OCEAN ACOUSTIC WAVE PROPAGATION IN RANDOM MEDIA (*IN MEMORY OF DR. BARRY J. USCINSKI)*

Terry E. Ewart Applied Physics Laboratory, Univ. of Washington, USA
School of Oceanography, Univ. of Washington, USA

1 INTRODUCTION

Studies of Wave Propagation in Random Media, WPRM, in ocean acoustics have proven useful to test evolving theories, because most theories purporting to explain the statistics of WPRM require that the index of refraction statistics are stable in space and time. Barry Uscinski developed (simultaneously with others) the Moment Equations for a wave traveling in a medium with a random index of refraction. He published several papers on WPRM theory in the 70's. In 1959 I conducted a fluctuation experiment at 60kHz across the mouth of Quilcene Bay, Washington State. The observed Scintillation Index was not small, indicating that neither the Born nor the Rytov extension approximations could be used to predict it; this left us without a theoretical framework. Later in 1971 and 1977 we did experiments to measure the oceanography and acoustic fluctuation statistics at Sonar frequencies (2-13 kHz) over an 18 km path at Cobb Seamount. Barry came to visit me in 1979 with a keen interest in using my experimental data to test his theories. Our intense collaboration from 1981-1983 at Cambridge with Charlie Macaskill produced several papers connecting Moment Theory predictions with my experimental results. In 1996 Macaskill, and I produced incredibly accurate predictions of the observed intensity power spectra using a numerical solution of the 4th ME together with a full (3D + time) ocean model. Barry's theoretical work and his efforts to find supporting data produced the successful juxtaposition of theory and experiment described in this paper. Barry and I often discussed the philosophy of science and enjoyed this quote from Voltaire [1].

> Les anciens qui ont raisonné sur la physique, sans avoir le flambeau de l'expérience, n'ont été que des aveugles qui expliquaient la nature des couleurs á d'autres aveugles. - Voltaire ($\approx$ 1745)

2 THE EARLY OCEAN ACOUSTIC WPRM EXPERIMENTS.

Before Barry Uscinski and I began our long term collaboration in 1979, we at the University of Washington's Applied Physics Laboratory had carried out several ocean acoustic WPRM experiments. In these experiments we really did not have a solid theoretical framework for the design of those experiments. The first experiment I designed was the 1959 Quilcene Bay experiment carried out in a small inlet at the head of Dabob Bay, which lies off the West end of Hood Canal in Washington State. The later experiments known as the "Cobb" experiments were done in the vicinity of Cobb Seamount. Our experimental data demonstrated that the relative intensity was not small, i.e. $\delta A/A$ was not small compared to one. This in itself rules out the use of Born or Rytov extension theories to predict the experiment outcomes. This remained a quandary for us until 1979 when Barry's interest in finding data to support his theories led to our joint research.

2.1 THE 1959 QUILCENE BAY EXPERIMENT.

The transmission experiment across the mouth of Quilcene Bay was carried out over a wholly refracted 1100 m transmission path located below the seasonal thermocline. It consisted of a 60 kHz, three-element ringstack self-erecting transmitter and a horizontal receiving array with transducers at

0, 5, and 15 ft. along a self-leveling bar (Fig. 1). The phase and amplitude measuring apparatus was designed using electronic modules from the Navy's 3D acoustic range at Whitney Point plus other equipment. It could record the phase relative to a 60 kHz crystal oscillator to an electrical degree or about 50 ns, and the amplitude to about 1%.

2.2 OTHER EXPERIMENTS IN THE LITERATURE

Several acoustic transmission experiments had been reported in the 1950s through the 1970s (e.g., Kennedy, 1969 [2]). Kennedy reported 48 hours of observational data; the log amplitude data were filtered to a 10 hr period, which left out the energy in the log intensity spectrum near the inertial period where the spectral energy is the highest. The 1975 AFAR experiment [3–5] resulted in an extensive analysis and comparison with theory for 7.8 days of data taken at three frequencies from 0.4 kHz to nearly 5 kHz. The results included a good summary of the oceanographic data taken with moorings, CTD profiles, and ship-towed sensors. They obtained the parameters of the Garrett and Munk [6] formalism, and their predictions of the intensity correlations and the mutual coherence functions showed reasonable agreement with the observations. Another experiment, the Acoustic Variability Experiment (AVEX) conducted in 1979 was operated over a 400 m path at 20 kHz. Considerable oceanography data were taken simultaneously with the acoustic transmission data over a 24 day period, but the proximity to the shore and the relatively shallow water certainly did not yield index of refraction statistics stable in space and time. Other experiments are found in the literature of that period, but in general such experiments did not have the oceanographic data to support theoretical comparison, or the statistics were not sufficiently stable in space and time to allow such comparison.

3 THE COBB SEAMOUNT EXPERIMENTS

In the late 1960s the U.S. Navy was interested in studies of sonar bearing error (SBE). I saw the chance to get funding to study WPRM in the open ocean, and in 1969 received support from the Navy to conduct an experiment designed to study both SBE and WPRM. The plan was to place a transmitting tower on a subsidiary peak 1000 m deep and 18.1 km from Cobb Seamount located to the Northwest of 48N and 130W off the coast of Washington State. The receiving tower, deployed at 1000 m depth on the flank of Cobb Seamount, had a 15 m self-leveling horizontal arm with transducers spaced at 0, 5, and 15 m giving 5, 10, and 15 m separations to study SBE and WPRM at 4 and 8 kHz. The towers were 15 m tall so that the bottom returns from the seafloor near the towers would not contaminate the direct path arrivals (Fig. 3) and (Fig. 4). A pulse was sent each 15.73 s. Extensive use of CTD's and our SPURV vehicles (Fig. 2) to measure the transmission path environment were deployed.

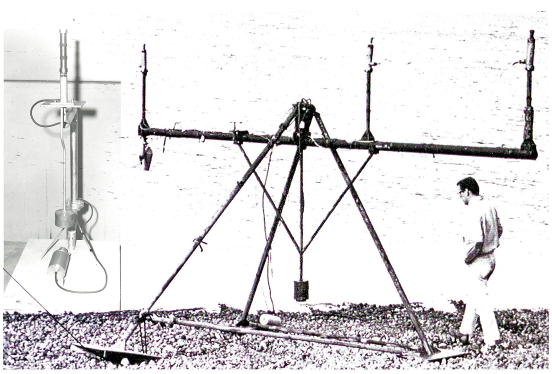

Figure 1: 1959 Quilcene Bay receive and transmit arrays.

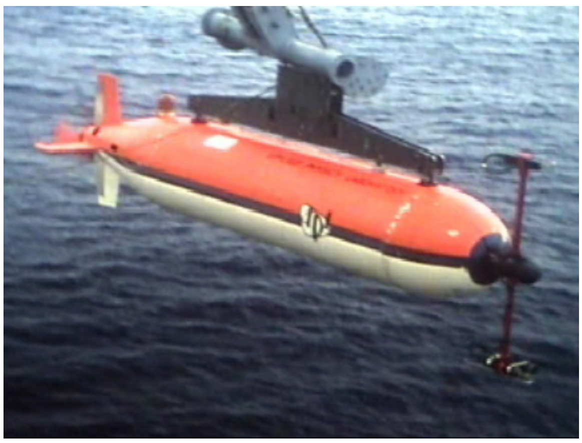

Figure 2: Self Propelled Underwater Research Vehicle - SPURV.

