Naval Research Laboratory
Stennis Space Center, MS 39529-5004

NRL/MR/7180--03-8297

Fluctuations of High-Frequency Acoustic Pulses in Three Shallow-Water Experiments

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March 6, 2003

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
March 6, 2003

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Fluctuations of High-Frequency Acoustic Pulses in Three Shallow-Water Experiments

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0602435N

5d. PROJECT NUMBER
71-6845-01

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Marcia A. Wilson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Acoustics Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/MR/7180--03-8297

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

10. SPONSOR / MONITOR'S ACRONYM(S)
ONR

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

High-frequency acoustic propagation and scattering experiments were conducted near Panama City, Florida, in August of 1991 and 1993, and in Eckernförde Bay, Germany in May 1993. Environmental measurements were made in conjunction with acoustic measurements. The water depth at all sites was approximately 30 m. Sources and receiver arrays were mounted 6 to 8 m from the bottom and were separated by about 80 m. Data were obtained from 20 to 180 kHz. Means, standard deviations, and coefficients of variation of 100 to 150 direct path pulses for each frequency characterize two scales of temporal variability in the data. The short term variability with a period of several seconds was attributed to wind waves while the larger scale changes with a period of several minutes were related to internal waves. The amplitude of the fluctuations depended on a combination of factors including the depth and slope of the thermocline, turbulence from internal waves, wind waves, tides, and current interactions, and whether or not multipath arrivals interacted at the receiver array. Spatial variability was noted among several closely spaced hydrophones. Differences among frequencies depended on environmental factors that were changing with time of day when data were collected, as well as wavelength and beam pattern effects.

15. SUBJECT TERMS
High-frequency acoustics; Fluctuations; Shallow-water

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL	41	Marcia A. Wilson
					19b. TELEPHONE NUMBER *(include area code)* (228) 688-4862

Standard Form 298 (Rev. 8-98)
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FLUCTUATIONS OF HIGH-FREQUENCY ACOUSTIC PULSES IN THREE SHALLOW-WATER EXPERIMENTS

INTRODUCTION

An understanding of the effects of the shallow water environment on propagation of high frequency acoustic signals is needed to improve the performance of sonar systems in littoral regions. Increased interest in shallow water as a military arena led the Naval Research Laboratory (NRL) to conduct several high-frequency shallow water acoustic propagation and scattering experiments in recent years. Stanic, et. al. have described earlier scattering experiments conducted at sites near the Florida coast in about 30 m of water.[1,2] This report presents the results of three shallow water fluctuation experiments. Fluctuations in the magnitudes of received signals impose limits on sonar system performance, unless they can be compensated for by appropriate signal processing methods. If the physical causes of fluctuations can be determined, the Navy will be better able to predict and deal with the fluctuations found in similar areas. If the fluctuations change with frequency, this fact may be used to select frequencies that yield the best performance.

Two of the experiments to be described were conducted near Panama City, Florida in August 1991[3] and August 1993,[4] and the other was conducted in May 1993 in Eckernförde Bay, a part of the Baltic Sea along the northern coast of Germany. The May 1993 experiment was an international effort with participants from 18 organizations including the German laboratory Forschungs-anstalt der Bundeswehr für Wasserschall und Geophysik (FWG) and the University of Kiel.[4] In each experiment, measurements were designed to determine fluctuation statistics as well as temporal and spatial coherence of acoustic signals scattered from the boundaries and propagated in the water column. Environmental data were also collected. The 1993 experiments also quantified acoustic energy transmission into the sediment and the subsequent scattering within the sediment.

NRL has processed and analyzed various parts of the extensive acoustic data sets collected in these experiments. The primary emphasis of this report is on fluctuation statistics for signals propagated via the direct path. These statistics include means, standard deviations and coefficients of variation (standard deviation divided by the mean). Time series plots of received pulse envelopes from the direct and bottom interacting paths are shown to compare characteristics of the signals at different frequencies.

Manuscript approved February 3, 2003.

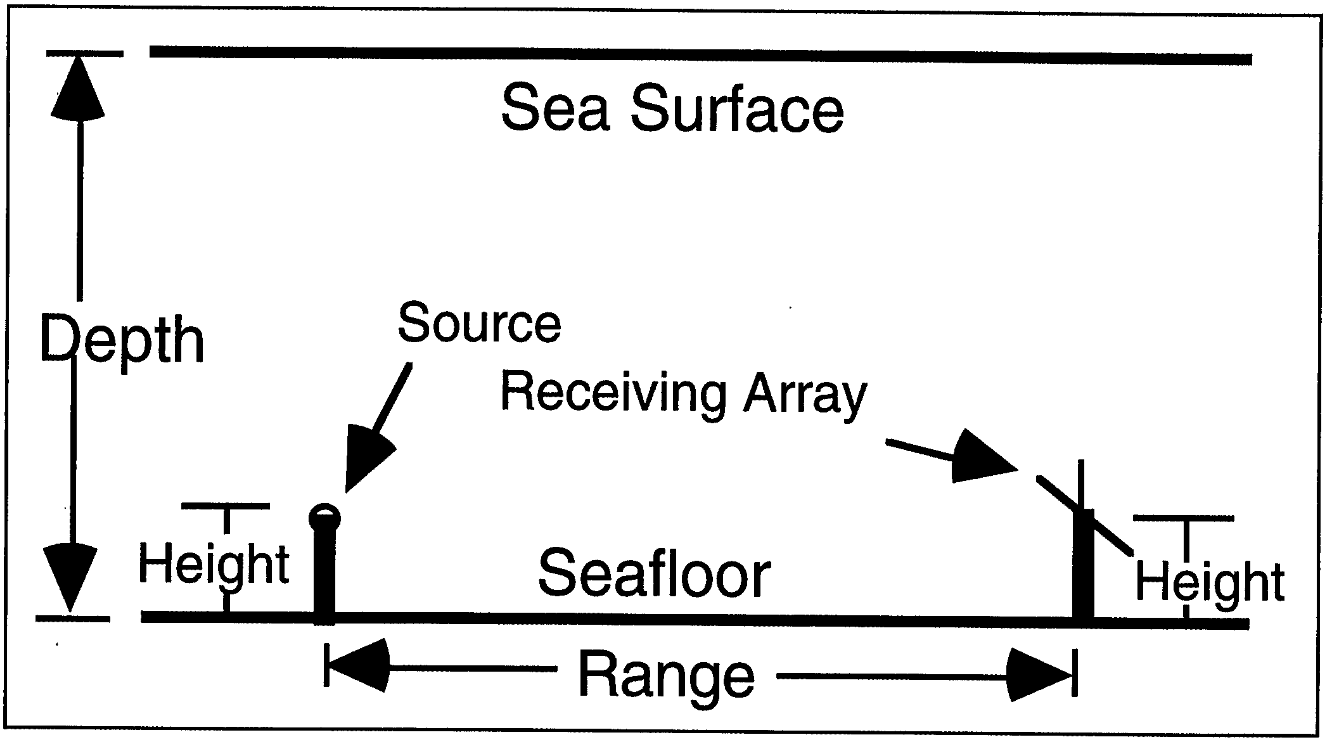


Fig. 1. Geometry used in all three experiments, with small differences in range, height and depth. In the Panama City 1991 experiment, the range was 90 m, the depth was 30 m and the heights of the source and the receiving array vertex were 7.6 m. In the Eckernförde Bay experiment, the range was 81 m, the depth was 27.4 m and the heights were 6.85 m. In the Panama City 1993 experiment, the range was 76 m, the depth was 30.5 m and the heights were 7.4 m.

EXPERIMENTS

General Description

The NRL measurement system has been thoroughly described in previous publications.[5,6] It consists of two stable towers used to support acoustic sources, receiving arrays, and electronic packages. In the present experiments, two acoustic sources, mounted on one tower, were used to cover the frequency range from 20 to 180 kHz. Vertical and horizontal receiving arrays were located atop both towers to collect direct path, and forward and backscattered data. Selected data received at the forward scatter tower are considered here. The source-receiver geometry used in these three experiments for direct path measurements is shown in Fig. 1. The horizontal and vertical receiving arrays for all three experiments are shown in Fig. 2, along with the labels and positions of hydrophones on the array. Data from several hydrophones of each array were examined and compared. These comparisons were made with

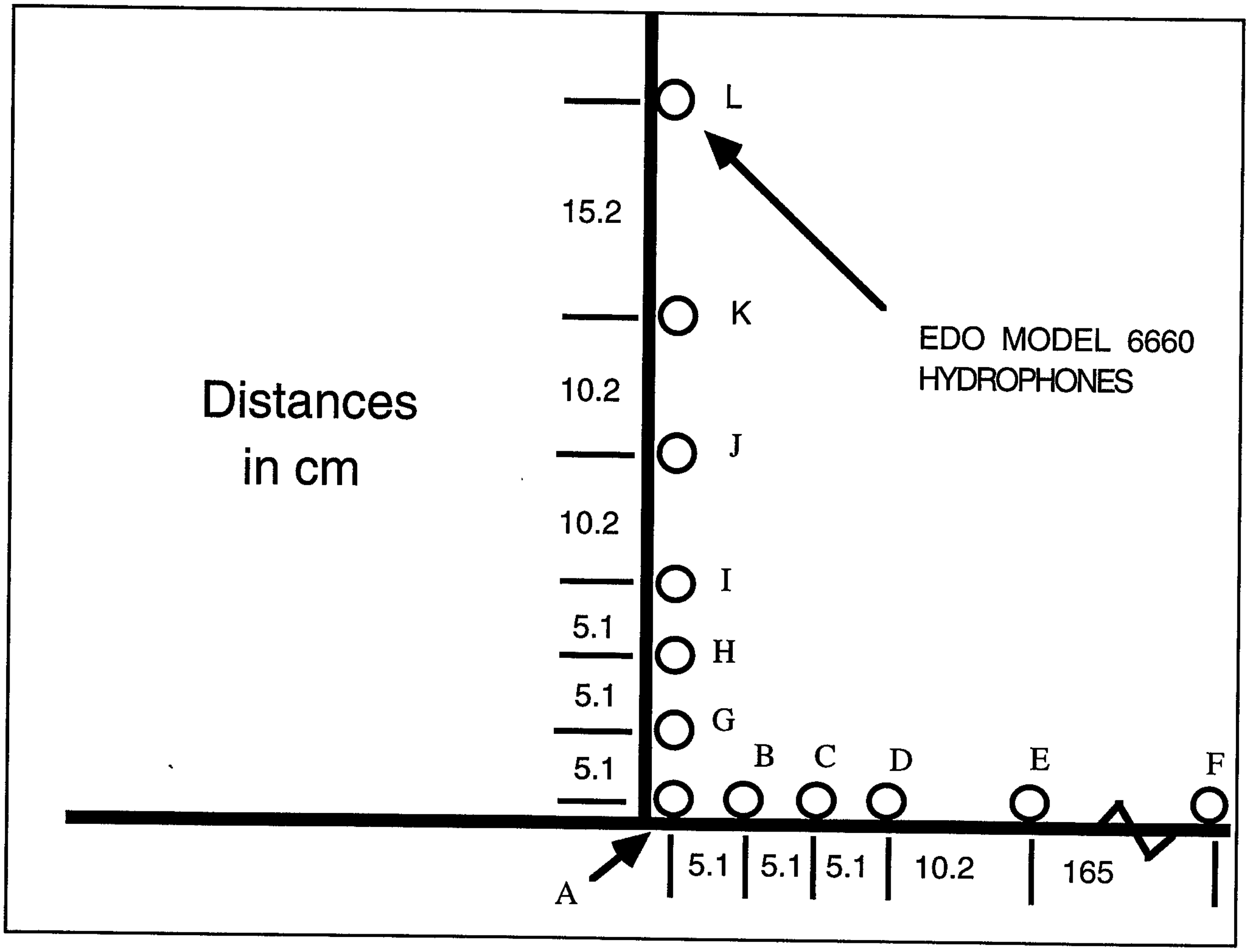


Fig. 2 Hydrophone labels and positions on the receiving array.

respect to distance from hydrophone A, at the vertex of the two arrays. The sources and receiver arrays could be electronically rotated in both tilt and azimuth. High frequency, narrow beamwidth transmissions before each run assured that sources and receivers were properly aligned.

Figure 3 shows relative measured source levels at beam angles from 1° to 12° for most of the frequencies used in these experiments. A 29.2-cm diameter circular piston transducer was used for frequencies between 20 and 90 kHz and a 19-cm diameter projector of similar design was used from 90 to 180 kHz, so that 90 kHz data could be obtained with each source. The same two sources were used in all three experiments. The width of the beams, especially at the lower frequencies, resulted in some elongation of the received signal.

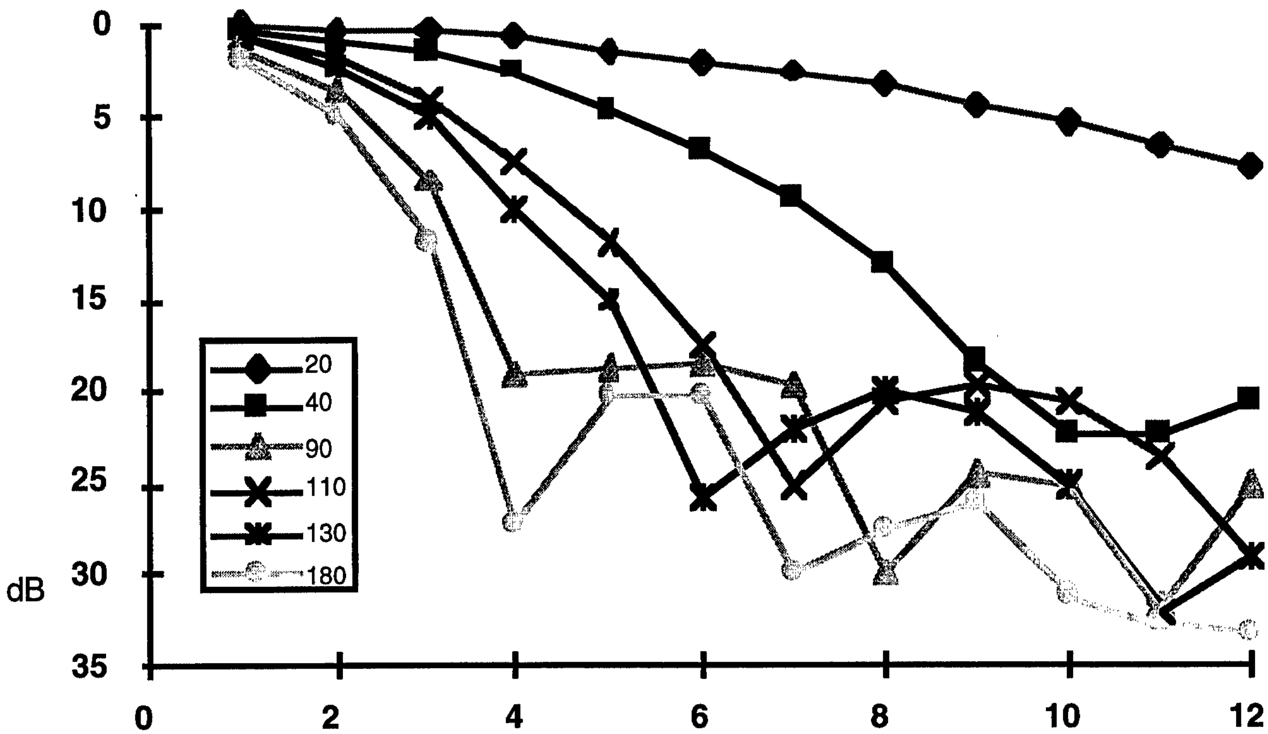


Fig. 3 Intensity of beam at 1° to 12° from maximum response axis.

