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Acoustic Volume Scattering at the Bermuda Ocean Acre Site (Cruise 14 and Related Earlier Studies)

Norbert P. Fisch
Special Projects Department



3 January 1977

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PREFACE

This study was performed under NUSC Project No. A-626-02, "Biological Reverberation As It Affects ASW Operations," Principal Investigator, C. L. Brown, Jr. (Code 311), and Navy Subproject and Task No. SF 52 552 701-TU0203, Program Manager, A. Franceschetti (SEA 06H1-4).

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total-column strengths at night were only 3 to 4 dB above daytime levels. Because of this small difference, the latter result is considered inadequate in describing the large diurnal variations associated with the vertical migration of scatterers. Unlike earlier results, night-to-night variability of scattering strength during the stable period was as large as 10 dB for all of the frequencies over most of the water columns. At all of the frequencies, nighttime scattering strengths peaked within 120 m of the surface. At 13.50 and 15.50 kHz, additional contributions occurred in the depth interval from 250 to 550 m. The spectra of total-column strengths exhibited a broad resonance centered about 9.00 kHz which was unlike the low- and high-frequency resonances found in earlier studies. Scattering strength at 3.85 kHz experienced an increase from spring to summer, although the amounts were not the same in two different years. An inverse trend was noted in the 15.50-kHz data. Statistical tests of means and equivalence of distributions supported the argument that variations among profiles from different seasons or years were significantly greater than those among the day-to-day profiles.

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ACOUSTIC VOLUME SCATTERING
AT THE BERMUDA OCEAN ACRE SITE
(CRUISE 14 AND RELATED EARLIER STUDIES)

INTRODUCTION

Biologically caused volume reverberation continues to be a major source of interference in the performance of present-day active ASW sonar systems. The ability of living organisms to scatter acoustic energy can cause masking of the echo signal of a submarine target so that the target is completely obscured by the background reverberation level. The primary mechanism producing this phenomenon is recognized as the damped resonant oscillations by which the gas-filled swim bladders of certain fishes respond to the acoustic excitation. These fishes inhabit most ocean areas and form sound-scattering layers (SSL).¹

Composition and behavior of the SSL have been the subject of numerous studies by both military and civilian institutions. Our knowledge of the geographical, seasonal, and diurnal variation and the frequency and depth dependence of volume scattering have been derived experimentally from acoustic as well as biological measurement programs.^{2,3,4}

One of the most systematic and comprehensive investigations into the biological nature and composition of the SSL and their acoustic characteristics has been the Ocean Acre Program,^{5,6} a seasonally repeated study concentrating on a 1-deg square of ocean area located approximately 30 nmi southeast of Bermuda.

The present report discusses and analyzes the acoustic data obtained during USNS SANDS' Ocean Acre Cruise 14, the last of the series, that took place in June 1972. In addition, these data are compared with previously reported Ocean Acre results.^{7,8} For ease of interpretation, the investigation results have been divided into four categories: diurnal variations, daily variability, frequency dependence, and seasonal dependence of volume scattering strength. Before the results are discussed in detail, the experimental procedure and theoretical expressions used in calculating volume scattering strengths are summarized.

EXPERIMENTAL PROCEDURE

The data acquisition and reduction systems employed during the Ocean Acre experiments have been previously described in detail.⁷ Generally, the data were obtained with highly directional, downward-pointing transducers operating at frequencies of 3.85, 5.00, 7.00, 9.00, 13.50, and 15.50 kHz with 5-msec pulse lengths.

The reverberation signals received by all transducers were envelope-detected, ensemble-averaged over eight consecutive pings, and converted to scattering strengths as a function of depth. The resulting scattering-strength profiles were also integrated over depth to yield "scattering strengths of the water column" (column strengths) for comparison with the data of earlier investigations.

THEORY

Volume scattering strength is a quantity that expresses in decibels the unit-volume backscattering coefficient. Assumptions forming the basis for the model of volume reverberation used in this analysis have been described previously.⁸

In logarithmic form, the equation defining the scattering strength as a function of the reverberation voltage level V_R due to a scattering volume located at range r is

$$10 \log \frac{m_y}{4\pi} = 20 \log V_R + 20 \log r - 20 \log R_R - 20 \log P_0 - 10 \log \frac{cr}{2} - 10 \log \Omega, \quad (1)$$

in which

- R_R is the receiving voltage response of the constant-gain measurement system;
- P_0 is the transmitted, on-axis, farfield, rms sound pressure referred to a unit distance from the source;
- c is the sound speed in water;
- τ is the pulse length;
- and Ω is the solid angle at the source subtended by the reverberating volume or, in other words, the opening angle of the ideal two-way beam pattern having uniform response within Ω and none beyond.⁹

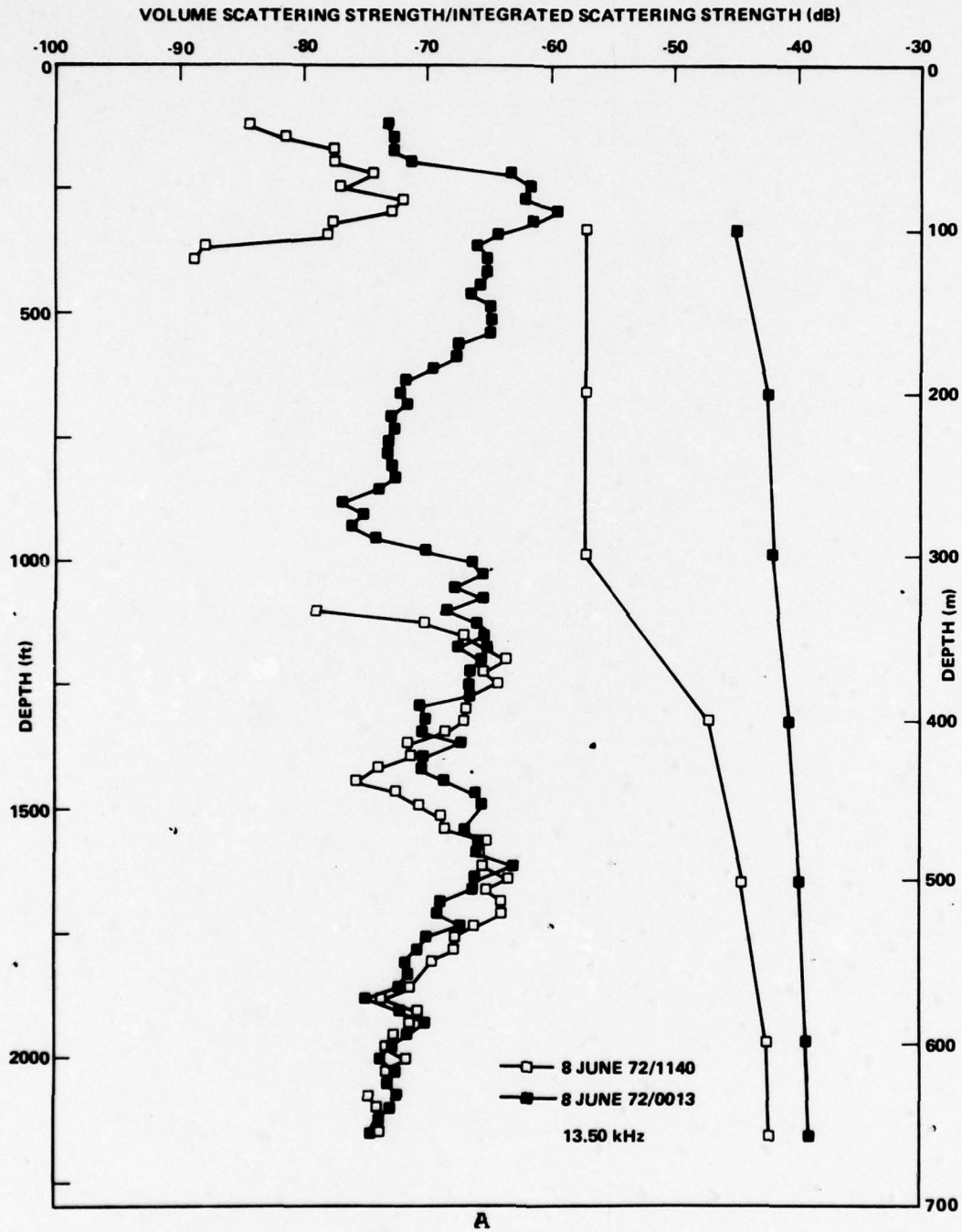
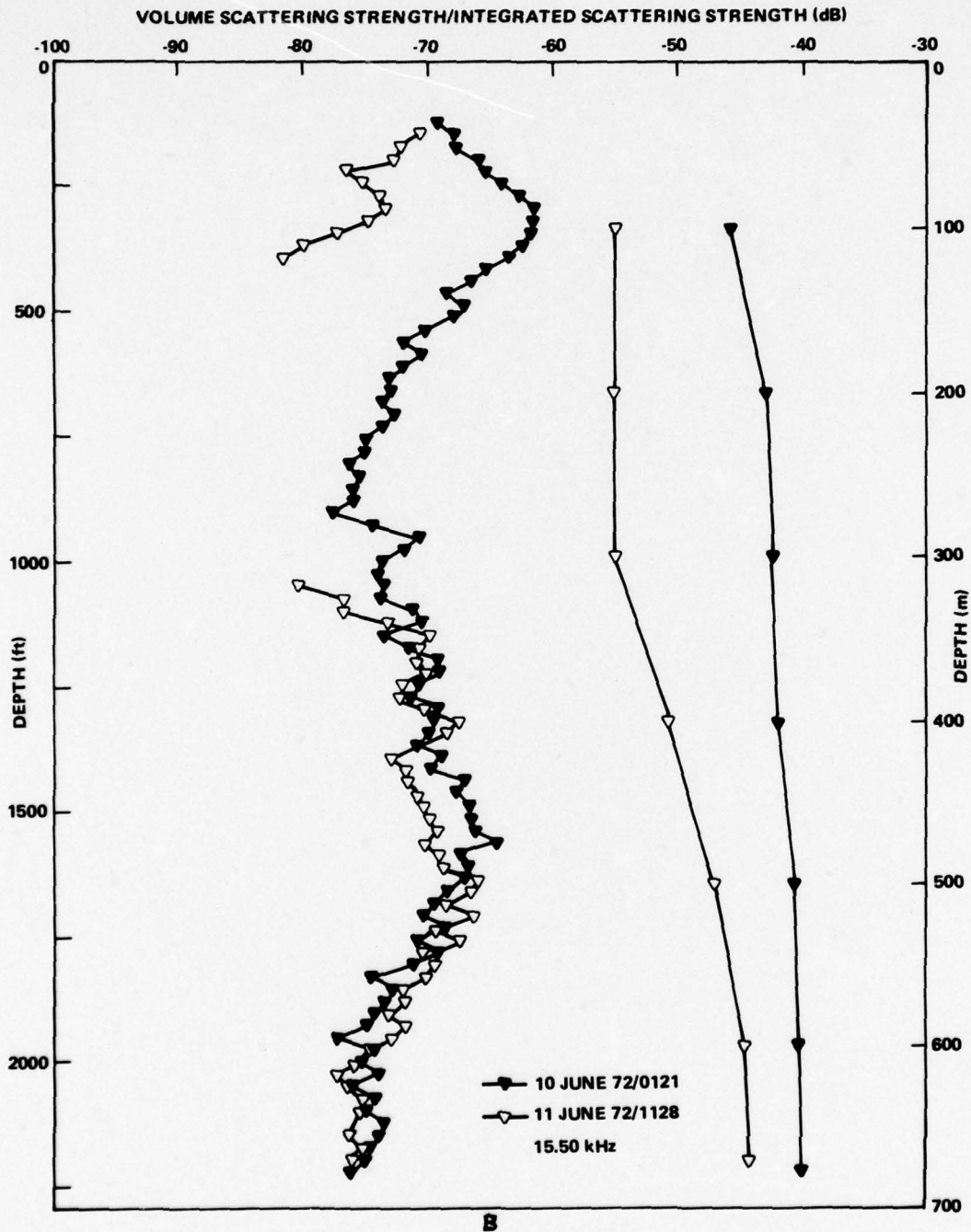


