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RECENT FINDINGS ABOUT THE DEEP
SCATTERING LAYER[1]

By

J. B. HERSEY, H. R. JOHNSON AND L. C. DAVIS

Woods Hole Oceanographic Institution

ABSTRACT

Sound scattering observations in deep water are reported for the frequency range
from 2 to 20 kc. An explosive sound source was employed to give a sound having
high acoustic pressures throughout the frequency range. The receiver was directed
vertically downward in the water; the recorder allowed simultaneous recording over
several frequency bands. Scattering showed marked peaking as a function of both
depth and frequency down to 5 kc, but not below, so far as the observations extend.
Peaked scattering at all frequencies exhibits diurnal migration; thus there is continued
indication that marine animals are the principal scatterers throughout the frequency
range studied. The peaking as a function of frequency above 5 kc suggests that
common and abundant animals in deep water do not greatly exceed linear dimensions
of the order of 30 cm. The marked differences observed in the frequency and depth
dependence of scattering from place to place, compared with their reproducibility
over a limited area and time, suggest that the frequency dependence of scattering
may eventually be employed for limited identification of the animals.

INTRODUCTION

The occurrence of stratification of sound scattering, first discovered
in the Pacific Ocean [(2), (3), (4), (5) and (6)], has been found to be
nearly world-wide, and such characteristics as the correlation between
layer depth and altitude of the sun have been studied [(8), (9) and
(10)]. The hypothesis by Johnson (4) that the scatterers are marine

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animals is widely accepted, but there is no general agreement about their identity. Several animal groups have been proposed: Hersey and Moore (9) suggested euphausid shrimp, Lyman (10) proposed squid, and Chapman (7) suggested that fish are responsible. A recent discussion by Marshall (11) reviews previous analyses and suggests that certain bathypelagic fishes with swim bladders have appropriate distribution and habits to account for some of the scattering. Definite identification will depend on some direct means such as net towing or underwater photography. However, acoustic observations are of value in approximating the size and distribution of the scatterers. The present paper describes an approach to this end by investigating their frequency dependent characteristics.

The acoustic record, plotted as a function of time, presents the combined echo level from all scatterers in a volume of water determined by the time after the emission of the sound signal and its own duration. Standard methods (2) for analyzing the scattering record give, as a function of distance from the sound source, the average fraction of sound energy scattered per cubic meter of water. This may be regarded as the total scattering cross section that "intercepts" the sound beam per cubic meter; it is dependent on the population density of scatterers, their size distribution, their acoustical properties, and the frequency of the sound signal.

The scattering cross section of an individual, in general not equal to the physical cross section it presents to the sound beam, depends on its physical size in relation to the wave length of the sound beam and on its own acoustical properties. Hence no acoustical measurement of cross section will yield the physical size distribution directly. Raitt (15) has observed the distribution of the acoustical cross section of individual scatterers by measuring the amplitude of many individual echoes from very short pulses of sound.

The detailed scattering properties of marine animals are expected to be complicated, and it is unlikely that theoretical expressions for their scattering can be derived by any practical effort. However, it is reasonable to expect that the effects of shape and size will turn out to be sufficiently similar to those of simpler forms of scatterers to permit some conclusions to be drawn about the size distribution from frequency dependence. In the usual treatment of the scattering problem, three regions of approximation, in which rather different types of frequency dependence hold, are useful from a practical standpoint:

  I. The scatterer is much smaller than the wave length of sound,
 II. The scatterer is comparable to the wave length, and
III. The scatterer is much larger than the wave length.

In I, Rayleigh [(16) vol. II, paragraph 296] has shown that the acoustic pressure of the scattered wave is proportional to the square of the frequency and to the volume of the scatterer regardless of its shape. Hence for wave lengths long compared with the scatterer, scattering should increase rapidly with frequency. In II, the scattering in any given direction may fluctuate considerably with frequency, depending on the acoustical properties of the scatterer compared with the medium. The general nature of results to be anticipated in marine scattering was outlined by Anderson (1), who computed in detail the back scattering from fluid spheres; he considered this to be a reasonable starting point for the study of marine animal scattering. In III, scattering is independent of frequency and depends only on the acoustical properties of the scatterer and the cross section it presents to the sound beam.

