmitted from a nearly continuous set of points around the perimeter of the region to be imaged, so that transform techniques may be used in the reconstruction. Ocean acoustic tomography relies on a relatively small set of complicated ray paths (Figure 1.2) which imperfectly and inhomogeneously sample the ocean. Reconstructions require geophysical inverse theory, one form of which was developed by Backus and Gilbert (1967) to treat imperfect and incomplete data.

In the paper which introduced tomography, Munk and Wunsch presented a solution of the inverse problem for the 2 dimensional problem with several sources and receivers distributed around a square region divided into boxes. These preliminary simulations suggested that data from 4 sources and 4 receivers could provide 16 independent pieces of information and adequately resolve a 1000 km. by 1000 km. region divided into 16 boxes. If more boxes were used, the ability to resolve any given box declined, but given the simplicity of the initial case, there were many prospects for improvement.

1.3 THE 1981 EXPERIMENT BY THE OCEAN TOMOGRAPHY GROUP

On the basis of these calculations and the transmission experiments mentioned above, the researchers involved in the various aspects of the problems came together as The Ocean Tomography Group and designed an experiment to demonstrate tomography as a practical observation technique (Ocean Tomography Group, 1982). This experiment was carried out during the first half of 1981, and much of the work described in this thesis was focussed on the particular application of tomography embodied by the 1981 experiment.

The 1981 experiment was designed to emulate MODE, (MODE Group, 1978), with interest focused on the dynamical evolution of mesocale features in a region south west of Bermuda. This location was chosen because a main purpose of the experiment was to demonstrate the utility of acoustic tomography as an oceanographic observation tool. It was thought best to avoid unexplored regions, in order to optimize the design of the array with archived data. In any case, the description of apparently new phenomena by the acoustics alone would have been regarded as questionable. The region was chosen to be out of the energetic Gulf Stream near field, so that the eddy energy would be moderate to weak, in order to avoid problems with important nonlinearities in the acoustics or dangerous mooring movement.

The experiment has been described in the paper by the Ocean Tomography Group (1982) but will be summarized here to fix ideas. The experimental layout is shown in Figure 1.4. 4 224 Hz sources and 5 WHOI and SIO receivers were moored in an array within a 300 km. by 300 km. box centered on 26 N, 70 W. The experimental array also included 2 conventional oceanographic moorings with current meters and temperature-pressure (T-P) recorders. During the course of the experiment, 3 CTD and bottle hydrographic surveys were made by NOAA ships in the region, and several AXBT flights were made by the Navy, in order to have traditional measurements in the region for comparison with the tomography results.

A typical sound speed profile for this region is shown as Figure 1.5, showing the strong waveguide with the axis at about 1300 meters depth. The sources and receivers were mounted on subsurface moorings to reduce leaning in currents. Instrument depths were nominally 2000 meters, well below the sound speed minimum. When both source and receiver are located on the sound channel axis, pairs of rays with equal, even numbers of turning points but opposite launch angle sign have identical travel times if the profile is range indepedent. The actual ocean is range-dependent, but the degeneracy can still impede peak resolution and identification. Off-axis geometry breaks this degeneracy. Moving source and receiver off the sound channel axis also decreased the number of rays received, but did not greatly reduce the number of useful rays. Most