Figure 3: 1970-71 Cobb Seamount experiment self-leveling receiving array.

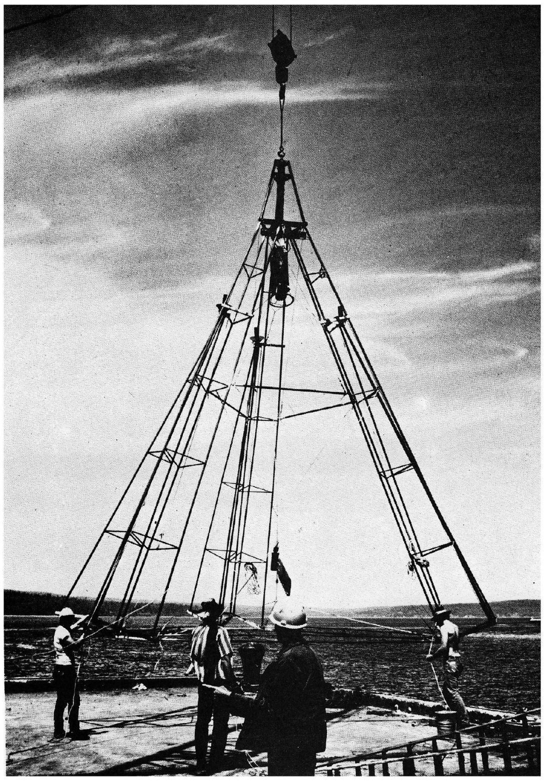

Figure 4: 1970-71 Cobb Seamount experiment transmitter array shown with legs folded. The 8-element self-erecting transmitting transducers are at the top of the tower. Prev. pub. in Ewart 1976. [7]

3.1 THE FIRST ATTEMPT

The 1970 experiment was a success in that both towers were deployed upright on the bottom, but only a very short data set was collected. Very bad weather during the recovery phase caused us to lose both towers and the data, but the team remained confident that the experiment could be done if tried again. (While at sea we decided to use telemetry to transmit the data to the ship in the next attempt. Then, we could collect the data without recovering the equipment.) With our IBM 1130 computer [8] on board, we could analyze the data as it came in (See Fig. 5). This machine was the third seagoing computer in the United States after the PDP-5 on the Coast Guard Ship *Evergreen*, and WHOI's IBM 1620 operated by Carl Bowen. The computer interface could write and read voltages, frequencies, and digital words. It also had a 3-D acoustic tracking system with ray bending, pitch, roll, heading, and time delay corrections that allowed us to position devices in the ocean within a few meters precision with respect to an acoustic bottom navigation beacon and North. The tracking data made the upright deployment of the towers on the ocean floor possible, though it took 25 tries with the transmitter tower before the leg contact sensors and the tip angles, telemetered by the tracking system, signaled that we could release it. The low spring constant in the 1000 m of 1/2 in nylon line from the U-frame on the stern to the tower gave us the time we needed to make the decision to release.

3.2 THE 1971 EXPERIMENT

The experiment known in the literature as the Cobb experiment was a redeployment in 1971 of the troublesome 1970 experiment with a few engineering modifications and better launch and recovery techniques. A 50 kHz phase shift modulated data encoding system was implemented between a transmitting transducer mounted above the receiver tower, and a receiving transducer hanging below a moored surface buoy with a radio frequency link to the ship. Also, a system was implemented to code the data, write it to magnetic tape, and also to decode the data and send it to our computer. As in the 1970 experiment, the data acquisition electronics automatically sequenced the 4 and 8 kHz data filters using frequency detection of the 4 kHz signal. *This feature turned out to be a mistake. A pod of whales, attracted to the experiment, frolicked above the receiving array, and their vocalizing triggered the system out of sync - 5 hrs of data were lost.*

Six days of data were collected in 1971 and oceanographic experiments, which included several operations with SPURV and a series of CTD casts, were completed successfully. A thorough review of both the oceanographic measurements and the acoustic phase and amplitude measurements, along with comparisons with a theoretical result from some work by Munk and Rosenbluth, [9] and some early work by Desaubies [10] are found in Ewart (1976). [7] Four major results were reported:

- The SBE for the 5, 10, and 15 m separations were very small; the horizontal resolutions corresponding to the travel time difference standard deviations of 3.3 μsec and 2.2 μsec for the 4 and 8 kHz data, respectively, were 6 m and 4.7 m at the 18.1 km range.
- The amplitude fluctuations were not small, i.e., $\delta A/A$ was larger than or near 1, so neither the Born nor the Rytov approximations applied.
- The theory of Munk and Rosenbluth, [9] based on the ocean internal wave model of Garrett and Munk, [6] compared well to the slope of the phase fluctuation spectrum and the phase difference spectrum for the 5, 10 and 15 m separations, but the energy levels differed considerably. Predictions of the travel time and log amplitude spectra, as well as comparisons of the oceanographic data and the predictions of the Garrett–Munk [6] internal wave model also differed considerably.
- This result was clarified further in theoretical work by Desaubies [10] and Munk and Zachariesen, [11] where the phase spectra were predicted using a Garrett–Munk spectrum of ocean internal waves to represent the medium and the Rytov approximation for the log amplitude and phase fluctuations. In these papers the phase spectra predictions matched the measured values fairly well, but the log amplitude fluctuation spectra predictions still differed dramatically as a function of temporal frequency.

It is important to note that in spite of this experiment/theory confrontation, the use of Rytov to predict intensity fluctuations continued in the 1980s and 1990s, even where it was clear that the relative amplitude fluctuations were not small. There was also considerable material in the literature on the Path Integral approach to WPRM theory. One of Uscinski's PhD students did a thesis showing that the Path Integral and the Moment theory approaches give the same answers when the same set of approximations are made. See Uscinski, Macaskill, and Spivack 1986 [12].

3.3 SIGNAL PROCESSING ISSUES

Our studies of oceanography and acoustic propagation theory and experiment, also required us to examine signal processing issues. In the mid 70's John Ehrenberg and I studied these issues in the context of processing the Cobb data, and developed the Multiple Dimensional Matched Filter or MDMF. Together with one of our graduate students, Randal Morris, we developed and tested the MDMF code, published in 1978. [13] Later in 1984 Brad Bell and I [14] used Brad's newly developed optimization code <minbmb> to implement a much faster version of the MDMF. The appropriate matched filter is applied to each of the multi-paths simultaneously. This eliminates the interference between the arrivals when their matched filter outputs overlap in travel time. This is particularly important when accurate estimates of the travel time and amplitude are required. For our purposes here, all of the data pulse recordings in both of the Cobb Seamount experiments, and a later experiment in the Arctic were analyzed with ever faster MDMF codes, but the principle concept is the same - to obtain the travel time and amplitude independently for each received path. The concept is especially applicable to narrow bandwidth signals where the matched filter output is extended in time.

3.4 CONNECTING EXPERIMENT AND THEORY

Ever more accurate predictions of the Cobb intensity spectra were obtained, as the acoustic fluctuation theory and the oceanographic models for the internal wave field, the finestructure, and the tides were improved. Even the very early moment equation predictions, i.e., Uscinski *et al.*, [15] and Ewart *et al.* [16], were a distinct improvement over those based on the Rytov approximation. Barry Uscinski's energy and fellowship made that 1.5 year period at Cambridge working with Barry and Charlie one of the highlights of my professional life. In these papers the theoretical predictions utilized a zeroth order solution with a first order correction of the fourth moment equation, and an inclusion of finestructure with the Garrett–Munk internal wave model. The form of the spectral predictions and their integrals (the scintillation indices) were much closer to the measured values. Although confident that we were on the right track, we needed an improved model for the index of refraction statistics, and a more accurate evaluation of the theory. Both of those improvements were made in the context of the 1977 experiment.