Projector beamwidths between -3 dB-down points are given in Table I. Pulse lengths were varied, but for present purposes, only data with pulse lengths of 0.5 ms or 1.0 ms were selected for analysis. During a measurement sequence, numerous pulses were generated at 1 second intervals for each frequency.

The received signal from each hydrophone was fed through a computer controlled amplifier, band shifted to 5 kHz, low pass filtered, sampled at 20 kHz, and recorded on an optical disk.[5] This facilitated quadrature sampling and calculation of the envelope of the data for statistical analysis. The envelope derived from the pulsed cw time series has one sample every 0.1 ms and there are over one thousand points in the envelope for each received pulse. The digitizing software was designed so that recording of each pulse started at the same time relative to the emission of the source pulse. All pulses for one receiver could then be averaged with confidence that the pulse start times were the same within one tenth of a millisecond. Examples of the envelope of the entire time series were obtained from the cw data, plotted and checked before extensive processing was done on a complete data set. Some

TABLE I
SOURCE BEAMWIDTH

Frequency (kHz)	Source (cm)	-3-dB Points (deg.)
20	29.2	16
40	29.2	8.7
60	29.2	5.8
90	29.2	3.5
110	19	4.4
130	19	3.7
150	19	3.2
180	19	2.7

sets were not usable due to errors in triggering time or insufficient signal-to-noise ratio. Part of the envelope, starting a few points before the direct arrival and ending several points after the bottom arrival, was extracted from each original envelope for analysis, and a mean envelope, standard deviation, and coefficient of variation were calculated for each set. Also, time series were created to show pulse to pulse variability at a specific time within the part of the envelope of interest.

Detailed analysis of bottom characteristics was provided through box cores taken in both measurement areas in 1993.[7] Bottom characteristics were also measured, although not as extensively, at Panama City in 1991. Other environmental data were collected using conductivity-temperature-depth (CTD) probes, current meters, wave height measurement devices, and wind speed and direction instruments.

Panama City, Florida 1991

The first of the three experiments was conducted about 48 km off Panama City in the Gulf of Mexico as shown in Fig. 4. A sound speed profile (SSP) and resulting ray trace are shown in Fig. 5. The sound speed increased gradually from 1541 m/s a few meters below the surface to 1542.6 m/s at 18 m, then decreased to 1538 m/s near the bottom. The range between towers was 90 m, the depth was 30 m, and the sources and receivers were 7.6 m above the seafloor. Sand ripples with an average (RMS) wave height of 0.5 cm characterized the bottom,[3] producing a moderate acoustic reflection.[8]

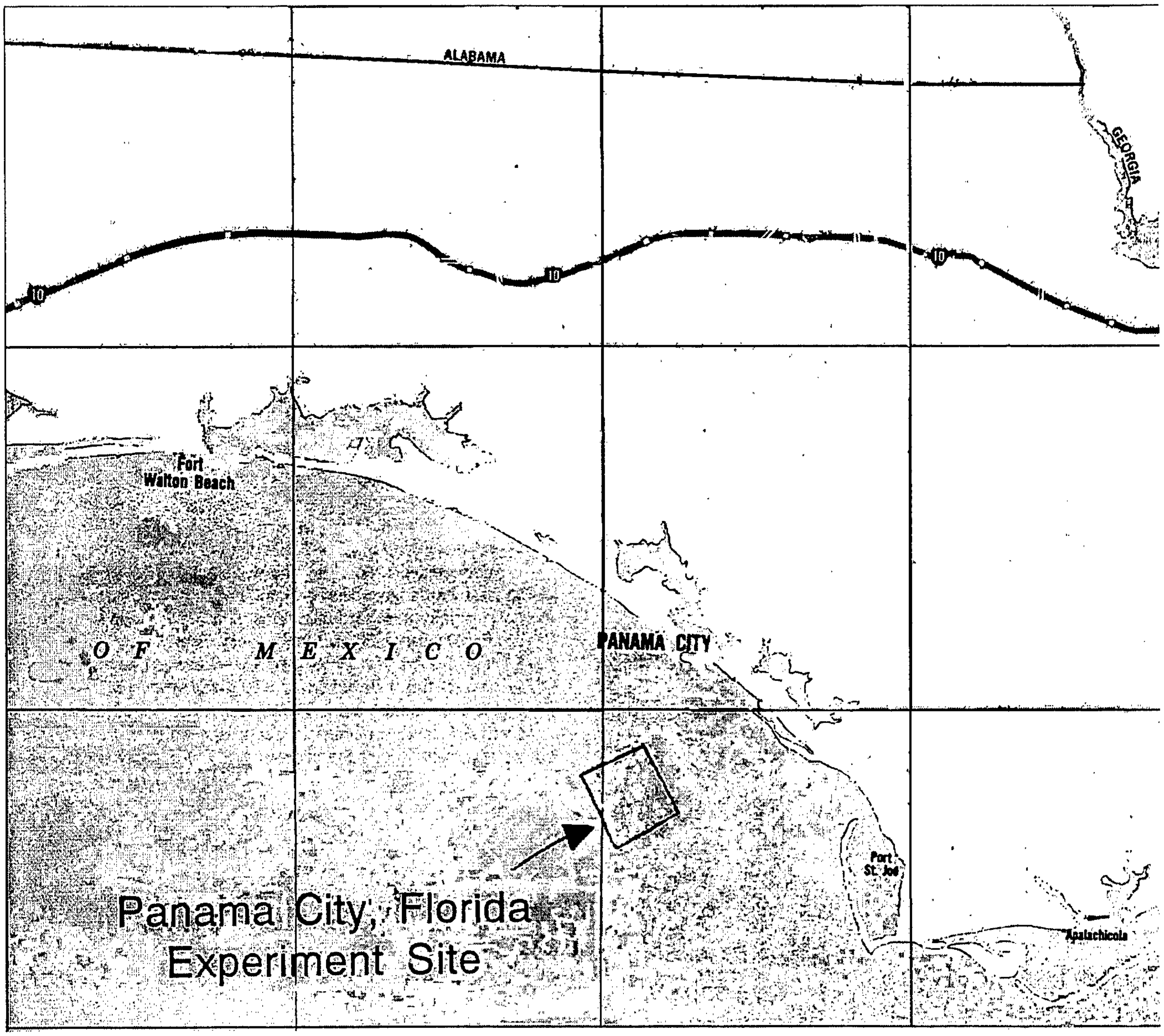


Fig. 4 Map showing area of Panama City experiment sites

Source frequencies of 25, 40, 60, 90, 110, 130, 150, and 180 kHz were used. Pulses 1 ms in length were transmitted at 1 s intervals until 100 consecutive pulses were recorded. Most of the examples from this experiment are from hydrophone B (Fig. 2). At 25 kHz, data were analyzed for 5 hydrophones: B, C, and F, along the horizontal array 5, 10, and 190 cm from the vertex, and G and I, on the vertical array 5 and 15 cm from the vertex.

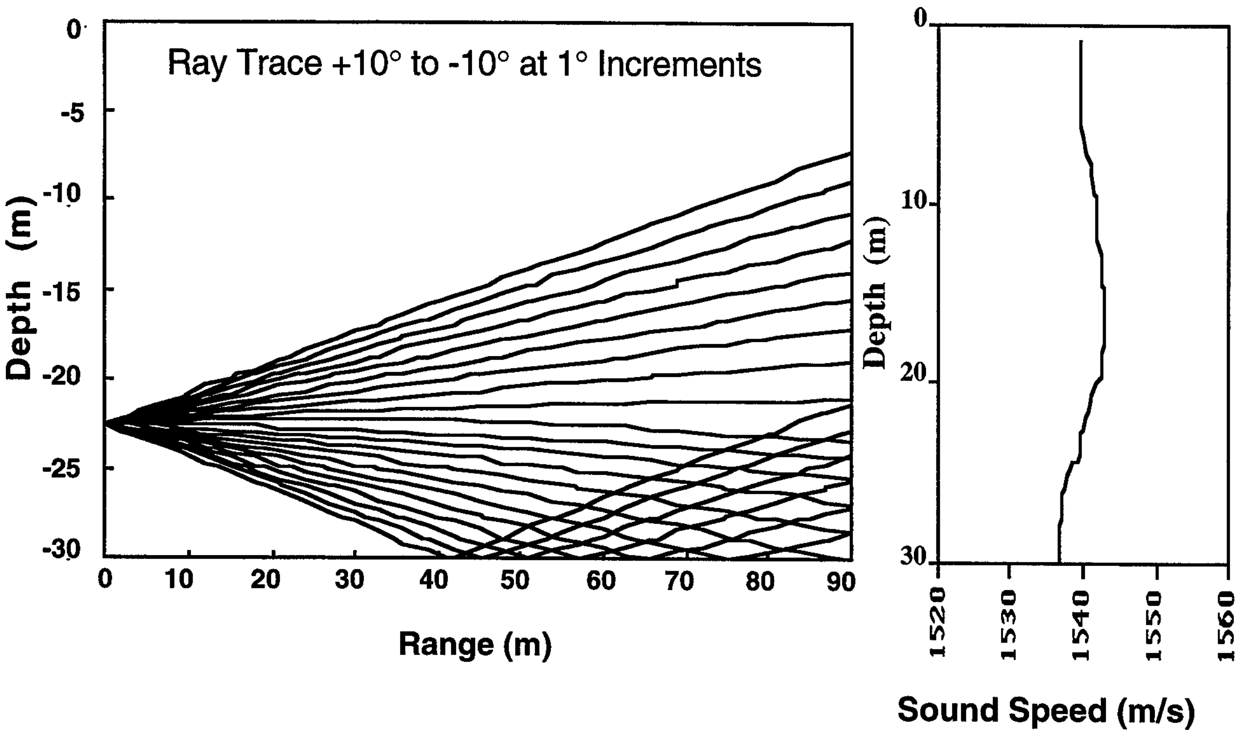


Fig. 5. Ray Trace for +10° to -10° at 1° increments from the 1991 Panama City experiment site using sound speed profile at right.

Eckernförde Bay, Germany

In Germany, the propagation experiment was conducted near 54°30'N and 10°E. Before deployment in Eckernförde Bay, the acoustic sources, receivers, and underwater electronics package, previously used only in sand and shell environments near the United States coastline, were mounted on lighter stabilizing platforms which would not sink into the mud bottom of the bay. The source tower was positioned south-southwest of the forward scatter receiving tower so that the path between them was approximately perpendicular to the direction of the length of Eckernförde Bay, as shown in Fig. 6. The sources and receivers were separated by 81 m and the water depth was about 27 m. The horizontal structure below which the sources were attached and above which the receiver arrays were mounted was 6.85 m above the flat bottom. Figure 7 shows that the sound speed was about 1476 m/s at the surface, 1467 m/s at 15 m, 1451 m/s at 18.6 m, and remained at 1448 from 23.8 m to the bottom. As a result, upward-going rays were refracted downward in the extreme negative gradient region of the sound speed profile.

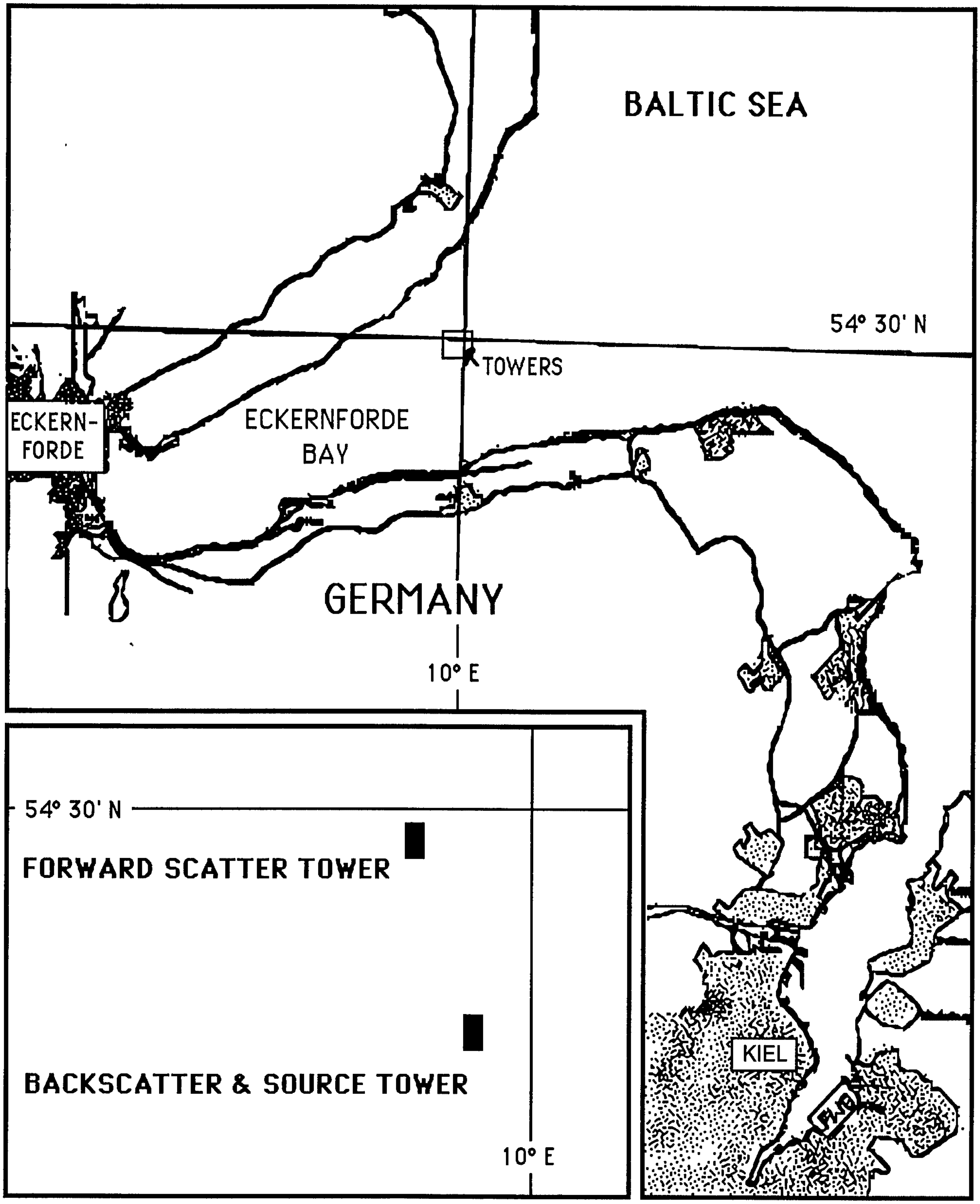


Fig. 6. Location of May 1993 experiment in Eckernförde Bay off the coast of Germany, with insert showing relative tower positions.