Figure 1. Diurnal Variations of Scattering Strength, Ocean Acre Cruise 14



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Scattering-strength profiles calculated by equation (1) and presented below were obtained for an ensemble average of returns from eight consecutive 5-msec pulses transmitted with constant p_0 in a period of approximately 1 min. Produced on a high-speed printer, the graphs are composed of a finite data point for every 25 ft (7.6 m) of depth, each representing a 10-msec time-average value. They are corrected for noise by subtraction of the mean square of the ambient-noise voltage from the mean square reverberation-plus-noise voltage.

Integrated or column scattering strengths were generated from the profiles by the following process:

$$10 \log \left[\int_{z_1}^{z_2} \frac{m_v}{4\pi} dz \right] \approx 10 \log \left[\sum_{i=1}^N \frac{m_v(z_i)}{4\pi} \Delta Z \right], \quad (2)$$

where z_1 and z_2 are the initial and final limits of integration over depth z . For the cumulative summation, depth increments of $(\Delta z) = (25/3)$ yd, equal to the resolution of the profiles, were chosen, and results are presented for selected depths.

RESULTS

DIURNAL VARIATIONS

Typical examples of scattering-strength results for stable, nonmigratory layer configurations both at midday and in the middle of the night are presented in figures 1A and 1B. The open symbols signify daytime values, and the solid symbols denote nighttime values.

Concentrations of scatterers resonant at 13.50 and 15.50 kHz are very similar for both day and night measurements, especially below a depth of 350 m where the main body of scatterers is located. This trend had also been observed at these frequencies during the two previous summers.⁸ The major nighttime peak is centered at a depth of approximately 100 m, with a pronounced drop-off toward shallower depth, indicating the absence of scattering contributions from immediately below the surface. The daytime profile in the upper 330 m is 10 to 15 dB below the night-

time profile. However, from 120 to 330 m, the signal was below the measurement threshold of the data acquisition system, and the scattering strength was at least as low as -100 dB. No results are plotted above 40 m because transducer ringing contaminated that portion of the data. Reverberation signal levels during the daytime at all of the lower frequencies were also below measurement threshold, thus making a diurnal comparison at these frequencies impossible.

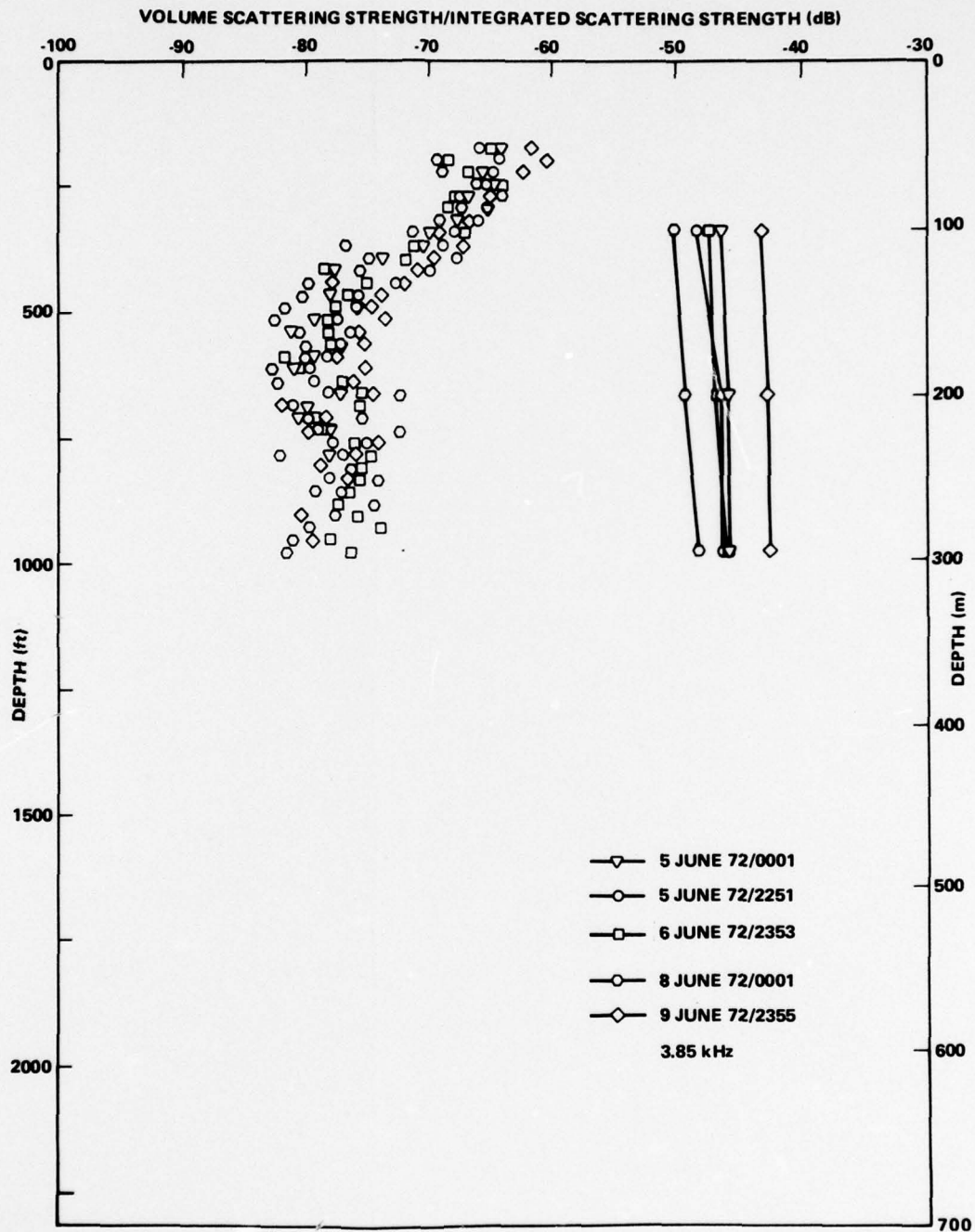
To the right of the profiles in figure 1, a cumulative summation of scattering strength over depth is displayed in 100-m increments, showing a maximum day-night difference of 12 to 15 dB for both data sets to a depth of 300 m. Below this depth the day and night column strengths converge to within 3 or 4 dB of each other in the vicinity of 650 m. These deepest values correspond to the scattering strength of the water column usually reported in the literature as the result of measurements performed with explosive sound sources. The rather close agreement between daytime and nighttime total column strengths is evidence that this latter form of result is not a true indication of the large diurnal variations caused by the vertical migration of scatterers.