4 MATE

4.1 THE MATE ACOUSTIC HARDWARE AND DEPLOYMENT

The results from the 1971 Cobb Seamount experiment led to the design of MATE (Mid-Ocean Acoustic Transmission Experiment) carried out in 1977 to study WPRM and SBE for a much larger horizontal aperture of 235 m. The MATE acoustic apparatus consisted of a 15 m tall transmitting tower deployed on the same undersea peak as in the 1971 experiment, and two 15 m tall receiver towers deployed at the same depth on the flank of Cobb Seamount. The transmitting tower was very similar to the one seen in Fig. 4. The two receiving towers deployed in the new experiment differed from the one used in the earlier experiment, as two receiving transducers, separated by 3 m, were gimbaled at the apex of the tower to self-erect (Fig. 7). The repetition rate was the same as the earlier experiment, but the pulse types and frequencies were expanded to send a broad band (Q $\approx$ 1.5) Taylor weighted FM slide signal followed by a narrow band (Q $\approx$ 6) signal at nominal frequencies 2, 4, 8, and 13 kHz, making a total of 8 pulse types (each repeated every 125.83 s). The 13 kHz signal was originally intended to be 16 kHz, but the transmission loss was too high over the 18.1 km path. Using the broad band signals eliminated possible 2π ambiguities in the multipath analysis, and the narrow band signal was processed to obtain the travel time and amplitude values. This allowed us to better understand the acoustic frequency dependence of the scattering. The incident with the whales in the 1971 experiment led us to remove the automatic feature for the acoustic frequency data acquisition filters from the earlier design, and replace it with an acoustically controlled command link incorporated into our seagoing acoustic tracking system. MATE was originally planned for 1976, but because our Chief Mechanical Engineer was injured, we used the ship time to return to Quilcene Bay. This allowed testing of the equipment launch operation and an opportunity to gather data using the entire system. The results are reported in Ewart *et al.* [17]. The data processing tested the MDMF software; it was clear that the data could not have been analyzed with traditional methods. That paper presents and discusses the MDMF data analysis techniques, the likelihood surfaces and the errors in the technique. The experiment was a good test of all of the hardware and the pulse analysis techniques.

As in the 1971 experiment, everything was deployed from the fantail of a Navy AGOR research vessel. Our van-mounted computer system (at that point in time a Digital Equipment Corp. PDP 11/10) provided a tracking plotter to the ship's bridge to guide the Captain or First Mate in controlling the ships operation, as we did in the earlier experiment. The ship's position was maintained over the desired launch site using the wind, the ship's bow thruster, and the ship's main screw in a balance of forces for long enough to deploy the towers. The towers were released on the bottom, and the precision of the launch to within a few meters of the desired locations could certainly be credited to the ship's crew learning to control a ship while looking at a 10 inch Tektronix plot of their location relative to a bottom beacon. Because the acoustic data taken by the receiving tower electronics were telemetered to the ship, SPURV runs and CTD casts could be made anywhere in the region of the transmission path.

Figure 5: Computer in the Van. prev. pub. in Ewart and Floyd 1969 [8]

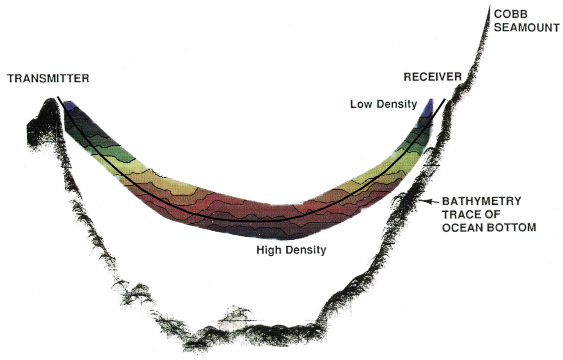

Figure 6: Bathymetry trace, down ray, and SPURV potential density contours.

4.2 OCEANOGRAPHIC AND ACOUSTIC THEORETICAL CONSIDERATIONS

The experiment oriented theory behind the design of the oceanographic component borrowed heavily from open ocean internal wave research being conducted in the 1970s. Internal waves can be described spectrally by two horizontal wavenumbers, a vertical wavenumber and a time frequency variable connected with a dispersion relation. Many researchers included the presence of finestructure to describe ocean fluctuations. In keeping with today's ocean literature one would use the term ”spice” to represent what we called finestucture. This name change is probably good, as many authors have used finestructure to include internal waves together with the ”other stuff.” Our measurements showed that the acoustic index of refraction spectrum in the MATE environment was statistically isotropic in the horizontal, as reported by others, e.g. the 1984 Aha Huliko'a report. [18] The finestructure (or spice) spectral bands have very low horizontal wavenumbers, high vertical wavenumbers, and low time frequency dependence, but are not connected with a dispersion relation, as in the case of internal waves. This is the quite complicated, but necessary, representation of the index of refraction spectrum we sought. One important consideration is that the “moored spectrum,” (the projection of the index of refraction spectrum on the time frequency axis) had a measured slope of –1.7, not –2.0, as predicted by the Garrett and Munk [6] model. Differences in the other projections of the 4D spectrum and the complexity of the MATE ocean model can be seen in the analytical form of the internal wave, finestructure and tides oceanographic model found in Section III of Macaskill and Ewart. [19] The model we seek for acoustics is the Fourier transform of the ocean spectral model (with two spatial separations and a time difference), as the correlation function integrated along the ray is required as input to the fourth moment theoretical treatment. This is the “projected” or “transverse” correlation function, and it is based on the MATE oceanographic experiment model of the internal wave field and the finestructure discussed in Levine *et al.* [20] and Levine and Irish. [21] For the MATE lower path the integral of the correlation function along the ray and the integral in the horizontal differ very little.

Given the complex field, E, of a propagating acoustic wave at a point in space-time, we can form the fourth moment as the expected value $m_4 =< E_1 E_2^* E_3 E_4^* >$, where the subscripts refer to a point in space-time. If we collapse the complex field to the intensities by letting $E_1 E_2^*$ and $E_3 E_4^*$ be replaced by I_1 and I_2, at the same (or different) frequencies, we have the expected value of the intensity correlations where now $m_4 =< I_1\ I_2 >$. It is the theoretical and experimental values of m_4 that we wish to compare.