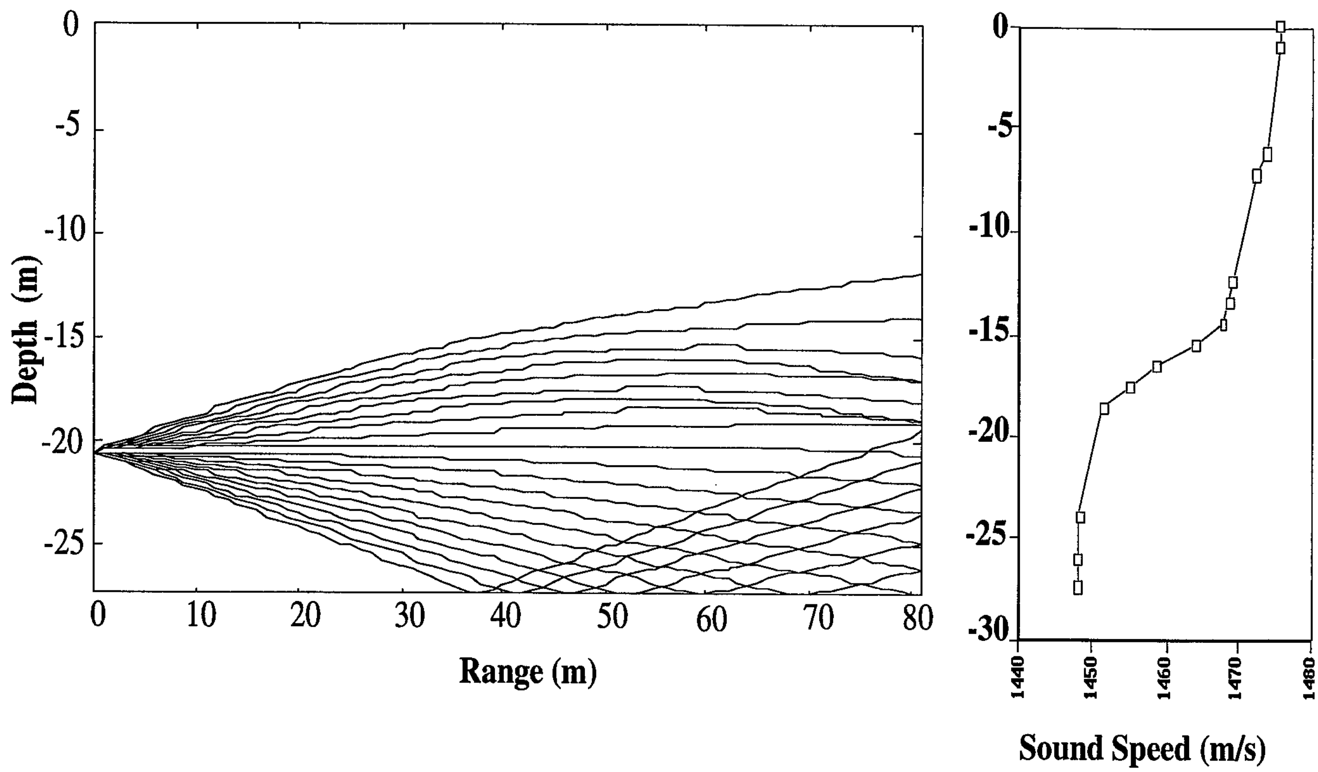


Fig. 7 Ray trace for +10° to -10° at 1° increments from sound speed profile at right, taken May 14, 1993 in Eckernförde Bay off the coast of Germany.

While the primary objective of this experiment was to identify seafloor scattering mechanisms, sea surface scattering and direct path propagation measurements were also carried out in a manner similar to that of the 1991 Panama City experiment. Pulses 0.5 and 1 ms in length were transmitted at 20, 40, 60, 90, 110, 130, 150, and 180 kHz. Only the 29.2-cm diameter transducer was used for 90 kHz in this experiment. The 60 kHz data were not usable due to trigger malfunction. Prior to each frequency change, source pitch angles were adjusted to ensure that the maximum response axis of the source was directed toward the array on the forward scatter tower. The vertical angle (pitch) of the source is known to have been set to 0.4° upward for 20 to 90 kHz and to 2° upward for frequencies from 110 to 180 kHz. The Eckernförde Bay data set is the only one of the three for which all necessary source levels, gains and calibration values were available, so it is the only one in which a comparison of mean received levels can be made among different frequencies and receiving hydrophones.

More data were analyzed from the Eckernförde Bay experiment than from the other two experiments. Results from this data will therefore be described first and given the main emphasis. Where only one example is needed, it will normally come from this experiment. For each frequency and pulse length combination, 150 pulses were generated and digitized. Both 0.5 and 1.0 ms pulse length data sets were analyzed. For the longer pulse lengths, at 20, 90, and 150 kHz, 11 receiving hydrophones, hydrophone A, and those about 5, 10, 15 and 25 cm from it on the horizontal array and 5, 10, 15, 25, 35, and 50 cm from it on the vertical array were used (A to E and G to L in Fig. 2). Hydrophones A and D, the one 15 cm from A along the horizontal array, were used with the longer pulse length data for 40, 110, and 130 kHz and for all six frequencies with the shorter pulse length data.

Panama City, Florida 1993

This experiment was carried out in August 1993 about 40 km south of Panama City in the area indicated in Fig. 4.[4] A typical sound speed profile and ray trace are shown in Fig. 8. At the time this profile was obtained, there was a fairly steep gradient, with sound speed changing from 1542 m/s at 12.5 m depth to 1535 m/s around 19 m. The water depth was 30.5 m, the distance between towers was 76 m, and the sources and horizontal segments of receiving arrays were 7.4 m from the bottom. Strong storms that occurred since the 1991 experiment had changed the bottom characteristics. The bottom was coarse grained sandy sediment mixed with shell hash, numerous large mollusk shells, and coralline algae fragments, and had a uniformly high acoustic reflectivity.[8]

For each frequency and pulse length combination, 150 pulses were generated and digitized. Measurements designed to obtain fluctuation data, in which the main lobe of the transmitter beam pattern was along the direct path to the receiving hydrophones, had poor signal to noise ratios, making them unusable. However, bottom scattering measurements were made with the source at a -30° pitch angle. At 90 kHz, the source had a strong sidelobe at about 30°. This data set had good signal to noise and it was possible to extract 90 kHz direct path fluctuation data from it. This set was analyzed for the

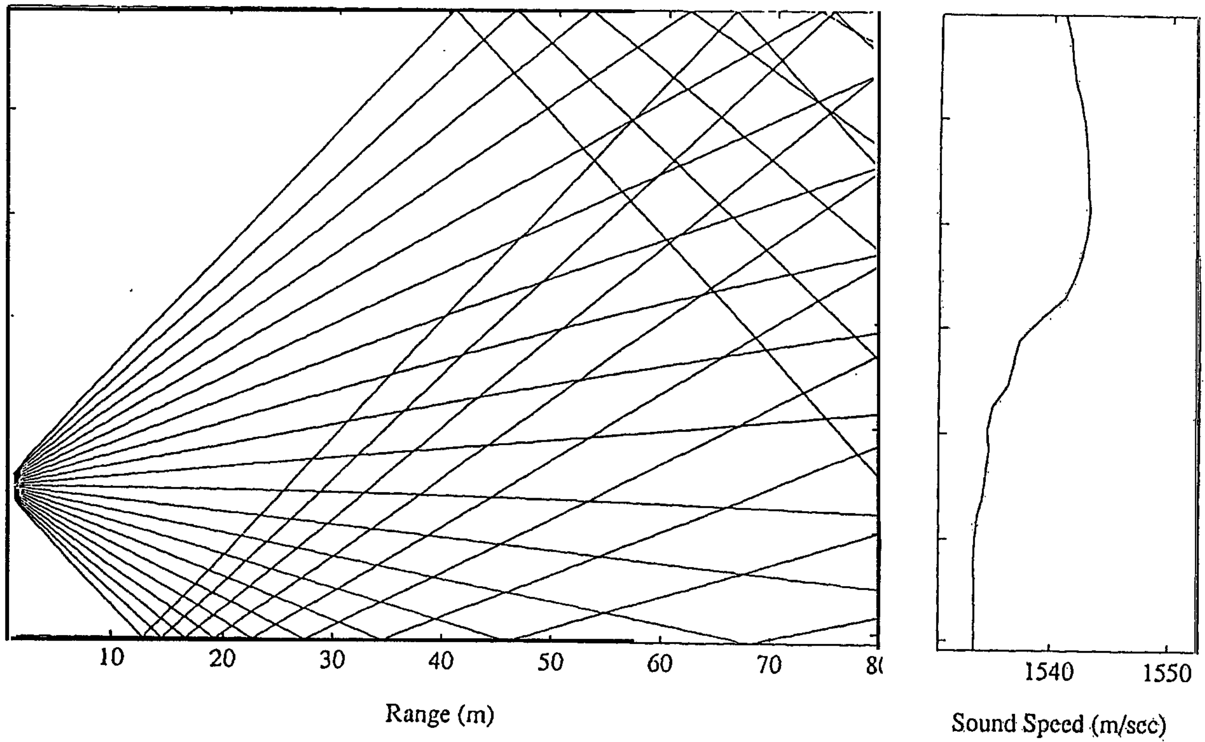


Fig. 8. Ray trace for +10° to -10° at 1° increments from sound speed profile taken during Panama City 1993 experiment.

vertex hydrophone (A), those hydrophones about 5, 10 and 15 cm from it on the horizontal array (B, C, D) and those approximately 10 and 15 cm from it on the vertical array(H, I) (Fig. 2).

RESULTS

Eckernförde Bay

The part of a typical envelope containing direct and later arrivals is shown in Fig. 9. The first peak is the direct path. Calculations using simple geometry indicate that the bottom return should begin between the eighth and ninth point of this peak. In this and most cases, especially for the higher frequencies with narrow beam patterns, the bottom returns are very weak. The next large peak is the surface return. It is followed by returns which have interacted with the

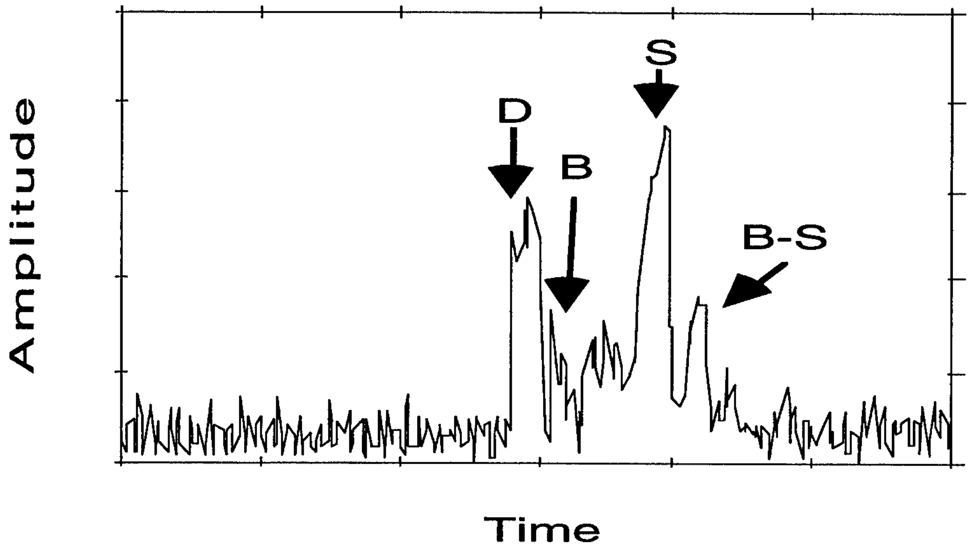


Fig. 9. Envelope of a single pulse showing direct(D) and bottom(B) arrivals, surface arrival(S) and bottom and surface(B-S) arrivals. This is a 110 kHz sample.

both surface and the bottom. Figure 10 shows expanded examples of the direct path and bottom return portion of envelopes averaged over the 150 1.0 ms pulses for hydrophone A. Received pulse widths are longer than the transmitted 1 ms for 20 and 40 kHz signals, which have wide beams. At 20, 110, and 150 kHz there are later returns which are 1 ms in length, suggesting sub-bottom or off-axis scattering.

For each of the 150 pulse envelopes at a given frequency and pulse length, a direct path data point was taken at a consistent number of samples after transmission of the source pulse began. These 150 points constitute a time series representing the pulse to pulse variability. Analysis of a source pulse identical to the transmitted signal showed that the envelope of the source amplitude became stable after two or three points. In 1.0 ms pulses there were 10 points, but in 0.5 ms pulses the direct arrival ended after the fifth point, therefore a time series containing the fourth or fifth point after the start of the direct arrival was used to represent that set in the statistical analysis for 0.5 ms and 1.0 ms sets. Figures 11 and 12 show pulse to pulse variability in

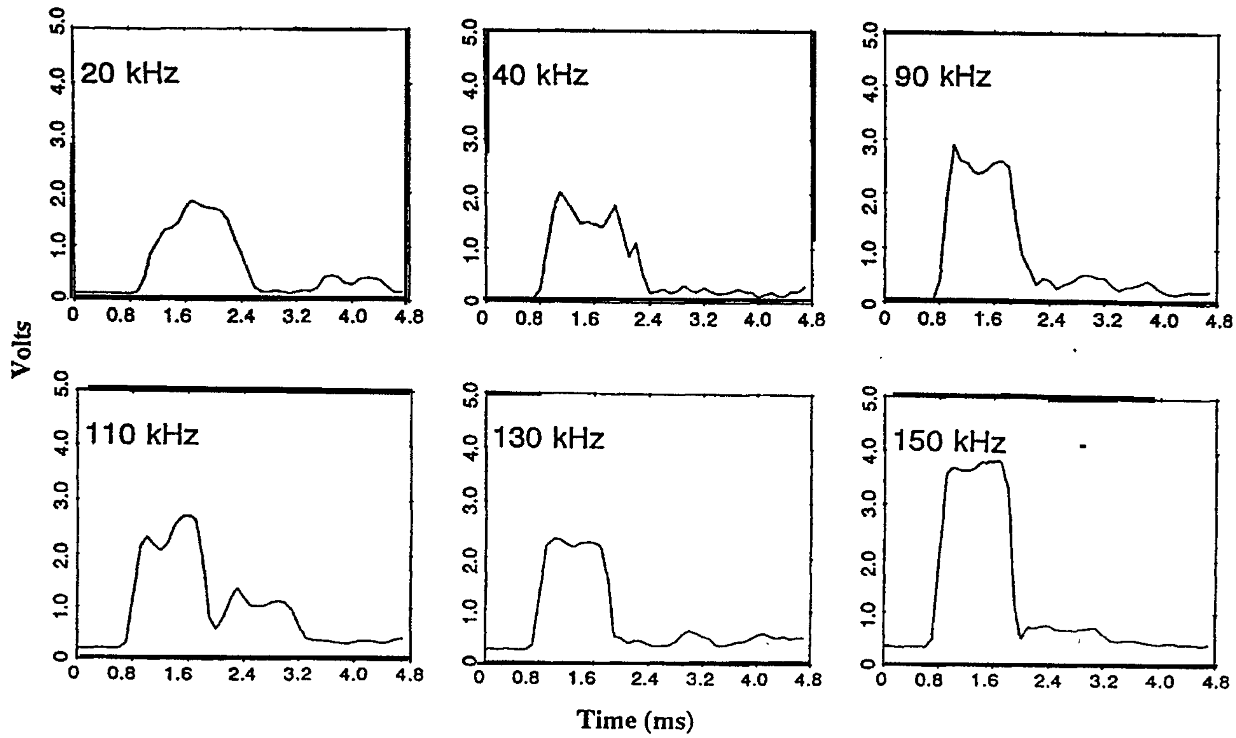


Fig. 10. Mean envelopes of received signals from direct and bottom paths of Eckernförde Bay, Germany 1993 experiment.

hydrophone A raw data. Although several frequencies are shown, different frequencies were transmitted one at a time with several minutes between sets.

Figure 13 shows calibrated means and standard deviations for each set of pulses as a function of pulse length and frequency. Means at 20 and 90 kHz were the highest, near -30 dB. Means plus or minus one standard deviation ranged between -40 and -60 dB for the other frequencies. For the same frequency, 0.5 and 1.0 ms pulse length means were similar enough and standard deviations large enough to cause overlap within standard deviation. In general, pulse length did not have a significant effect on the results. The low means and high standard deviations at 180 kHz were due to very low signal-to-noise ratios, so these data were not processed further. The likely cause of the low signal-to-noise was vertical misalignment of source and receiver. The relatively high means and low standard deviations at 90 and 150 kHz indicate that source alignment did not affect the data at frequencies other than 180 kHz.

