Proceedings of The Institute of Acoustics

SOME RECENT EXPERIMENTS ON ACOUSTIC FLUCTUATIONS IN THE SEA

J.R. Potter[1,2] and S. Miller[2]

[1] *SACLANT ASW Research Centre, La Spezia, Italy*
[2] *Dept. App. Math. Theor. Physics, University of Cambridge, UK*

Abstract

In October 1985 a joint experiment between the SACLANT Centre, Italy and D.A.M.T.P., Cambridge, UK was carried out in the Tyrrhenian Sea, Mediterranean to investigate acoustic fluctuations due to oceanographic inhomogeneities on the scale of internal waves. Acoustic signals were generated by broad-band explosive charges. Two hydrophone arrays were used to receive the signal. The first was a reference array with 4 elements, moored close to the source, which recorded the signature. The second was a vertical 32-element hydrophone array with 2 m element spacing moored 5 km away from the source. Signals were received within a frequency range of 50 to 2000 Hz. In all 233 transmissions were made, at varying intervals between 15 and 60 min. Simultaneous oceanographic observations of temperature, salinity and sound speed were made by a towed oscillating body which will allow a direct estimate of the inhomogeneity scales. The experiment used broad-band sound sources so that cross-frequency correlations could be calculated. The future aim is to deduce the complex amplitude transmission function of the ocean and to study its spatial and temporal behaviour. As a preliminary analysis, relative arrival times down the receiving array have been calculated for some events and are presented here. The results are shown to be consistent with multiple scattering theory. A second experiment has also been carried out, during July 1986 in the Levantine Basin, Mediterranean. This second experiment used a CW source and recorded the sound field at a spread of depths and ranges.

Introduction

Fluctuations in the acoustic field associated with a source in the ocean have long been acknowledged, but only in the last decade have theorists begun to develop the complex theory of multiple sound scattering required to explain them. This theory is now in the process of being tested experimentally. One major source of fluctuation is the variation in sound speed along a ray path. This variation is attributable to physical oceanographic processes such as internal waves. For sound frequencies above 50 Hz such variations cause the ocean to act as a random scattering medium. The sound fluctuations produced will have a spatial structure which is both frequency and time dependent. Temporal structure is imposed by the time-dependence of the variations in the medium.

Two benchmark experiments which investigated the time dependence of acoustic fluctuations in the ocean were performed at Cobb Seamount in 1971 and 1977 [1,2]. These experiments were conducted with a single receiver and fixed source–receiver geometry, and at discrete frequencies. Predictions from Born and Rytov scattering theory did not give adequate agreement with the experimental results. In the last five years many advances have been made in multiple scattering theory which yield results more in agreement with the experimental data [1].

SOME RECENT EXPERIMENTS ON ACOUSTIC FLUCTUATIONS IN THE SEA

Solutions to the multiple scattering equations have now been further extended to include the cross-frequency correlation [3] and have been applied to the 1977 Cobb seamount data [4]. In parallel with the theoretical advances, numerical simulations have predicted spatial structure which is not apparent from the ensemble average theoretical solutions [5]. The aiwex acoustic transmission experiment (AATE) conducted in the arctic during 1985 [6] extended the Cobb experimental work by using four discrete frequencies and recording the signal continuously in the vertical.

In order to further explore these new theoretical and numerical results the D.A.M.T.P. and the SACLANTCEN decided to conduct experiments in which the acoustic field fluctuations could be observed, not only in space and time but also over a wide and continuous range of frequencies, complementing the AATE. The first experiment was carried out in October 1985 using broad-band sound sources. A second experiment was performed in June 1986 using a CW source which produced sound received at a spread of depths and ranges. Some results are now available from the first experiment and are presented below.