The following excerpts from Macaskill and Ewart 1996 [19] is included here to show how the ocean model enters the intensity spectra predictions. Consider the general case of acoustic waves with wavenumbers k_1, k_2 propagating simultaneously in a random medium, defined by a scattering function h, with tranverse correlation scale L_v. We define cartesian coordinates (x, z), $(y-$dependence is suppressed), where the horizontal (range) direction is aligned with x and where the vertical direction (depth at MATE) is aligned with z. We write the (parabolic) fourth moment equation for a point source initial condition in the form (See Uscinski and Macaskill, 1985 [22], Uscinski, 1989 [23], Ewart et al

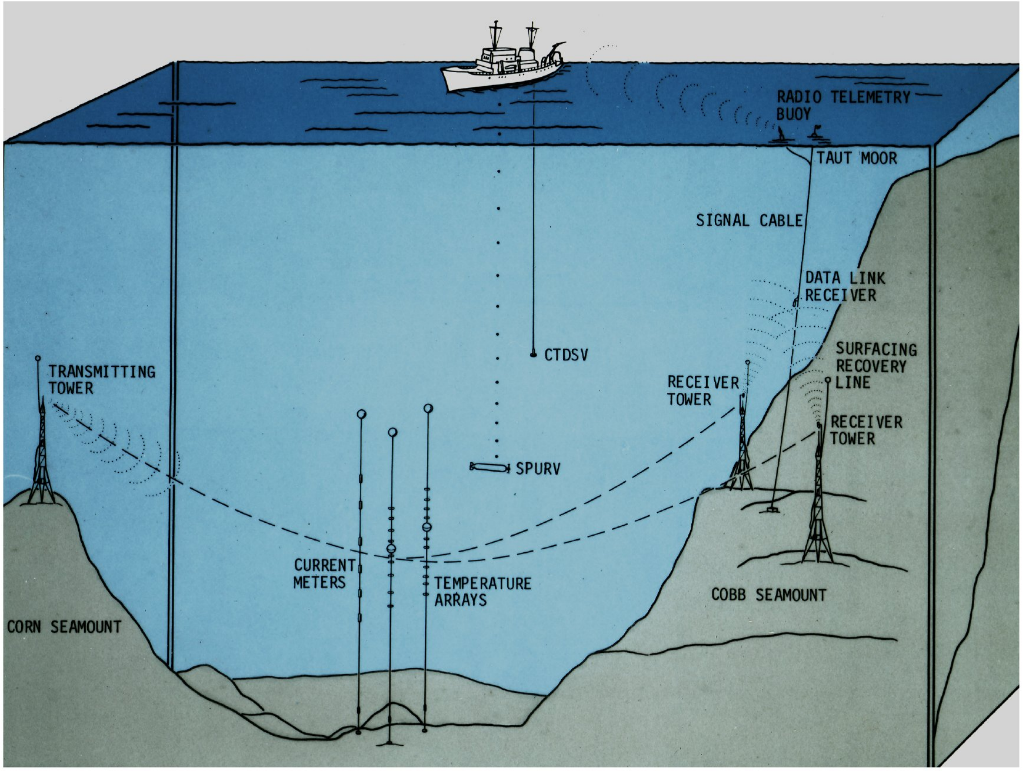

Figure 7: Cartoon showing the layout of the MATE apparatus.

1985 [24])

$$\frac{\partial m_4}{\partial X} = -\frac{i}{X^2}\frac{\partial^2 m_4}{\partial\bar{\zeta}\partial\bar{\eta}} - \frac{i}{X^2}\frac{\partial^2 m_4}{\partial Z\partial U} - \Gamma h(X\bar{\zeta}, X\bar{\eta}, XU, \tau; r)m_4, \tag{1}$$

where the time interval between observations is $\tau = t_1 - t_2$, the acoustic wavenumber ratio $r = k_1/k_2$, the scaled range $X = x/k_1 L_v^2$, and $m_4(x = 0) \equiv 1$. Here the strength parameter $\Gamma = k_1^3 L_v^2 \mu^2 L_p$, where, $\Gamma X = \Phi^2$, the R.M.S. phase fluctuation,

$$L_p = \int_{-\infty}^{\infty} < n(x, 0, 0)n(x', 0, 0) > d(x - x'), \tag{2}$$

and $1 + \mu n(x, z, t)$ is the refractive index, μ is the rms refractive index variation and the angle brackets mean ensemble average. The horizontal integral scale, L_p, measures the range-averaged fluctuations introduced by the projection onto the vertical in equation (2) and L_v is the vertical correlation scale. The scattering function h is where the medium statistics enter into Eq. 1.

The transverse coordinates $\bar{\zeta}, \bar{\eta}, U, Z$ (Uscinski and Macaskill, 1985) are defined implicitly by:

$$\begin{aligned} k_1 L_v z_1/x &= Z + \tfrac{\bar{\zeta}}{2} + \tfrac{\bar{\eta}}{2} + \tfrac{U}{4} \\ k_1 L_v z_2/x &= Z - \tfrac{\bar{\zeta}}{2} + r\tfrac{\bar{\eta}}{2} - r\tfrac{U}{4} \\ k_1 L_v z_3/x &= Z - \tfrac{\bar{\zeta}}{2} - r\tfrac{\bar{\eta}}{2} + r\tfrac{U}{4} \\ k_1 L_v z_4/x &= Z + \tfrac{\bar{\zeta}}{2} - \tfrac{\bar{\eta}}{2} - \tfrac{U}{4} \end{aligned} \tag{3}$$

while the scaled range is given as $X = x/(k_1 L_v^2)$. The fourth moment is defined as

$$m_4(\bar{\zeta}, \bar{\eta}, U, Z, X, \tau; r) =< \psi(x, z_1, t_1; k_1)\psi^*(x, z_2, t_2; k_2)\psi(x, z_3, t_2; k_2)\psi^*(x, z_4, t_1; k_1) > \tag{4}$$

with $\psi(x,z,t;k)$ the complex envelope of the pressure field P, defined by

$$P(x,z,t;k) = \psi(x,z,t;k)\frac{1}{\sqrt{x}}e^{ikx}. \tag{5}$$

We assume the medium to be (locally) statistically homogeneous in the vertical, so that there is no dependence of the fourth moment on the mean transverse location Z and hence the second term on the right hand side of (1) can be dropped and U appears only parametrically in the equation via the scattering term. (This has been shown from data to be well-founded for the MATE lower path.)

m_4 depends on the four locations (x_1, z_1), (x_2, z_2), (x_3, z_3) and (x_4, z_4) but for comparison with intensity data we take $z_1 \to z_4$ and $z_2 \to z_3$ so that $U = 0$, and $\bar{\zeta} = (z_1 - z_2)/(XL_v)$ gives the normalized vertical separation, and

$$m_4(\bar{\zeta}, \bar{\eta}, X, \tau; r) =< I(x, z_1, t_1; k_1)I(x, z_2, t_2; k_2) >=< I_1 I_2 > \tag{6}$$

i.e. the fourth moment reduces to the cross correlation of the intensity $I(x,z,t;k)$ at two depths, times and acoustic frequencies. (We have dropped the dependence of m_4 on U as U no longer appears in our equations.) The cross scintillation index is $S_{12} =< I_1 I_2 > -1$, where we have normalized the intensity by its mean. and $S_{11} =< I^2 > -1$ is then the scintillation index. (S.I.). (For brevity we are only going to consider here the case where $k_2 \equiv k_1$, and hence not discuss the predictions of the cross scintillation index.) With these considerations the scattering function h is:

$$h(\bar{\zeta}, \bar{\eta}, \tau) = 2 + 2\Big\{f[\bar{\zeta} + \bar{\eta}, \tau] - f[\bar{\zeta}, \tau] - f[\bar{\eta}, 0]\Big\}. \tag{7}$$

In (7) the normalized transverse correlation is given by $f(\bar{\zeta}, \tau)$, where if $g(\Delta x, \Delta z, \tau)$ is the correlation of sound-speed variations, then

$$f(\Delta z, \tau) = \int_{-\infty}^{\infty} g(\Delta x, \Delta z, \tau)\, d\Delta x \Big/ \int_{-\infty}^{\infty} g(\Delta x, 0, 0)\, d\Delta x. \tag{8}$$

or in the normalized coordinates $\bar{\zeta}$ and $\xi = \Delta x/L_h$, with L_h the horizontal correlation length, we have

$$f(\bar{\zeta}, \tau) = \int_{-\infty}^{\infty} g(\xi, \bar{\zeta}, \tau)\, d\xi \Big/ \int_{-\infty}^{\infty} g(\xi, 0, 0)\, d\xi \tag{9}$$

In what follows we will present the data and spectral projections from the 3D + time model of the oceanographic data. From there it is a simple task to obtain $g(\Delta x, \Delta z, \tau)$, and then $g(\xi, \bar{\zeta}, \tau)$ in (9) to get the scattering function, h, and predict m_4.