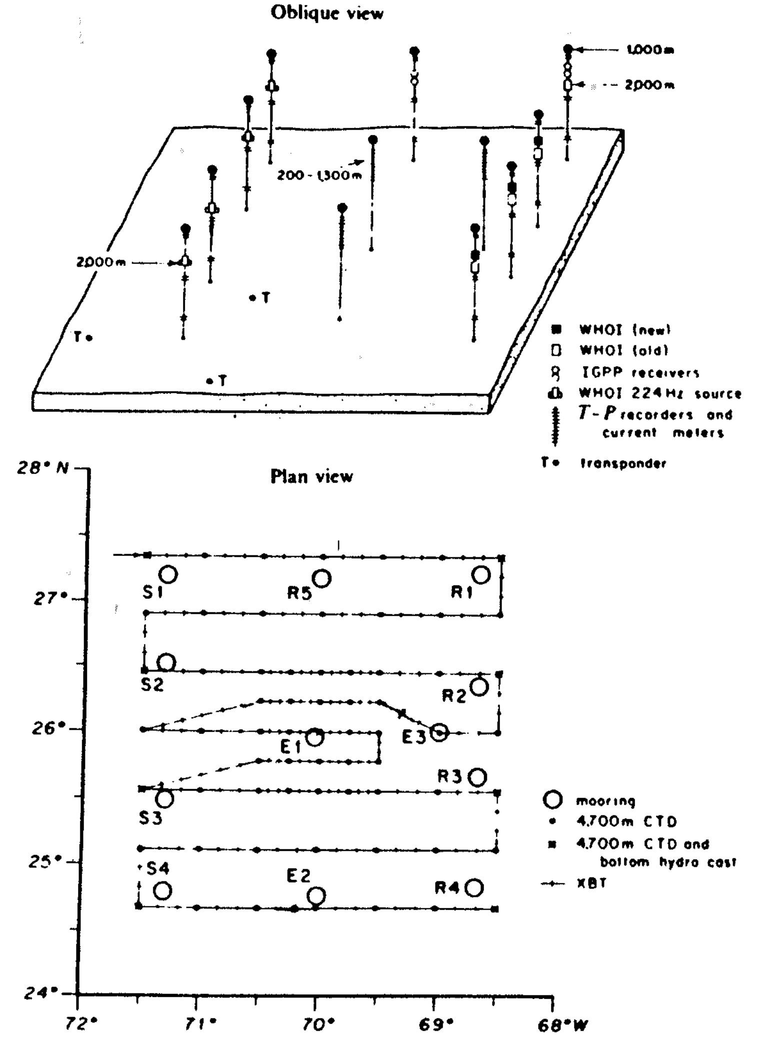
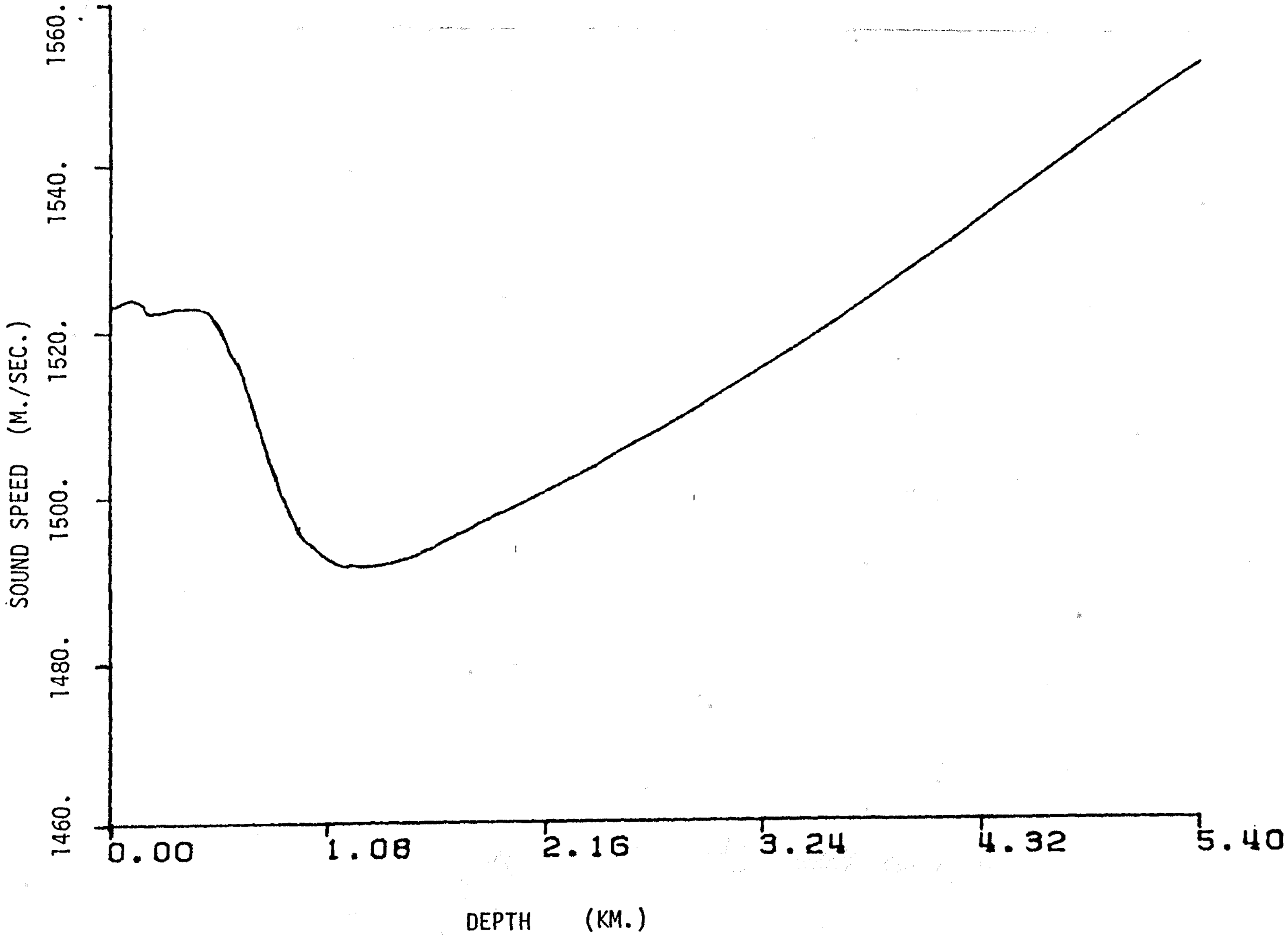