The broad-band sound experiment in October 1985

We wished to investigate sound field fluctuations due to inhomogeneities in the refractive index of the ocean on the scale of internal waves and to compare the results with predictions from theory. The theory requires, as input, a knowledge of the refractive index variations in the ocean, in order to predict the acoustic fluctuations. The experiment therefore had to measure both acoustic and environmental fields, with equal emphasis. The experiment was conducted in the Tyrrhenian Sea (Fig. 1) over a period of five days, using 2.3-g explosive charges as broad-band sound energy sources. The sound signal was recorded within a few hundred metres of the source with a 4-element reference array and also at a range of 5 km with a 32-element vertical array (62 m long) within a 2 kHz bandwidth. The signals were recorded close to the source, before appreciable distortion due to the medium occured, to provide a reference signature. Comparison of the reference and 5 km distant recordings of the signal will allow the ocean transfer function to be calculated without risk of contamination from inter-shot variability. This task has not yet been completed.

The R/V Maria Paolina G. deployed the sound sources and handled the data acquisition whilst a second ship, the R/V Magnaghi, made environmental observations (Fig. 2). The moorings for both arrays incorporated thermistor chains which operated throughout the experiment. In addition, some CTD and XBT data was collected from the R/V Maria Paolina G.

In all 233 shots were made, at varying intervals of 15, 30 or 60 min. The spacing of the elements in the arrays and the length of the arrays were fixed. The range from the source to distant receiving array and the maximum data sampling rate were limited by the radio data-link. Within these constraints, the experiment was designed to fulfill, as far as possible, the following requirements:

(a) In order to resolve the vertical sound fluctuation structure, its decorrelation length should be much larger than the hydrophone spacing in the recording array (2 m).

(b) The vertical structure should decorrelate over a smaller distance than the array length (62 m).

(c) The receiver should be at a range where the fluctuation structure is well developed.

(d) The geometry of the source and receiver array should be such that the direct path (eigenray which does not interact with the upper and lower surfaces) arrives at a time well separated from the other arrivals with respect to the pulse length.

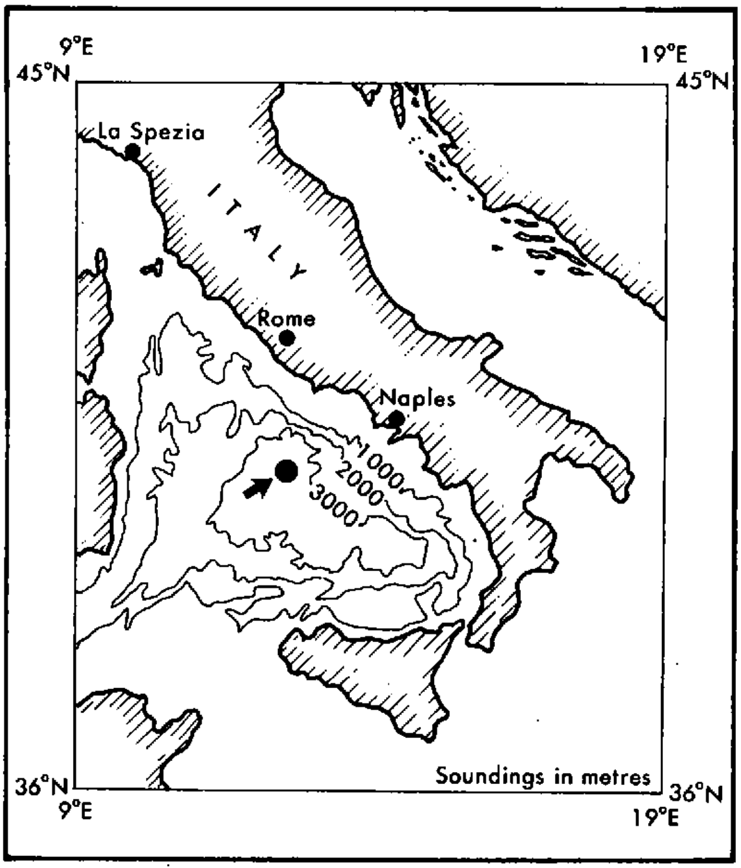

Fig. 1. The location of the experiment in the Tyrrhenian Basin, indicated by an arrow. The local bathymetry is shown at 1000-m contour levels.