4.3 THE TIDES, INTERNAL WAVES, AND FINESTRUCTURE EXPERIMENT

In the middle of the MATE transmission path two temperature moorings each with one current meter and one current meter mooring with some temperature sensors were deployed for 24, 18, and 14 days, respectively, with the current, temperature, and conductivity sensors deployed over the vertical height spanned by the "down" ray of the acoustic experiment. The launch used the same acoustic tracking system as for the acoustic towers. The SPURV vehicles made many runs in differing operational modes including depth cycling above and below the "down" acoustic ray, depth cycling over the span of the moorings, and several isobaric runs over ranges much longer than the acoustic path (some with two legs at right angles to one another to study both the homogeneity and the isotropy of the spectrum of the index of refraction fluctuations).

A total of 119 profiles were obtained with our shipboard CTD including a yo-yo run over the depth span of the moorings. The focus of the oceanographic experiment design spanned the range of temporal and spatial scales that affected the acoustic transmissions, and provided sufficient data to produce the time and space model we required. These scales were 0.1 m to 100's of meters in the vertical and 0.1 m to 1000's of meters in the horizontal over time scales from 0.1 s to many days. The analysis of data taken with the CTD, the moorings, and SPURV provided the spectra and coherence projections that comprised the basis of the MATE 4D ocean model. All of the sensors worked flawlessly except that we were unable to run two SPURV's simultaneously to measure the towed vertical and horizontal coherences.

The MATE oceanography and all of the apparatus are discussed fully in the papers by Ewart and Reynolds [25] and by Levine *et al.* [20] The "Moored" displacements (computed from the potential temperature records) and velocity spectra are shown in Fig. 8. The spectral falloff of –1.5 for the displacement spectrum and –1.8 for the current spectrum was later refined to be –1.7 for both spectra. The "Dropped" spectra from vertical segments of a yo-yo series of CTD drops, and the "Towed" spectra for East and North going segments of a SPURV isobaric run are found in Fig 9. The lines for the "rt" parameter show the energy levels from the Desaubies internal wave model. [26] The "Moored" spectra of the displacements and currents (see Levine *et al.* 1986 [20]) are dominated by the spectral tide lines and a spectral slope of –1.7 versus the –2.0 value, as discussed previously. The towed spectrum is characterized by a slope change at a wavenumber of about 0.03 cpm, [20] as has been seen in SPURV runs in many ocean regimes. [27] Careful modeling of the oceanography statistics provided the required 4D ocean model.

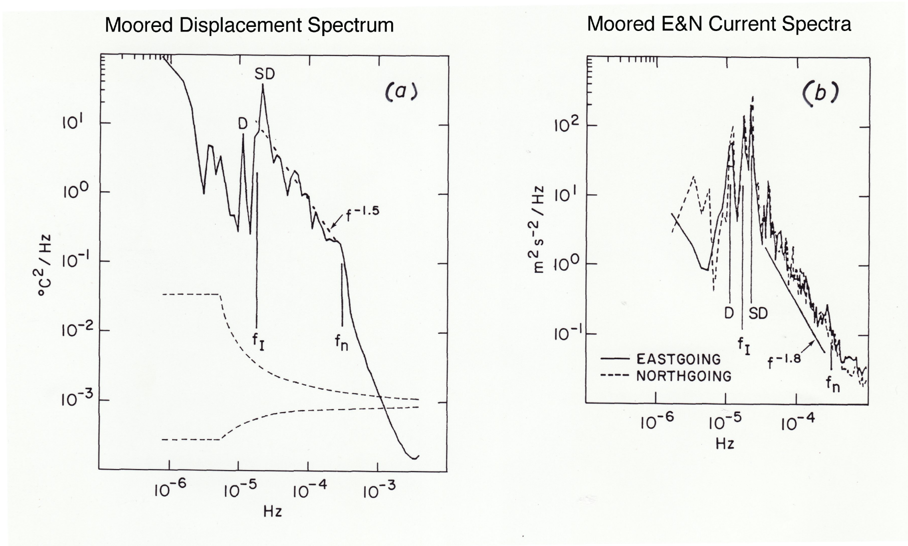

Figure 8: MATE Moored displacement & current spectra. Prev. pub. in Ewart and Reynolds 1984. [25]

4.4 THE ACOUSTIC TRANSMISSION EXPERIMENT

A plot of the bottom topography, recorded by the ship's fathometer, the acoustic ray, and the potential density contours measured using SPURV to depth cycle above and below the computed ray are found in Fig. 6. Here the scale of the potential density contours relative to the 18.1 km transmission path provides a visual guide to the size of the internal wave oscillations in the horizontal and vertical given the 17 to 1 horizontal to vertical scale. This is a snapshot of the potential density (roughly the same as the sound velocity perturbations) that the sound field passes through from source to receiver; the SPURV vehicle took a little over two hours to make the transect from source to receiver.

The acoustic transmission data were taken on the lower path 14.2 days to tower 1, 7.4 days to tower 2, and on the upper path 2 days to both towers. An inertial period of intensity data, plotted for both the upper and lower paths with the travel time data plotted below, is found in Fig. 10. The statistics of the intensity data varies greatly from one frequency to another and from upper path to lower path. The upper path travel time fluctuations included more high-frequency content. The travel time was virtually identical for all four frequencies on each path. A plot of the MATE oceanographic model (black lines), the MATE travel time spectrum (blue line) and the MATE "moored" spectrum (green line) each normalized to integral one (Fig. 11) shows agreement of the MATE models with the data sets. The