Since marine animals vary in size from a fraction of a centimeter to a few meters, it is apparent that they may occupy in turn any of the three regions of approximation discussed above for the ordinary sonic and lower ultrasonic frequencies. A study (3) has been made in which scattering at 10, 20, 40 and 80 kc was observed in rapid succession to investigate frequency dependence in the deep scattering layer. The results indicated that the scattering does not follow the Rayleigh law. By extending sonic observations to lower frequencies it should be possible to find the region where the wave length is much larger than the largest abundant scatterers and hence determine where scattering falls off sharply as the frequency is decreased. The present paper describes an investigation in which scattering was recorded down to 2 kc in an attempt to do this by means of a technique which allowed simultaneous recording of several frequency bands.

OBSERVATIONS

The first observations were made in the vicinity of Lat. 38° 30' N Long. 71° W on cruises of the R/V CARYN from 2 to 11 August 1949 and of the R/V ATLANTIS from 22 to 30 September 1949. A third cruise, on the R/V ATLANTIS between January and April 1950, covered a considerable area between Cape Cod and the Antilles.

The sound source employed was a ½ lb. block of TNT which was detonated at a depth of about ½ m and 30 to 50 m from the receiver. The receiver was a somewhat directional rochelle salt transducer towed at shallow depth astern of the observing ship on the first cruise; subsequently it was mounted in the keel. In both cases the transducer was directed vertically downward. Sounds received by the transducer were filtered by band-pass filters in the separate channels of a multi-

channel amplifier, rectified, and then fed to galvanometers to be recorded photographically. Fig. 1 shows representative records. Here four channels were employed and three were recorded at two dynamic levels, roughly 20 db apart, thereby allowing both loud and faint sounds to be recorded on the same record. Timing markers, vertical lines 1/100 seconds apart, were recorded by a suitably controlled interrupter with every tenth line accentuated to facilitate scaling. Depth in meters and the corresponding travel times are indicated below the record. The explosion provides an intense source of sound at all frequencies, and the filtered amplifiers provide a means of recording scattering from the explosion in various frequency bands. The receiver, directed vertically downward, discriminates against sound scattered from surface waves or from scatterers in the water at wide angles from the vertical.

Fig. 2 is a series of records from the CARYN cruise in which various frequency bands from 19.6 to 2 kc were employed. The 19.6 kc filter was used throughout the series for comparison. The change in character from one band to another is apparent from an inspection of the records. Observe that there is a peak of scattering at about 140 m on the 15 and 19.6 kc traces which does not appear at any of the low frequencies. Similarly, the very prominent scattering at 400 to 500 m at 15 and 19.6 kc is reproduced at 10 kc but at no lower frequency. At 8 kc a peak of different shape and of slightly different depth is recorded. At 5 kc a much broader and deeper peak is recorded, while at 2 kc there is no evidence of peaking. The very sharp character of the peak at 400 to 500 m on the 19.6 kc trace is found consistently only in certain localities in the Atlantic; it is best known just north of the Gulf Stream where this series was recorded. Fig. 1 shows a more usual recording in which the deep scattering layer (i. e., on the 15 kc trace) is broader and more diffuse; this record was also made north of the Gulf Stream but at a different location.

A General Radio Sound Analyzer (Type 760A) was used to examine in detail the peak at 5 kc. Fig. 1 shows three records in which the Analyzer was employed as a filter at 3, 5.5, and 7.5 kc. In the first (3 kc) the scattered return is relatively low in amplitude compared with the second (5.5 kc), while the third (7.5 kc) is of lower amplitude and is somewhat different in character, since the shallower peak begins to appear here. We had no means of examining in such detail the transition from one frequency band to another above 7.5 kc.