FIGURE 1.4 SKETCH OF THE LAYOUT OF THE 1981 OCEAN ACOUSTIC TOMOGRAPHY EXPERIMENT. (TAKEN FROM NATURE 299 BY THE OCEAN ACOUSTIC TOMOGRAPHY GROUP, 1982).

FIGURE 1.5 TYPICAL SOUND SPEED PROFILE (FROM A NOAA CTD STATION NEAR 26 N 70 W.)



of the rays eliminated by this position shift stay close to the channel axis, and have nearly identical travel times, indistinguishable by the practical system. Each source-receiver pair defines a vertical plane through the box along which the rays which leave that source and reach that receiver propagate. Figure 1.2 shows a typical source-receiver path with a number of rays, while Figure 1.6 shows the time evolution of an arrival pattern for one of the source-receiver pairs during the 1981 experiment.

Changes in the arrival pattern can be caused by several mechanisms besides the variation of the ocean sound speed. For the system to be useful, these other sources of variance must be considered as noise, and must be reduced to levels far below the mesoscale travel time changes. As a basis on which to design the 1981 experiment, MW estimated the sound speed variations for the mesoscale at about 200 msec, requiring a noise level somewhere below 10 msec. After the experiment was in the water, comprehensive calculations of rms expected variations based on the data from the MODE experiment revised the original estimate downward to about 40 msec, making the error requirements far more stringent.