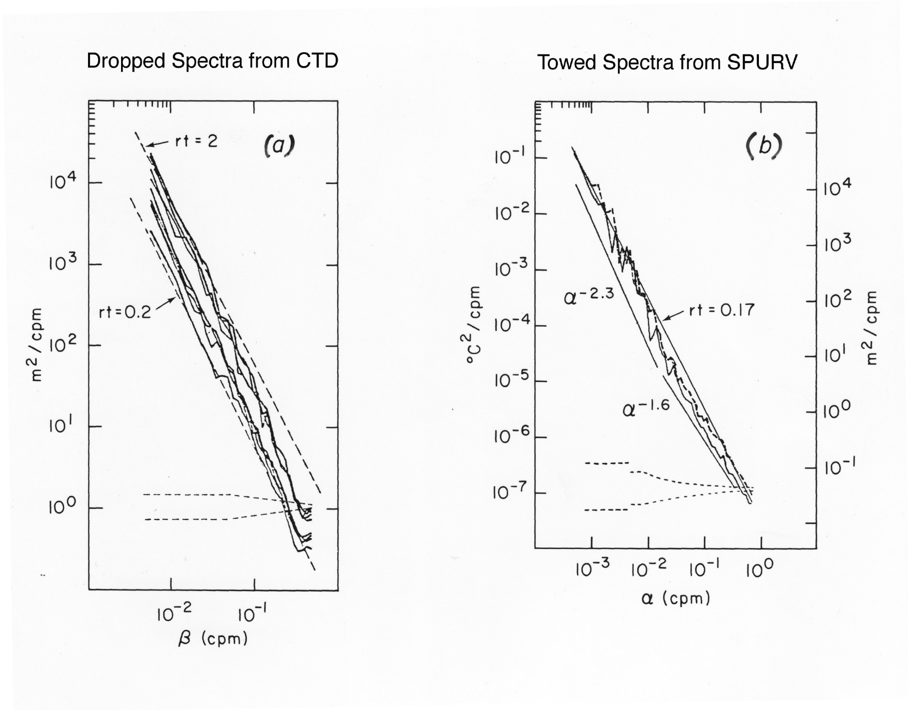

Figure 9: The MATE "Dropped" and "Towed" spectra. Prev. pub. in Ewart and Reynolds 1984. [25]

tide line spectral content is plotted separately for the diurnal, the semi-diurnal, and the first overtone of the semidiurnal tides. The spectral energy of the tide lines was removed from the "moored" data and the travel time data using an optimizer. The three frequency bands have distinctly differing behavior: finestructure, "spice," in region I below the inertial frequency, internal waves in region II, and high frequency fluctuations in region III above the Vaisala frequency. The "moored" spectrum (temporal spectrum of displacement at a point in space) has a falloff slope of –1.7, and the travel time spectrum has a falloff slope of –2.7. This increase in slope arises from the internal wave dispersion relation (The 3D + time spectral model of internal waves is constrained by this relation.), and further exemplifies the accuracy of the ocean model.

The predictions of the spectra of the intensity records at the four MATE frequencies (2083, 4167, 8333, and 12500 Hz) with a repetition period of 125.8 s were first presented in Ewart and Reynolds (1984) [25] based on the moment theory results from Uscinski *et al.* (1983) [15] The Uscinski *et al.* spectra were computed (Fig. 12) using four different models of the internal wave field. In this Figure P refers to the slope of the transverse spectrum in frequency for the Levine and Irish, Desaubies, and the Garrett and Munk internal wave models. The spectra for each acoustic frequency has been offset by a decade, and the spectrum was computed from $I/ < I >$ for each frequency. Two different windows were used to estimate the spectra above and below the inertial frequency. The theory does well with the spectral behavior, but less well with the (S.I.). In later work $P = -2.7$, as seen in Fig. 11 in the travel time spectral falloff. (*Murray Levine's Phd thesis covered the internal wave and finestructure aspects of the oceanography, Steve Reynolds PhD thesis covered the acoustic aspects of the experiment, and Randall Morris' PhD thesis covered the signal processing design using the MDMF filter to separate the multi-path arrivals.*)

An important aspect of the Cobb 71 experiment was the estimate of the SBE using super-resolution techniques. For the 235 m separation of the two receiving towers at MATE, the travel time differences between one top transducer and one bottom transducer (that were at very nearly the same depth) were used to estimate the bearing error. The standard deviation of the time difference for those two transducers was ±68 μsec, which puts the horizontal resolution at ±8 m for 18.1 km range. This differs little from the ±6 m resolution for the 15 m separation in the 71 Cobb experiment. This limits the horizontal aperture that can be processed coherently to separations of something around 15 m,

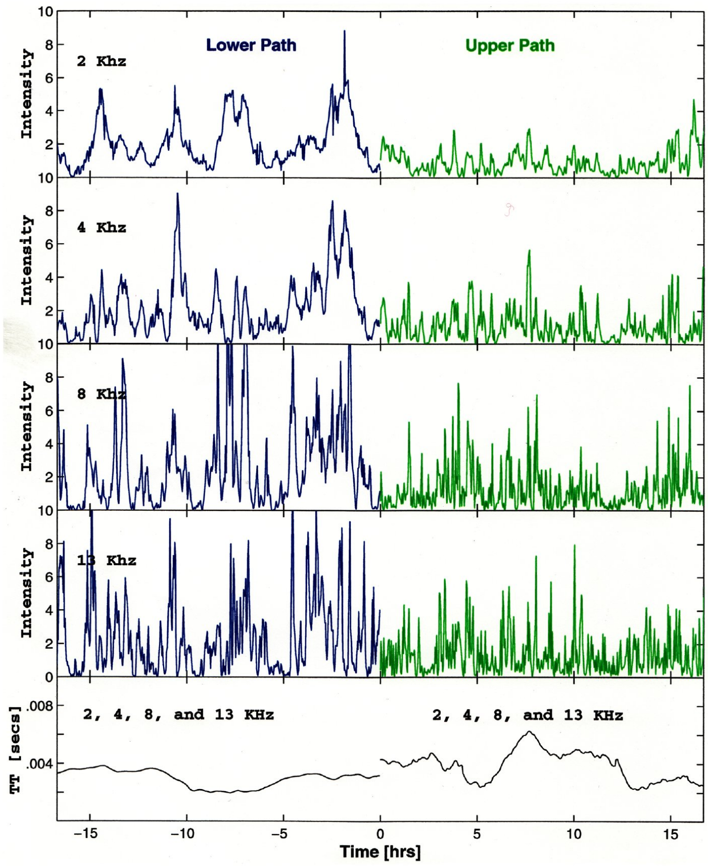

Figure 10: The MATE intensities and travel times for an inertial period of each path.

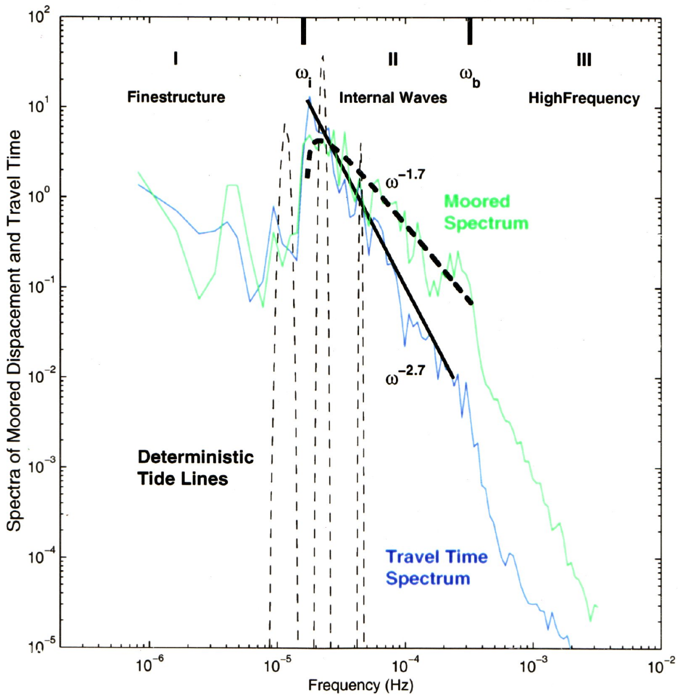

Figure 11: The MATE travel time and displacement spectra and the MATE ocean model.