Several sequences of records taken at 5 and 10 minute intervals were made through both sunrise and sunset. Although there are striking individual differences in the various sets of observations, all

show marked evidence of vertical migration of some of the scatterers at all frequencies. This is illustrated by Fig. 3, showing selected records taken from a series from 1410 to 1850 on March 4, 1950 at Lat. 29° 00′ N, Long. 62° 05′ W. (The time of local sunset was 1815.) All four records were taken at the same gain settings of the analyzer, and relative amplitudes on the same frequency trace from record to record at a given depth may be compared as a rough measure of the concentration of scatterers there. The record at 1410 is a typical mid-day record for this region. The scattering from 0 to about 75 m on the 20 and 15 kc traces and from 0 to about 150 m at the lower frequencies is probably a combination of scattering from surface waves and scatterers in the water. In many instances, peaks of scattering are reproducible at shallower depths, but generally the record is not usable for about 0.1 sec. after the shock wave (i. e., 75 m). On the 20 kc trace a somewhat complicated layer extends from about 250 to 290 m. At greater depths no scattered return is above the general background level on the sensitive trace. On the 1627 record this layer is not evident, the scattering being diffuse and of low amplitude at depths greater than about 110 m. On the 1805 and 1850 records, however, marked stratification is found from about 75 to 180 m where none was previously evident. On the 15 kc traces a somewhat more striking migration is seen where a mid-day layer extending from 380 to 650 m apparently split by 1627, the shallower portion migrating to a very shallow depth by 1805 (55 to 220 m); meanwhile the deeper portion, though still identifiable as a layer at about its mid-day depth throughout the series, apparently weakens in concentration between 1805 and 1850 to a small fraction of its mid-day amplitude. At 10, 8, and 5 kc the scattering is diffusely distributed in depth to slightly deeper than 1000 m. Hence the migration is not evident progressively through these records. However, an increase in the scattering amplitude at the shallower depths is evident at all three frequencies between 1805 and 1850, which coincides with a general decrease in the scattering amplitude at depth. These records were selected from a more detailed sequence which demonstrates that the changes described took place in a gradual manner throughout the period covered.

DISCUSSION

The examples of scattering records in Figs. 1, 2 and 3 are not representative of all of the variations that have been observed amongst the 200-odd records which have now been taken in the western North Atlantic, but they may be taken as typical. The records of each figure, taken within a few miles of one another, are reproducible, in

general character at least. However, the locations for the three figures differ, and there is correspondingly considerable variation from one figure to another, not only in the character of the depth dependence at any one frequency but also in even the most general aspects of the frequency dependence. For example, in the case of Fig. 2, the 10 kc record is very similar to those at 15 and 19.6 kc but different from those at 8 and 5 kc, whereas in Fig. 1 the 10 kc trace is strikingly different from all frequencies but 7.5 kc. Again in Fig. 3 the 10, 8, and 5 kc traces are all rather similar. Other individual features, such as the peak in Fig. 2 at 70 m depth on the 15 and 19.6 kc traces, which do not appear at the lower frequencies, have proven to be reproducible in local areas that may be miles in extent. Diurnal migration, which is observed at all frequencies for which there are scattering peaks, is strong evidence that marine animals are the principal scatterers. Hence, observations of this type provide a means of following the migration and of determining the extent and concentration of different groups of marine animals, discriminated from one another by means of frequency dependence.

All records obtained thus far show some evidence of variation of scattering with both depth and frequency. No pronounced peaking as a function of frequency has been observed below 5 kc. This suggests that no heavy concentrations of animals larger than 30 cm, the wave length at 5 kc, have been encountered during the observations and hence are not commonly found in the western North Atlantic. However, since the frequency region below 2 kc has not been investigated extensively, and since we know little in detail of the exact manner in which marine animals scatter sound, it is premature to conclude that this is necessarily so. Further, for the latter reason we cannot now predict the detail with which it may be possible to interpret the sound scattering through the region of peaking. However, it seems possible that the scattering variation with frequency may tell enough about the physical size of the scatterers to allow some limited identification of kinds of animals, particularly if the mode of taking the scattering observations allows the determination of other characteristics such as schooling habits, movement of groups or individuals, or other features that would aid identification.