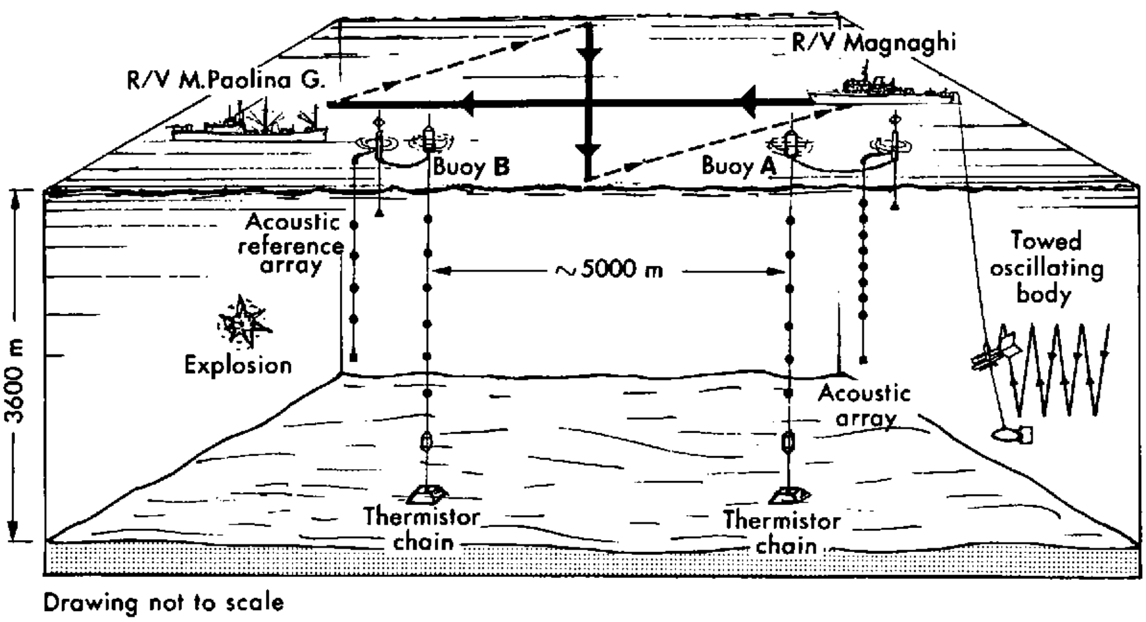

Fig. 2. A three-dimensional presentation of the experimental layout. The R/V Maria Paolina deployed the sources and acquired the acoustic data. The R/V Magnaghi towed an oscillating body with STD and sound velocity sensors in a cruciform path, shown as a solid line. The moorings for both the reference array (buoy B) and the 32-element recording array (buoy A) incorporated vertical thermistor chains.

In order to evaluate the experimental parameters, it was necessary to use a model of the ocean and its irregularities for predicting the sound fluctuation scales. Previous oceanographic studies of the experimental area [7,8] provided adequate estimates of the ambient sound speed profile and its stability. The sound speed profile has a high speed region near the surface, reducing to a minimum at about 80 m depth, below which there is a nearly linear increase in sound speed with depth. The level of internal wave activity and the likely scale and strength of the refractive index irregularities were more difficult to estimate. The geographically nearest values were for the Gulf of Lions reported by Williams [9]. Given the dimensionless energy parameter, the vertical stratification scale and the buoyancy frequency, it is possible to estimate the parameters associated with requirements (a), (b) and (c) above [1]. The requirement for (d) was calculated by using an eigenray program and the known sound speed profile, and showed that the source and receivers must be below about 300 m. It was found that at 1 kHz frequency and 500 m depth, the vertical scale of the sound fluctuations should be some 50 m. The maximum fluctuation intensity would then be at about 15 km range. This range exceeded that of our radio data-link and so a compromise was reached by deploying the sources at a depth of 400 m and placing the top of the receiving array at 224 m at a range of 5 km. The consequences of the compromise are that for this range and with an upper recorded frequency of 2 kHz the fluctuations are not fully developed and have a vertical scale which is comparable to the array length rather than smaller.

Simultaneously with the acoustic measurements, the R/V Magnaghi deployed a towed oscillating body (described in [10]) with STD and sound velocity sensors, through the region of propagation in directions parallel and perpendicular to the line of propagation (Fig. 2). The towed oscillating body executes a continuous zigzag path in a vertical plane. Some of the velocity profile results along this path are displayed in Fig. 3.