DAILY VARIABILITY

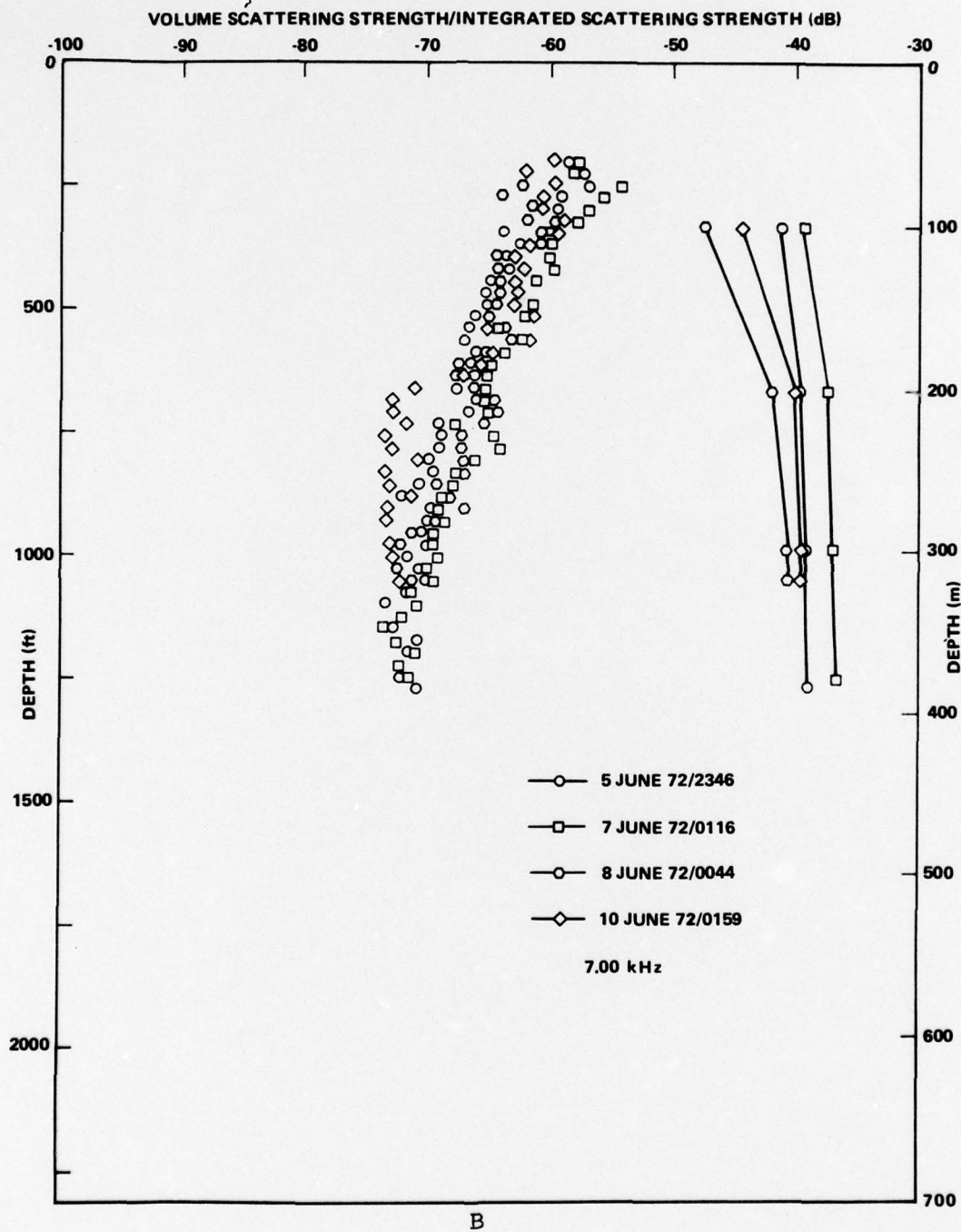
Figures 2A, 2B, and 2C indicate the variability of scattering strength observed at the Ocean Acre site during a period of five days. Results derived from nighttime measurements are shown for 3.85, 7.00, and 15.50 kHz. Five sets of data are available at 3.85 kHz and four each at the other frequencies. Results for 5.00 and 9.00 kHz were similar to these.

A notable similarity among the groups of profiles is that variations as large as 10 dB occur for each of the frequencies over most of the water column. On the whole, major features in the shapes of the profiles, such as the peak in the depth interval from 50 to 100 m and the decline in values below that depth toward a depth of 250 m, are also common in each set as well as among the various sets.

Even though the profile values may vary at any given depth by as much as an order of magnitude regardless of the frequency, the associated total-column strengths exhibit a certain trend. Maximum daily variations of 6 dB are found



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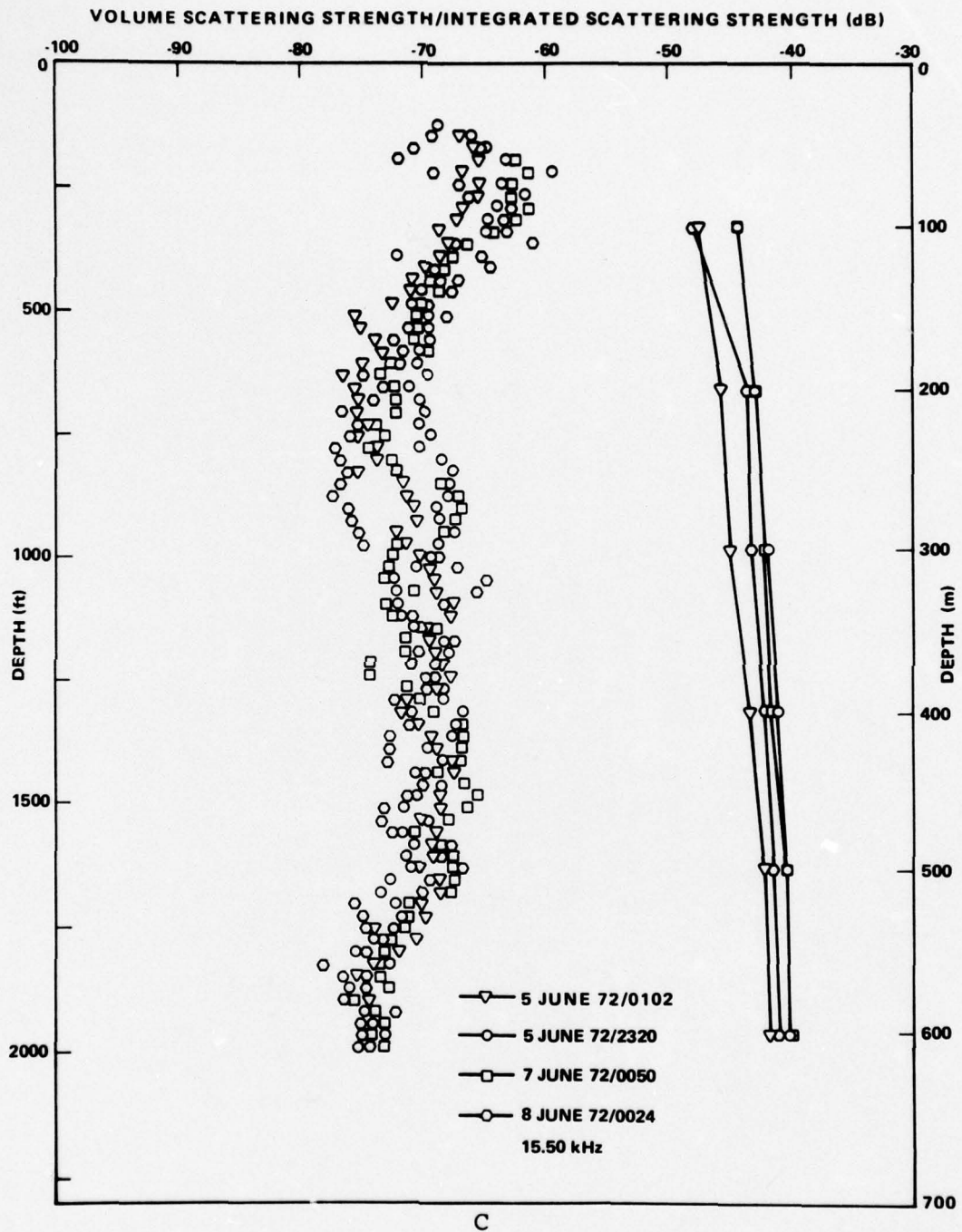


Figure 2. Daily Variability of Scattering Strength, Ocean Acre Cruise 14.