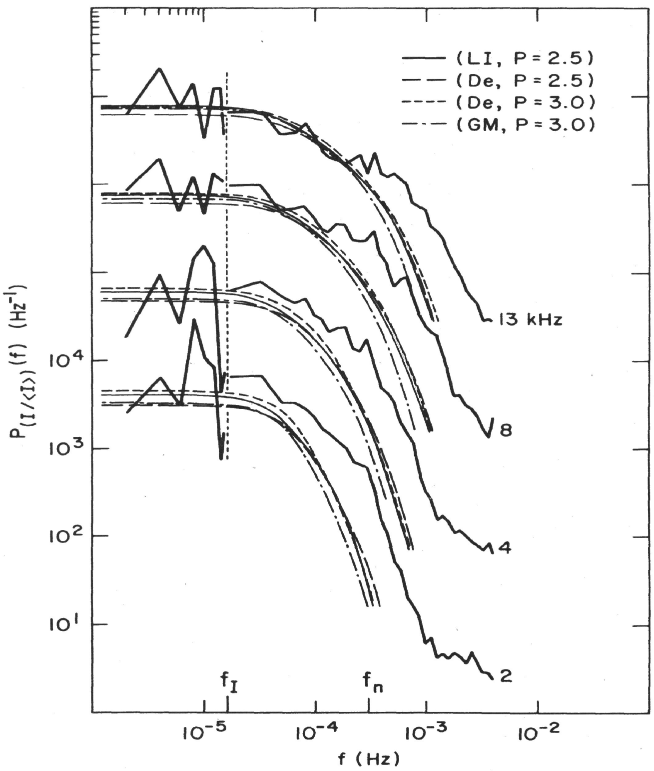

Figure 12: The MATE intensity spectra versus Uscinski *et al* theory using 4 IW spectral models. Prev. pub. in Ewart and Reynolds 1984. [25]

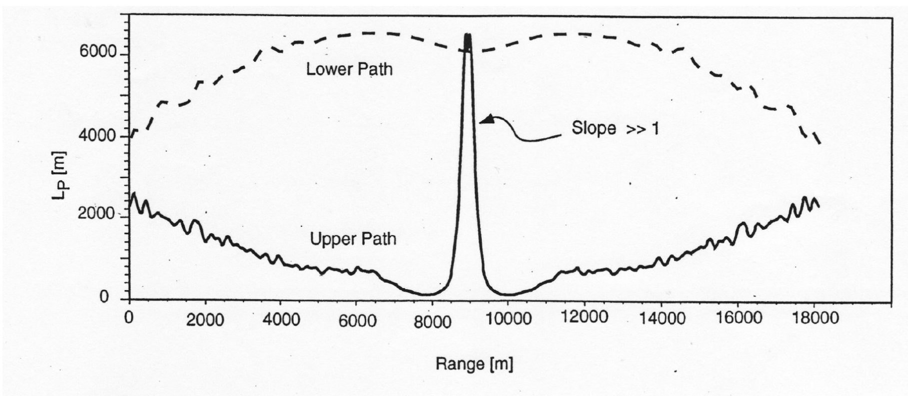

Figure 13: L_p along the “up” and “down” rays.

due to the fluctuations in travel time difference that result from the larger oceanographic scales.

Using Eq. (1), Macaskill and Ewart [19] computed a numerical solution of the 4th moment equation using the MATE oceanographic model of internal waves and finestructure, as it had evolved by the 1990's, to predict the observed MATE intensity spectra found in Fig. 14 with the predictions plotted in blue. The rise in spectral energy at the inertial frequency observed in this plot had never been predicted (or observed) before The agreement at 2, 4, and 8 kHz of the predicted and the observed spectral levels as a function of time frequency is very good. Above the Vaisala frequency the theory matches the observations to a much better accuracy than in Ewart and Reynolds [25]. The same spectra are plotted in a variance preserving plot (equal areas under the curve represent equal variance) in Figure 15. Here the 13 kHz prediction is quite high compared to the data spectrum. This failure to fit the variance is caused by the fact that the amplitude scaled time shifted replica fit to the data under-predicts the signal energy at 13 kHz, whereas the model and the data fit very closely at the other three frequencies. Figure 15 represents a critical test of the theory and experiment, as it emphasizes frequency regions where the prediction is low or high with regard to the data spectra. Macaskill and Ewart also present the intensity cross covariance predictions for pairs of frequencies; they do not agree as well with the data as the autocovariances or autospectra do, but are a significant improvement over the earlier predictions of Ewart and Reynolds [25] and Ewart *et al.* [24] Our long quest from 1959 to understand the intensity fluctuations thus came to a satisfying result.

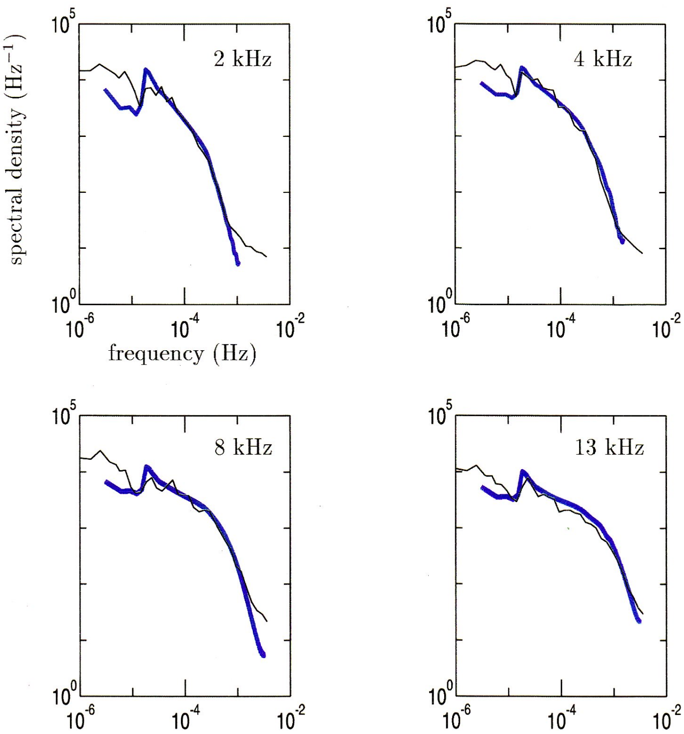

Figure 14: Measured intensity spectra (black) with predictions (blue). Prev. pub. in Macaskill and Ewart 1996. [19]

4.5 THE MATE UPPER PATH

Figure 10 shows an inertial period of the upper path data for all four frequencies. Attempts to predict the intensity and phase spectra for that data were not fruitful. Three problems are clear:

- The concept of a vertical correlation length, L_v, or an integral horizontal correlation scale, L_p,