Examination of the pulse-to-pulse time series data shown in Figs. 11 and 12 reveals two time scales of variability. There were trends taking place gradually over the entire 150 second measurement, and short term variations. The period of the trend seems to have been about 1.5 to 2 minutes, although the measurement was not sufficiently long to determine this period with certainty. The period of short term variations was around 4 seconds. Statistics for each of these time scales are more meaningful than those given in Fig. 13 for the total time series.

Figure 14 shows the pair of time series that result when the two scales of variability are separated for 130 kHz, where the greatest change in amplitude occurred. This was accomplished by using a 20-point moving average to obtain the trend of the data and then subtracting this trend from the original time series to obtain short term variability. Both scales of fluctuations occur about the same mean, but the short term variability is shown centered on zero because the mean was subtracted along with the trend so the two would not overlap in the plot. The largest fluctuations in amplitude are related to the longer time scales, in which undulations span a large number of pulses. Longer term amplitude changes of the 130-kHz example in Fig. 14 are as large as

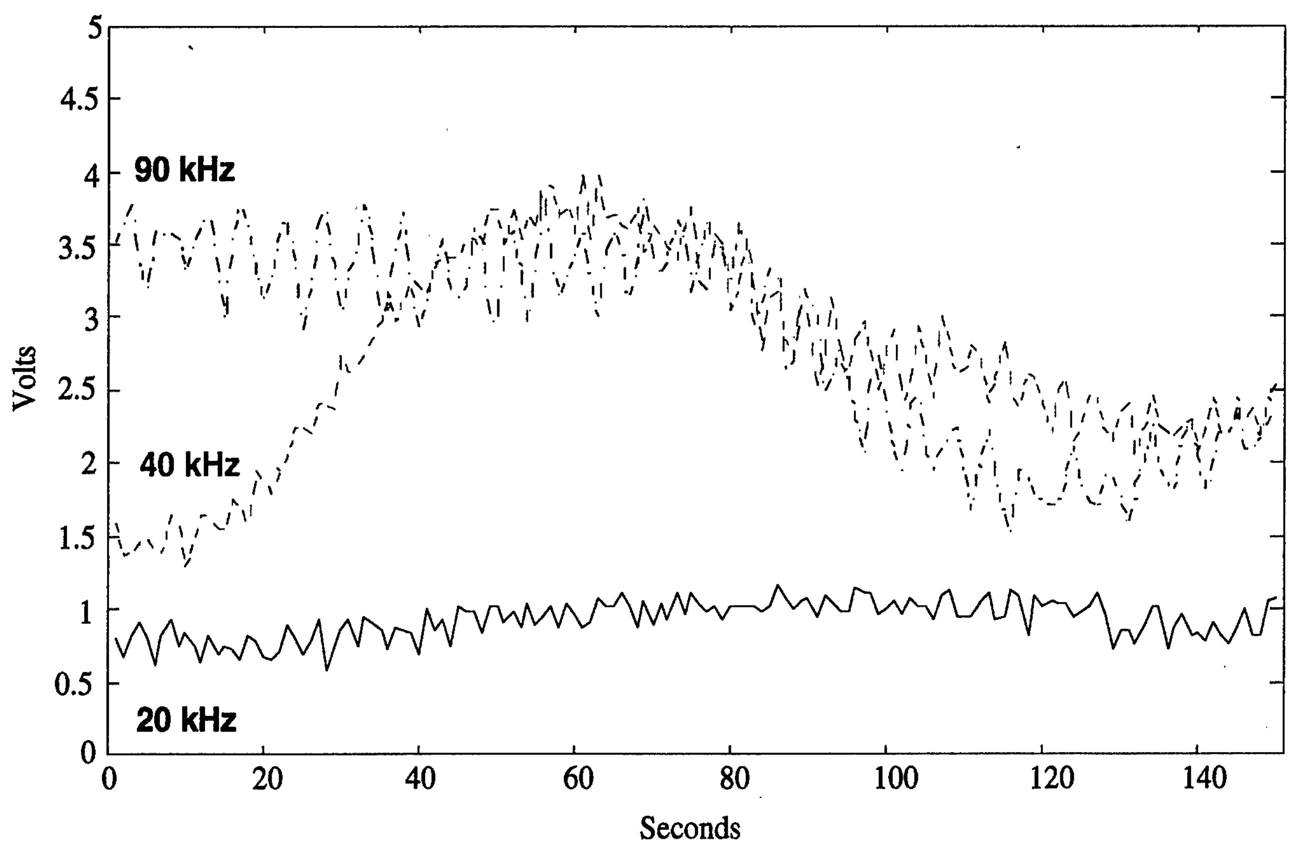


Fig 11 Variability between pulses for 0.5 ms pulse length sets at 20, 40, and 90 kHz in Eckernförde Bay.

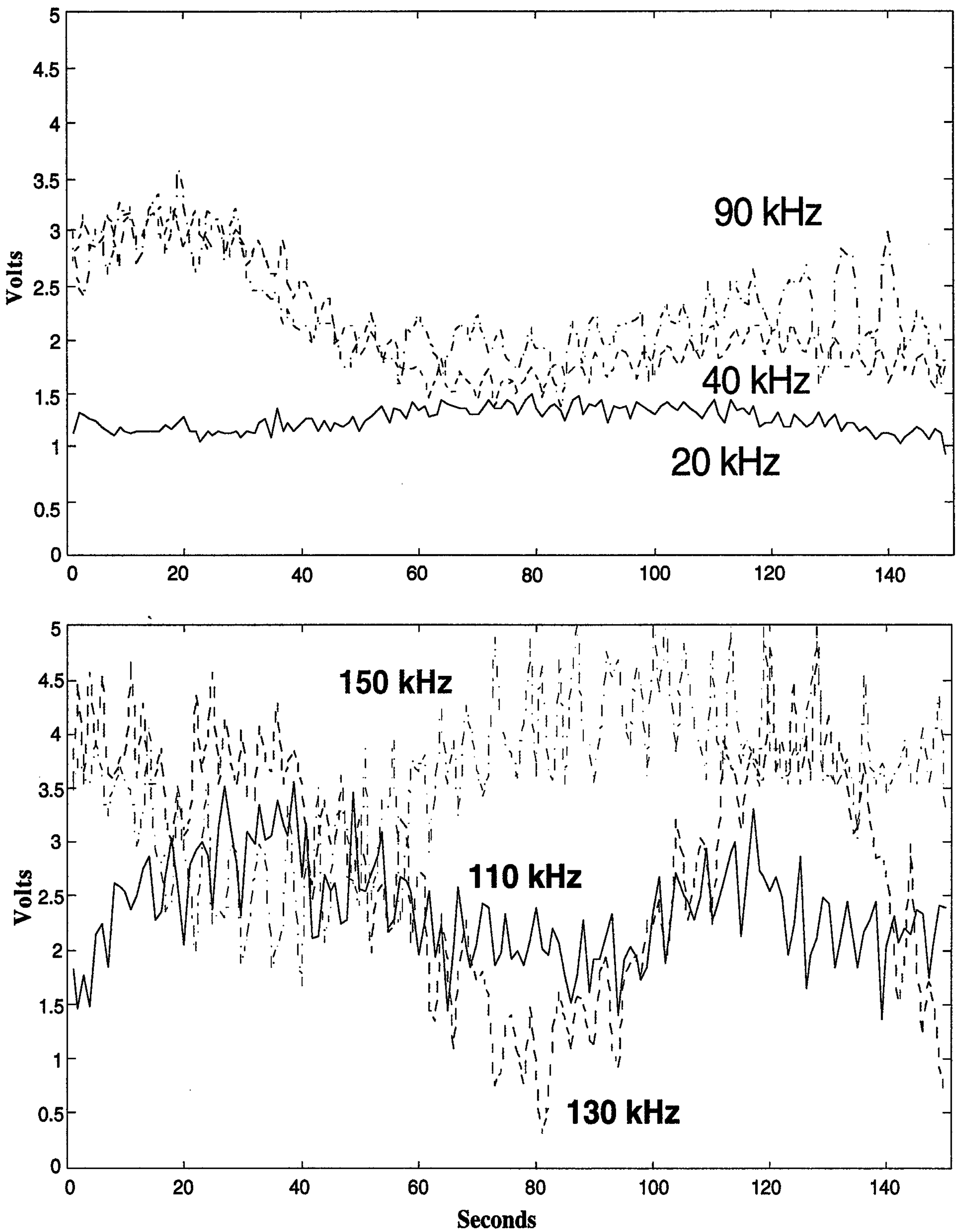


Fig. 12 Variability between pulses for 1 ms pulse length sets in Eckernförde Bay.

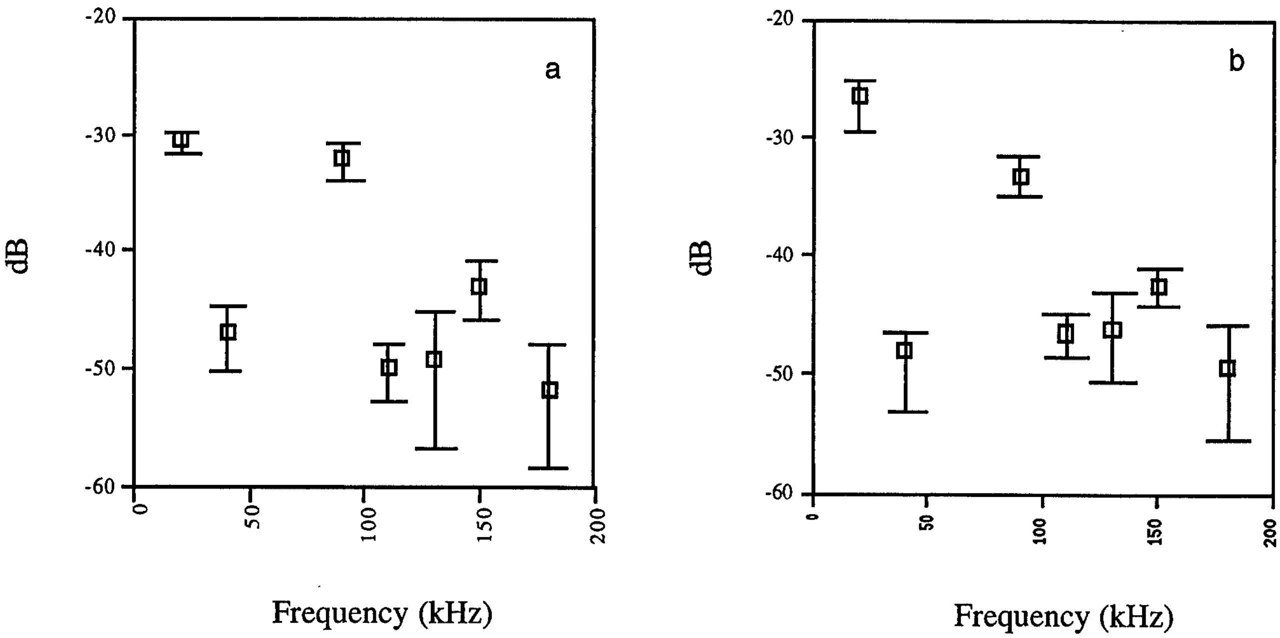


Fig. 13 Mean and standard deviation of 0.5 ms (a) and 1.0 ms (b) pulse length data for hydrophone A at each frequency in Eckernförde Bay.

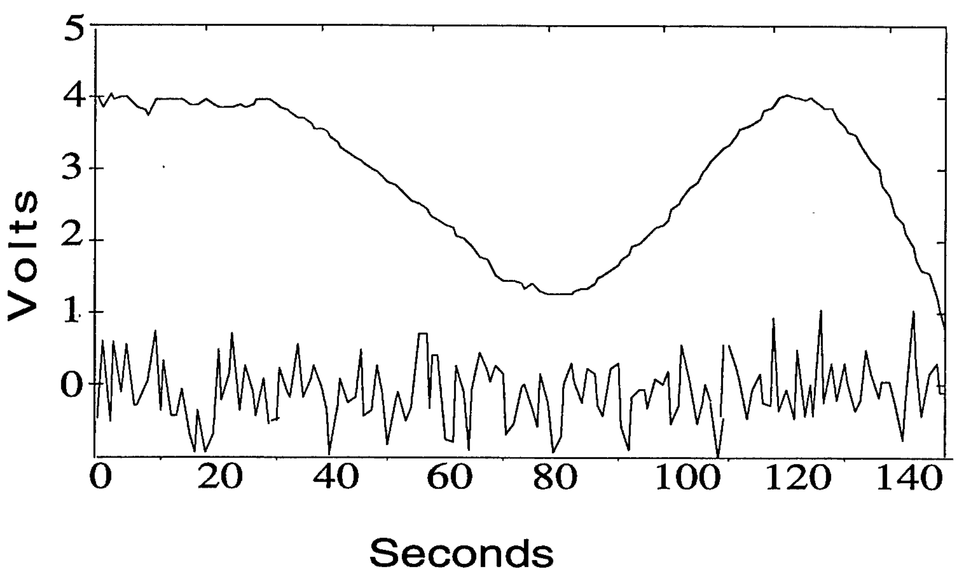


Fig. 14. Variability in data can be separated into trend and short term variability. This example is from the 130 kHz, 1 ms data set taken in Eckernförde Bay.

4 volts. The short term pulse-to-pulse amplitude variation is less than 2 volts. Figures 11 and 12 indicate that the amount of variability for each scale changes with frequency.

Figure 15 compares coefficients of variation for the short term variability and trend versus frequency and pulse length for hydrophone A. Coefficients of variation were higher for the trend than for short term variability at all frequencies and pulse lengths. Only the 130 kHz trend data for 0.5 ms pulses had a coefficient of variation greater than 0.3 (0.54). Trend coefficients for both 0.5 and 1.0 ms pulses at 40 kHz were about 0.3, but in general the three higher frequencies (100, 110 and 150 kHz) had higher coefficients of variation than the three lower frequencies (20, 40 and 90 kHz).

Figure 16 shows means and standard deviations for the 90-kHz trend and short term variability as a function of horizontal and vertical distance from hydrophone A. Along the vertical array, mean amplitudes varied between -31 and - 37 dB. Standard deviations along the vertical array were lowest at the two hydrophones farthest from the vertex. For the trend, standard deviations were 0.3 dB at 51 cm from the vertex and about 2 dB at 5 cm from the vertex. For short term variability, standard deviations were about 0.5 dB for the two hydrophones at 36 and 51 cm from the vertex and about 1 dB closer to the

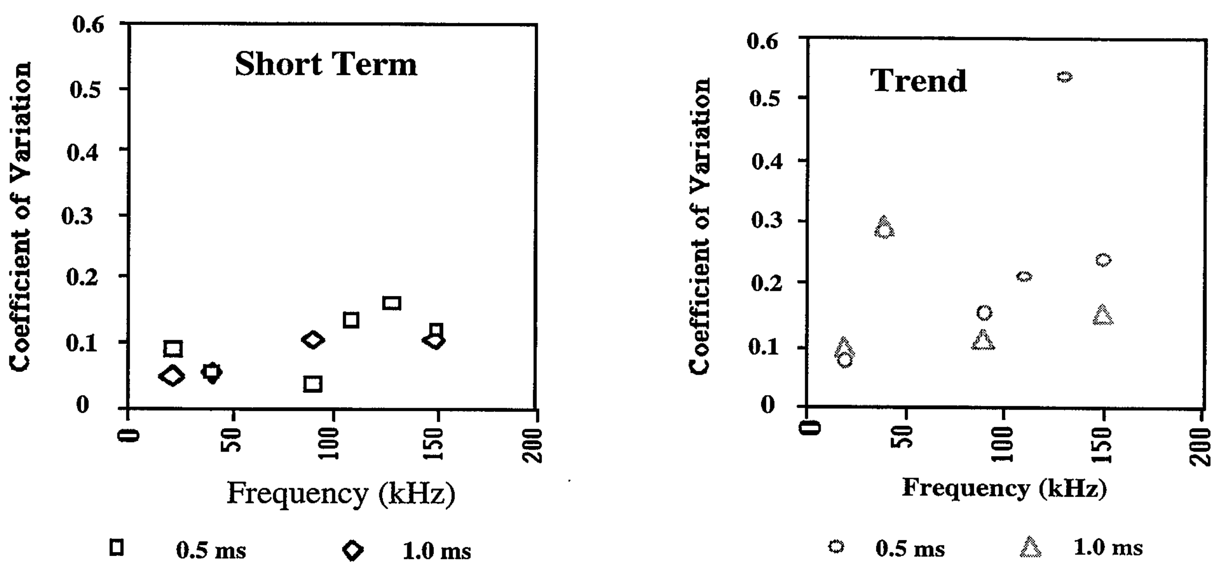


Fig. 15 Direct path coefficients of variation for each frequency and pulse length separated into two time series, the short term variability and trend at vertex hydrophone A, for Eckernförde Bay.