3

at 3.85 kHz. At 7.00 kHz the largest daily change amounts to approximately 4 dB. At 15.50 kHz the integrated scattering strengths at 600 m differ by no more than 1 dB. Thus, it is apparent that the scattering strength of the water column is a less variable quantity at the higher frequencies when compared on a daily basis. Therefore, the conclusion reached in previous studies⁸ that variability in the profiles too was smaller at the higher frequencies has to be revised. In the present data, an order-of-magnitude variation in the profiles is noted across the whole frequency range in a matter of only a few days.

An important point is that a single value of scattering strength, such as the integrated scattering strength of the water column, is simply not an adequate description of the volume reverberation conditions in a specific location on a short-term basis. A more valid description is given by the scattering-strength profile, but it should be remembered that at any fixed depth, daily variations in scattering strength are generally larger than the fluctuations associated with small changes in depth, i.e., those from one data point to the next. This phenomenon is obviously the result of the dynamic nature of the SSL and should not be overlooked in applications to acoustic modeling of, for example, convergence-zone propagation loss.

FREQUENCY DEPENDENCE

In figures 3A through 3F, nighttime scattering strengths are shown for comparison at six frequencies. Each graph consists of two profiles and their associated cumulative column strengths. For diversity, profiles with the highest and lowest total-column strength have been selected from among those night periods for which complete frequency coverage existed.

Regardless of frequency, nighttime scattering peaks are situated within 120 m of the ocean surface. The magnitude of these peaks varies by 12 dB from -64 for the lower peak at 3.85 kHz to -52 dB for the higher peak at 9.00 kHz. In the depth interval from 120 to 250 m, there is a gradual decrease in scattering-strength values. In support of earlier measurements at the Ocean Acre site, this decrease below the shallow peak is most pronounced at 3.85 kHz, reaching levels below those of any of the other profiles. The profile shapes for the intermediate frequencies of 5.00,

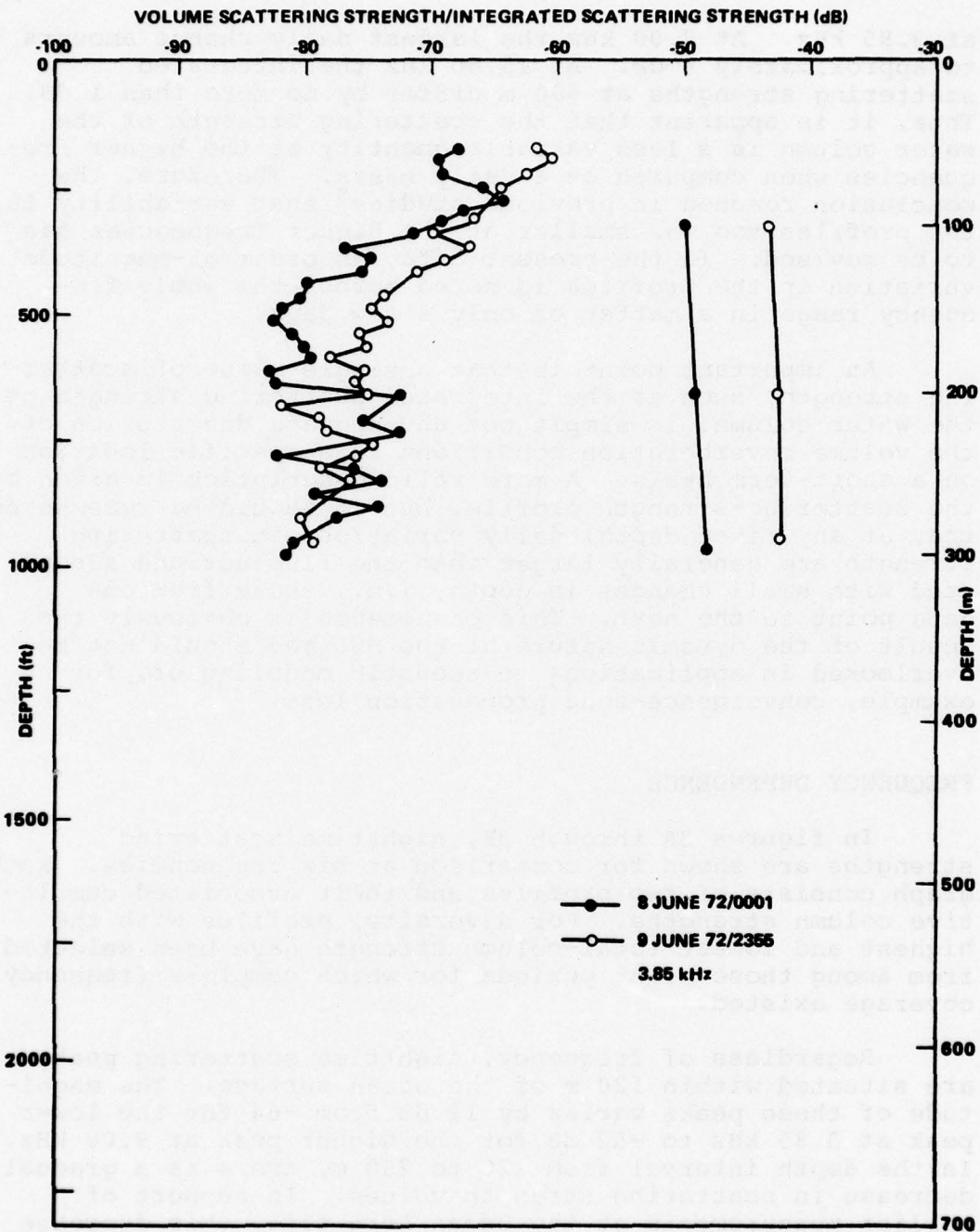


Figure 3A through F. Frequency Comparison of Nighttime Scattering Strengths at the Ocean Acre Site

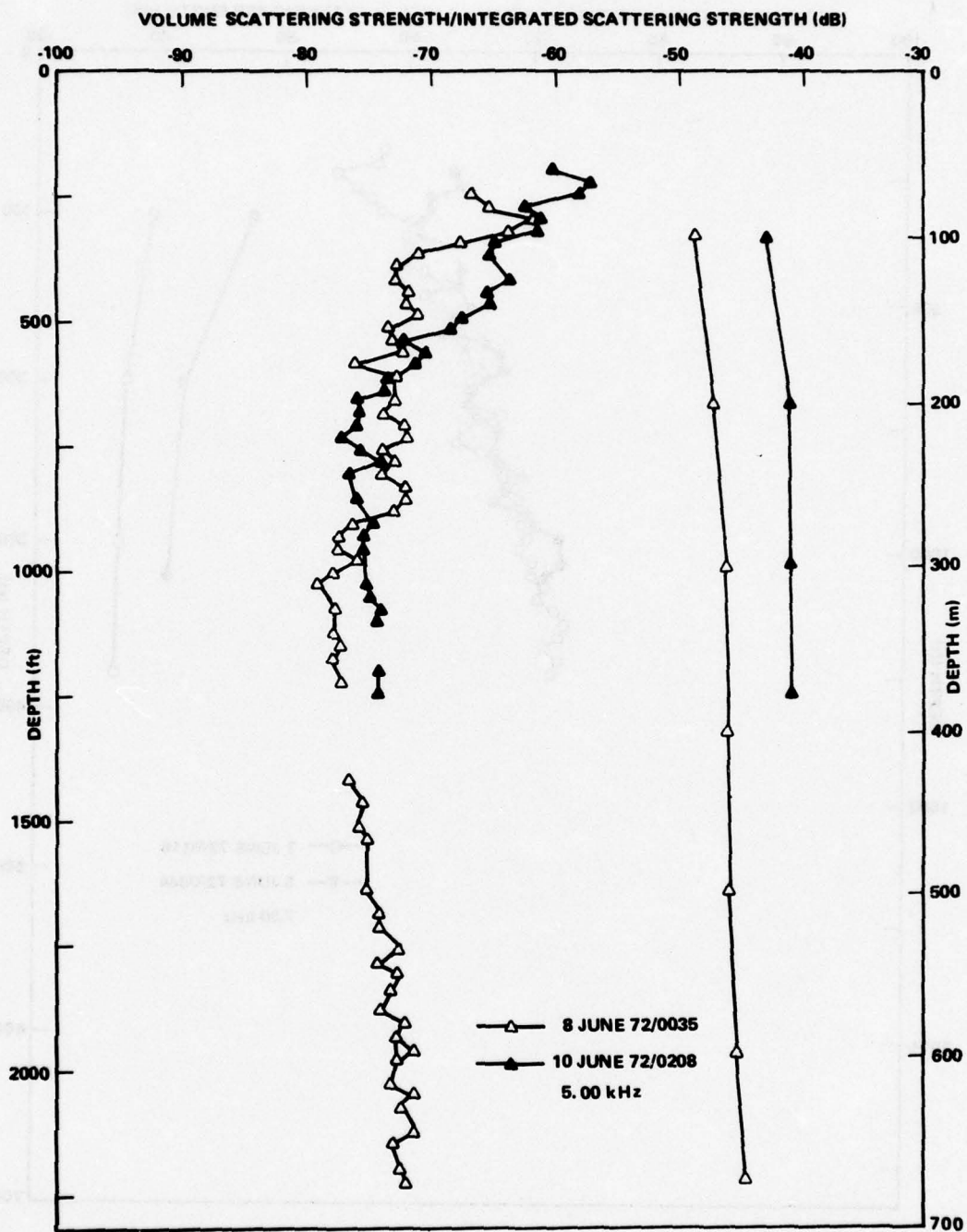


Figure 3B.