Much of the justification for such a prediction must rest on a satisfactory demonstration that the supposed scatterers are present and are capable of scattering sound as observed. In the series of observations discussed here, net tows at different depths were made only on the August 1949 cruise of the R/V CARYN. These were made with a pair of ¾ m stramen nets towed at speeds from 1.5 to 2 knots.

The biologist making the collections aptly remarked that such an operation would catch only "the maimed, the halt and the blind." However, daytime hauls below 250 m did catch appreciable numbers of animals whose lengths were comparable with the wave length over much of the frequency range observed. The question whether planktonic forms have adequate scattering cross sections to account for observed scattering coefficients is not completely answered. Nevertheless, a good indication that they do comes from unpublished measurements of scattering from small inshore shrimp made by Mr. P. F. Smith at Woods Hole. At frequencies between 20 and 30 kc he found that shrimp [*Palaemonetes vulgaris* (Say)], roughly 2.5 to 3.5 cm long, had quite adequate scattering power to account for the scattering coefficients observed for the peak of the scattering layer given in the University of California work (2), assuming concentrations of the order of 20 shrimp per cubic meter. Thus it seems reasonable to suppose that planktonic crustaceans of various sizes may be capable of scattering sound over a considerable frequency range with sufficient power to account for much of the observed scattering. Of course, this does not preclude the possibility that other types of animals, not necessarily all planktonic, can scatter sound sufficiently to be observed in the scattering layers of the deep ocean.

CONCLUDING REMARKS

1. Peaks of sound scattering as a function of frequency occur in the deep ocean for frequencies at and above 5 kc, suggesting, by analogy to the scattering properties of simple geometrical forms, that the physical size of the common abundant scatterers is comparable to the wave length above that frequency, i. e., wave lengths less than 30 cm.

2. Observations of diurnal migration at all frequencies where peaking occurs is a strong indication that the scatterers are zooplankton. Other measurements indicate that planktonic crustaceans or other associated organisms such as fish probably have adequate scattering power to account for the observed scattering.

3. Sound scattering as a function of both depth and frequency is reproducible, in general outline at least, over limited areas, but it varies considerably over the part of the ocean studied. This suggests that concentrations of different animals characteristic of a given general locality control the observed scattering, thus providing a limited means of identifying them.

ACKNOWLEDGMENTS

ment, has contributed greatly to the completion of this study and is much appreciated. Mr. Willard Dow designed the five channel analyzer and several other components of the electronic gear. Mr. Sydney Knott designed and constructed both the oscillograph camera, with which the records were taken, and the handling gear for towing the receiver from the R/V CARYN. Mr. P. F. Smith assisted in taking the first observations and Mr. Frank Mather made the net tows on the CARYN. Dr. Hilary B. Moore and Mr. W. E. Schevill have assisted the work considerably by discussing the findings with the authors and by giving most helpful criticism of the manuscript.