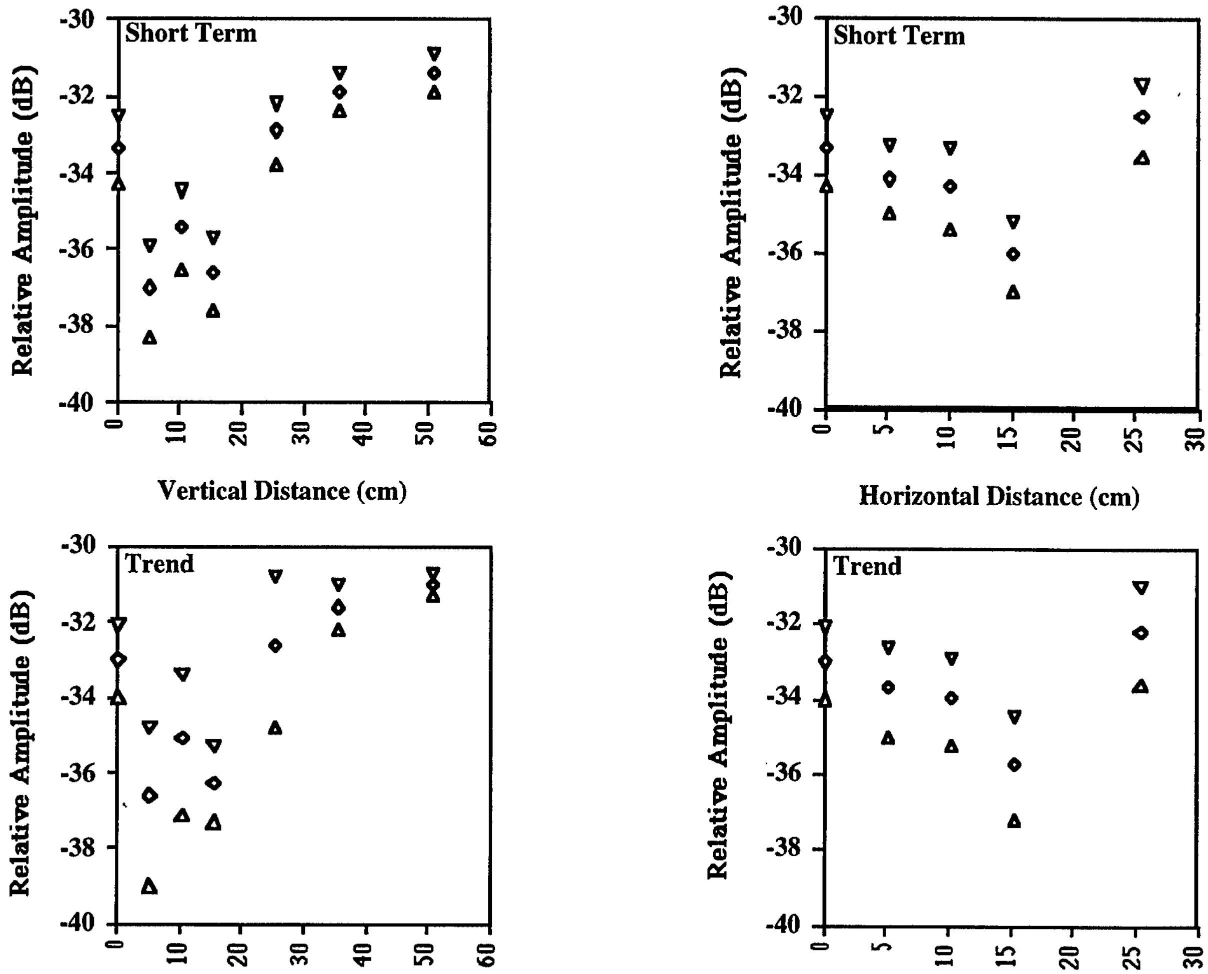


Fig 16. Spatial fluctuations of means and standard deviations for two scales of variability of 90 kHz data from Eckernförde Bay.

vertex. Along the horizontal array, mean amplitudes ranged from about -32 to -36 dB. Standard deviations did not change significantly with horizontal distance from the vertex and were about 1 dB for both trend and short term variability.

Fig. 17 shows coefficients of variation as a function of horizontal and vertical distance from hydrophone A for trends and short term variabilities at three frequencies. For the trends at 20 kHz, coefficients of variation were about 0.1 for all horizontal separations. While the variability of the 90 kHz trend data was slightly higher than 0.1 and that for 150 kHz data set was higher still, no values were much more than 0.2. Corresponding results for the

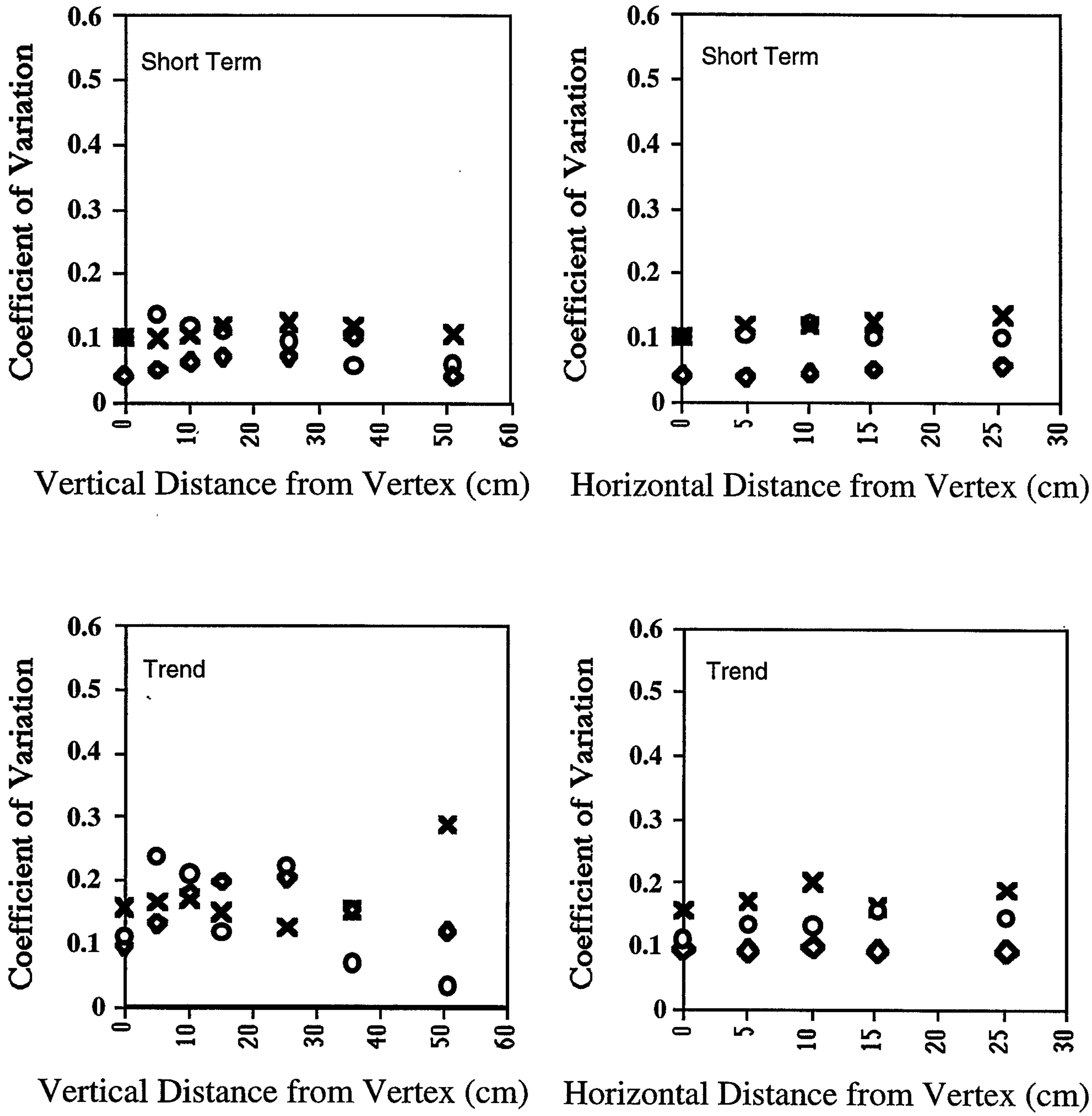


Fig. 17 Spatial variability of coefficients of variation for trend and short term fluctuations from three frequencies of Eckernforde Bay data. The ◊ is for 20 kHz data, the **O** is for 90 kHz data and the **X** is for 150 kHz data.

short term variability of the same three data sets as a function of horizontal distance from the vertex phone show coefficients of variation for 20 kHz were around 0.05 for all phones and for 90 and 150 kHz were at or slightly above 0.1.

The frequency dependence did not seem to change with horizontal distance from the vertex phone. The variability in the trend along the vertical array at 20 kHz was between 0.1 and 0.2 at all distances from the vertex. The 150 kHz trend coefficients of variation were between 0.1 and 0.2 for all except the highest location, where it was 0.3. Coefficients or variation for 90 kHz changed significantly with distance, being as high as 0.23 at 5 cm and as low as 0.04 at 51 cm. The short term variabilities for 20 and 150 kHz changed little along the vertical array. The 90 kHz short term variability generally decreased with vertical distance from the vertex. Overall short term variability levels were about the same for vertical and horizontal distances from the vertex, while variability in the trend changed more with vertical distance than with horizontal distance.

Panama City, 1991

In the signal envelopes from 1991 Panama City data shown in Fig. 18, a weak bottom return overlaps the end of the direct path after 0.8 ms. The width of the observed peak and its shape are strongly correlated with the beam pattern for each frequency. The bottom return is especially evident at 110 kHz.

Figure 19 is a time series plot of pulse to pulse variability of the direct arrival for three frequencies. Long and short term variability are evident and similar to those observed in Eckernförde Bay (Fig. 14). Therefore, the data were processed to provide trend and short term variability time series for each frequency for hydrophone B and for several hydrophones at 25 kHz. An example of the separated data for one of the 90 kHz sources is shown in Fig. 20. The statistics for these time series are shown in Figs. 21 to 23. Note that two sets of data were collected at 90 kHz, one for each source. The period for short term variability was about 3 s. The period for the trend was longer than the measurement time of 100 s except for 110 kHz which had a period about 90 s.

Figure 21 shows the means and standard deviations for the trend and short term variability. Means for 60 and 110 kHz were well below the means of the other frequencies for the same sources. Means for the higher frequency source were generally higher than for the lower frequency source. The 20, 40, and 150 kHz trend data have notably small standard deviations while 110 kHz has a large standard deviation. Except at 110 kHz, standard deviations for the short term are larger than for the trend.

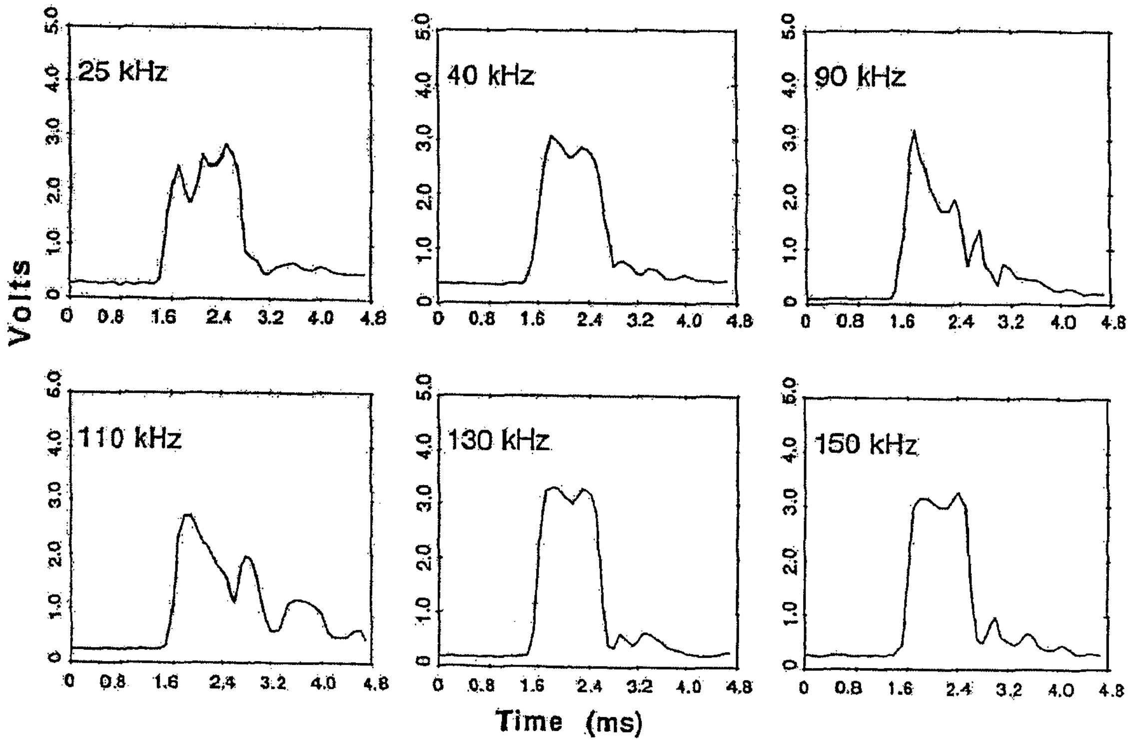


Fig. 18. Mean envelopes of received signals from direct and bottom paths of Panama City 1991 experiment.

Coefficients of variation for the trend and short term variability are shown in Fig. 22. Except for 110 kHz, the coefficient of variation was larger for the short term variability than for the trend. Coefficients for the short term variability were between 0.09 and 0.19, except for 60 kHz where it was 0.28. Coefficients for the trend were between 0.02 and 0.13, except for 110 kHz where it was 0.31.

Figure 23 shows coefficients of variation at 25 kHz for several positions along the horizontal and vertical arrays. Both the short term variability and the trend showed little change with either vertical or horizontal distance from the vertex. Coefficients for the short term variability were between 0.13 and 0.19 and coefficients for the trend were between 0.03 and 0.07.