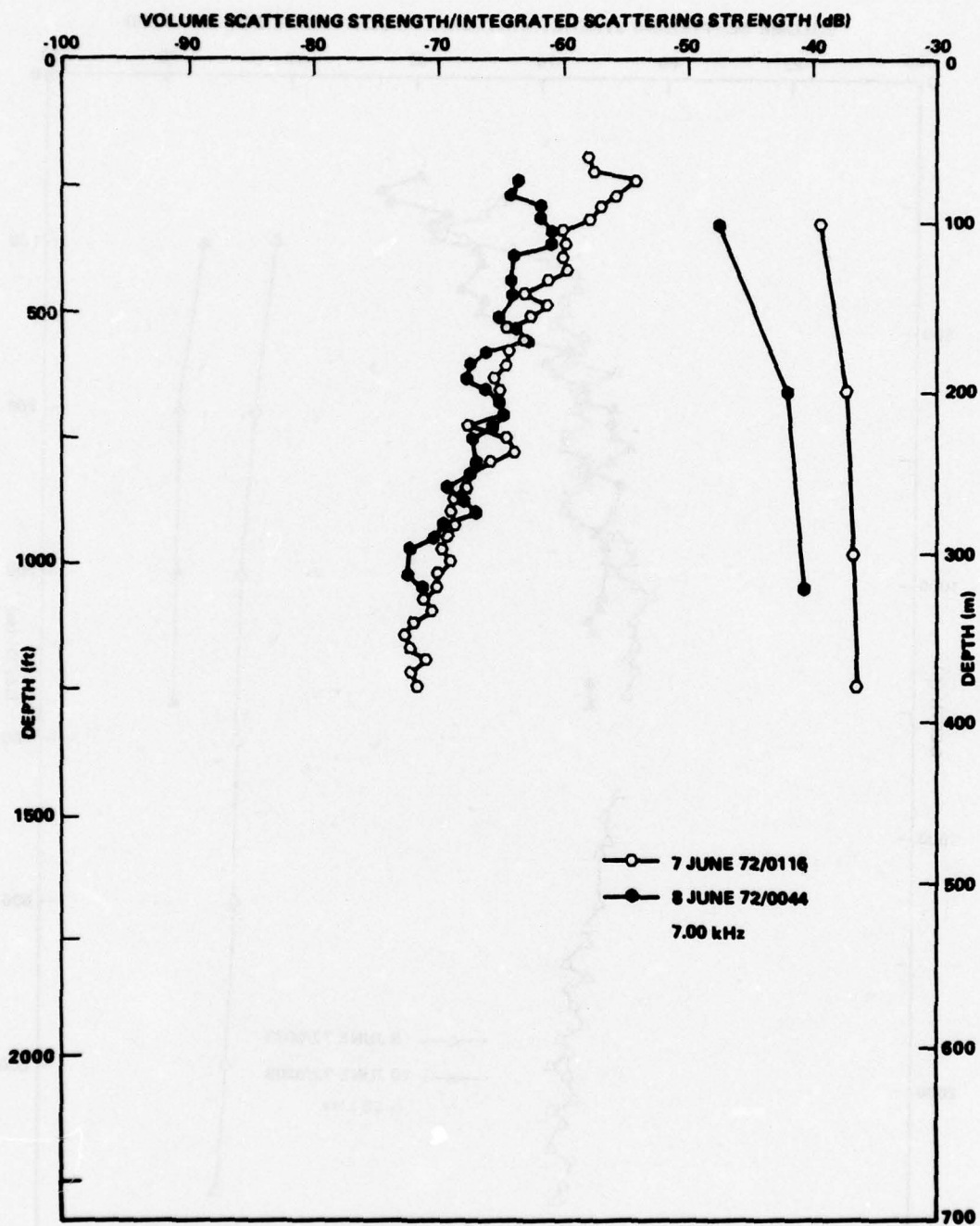


Figure 3C.

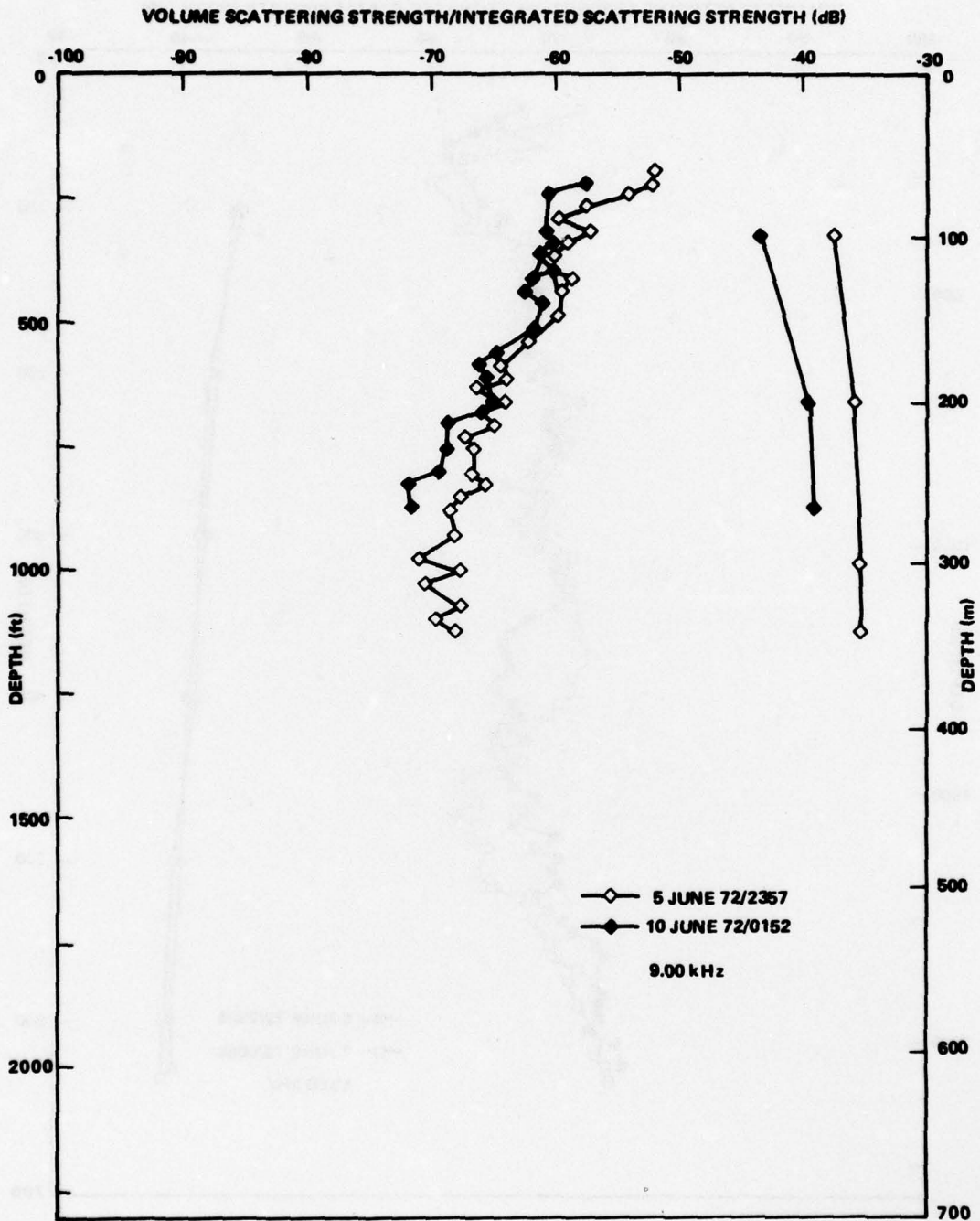


Figure 3D.