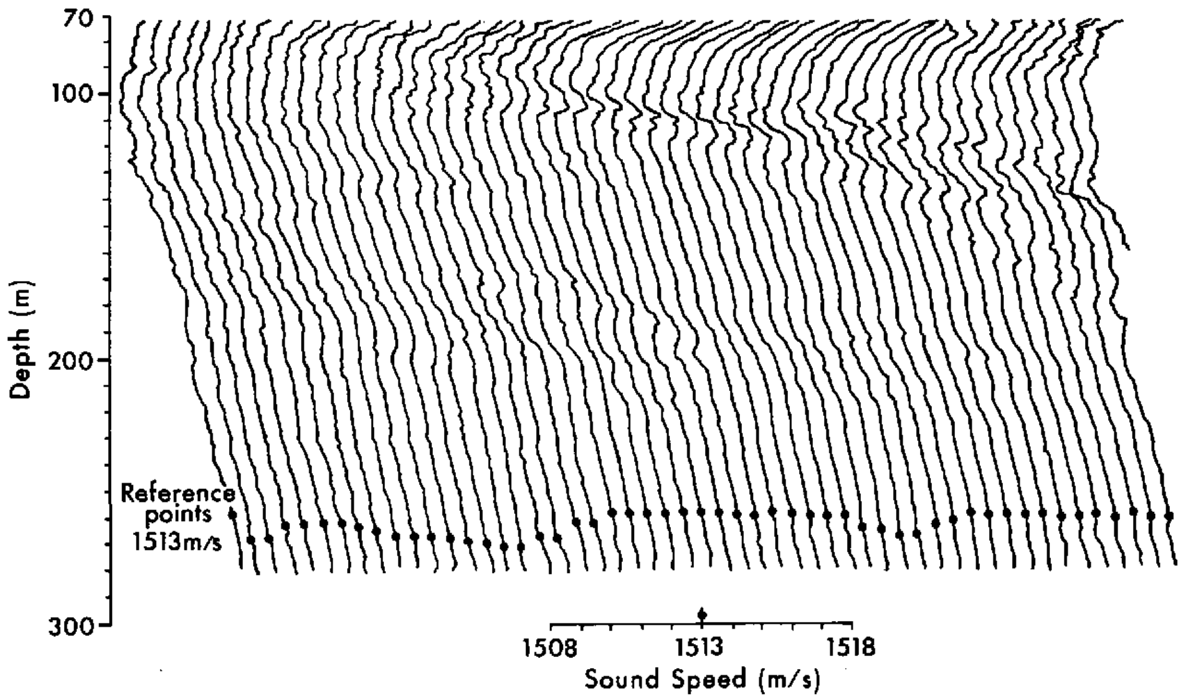

Fig. 3. A waterfall diagram of the sound velocity results, from the towed oscillating body. Each profile is offset by 0.6 m/s for clarity. Sound velocity irregularities can be seen which both oscillate vertically and evolve from one profile to the next.

Analysis of results

The objective is to measure the acoustic field fluctuations down the 62 m array and to obtain the ocean transfer function by deconvolving the observed signal with the reference signal. The 233 shots allow us to investigate how the transfer function changes with time as well as with distance down the array. Ensemble averages can also be made for comparison with theory. The task of deconvolution poses many theoretical and numerical difficulties, since it is an inversion problem which is critically sensitive to instability in the input. As a first step, an analysis of the arrival time fluctuations has been carried out. This has permitted us to establish much concerning the stability and accuracy of the experimental results. As such it forms an essential preliminary to the deconvolution analysis, which is very sensitive to error. The spatial structure of the arrival time fluctuations is, moreover, of independent interest and this is the first time (to our knowledge) that such arrival time structure has been presented. We devote the remainder of this report to the arrival time results.