Panama City, 1993

Figure 24 shows the mean envelope of the 90 kHz data from the 1993 Panama City experiment. The bottom return arrived about 6 ms after the direct and had about the same amplitude. Figure 25 shows the total pulse-to-pulse variability of the direct signal at 90 kHz. Although the data show no obvious trend, a 20 point moving average was applied just as it was for the other

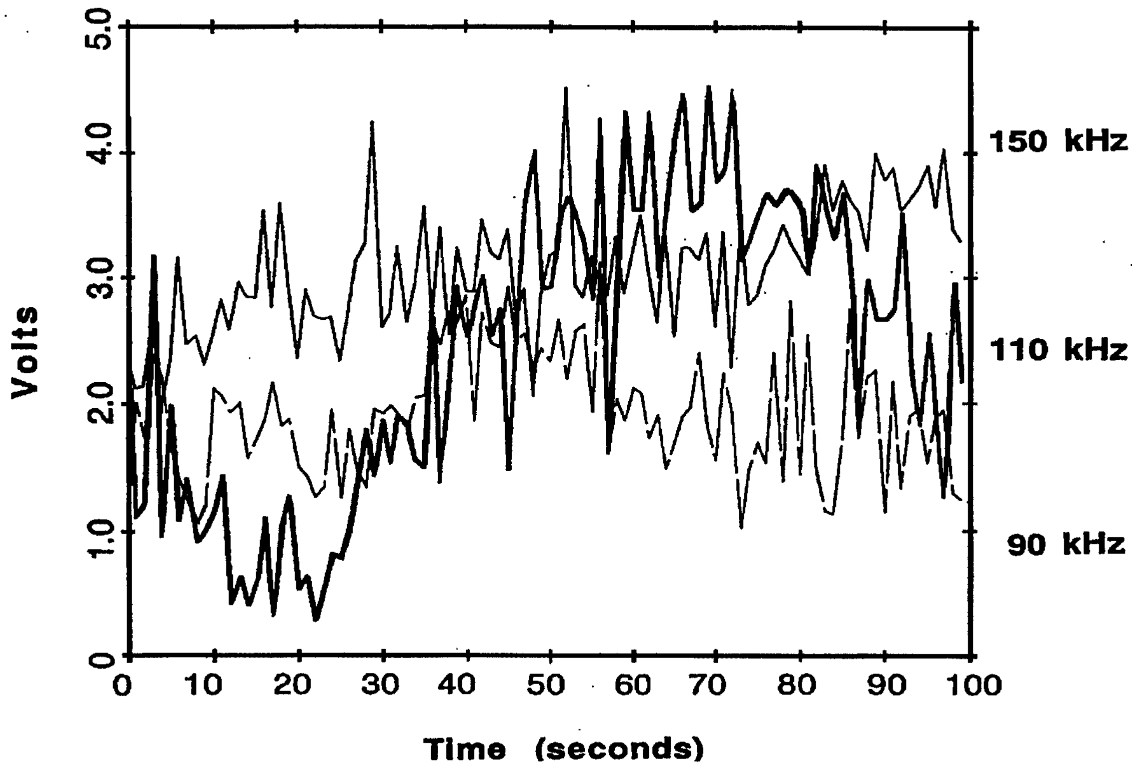


Fig. 19. Examples of variability between pulses for data from Panama City, 1991 experiment. The broken line is 90-kHz, the thick line is 110 kHz and the thin line is 150 kHz.

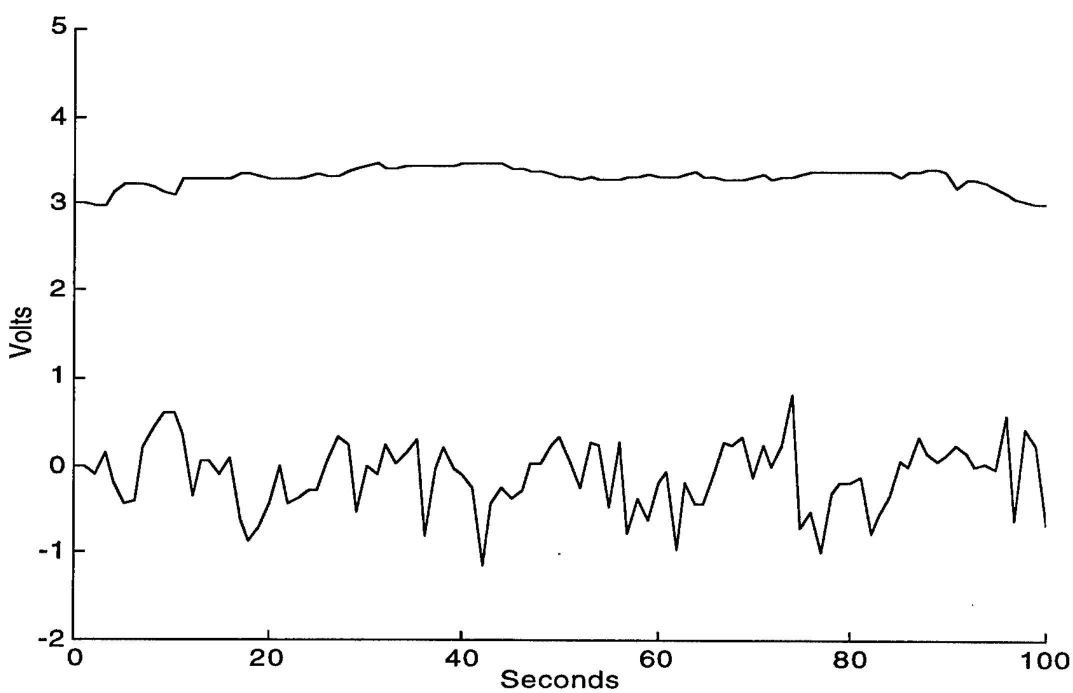


Fig. 20. Panama City 1991 90 kHz data separated into trend and short term variability.

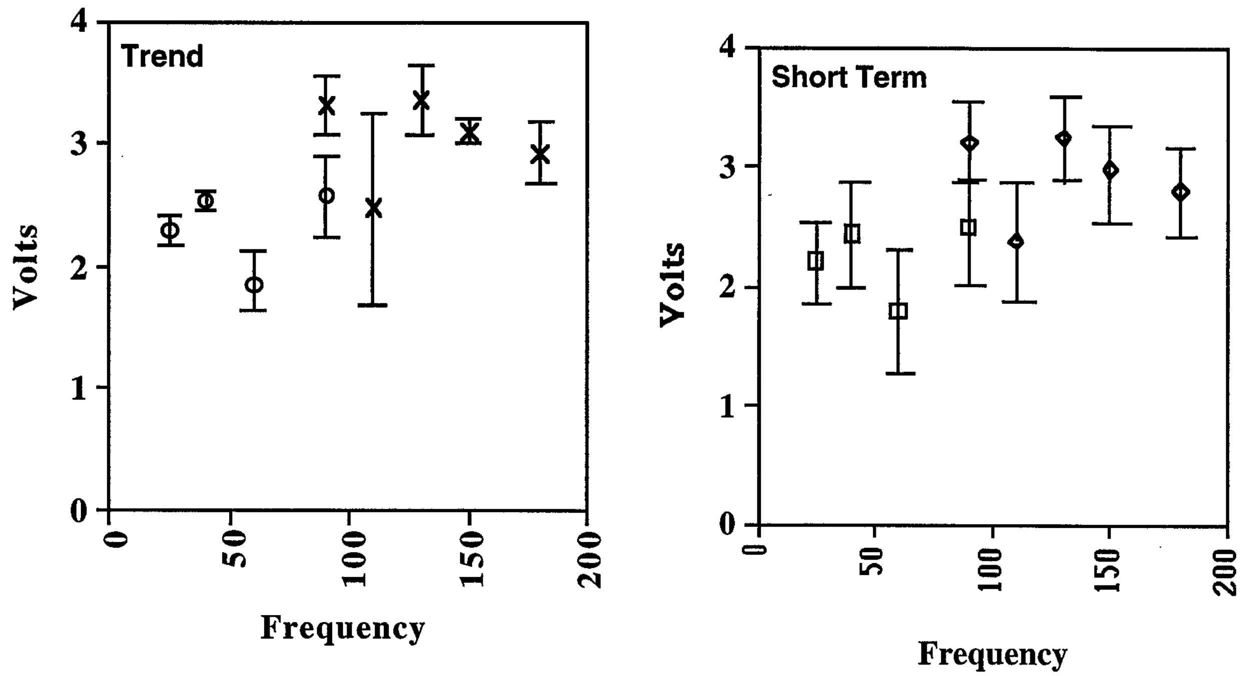


Fig. 21. Means and standard deviations for each frequency for the trend and short term variability for hydrophone B for Panama City 1991

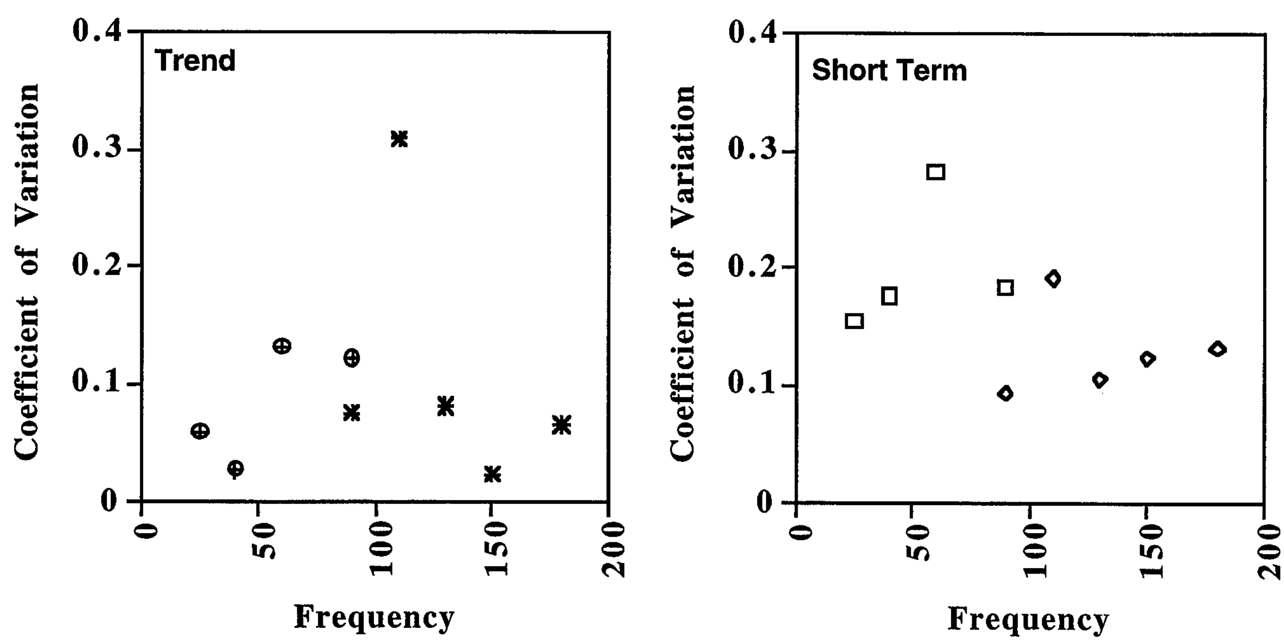
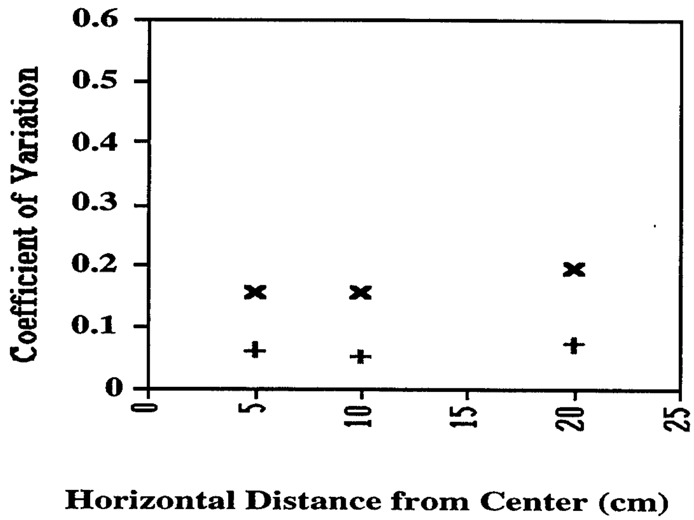


Fig. 22. Coefficients of variation for Panama City 1991 experiment, hydrophone B.



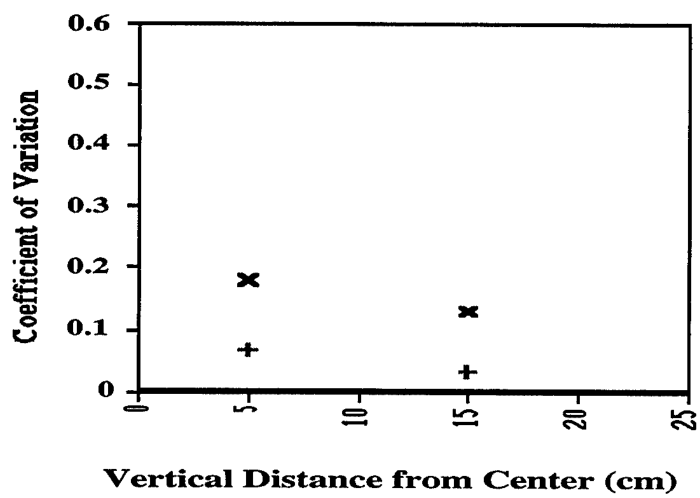


Fig. 23. Coefficients of variation for several different receiving hydrophones in the Panama City 1991 25 kHz data set vs. horizontal or vertical distance from the vertex of the array. **X** - short term, + - trend.

experiments; Fig. 26 shows the time series that result for data for hydrophone A. The amplitude of long term change is small and no periodicity is evident. The period of the short term variability is about 3 seconds.

Figure 27 shows coefficients of variation for short term variability and trend as a function of distance from the vertex of the vertical and horizontal arrays. The coefficients for short term variability were between 0.28 and 0.37 for all hydrophones. Trend coefficients were minimal, about 0.1 for all hydrophones. Thus, spatial differences were small. Also, it was not necessary to separate long and short term variability in this experiment because the variability of the trend was so low.

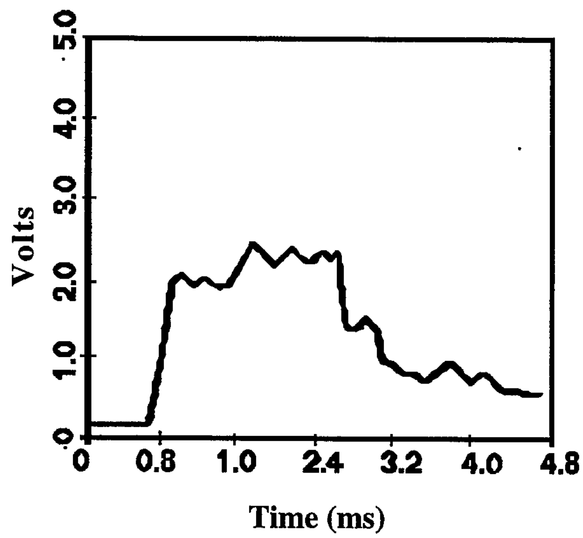


Fig. 24. Mean envelope of 90 kHz received signals from Panama City, 1993.