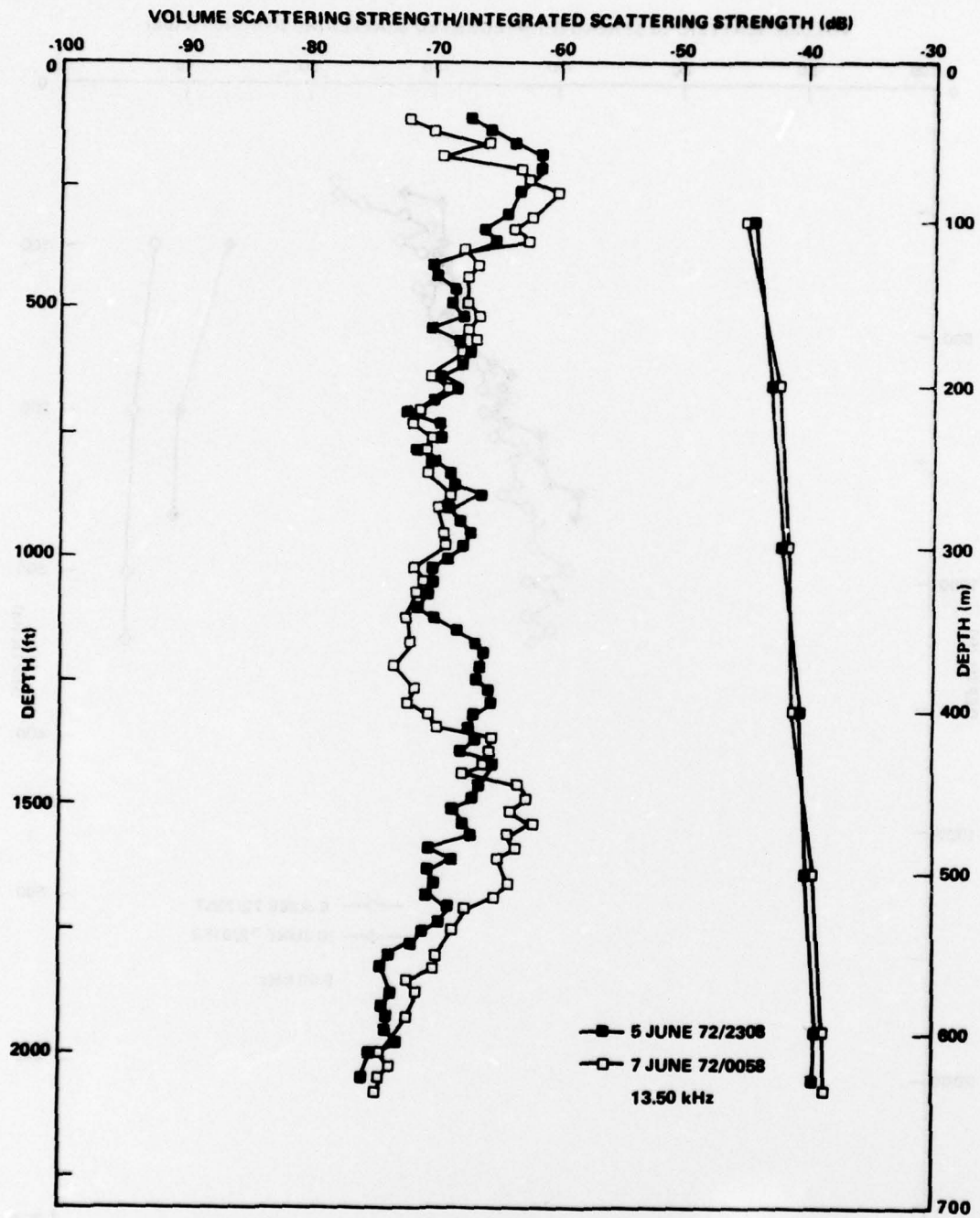


Figure 3E.

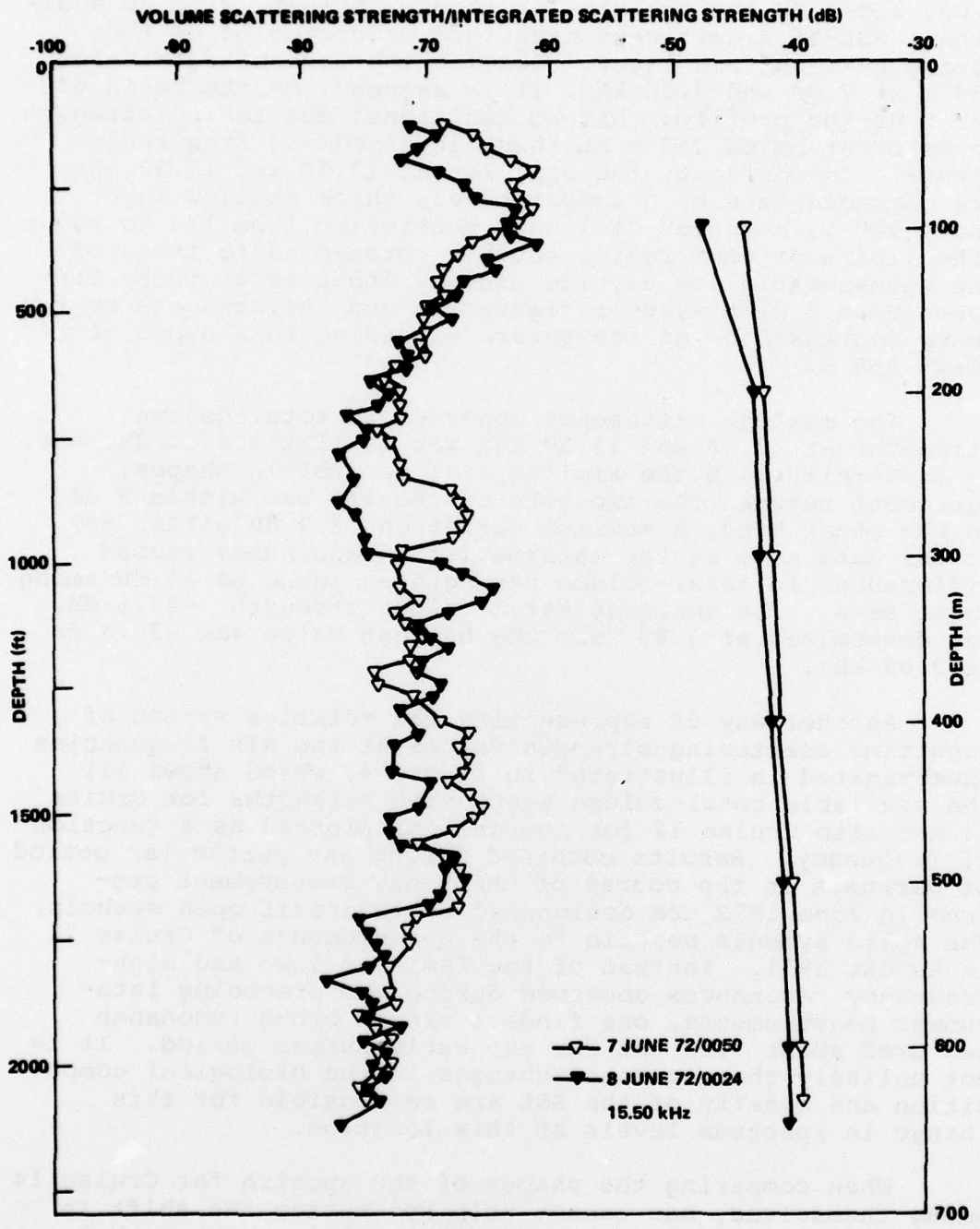


Figure 3F.

7.00, and 9.00 kHz are similar to one another, with no additional SSL of significant magnitude occurring below the strong near-surface layer. Despite the lack of data below 350 m at 7.00 and 9.00 kHz, it is assumed, on the basis of the 5.00-kHz profile, that no additional scattering-strength peaks exist below 350 m at these intermediate frequencies either. In contrast, the profiles at 13.50 and 15.50 kHz are characterized by a comparatively thick shallow layer above 120 m, a region of lesser scattering from 120 to 250 m (the limits of this region roughly correspond to those of the unmeasurable low daytime minimum observed at these frequencies and displayed in figures 1A and 1B), and one or two heavy aggregations of scatterers extending to a depth of at least 550 m.

The maximum difference observed in total-column strengths at 13.50 and 15.50 kHz was as little as 1 dB, and, in conformity with the similarities in profile shapes, agreement between the two sets of results was within 2 dB. On the other hand, a maximum variation of 4 dB within any of the data sets at the intermediate frequencies caused differences in total-column strength as large as 11 dB among these sets. The smallest total-column strength, -48.5 dB, was determined at 3.85 kHz; the highest value was -35.3 dB at 9.00 kHz.

Another way of representing the relative spread of nighttime scattering-strength values at the six frequencies investigated is illustrated in figure 4, which shows all the available total-column scattering strengths for Cruise 14 and also Cruise 12 for comparison, plotted as a function of frequency. Results obtained during any particular period of darkness in the course of the 5-day measurement program in June 1972 are designated by identical open symbols. The solid symbols pertain to the measurements of Cruise 12 in August 1971. Instead of the familiar low- and high-frequency resonances observed during the preceding late-summer measurements, one finds a single broad resonance centered about 9.00 kHz for the early summer period. It is not unlikely that seasonal changes in the biological composition and density of the SSL are responsible for this change in spectrum levels at this location.