Arrival time results

For the purposes of this analysis the arrival time is defined as the time of maximum intensity of the first peak of the received pulse. The data were real-time, low-pass filtered, with a transition band at 2-3 kHz, and then sampled and recorded at 6 kHz. Recorded data were interpolated at 8.3 μs intervals. Numerical and analytical results show that the expected error in the identification of peak intensity is less than one interpolation interval. The source–receiver separation could not be controlled sufficiently accurately to reveal absolute arrival times, and only relative arrival time fluctuations down the array can be determined.

The relative arrival time profile is a result of the deterministic ray path from source to receiver on which is superimposed a fluctuating component associated with sound speed variations. The expected decorrelation time for internal wave-induced fluctuations is about 8 h. If arrival time curves are averaged over a period of a day or longer, these and higher frequency fluctuations should statistically sum to zero. For the analysis below, the first 25 events of the experiment have been taken, spanning 23 h. Subtracting the average arrival profile from each of the 25 profiles leaves the fluctuating component, with an uncertainty in the absolute arrival time for each event. In order to relate consecutive profiles the uncertainty in the absolute arrival time must be removed, and so some time reference point must be taken for each event. We chose to take the lowest hydrophone (number one) as that reference.

The limitations to the interpretation of this data are then as follows:

(a) Genuine fluctuations at hydrophone number one will have been suppressed, and their inverse superimposed on the other 31 hydrophones.

(b) It is possible that ship motion has contaminated the record by varying the transmission path. The mean source to receiver range for the 25 events analysed was 4.95 ± 0.16 km. The low standard deviation of this range (3.3%) is not expected to contribute significantly to error.

(c) Nonverticality of the array does not affect relative arrival time directly, but changes in the vertical shape of the array could. Such motion could be brought about by surface wind stress on the buoys which form part of the mooring or by current shear. Rough calculations indicate that wind stress is too small an influence, especially since the experiment was performed in flat calm weather. Current shear would be readily identifiable if it had a different spatial or temporal scale than the fluctuations. This still leaves the possibility of internal wave current shear, which could produce relative arrival time fluctuations of the same spatial and temporal character as random scattering. This is a possibility which cannot be discarded without further investigation.

SOME RECENT EXPERIMENTS ON ACOUSTIC FLUCTUATIONS IN THE SEA

A contour plot has been drawn of arrival time deviations from the mean, plotted as a function of distance down the array and of time. The map is displayed as a three-dimensional surface and as a projected contour map in Fig. 4. The figure reveals both spatial and temporal structure of the fluctuations.