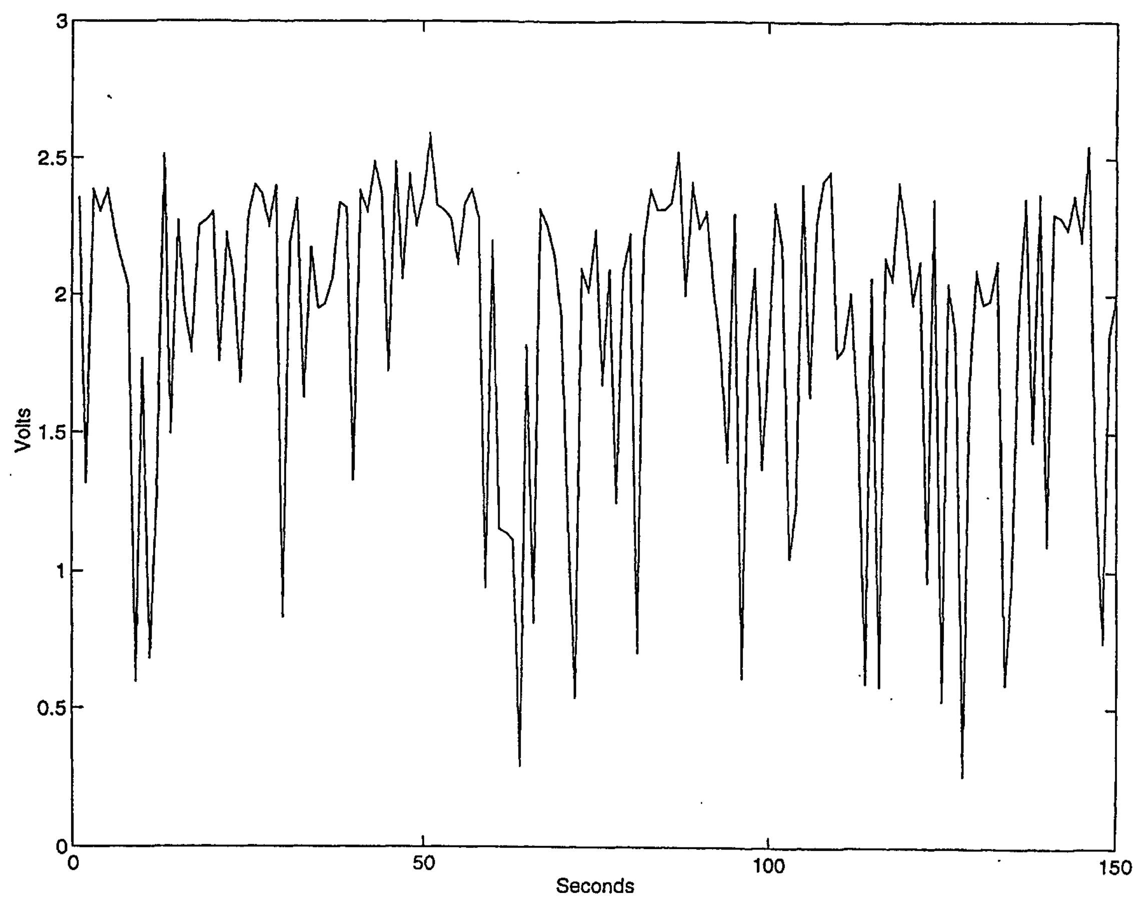


Fig. 25. Total pulse to pulse variability in 90 kHz Panama City 1993 data.

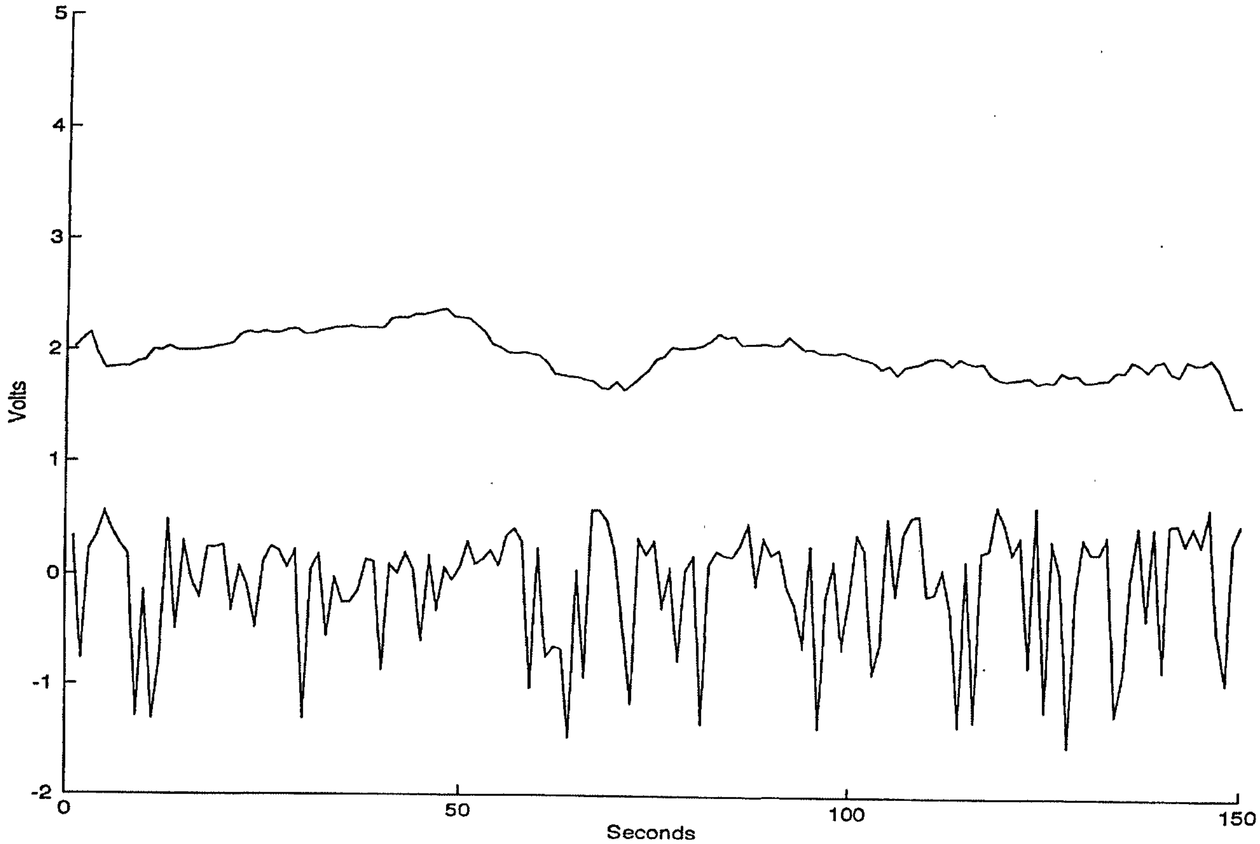
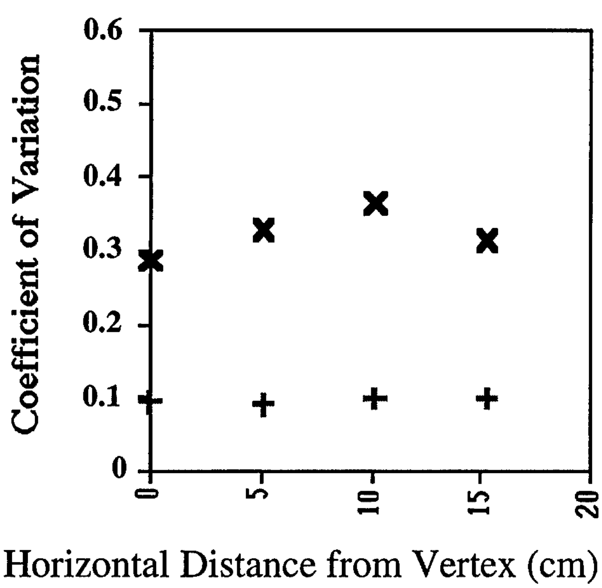


Fig. 26. Panama City 1993 time series separated into trend and short term variability.



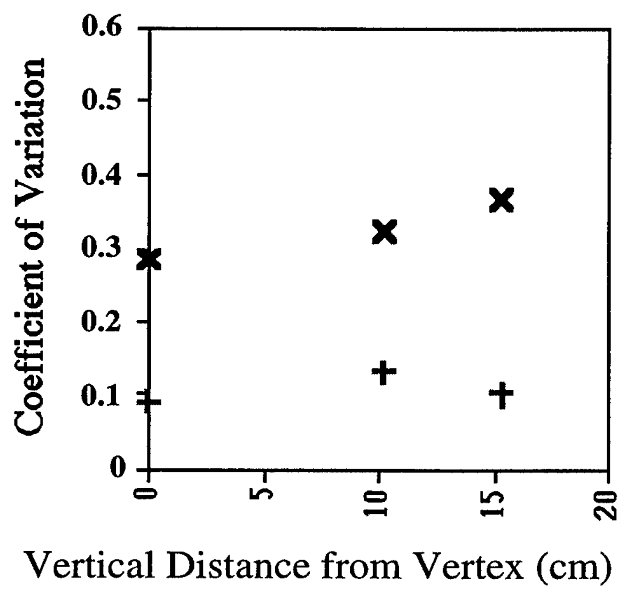


Fig. 27. Spatial variability of coefficients of variation for trend and short term fluctuations from 90 kHz data from Panama City 1993 experiment. **x** - short term, **+** - trend.

DISCUSSION

General Theory

Acoustic fluctuations are caused by small scale changes in oceanic thermal structure. In shallow water, wind waves are a major contributor to variability with periods of a few seconds, while internal waves generate variability on the order of minutes to hours.[9] The displacement amplitude (a) of swell orbitals generated by surface winds is given by

$$a = a_o \exp(-2\pi z/\lambda) \tag{1}$$

where a_o is the orbital displacement amplitude at the surface, z is depth, and λ is the surface wavelength.[9] The natural frequency of random short scale internal wave motions found around the world falls between the Coriolis (inertial) frequency, ω,

$$\omega = 2\Omega \sin \varnothing \tag{2}$$

and the Brunt-Väisälä (buoyancy) frequency, n(Z),

$$n(Z) = [\ -g/\rho\ d\rho/dz\ -\ g^2/c^2]^{1/2} \tag{3}$$

where Ω is the earth's angular velocity, $\varnothing$ is the local geographic latitude, g is the acceleration due to gravity, c is the speed of sound and ρ is the density of sea water.[10]

Eckernförde Bay

Internal waves

Friedrichs and Wright describe the internal waves in the Baltic and calculate their effects on a basin such as Eckernförde Bay, which has a shallow mouth.[11] The barotrophic internal wave associated with the overall Baltic seich forces a baroclinic internal wave moving at 30 cm/s in the 15 km long by 4 km wide bay with a 26 to 28 hour period. The change in sea level in Eckernförde Bay has been shown to correlate with the internal wave related to the Baltic wide seich to a greater extent than it does with the lunar tide cycle. Conditions were often right during April and May of 1993 to form a resonant standing wave with its first mode wavelength equal to the length of the bay.[11] Internal waves related to the Baltic seich, with periods of the order of one day, would have little effect on the acoustic measurements.

A detailed look at the Baltic Sea environment and Eckernförde Bay shows a mean surface salinity of 16 parts per thousand and mean near bottom salinity of 22 parts per thousand with a steep interface about 15 m below the surface corresponding to the thermocline shown in Fig. 7. This two-layered system is conducive to oscillations at the interface. For Eckernförde Bay in May, between 16 and 23 m depth the change in density with depth, $d\rho/dz$, was 0.129 $kg/m^3/m$.[11] The spectrum of acoustic data trend, taken 6.85 m from the bottom, peaks about 6.7×10^{-3} Hz with a period of 2.5 minutes (see Fig. 12). This is consistent with the observation that the buoyancy period is typically shorter near the thermocline where the density gradient is strongest.[12]

In the early afternoon, the tidal current was going out and the wind was from the southwest, reinforcing the outward flow of the surface water. The undertow would bring in water from the deeper layer as the tide pushed the upper layer out. Therefore, as the afternoon progressed, the thermocline would become shallower as indicated by the decrease in pitch of the maximum response axis of the acoustic sources, until low tide occurred and the process was reversed. Additional turbulence would be expected when the wind and the movement of the surface current were in opposite directions.[13] This may have contributed to making the period of the fluctuation in the trend more irregular in the 40 and 90 kHz runs. The 20 kHz data taken before and after the CTD measurements had very little variability in the trend. The beam pattern at this frequency was so wide that the amount of change in the depth of the thermocline and the angle of the maximum response axis did not change the amplitude appreciably in 2.5 minutes.

Wind waves

Wind waves can be a major contributor to short term variability. The short term variability of acoustic data sets from Germany exhibited periods from 3 to 5 seconds. Winds measured at Lighthouse Kiel[14] during the experiment on May 14 varied from 6.2 to 8.2 m/s. These wind speeds resulted in wind waves sufficient to induce only a small amount of short term variability, such as that seen in the 20 and 40 kHz runs. The change in current speed caused by wind waves would not, by itself, be enough to account for the short term variability seen in the higher frequency acoustic signals, but could combine with narrow beamwidths and intermittent multipath conditions, which will be discussed later, to give the results seen. The average surface winds, which were between 7 and 8 m/s while most of the data was collected, would produce an orbital displacement amplitude of 1.5 m at the surface When surface wavelength and displacement amplitude estimation techniques from Kinsman[13] were used with equation 1, the displacement amplitude of swell orbitals at the source depth of 20.5 m was 0.26 cm At 18 m, the depth of the thermocline at the time of the sound speed measurement in Fig. 7, there would be 0.56 cm of particle motion, which is a little more than half the acoustic wavelength at 150 kHz.

Current Speed Variability

Fig. 28 shows that there are fluctuations in the near-bottom current speeds in Eckernförde Bay which have approximately the same time scales as fluctuations in amplitudes of the acoustic signals in Fig. 13. The spectrum of the trend in the current speed variations indicates that the internal wave frequency near the bottom of the bay has a period of about 4 minutes. Short term current speed changes of about 2 cm/sec with a period about 6 seconds are attributed to wind wave orbitals. This amount of change in current speed would deflect the acoustic energy by a few hundredths of a degree. At 1 m from the bottom, maximum current speeds were about 10 cm per second but they were increasing with distance from the bottom.[15]

Multipath and thermocline depth changes

Some differences among frequencies, especially in the trend, result from changes in the environment between the times that data for different frequencies were collected. The sound speed profile in Fig. 7 was obtained at 19:21 (all times are local). The ray trace in Fig. 7 indicates that a 1° upward pitch angle directs the maximum response axis of the source at the array without a multiple direct path situation. A 0.7 m increase in the thermocline