When comparing the shapes of the spectra for Cruise 14 among themselves, one cannot help but notice the shift in distribution producing the relatively flat spectrum that resulted from data recorded for the nights of 9 and 10

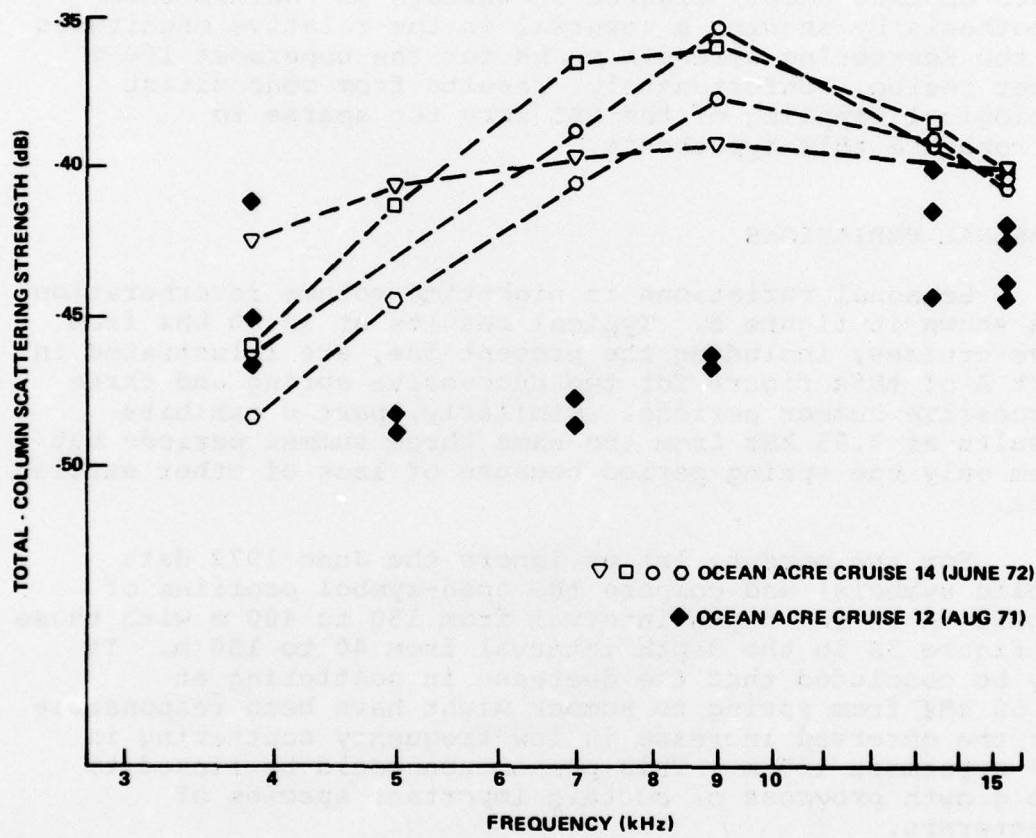


Figure 4. Comparison of Nighttime Column-Strength Spectra at the Ocean Acre Site

June 1972. Contributions at 9.00 and 7.00 kHz have been diminished, whereas the values at 5.00 and 3.85 kHz have been raised accordingly. Since dramatic changes in physical growth of the scatterers could not have occurred in such a short time interval to effect a shift in resonance of such magnitude, it is more probable that a vertical rearrangement of the scattering population within the water column took place on that date. Figures 3A through 3D confirm this hypothesis by showing a reversal in the relative magnitudes of the scattering-strength peaks for the uppermost 100-m water region. Unfortunately, results from concomitant biological sampling of the SSL were too sparse to corroborate this hypothesis.

SEASONAL VARIATIONS

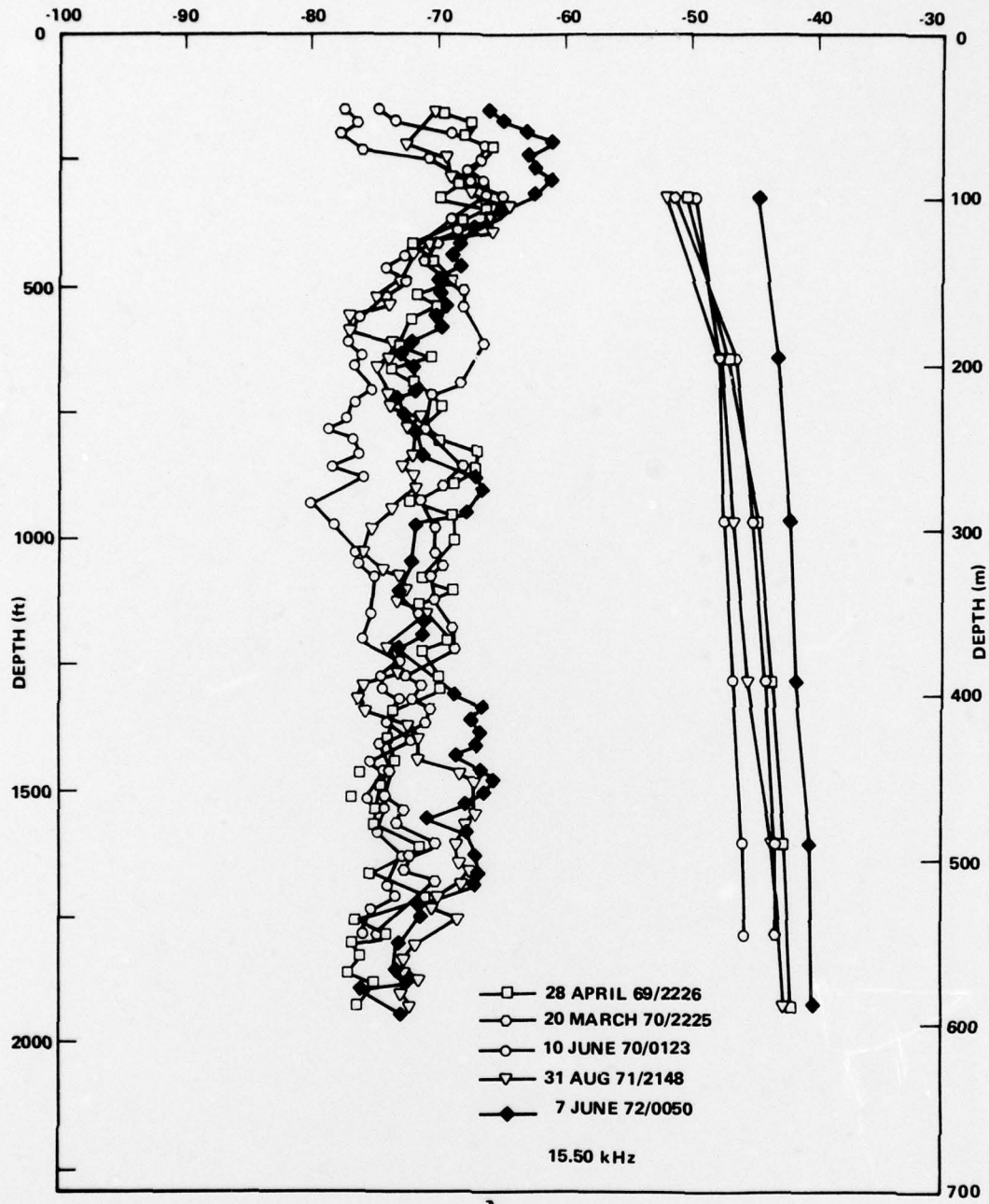
Seasonal variations in nighttime volume reverberation are shown in figure 5. Typical results at 15.50 kHz from five cruises, including the present one, are illustrated in part A of this figure for two successive spring and three successive summer periods. Similarly, part B exhibits results at 3.85 kHz from the same three summer periods but from only one spring period because of lack of other earlier data.

For the moment, let us ignore the June 1972 data (solid symbols) and compare the open-symbol profiles of figure 5A in the depth interval from 150 to 400 m with those of figure 5B in the depth interval from 40 to 150 m. It may be concluded that the decrease in scattering at 15.50 kHz from spring to summer might have been responsible for the observed increase in low-frequency scattering in the uppermost 150 m. This phenomenon could be linked to the growth progress of certain important species of scatterers.

Alternatively, one may visualize this seasonal shift in frequency response by reference to the open-symbol plots of column strength. These also demonstrate this inverse relationship between high- and low-frequency contributions at least between spring and early summer periods.