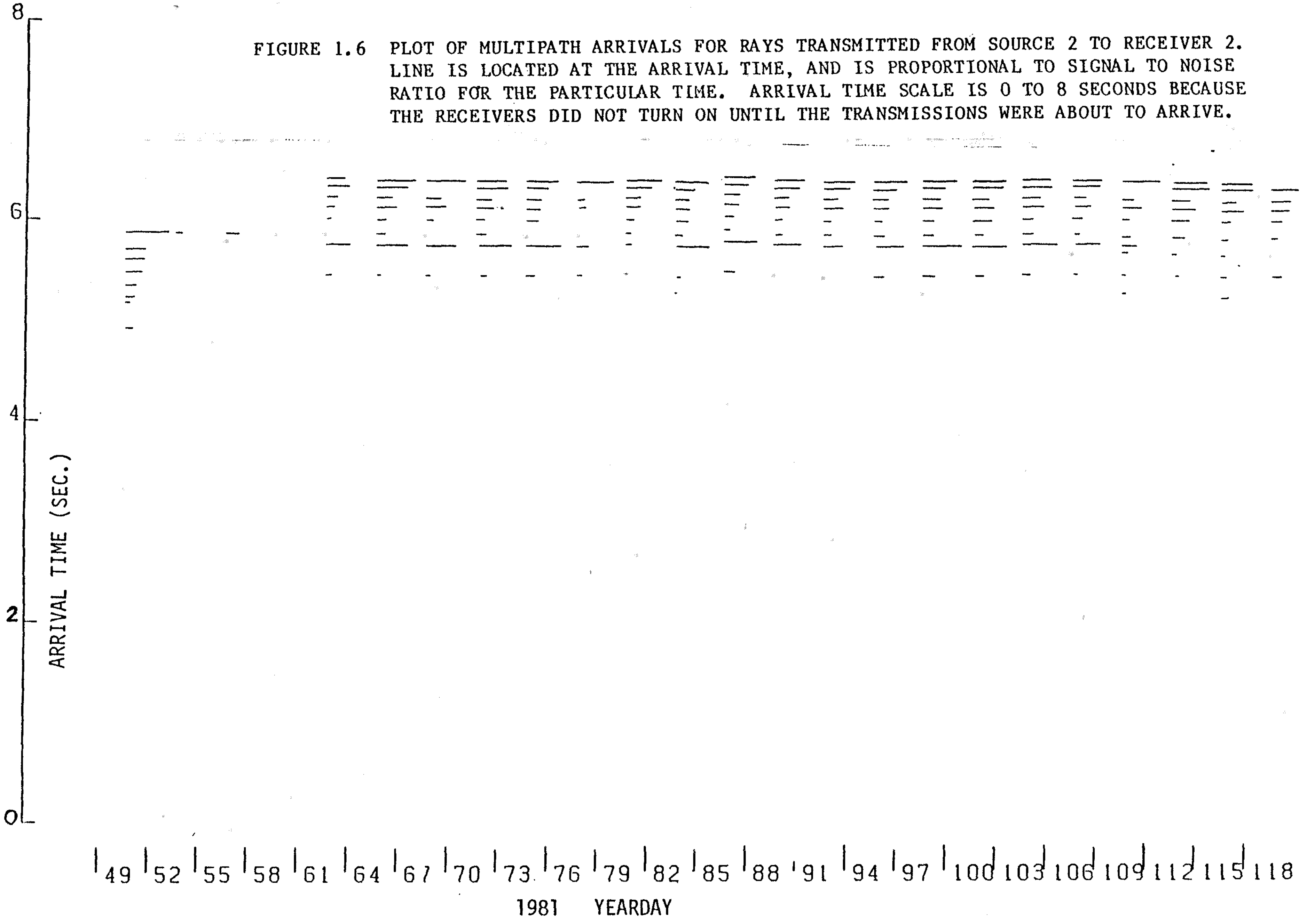


FIGURE 1.6 PLOT OF MULTIPATH ARRIVALS FOR RAYS TRANSMITTED FROM SOURCE 2 TO RECEIVER 2. LINE IS LOCATED AT THE ARRIVAL TIME, AND IS PROPORTIONAL TO SIGNAL TO NOISE RATIO FOR THE PARTICULAR TIME. ARRIVAL TIME SCALE IS 0 TO 8 SECONDS BECAUSE THE RECEIVERS DID NOT TURN ON UNTIL THE TRANSMISSIONS WERE ABOUT TO ARRIVE.

Because tomography is based on transmissions from sources to receivers, the data are very sensitive to errors in mooring position. Given a typical oceanic sound speed of 1500 m/sec, 15 meters of error in the length of a ray adds 10 msec. of travel time error. This is important when compared with 40 msec., the expected level of travel time changes due to the mesoscale field. Knowing the positions of the moorings is thus much more critical than with a conventional array of moorings. In addition, moorings can move around, leaning in response to ocean currents, so that horizontal position changes of 1000 meters are not unexpected for the top of a standard mooring in 5000 meters of water. The tomography moorings were subsurface, meaning that the tops of the moorings were syntactic foam floats or steel spheres at about 750 to 1000 meters depth, (see Figure 1.4), and were moderately taut in order to reduce the amplitude of the mooring motion. In spite of this design, instrument position shifts of 500 meters in the horizontal and 100 meters in the vertical were expected.

Tomography also requires a high degree of clock precision and accuracy over a long (4 months in the 1981 experiment) underwater deployment. The sources and receivers are autonomous, so it is possible for the clocks in each instrument to drift independently, adding errors to the travel time measurements. If these errors are to be kept to 1 msec over the course of the experiment, that means 1 millisecond in 4 months, or one part in 10^{10}. The quartz crystal oscillators available today cannot meet that standard, especially if they are subjected to the rapid temperature changes associated with mooring deployment. Rubidium oscillators can attain this accuracy, but consume far too much power, given the limitations to the battery power available at present.

The problem of mooring motion was solved by using a refined version of the mooring tracking system developed at Woods Hole Oceanographic Institition by Spindel, Porter, and Jaffee (1973). The system uses three transponders installed on the ocean bottom in a triangle surrounding the mooring, which are interrogated by another transponder on the mooring. The travel times for the pulses sent between these instruments can be converted to mooring position, allowing continuous tracking of the transponder on the mooring with an accuracy of about 1.5 meter. A model of the mooring is then used to estimate the motion of the source or receiver given the motion of the level at which the transponder was located. For this system to operate most accurately, the relative positions of the mooring and the three transponders must be surveyed (to within a few meters) relative to the mooring to be tracked. Tomography adds another complication, because the direction of the