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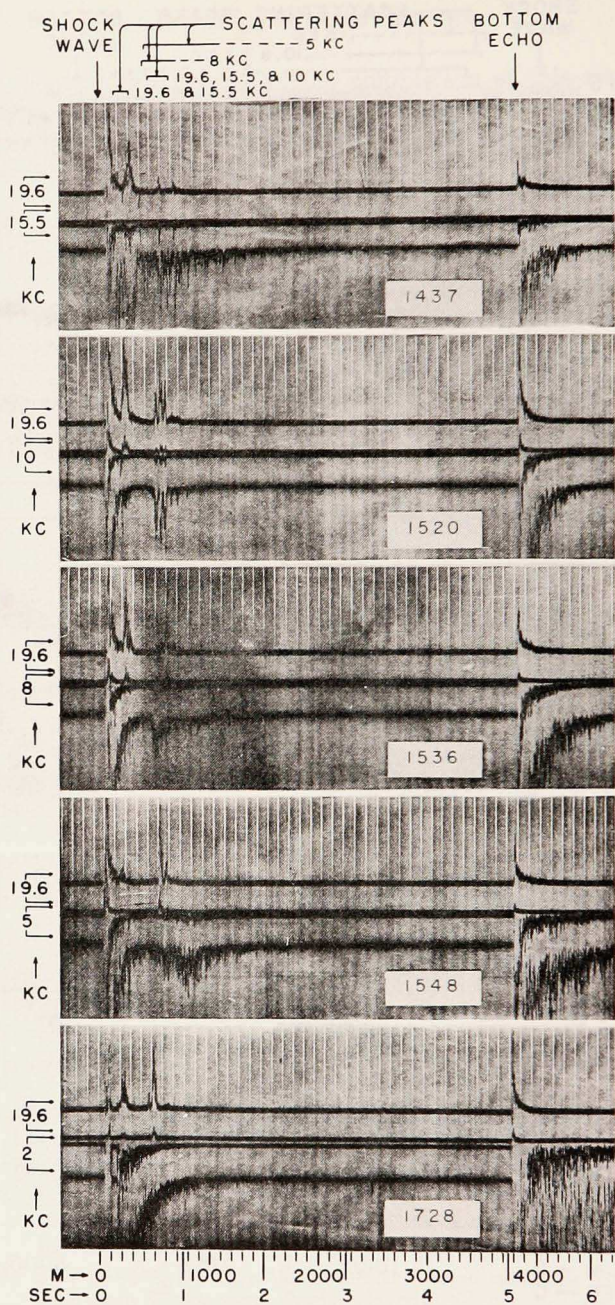
Figure 1. Representative scattering records.

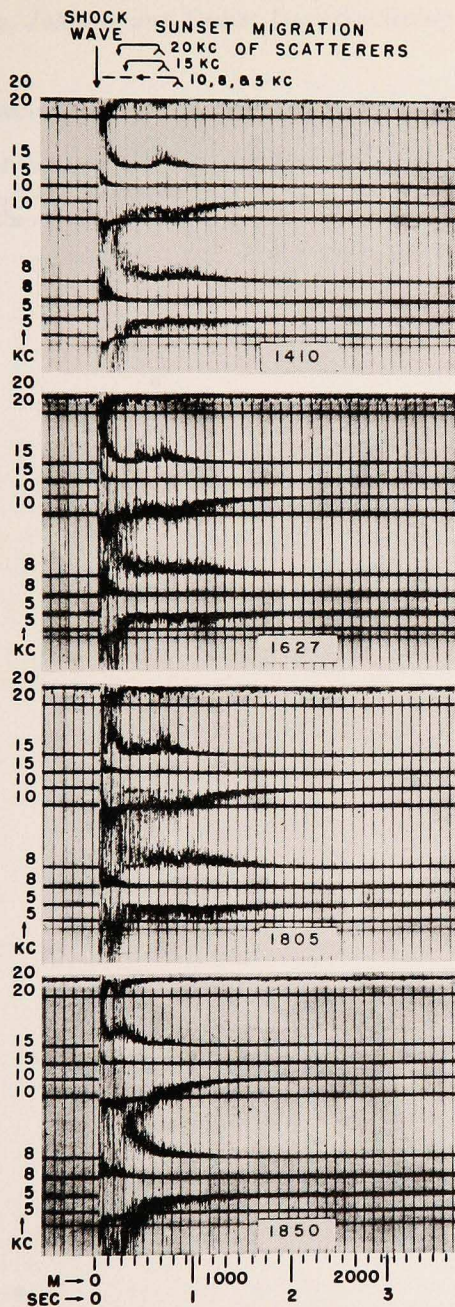Figure 2. Sound scattering at various frequencies at Lat. 38°30'N, 71°55'W.

Figure 3.   Sunset scattering record sequence.

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