If one now includes the data from the 1972 study (solid symbols) in this comparison, one finds this trend upset by the fact that, above 150 m, the 15.50-kHz data are of the highest levels yet measured and the associated

VOLUME SCATTERING STRENGTH/INTEGRATED SCATTERING STRENGTH (dB)



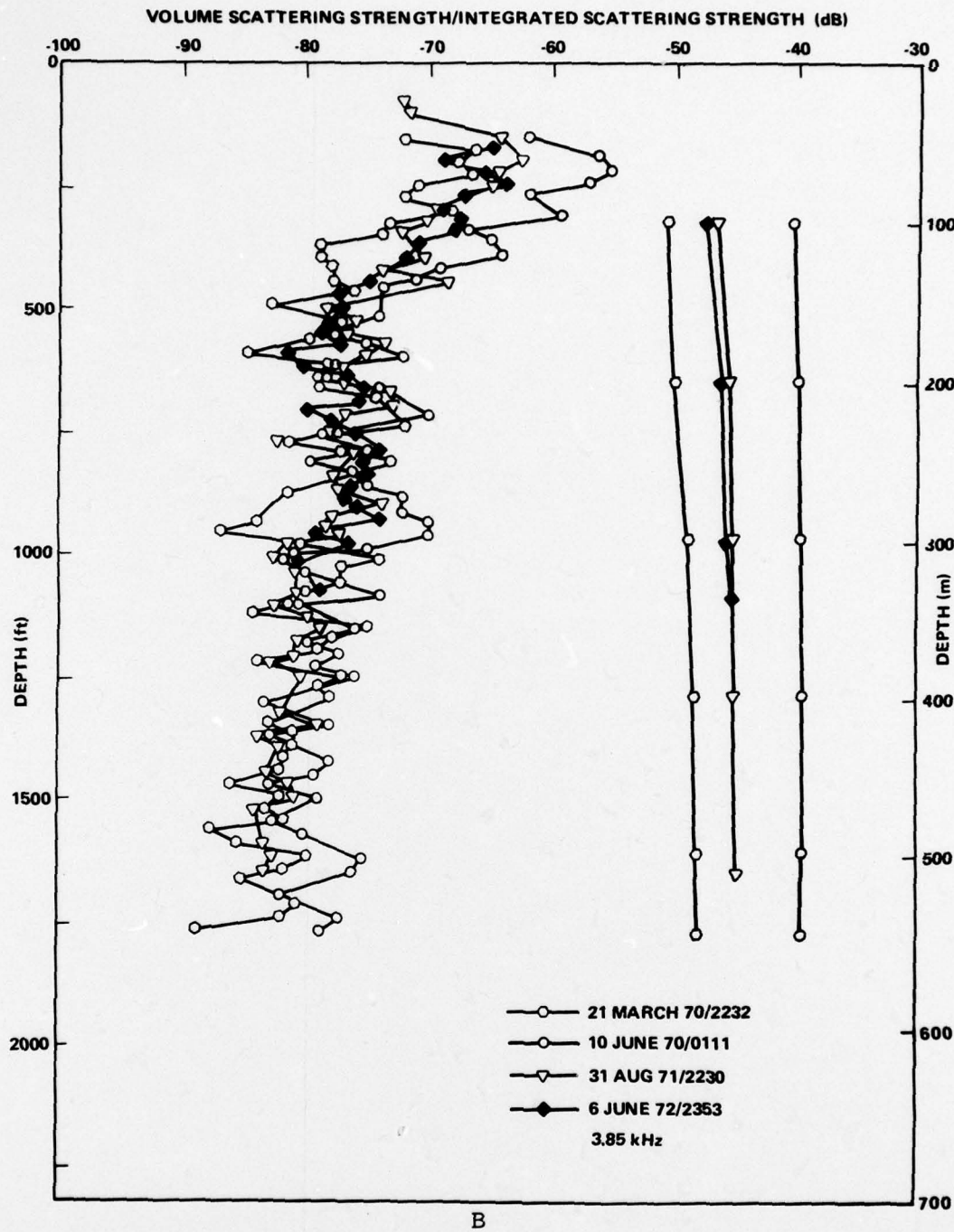


Figure 5. Seasonal Comparison of Nighttime Scattering Strength at the Ocean Acre Site

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column strengths are also largest, whereas at 3.85 kHz both the profile and the column strength are by far more reminiscent of those for late summer 1971 than for June 1970. Although, as a result of this acoustic observation, one may be tempted to surmise that the physical development of the scattering population had not progressed as far by early June 1972 as it had by the same time two years before, such an idea cannot be reconciled with the concurrently obtained biological data. The number of fish caught in the upper 150 m in June 1972 was twice as great as that netted in June 1970, and their average swimbladder volumes were almost the same size in both years.

On the basis of the foregoing observations, which were reached by visual examination of the high- and low-frequency profiles and accompanying column strengths, it may still be asserted that seasonal differences in scattering strength do occur at the Ocean Acre site and that there is an increase in low-frequency scattering from spring to summer. However, no consistent rate can be established for this trend to allow reasonably accurate predictions to be made. In terms of total-column-strength values, this seasonal increase varies between 3 and 8 dB for the 3.85-kHz case.

In view of the large day-to-day fluctuations found throughout the water column and described above in the discussion of figure 2, it was considered of interest to subject the data to some statistical analyses in order to test whether these variations were due to the profiles being significantly different and whether the "seasonal" profiles were, in turn, significantly different from the "daily" ones. The 3.85-kHz and 15.50-kHz data sets were treated separately.

For the analysis at 3.85 kHz, the topmost twenty-seven scattering-strength values occurring between 40 and 240 m were chosen from each of the five profiles depicted in figure 2A. From a two-way analysis of variance, it was determined that the five profiles from the Cruise 14 study are, in themselves, significantly different (with 99.90% probability) in the sense that they are not descriptions of a single distribution of scatterers. Furthermore, to test for equivalence of distributions, the H Rank-Sum test¹⁰ was employed with the supporting result that the five profile distributions could have come from the same distribution only 17% of the time because of chance alone.

Likewise, the four "seasonal" profiles of figure 5B were tested as a set in the above manner, yielding significant differences at the 0.00013 and 0.015 levels, respectively.

Finally, in a comparison of seasonal and daily variances, it was established that, because the former exceeded the latter greatly (18 to 1), the variations in the scattering-strength profiles described above as seasonal in nature on the basis of inspection were indeed seasonal (or even annual) and not merely daily characteristics when examined statistically.

The analysis of mean squares was also carried out on the 15.50-kHz day-to-day results of figure 2C and the seasonal data of figure 5A. In this case, the profiles were each represented by sixty-eight data points with a depth extent of 550 m. Although significant differences were found for both the daily and seasonal data sets, the ratio of the mean square of the cruise-to-cruise results to the mean square of the day-to-day results indicated a significance level of 0.18. Thus, one cannot be as confident that the spread of season means is greater than that of daily means at 15.50 kHz, although the indication is, nevertheless, in that direction.

SUMMARY AND CONCLUSIONS

The acoustical results of the final Ocean Acre experiment performed during Cruise 14 from 5 to 10 June 1972 have been presented and discussed from the standpoint of diurnal variations, daily variability, frequency characteristics, and seasonal trends. The significant features observed in both the scattering-strength profiles and associated integrated scattering strengths at 3.85, 5.00, 7.00, 9.00, 13.50, and 15.50 kHz apply to stable, non-migratory SSL configurations.

Comparisons of day and night profiles at 13.50 and 15.50 kHz indicate that the main body of scatterers resonant at these frequencies was located in the 350- to 550-m depth interval by day and in the 40- to 120-m depth interval by night. Daytime scattering-strength levels between 120 and 330 m were -100 dB (or lower), thereby causing an average day-night increase of 25 to 35 dB in this depth range. Otherwise, the largest diurnal differences in scattering

levels occurred above 120 m where they amounted to between 10 and 15 dB. Day-night differences of 12 to 15 dB in the integrated scattering strengths were observed down to 300 m; but the total-column strengths for the daytime approached the nighttime values to within 3 or 4 dB. Because of these small differences, total-column strengths are regarded as inadequate descriptions of the large diurnal variations in reverberation levels attending the vertical migration of scatterers. Diurnal variations at the other frequencies could not be presented because daytime levels at these frequencies were below measurement threshold.

Night-to-night variability of scattering strengths during the five-day measurement period was as large as 10 dB for all of the frequencies over most of the water column. This result is new in that variations of such magnitude had not been observed previously at 13.50 and 15.50 kHz.

Regardless of frequency, nighttime scattering-strength peaks were within 120 m of the surface. From 120 m to 250 m, a gradual decrease in level occurred at all of the frequencies but was most pronounced at 3.85 kHz. Only at 13.50 and 15.50 kHz, with profiles very similar, were there any noteworthy additional scattering contributions between 250 and 550 m. The spectra of total-column scattering strengths exhibited broad resonance peaks around 9.00 kHz, unlike the separate resonances at low and high frequencies observed in earlier studies.⁸ It is proposed that, when the shape of the spectrum changed from night to night, a change in the distribution of the scattering population within the water column became discernable (figure 4).

Inclusion of the latest Ocean Acre results (Acre 14) in a seasonal comparison did not considerably affect earlier conclusions that an increase in both the near-surface peak of the 3.85-kHz profile and the integrated column strength occurred from spring to summer. However, at almost identical times in early summer separated by two years, total-column strengths were obtained that differed by 6 dB. If the 15.50-kHz results are contemplated in conjunction with the trend in the 3.85-kHz data, differing annual rates in the physical growth progress of the resonant scatterers might be considered as responsible for this phenomenon. Statistical tests of means and equivalence of distributions were employed to support the argument that

variations in the cruise-to-cruise profiles were significantly greater than those in the day-to-day profiles of the last cruise so that cruise-to-cruise differences could be considered seasonal in nature. A high level of confidence was calculated for the 3.85-kHz data, whereas the 15.50-kHz case was less convincing.

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