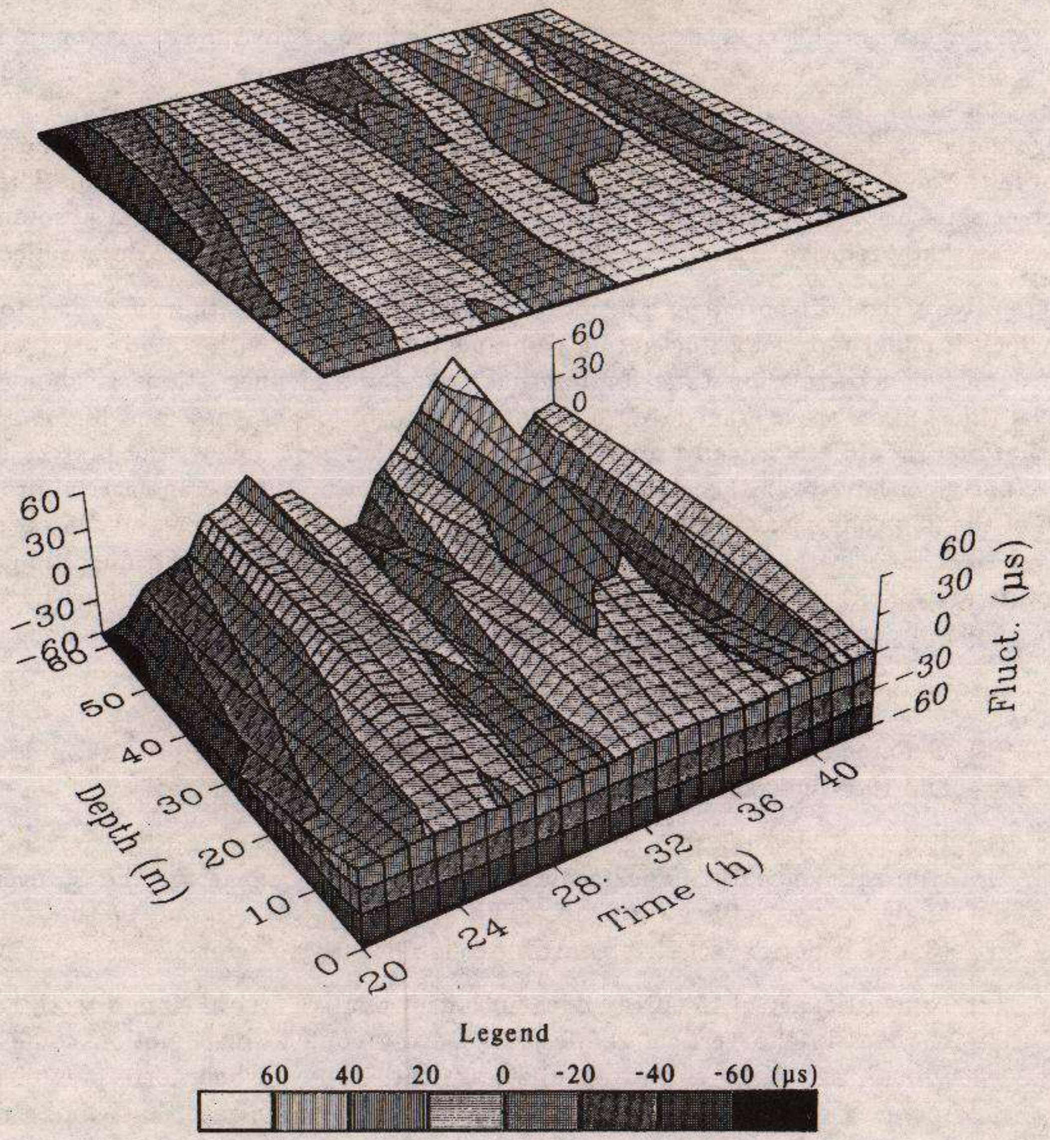

Fig. 4. A projection of a two-dimensional contour map with its associated three-dimensional surface shown below it. The vertical axis displays the relative arrival time difference down the array with respect to the first hydrophone, in μs. The horizontal axes show the depth down the array, in metres and the time of the event, in hours.

The spatial variations are coherent over the length of the array, demonstrating that the arrival time fluctuations are of long spatial wavelength. The amplitude of the peaks is some 50 μs. The theoretically expected spectrum of arrival time fluctuations down the receiving array can be calculated as a function of the autocorrelation function of the medium [11]. By using the spectral function for internal waves proposed by Munk and Zachariasen [12] one obtains a time fluctuation which has a spatial dependence inversely proportional to the third power of frequency [13]. Higher spatial frequencies therefore contain much less energy, and their amplitudes will quickly fall below the threshold of the original data interpolation interval of 8.3 μs. That the fluctuations can be seen at all is fortunate, since limitations imposed by data transmission facilities limited the range and frequency which in turn limited the arrival-time fluctuation amplitudes.

Figure 4 also shows the temporal variation, which has well-defined maxima at 27 and 37 h and minima at 20, 30 and 40 h. The temporal decorrelation is therefore of the order of 10 h. This agrees well with the theoretical results obtained from [11] and [12] who suggest that the vertical scale of the fluctuations due to internal waves would be some 50 m and that the fluctuation lifetime would be about 8 h.

The observed amplitude of the time fluctuations is less than expected from the Gulf of Lions energy parameter [9]. This is perhaps to be expected, since the Gulf of Lions is affected by a strong Mistral wind with intense air–sea energy coupling. Although internal wave energy could have propagated into the experimental area from far away, at least the area around the Tyrrhenian Sea was calm both immediately before and during the experiment. Realistic estimates of the amplitudes to be expected from theory cannot be produced until the environmental data collected at the time of the experiment is analysed.