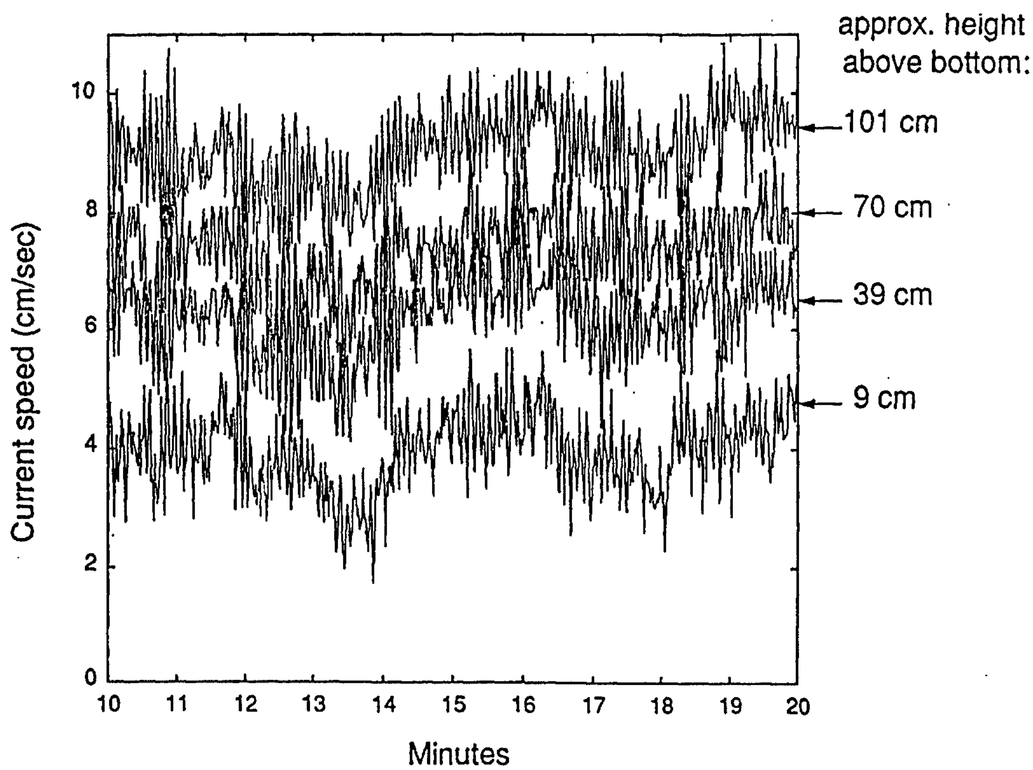


Fig. 28. Variability in near-bottom currents for Eckernförde Bay.[15]

depth as illustrated in Fig 29, would result in multipath arrivals. Prior to measurements at higher frequencies, which took place between 14:56 and 15:45, the optimum pitch angle was determined to be 2° upward. Modifying the measured sound speed profile by increasing the depth of the thermocline by 1.1 m and leaving the slope the same results in an optimum pitch angle of 2° upward, as shown in Fig. 30. However, the ray trace indicates that there are multiple direct paths at 2° and 4° at the receiver. For the lower frequency measurements, which began at 16:09, the source was directed upward at 0.4°. Figure 31 indicates that a downward shift of 4.1 m in the depth of the thermocline from about an hour before was required for 0.4° to become the optimum pitch angle. A large change in thermocline position is not unusual where internal waves are found. For this case, there are no multipaths. Figures 11 and 12 show less short term variability at 20 and 40 kHz and very little change in the trend level for 20 kHz, which has a relatively wide beam pattern. Even without multipath arrivals, a temperature change as little as 2°C in the thermocline could cause the ray that arrived at the receiver to change by

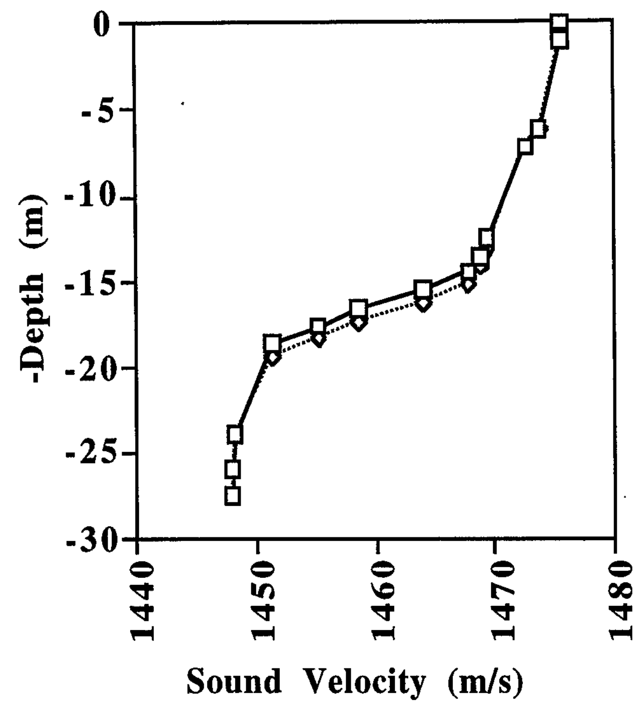


Fig. 29. Increasing depth of thermocline by 0.7 m would result in multipath arrivals at receiver depth.

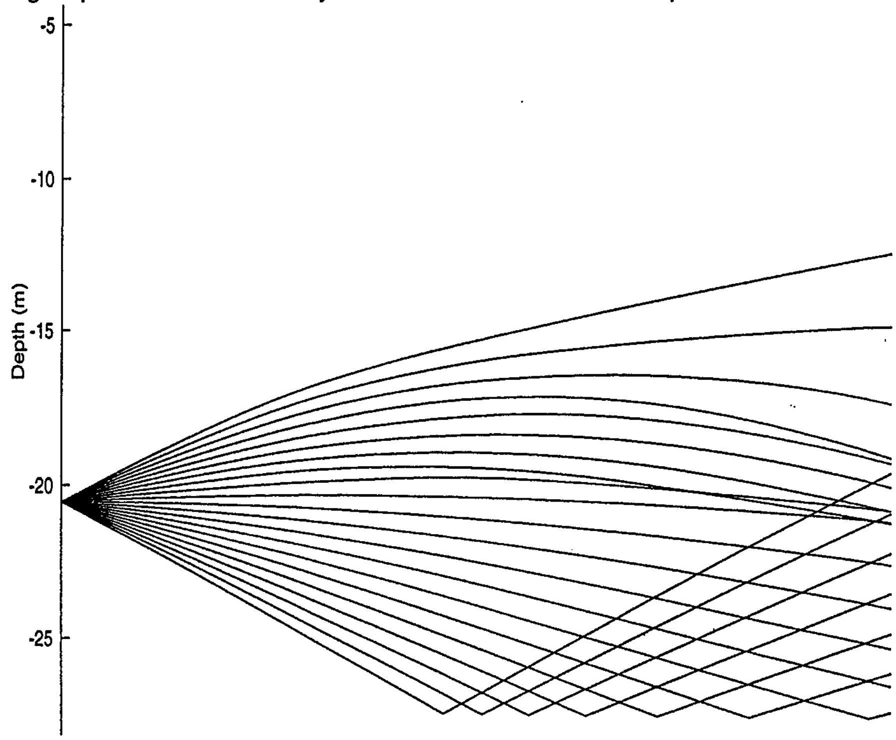


Fig. 30. For 110 to 180 kHz the source pitch was 2° up. The 2° ray is at 20.6 m depth at 81 m range in this ray trace along with the 4° upward ray. The depth of the thermocline was increased by 1.1 m from the measured depth to produce this picture.

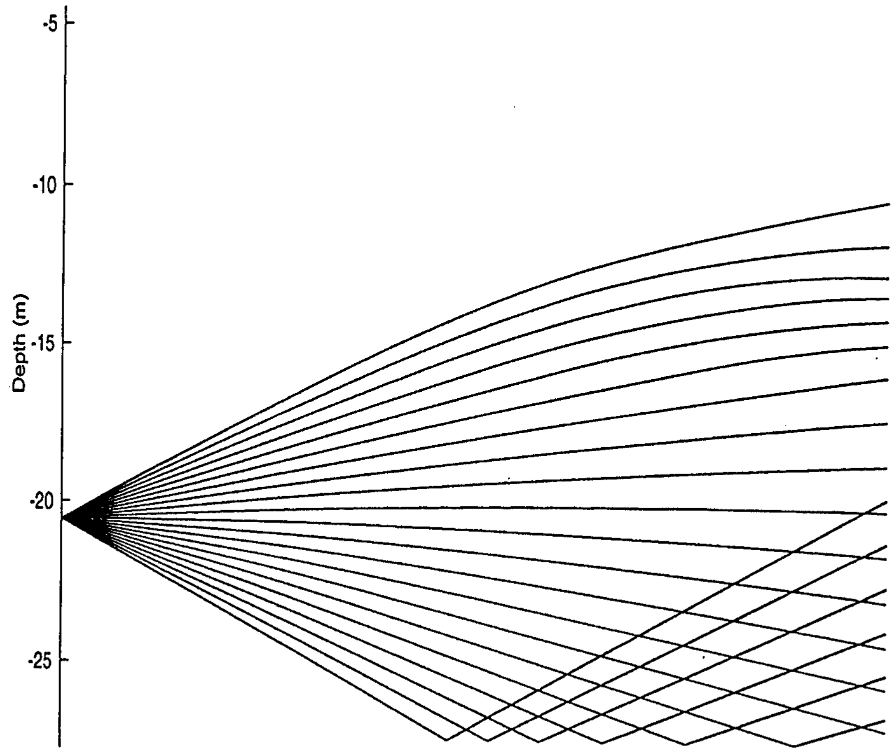


Fig. 31. Before the 90 kHz runs the source pitch was changed to 0.4° up. The measured depth of the thermocline had to be decreased by 3 m to make this the angle of maximum reception at the receiver.

1°, causing the amplitude of received signals to vary by a dB or more at the higher frequencies where the beamwidths are narrow. Phase differences between multipath arrivals, which change with the wind wave effect, could produce larger short term variabilities. Frequency differences shown in Fig. 13, therefore, show a combination of temporal and multipath effects.

Phone position effects

Comparisons of variability in means and coefficients of variation over the array are more reliable than frequency comparisons since the data for all channels were collected nearly simultaneously. In other experiments, transmission loss (TL) fluctuations of as much as 20 dB have been reported over a vertical distance of only a few inches in the vicinity of a steep temperature gradient[16] such as shown in Fig. 7, so the 1 to 5 dB standard deviations in the Eckernförde Bay data are not unreasonably high. The wavelength of the acoustic signal at frequencies over 100 kHz is of the order of 1 cm. Thus, an undulation of 0.5 cm due to internal waves or wind wave orbitals could make differences in the phase that would vary with the depth of the rays and the hydrophones, so that multipath interference at these frequencies would add to the amplitudes of the fluctuations in the trend and the short term variability.

Panama City, 1991

Wave height vs. time (Fig. 32) was recorded for the Panama City experiment in 1991.[17] There are, as usual, a combination of wavelengths shown, but the resulting periods for four such data blocks taken on August 23 ranged from 2.2 to 3.3 s. The period of the short term acoustic fluctuations for this time was about 3.1 s and also appears to be a combination of wavelengths (Fig. 19). High frequency fluctuations thus appear to be connected to swell and wind waves even though they give water particle motions of a centimeter or less at the

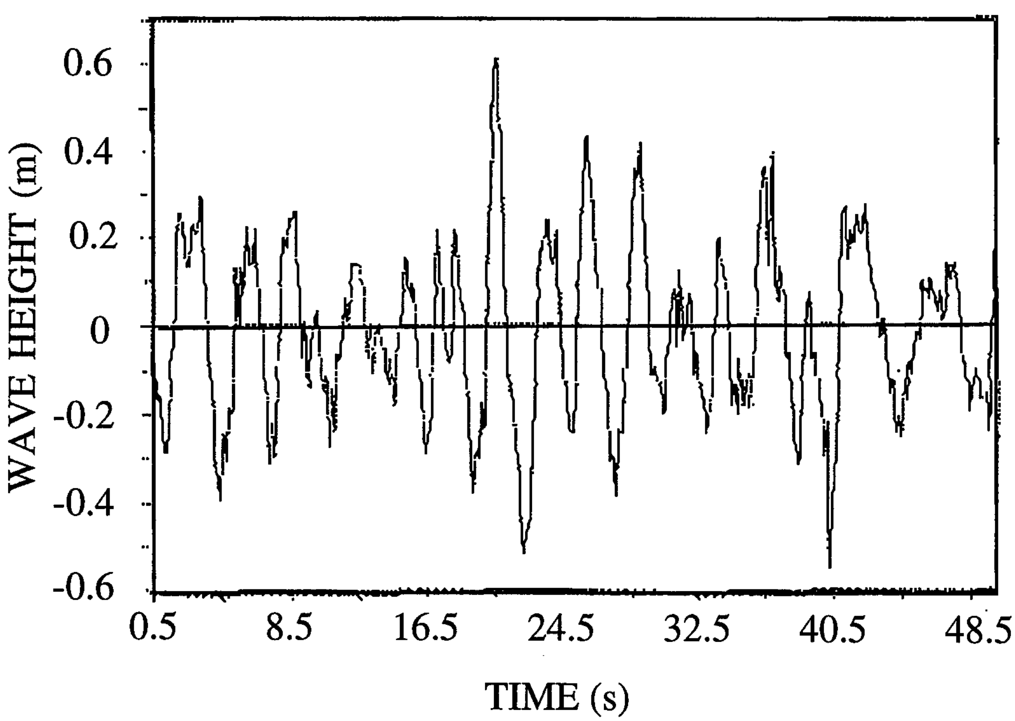


Fig 32. Waverider buoy data shows swell periods similar to that of the acoustic fluctuations.[17]

depth of the direct path acoustic transmissions. The connection may be due to the effect of the waves on the thermal structure of the water column rather than to the amplitude of particle motion they produce.

Panama City, 1993

A survey of all the CTD data taken during the Panama City 1993 experiment reveals that the depth of the thermocline varied by up to 7 m. Time of day for the readings varied as did state of the tides. Some correlation was found between the tide cycle and the depth of the thermocline in data from this experiment.[18]

Comparisons between Experiments

The gradients of the Panama City sound velocity profiles are not as steep as those for the experiment in Germany. Whereas the fluctuations in the trend were a major factor in the total variability in Eckernförde Bay, they were much smaller than the short term variability in the data from Panama City in 1991, except for the 110 kHz run. For Panama City in 1993, both the trend and short term variability have less sinusoidal character than the data from Germany. Panama City 1993 variations were lower than the Eckernforde Bay results for the trend along the vertical arm of the array and higher for the short term variability for both parts of the array. In both Panama City experiments, acoustic amplitude fluctuations had more random time series and large changes in the trend levels were rare. Random patches in the thermal structure of this water mass seem likely along with more random internal waves and multipath interference. In Panama City, stronger tidal influences gave greater short term variability than seen in Germany.

Sound speed profiles and ray traces shown in Figs. 4, 7, and 8 are those obtained closest to the day and time that the fluctuation data were collected, but were not taken at the exact time of the acoustic measurements. With the thermocline around 15 m depth, the upward traveling rays are bent down to form a convergence zone a few meters above and a few meters beyond the receiving tower in both 1993 experiments. Sound speed profiles taken in Eckernförde Bay on other days during the experiment showed the depth of the thermocline varying as much or more than it did in Panama City. Changes in the depth of the steep thermocline may be placing the convergence area closer to the receiving hydrophones during data collection than it would appear from the sound speed profiles shown thus making multipath interference a factor in the fluctuations.

SUMMARY

In these three experiments, the goal of measuring the effects of different shallow water environments on propagation of high frequency acoustic signals was accomplished. The temporal variability of the signal amplitudes was sensitive to changes in the environment that occurred at two different time scales. Fluctuations with a period of several seconds appear to correspond to the orbital motion of the water column caused by wind waves or swell and their effect on the thermal structure below. This is the main source of variability in the 1993 Panama City data and for most frequencies in the 1991 Panama City data. Amplitude variations with a period of 1.5 minutes or longer in addition to short term variations were especially common in the Eckernförde Bay experiment. The conditions in the bay are known to produce internal waves that give current speed oscillations with a period of 4 to 5 minutes near the bottom.[10] This mechanism, perhaps in conjunction with a multipath situation with gradually varying phase differences, could produce the fluctuations seen in the trend of the data from Germany.

Analysis of the direct path data has yielded statistics for a wide range of frequencies. The 1991 Panama City envelopes were similar to those from Germany, with features mainly representing the beam patterns. Below 90 kHz the source beamwidths were sufficient to result in time spreading of the signal beyond the 1 ms pulse length.

Coefficients of variation for the horizontally separated phones were more stable than those for vertically separated phones because changes in sound speed occur more gradually in the horizontal plane. These data show that there was good spatial coherence in the horizontal plane for up to 25 cm separations in both the Panama City and Eckernförde Bay environments.

ACKNOWLEDGMENTS

The author wishes to thank Dr. Richard H. Love for his careful review and many beneficial suggestions and Dr. Michael D. Richardson for providing some of the most helpful references on this topic. This work was sponsored by the Office of Naval Research with management by the Naval Research Laboratory under Program Element 0602435N.

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