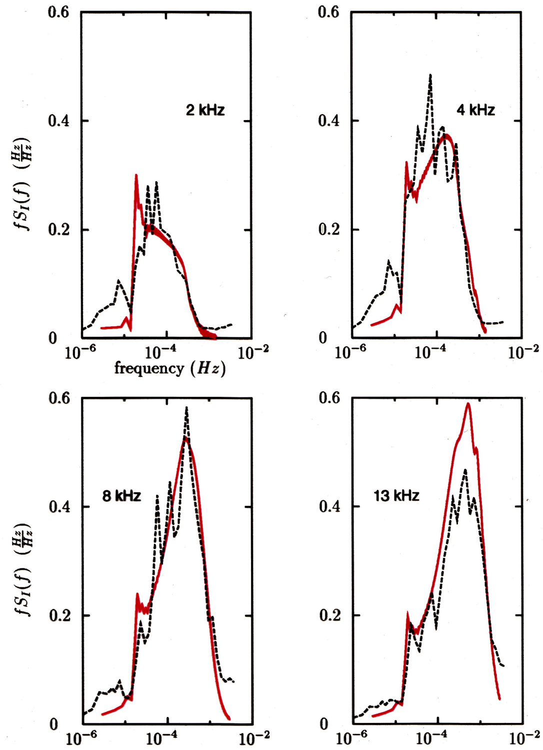

Figure 15: Variance preserving intensity spectra (black) with predictions (red). Prev. pub. in Macaskill and Ewart 1996. [19]

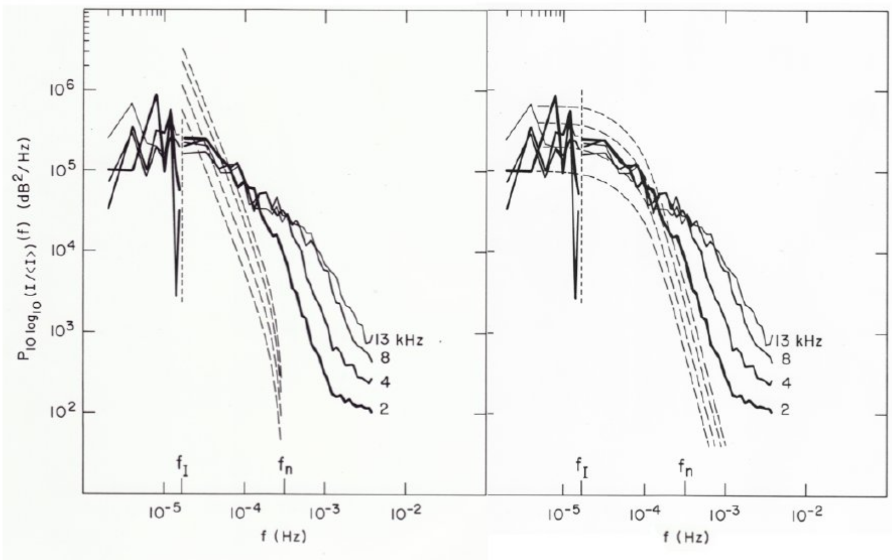

Figure 16: MATE intensity spectra versus Munk and Zachariesen theory (Left) and Flatté *et al* theory (Right). Prev. pub. in Ewart and Reynolds 1984. [25]

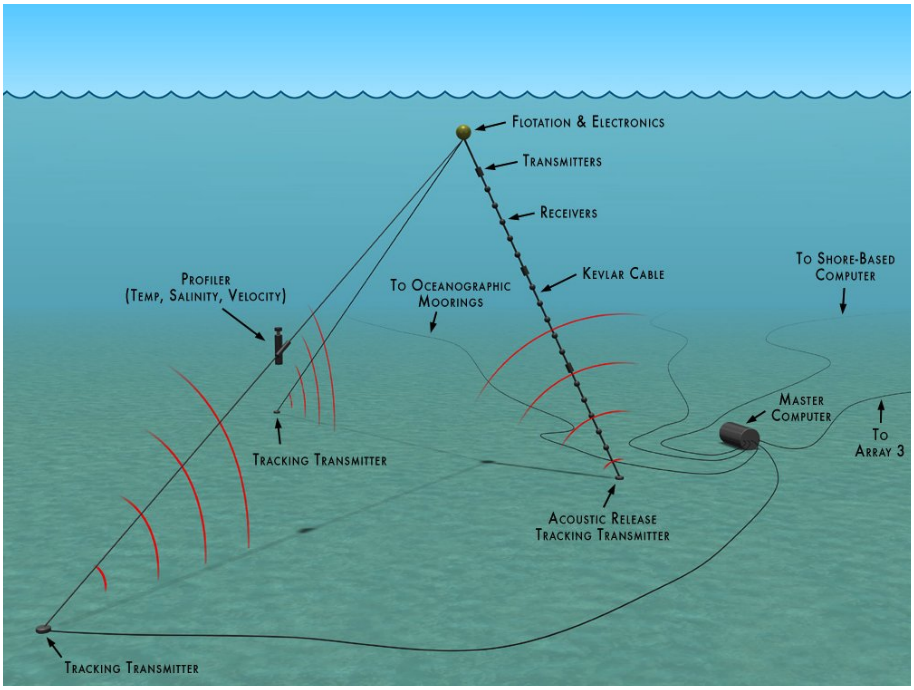

Figure 17: Cartoon of proposed vertical array.

does not apply for the upper path because the "up" ray turns inside of a single correlation length of the medium.

- There is not a unique spectrum of the index of refraction fluctuations in the thermocline region.
- There is very little theory available to model data that have the intermittent character of the index of refraction structure observed in the thermocline.

The smooth nature of L_p for the "down" ray is clearly distinct from the intermittent value along the "up" ray (Fig. 13). The upper path remains a perplexing problem.

4.6 APPROPRIATE APPLICATION OF THEORY

The use of the Rytov approximation to predict the Cobb and MATE experimental observations in refereed publications was central to the conflict concerning the correct application of theory to those observations [4,10,11]. For example, the re-computed Desaubies [10] and the Munk and Zachariesen [11] predictions of the MATE intensity autospectra for all four frequencies are plotted in the left side of Fig. 16. It shows that the slope and the scaling with acoustic frequency are in serious disagreement. The right hand side of Fig. 16 shows the predictions, using a modified GM internal wave model, from Flatté *et al.*, [28]. They presented only the 4 kHz prediction, which agrees with the observations fairly well, but here we have re-calculated the predictions for all four frequencies. Again, the Rytov scaling is equally inappropriate. The theoretical issues were partially resolved in Uscinski *et al* and Ewart *et al* [15, 16] and further resolved by Macaskill and Ewart [19] and Henyey and Macaskill [29]. Statistics of the medium were well modeled and an appropriate theory was applied.

4.7 CONCLUSIONS AND SUGGESTIONS FOR THE FUTURE

Barry Uscinski led the way toward this excellent theory-experiment comparison, and the 1996 publications should end the use of the Rytov approximation to predict experimental intensity results in Ocean WPRM where high Scintillation Indices are observed. The accuracy of the predictions at 2, 4, and 8 kHz tells us that the only way we could get better agreement between experiment and theory is to conduct another experiment with far longer time series. A good deal of attention would have to be paid to the space-time intensity cross spectra. The upper path results are quite different with very poor understanding of the theoretical issues, and an equally poor understanding of the oceanographic fluctuations. More recent oceanographic experiments have added to our understanding of the thermocline and mixed layer regimes, but there has been little added to our understanding of the acoustic fluctuations in that regime. The new experiment should address both the oceanographic issues and the acoustic fluctuation issues over a wide range of conditions including depth, range, and time. Such an experiment is described in the paper by Ewart *et al* 1997 [30]. A Cartoon of one of the arrays to be deployed in such an experiment is found in Fig. 17. Barry and I spoke on many occasions about such an experiment. An equally extensive oceanographic experiment would have to be done simultaneously.

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