Current and future work

We are continuing to work on the deconvolution of the reference signal with the received signal in order to obtain the ocean transfer function. In parallel, we intend to analyse the environmental data collected during the experiment in order to investigate the internal wave activity. In addition, there are current meter records taken on another experiment in the same area [8] and these are valuable since they span the period of our acoustic measurements. We intend to incorporate this current meter data into the environmental data that we collected in order to estimate the dimensionless energy parameter and properly describe the ocean acoustic environment.

A second experiment was carried out in the Levantine Basin, eastern Mediterranean, in June 1986 in order to study fluctuation structure in both vertical and horizontal directions. The prime difficulty was to sample the sound field over a spatial region that is large compared with the spatial decorrelation length within a time that is short compared to the expected temporal decorrelation. Constraints on the experimental design were similar to that of the broad-band sound experiment with one exception: since recordings had to be made over a spread of depths and ranges, it was impossible to guarantee a good temporal separation of the multipath arrivals. In order to separate multipaths more easily, a 3.6 kHz CW source with a pulse length of 10 ms was used. CW precludes cross-frequency correlation but obviates the need for a separate recording close to the source and allows signal reception over many different geometries. The intention is to use this data to map a quasi two-dimensional slice of the sound intensity fluctuations.

Acknowledgements

We wish to thank the many people who contributed to the planning and execution of this experimental program, both in all the support groups at SACLANTCEN and at D.A.M.T.P., particularly T. Akal and B. Uscinski. In adddition, P. Boni and E. Novotny contributed greatly in the analysis while R. Thiele and M. Richardson reviewed the science and gave valuable editorial assistance.

References

[1] T.E. Ewart, C. Macaskill and B.J. Uscinski, 'Intensity fluctuations. Part II: Comparison with the Cobb Experiment', J.A.S.A., Vol. 74, no.5, 1484-99, (1983).
[2] T.E. Ewart and S.A. Reynolds, 'The mid-ocean acoustic transmission experiment, MATE', J.A.S.A., Vol. 75, no.3, 785-802, (1984).
[3] B.J. Uscinksi and C. Macaskill, 'Frequency cross-correlation of intensity fluctuations in multiple scattering', Optica Acta, Vol. 32, 71-89, (1985).
[4] T.E. Ewart, C. Macaskill and B.J. Uscinski, 'The MATE acoustic frequency cross-correlations of intensity', J.A.S.A., Vol. 77, no.5, 1732-41, (1985).
[5] C. Macaskill and T.E. Ewart, 'Computer simulations of two-dimensional random wave propagation', IMA J. App. Math., Vol. 33, 1-15, (1984).
[6] T.E. Ewart and B.J. Uscinski, 'Aiwex acoustic transmission experiment (AATE). Proposal for research experiment', unpublished.
[7] R. Molcard and R.I. Tait, 'The steady state of the step structure in the Tyrrhenian Sea', SACLANTCEN SR-24, SACLANT ASW Research Centre, La Spezia, Italy, (1978).
[8] T.S. Hopkins, 'Recent observations on the intermediate and deep water circulation in the southern Tyrrhenian Sea', Oceanologica Acta, (in press).
[9] R.B. Williams, 'The AIM project: Internal waves and microstructure in the thermocline and their effects on acoustic propagation', SACLANTCEN SM-126, SACLANT ASW Research Centre, La Spezia, Italy, (1979).
[10] F. De Strobel, 'New oceanographic tools at SACLANTCEN', SACLANTCEN CP-19, SACLANT ASW Research Centre, La Spezia, Italy, (1976).
[11] B.J. Uscinski, 'Parabolic moment equations and acoustic propagation through internal waves', Proc. R. Soc. Lond., Vol. A 372, 117-48, (1980).
[12] W.H. Munk and F. Zachariasen, 'Sound propagation through a fluctuating stratified ocean', J.A.S.A., Vol. 59, no.4, 818-38, (1976).
[13] S. Miller, 'Time of arrival fluctuations produced by internal waves in the Tyrrhenian Sea', SACLANTCEN report (in preparation), SACLANT ASW Research Centre, La Spezia, Italy.