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Monostatic Acoustic Scattering from the Ocean Volume

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ABSTRACT

A monostatic volume-scattering experiment was conducted in the Atlantic with a piston transducer operated at 19.5 kHz and having a beam width of approximately 8° at the half-power points. This investigation was made to determine the correspondence between measured returns and a model based on the theory of isotropic scattering from a volume. Intensities from measured values were averaged and volume-scattering strength computed as a function of depth for several depression angles and for a range of pulse lengths. Scattering strength was found to be independent of the ensonified volume in regions of uniform scattering strength. Scattering strength profiles measured in two areas of the Atlantic display a decrease of scattering strength of approximately three orders of magnitude from near the surface to a depth of 1000 fathoms.

PROBLEM STATUS

This is an interim report on this problem; work is continuing.

AUTHORIZATION

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MONOSTATIC ACOUSTIC SCATTERING FROM THE OCEAN VOLUME

INTRODUCTION

In the study of monostatic acoustic scattering in the ocean, it is expected that the scattering from discontinuities in the volume will approximate the conditions of isotropic scattering. For pure isotropic scattering, the location or the phase of the scatterers is required to be random such that, statistically, there is no preferred direction of the scattered energy. Therefore, the scattered power density in any direction is directly proportional to the volume contributing, assuming a constant strength and density of scatterers.

A monostatic volume scattering experiment was conducted to determine the degree of correspondence between scattering from the ocean volume and that indicated by isotropic scattering theory. The question asked was: "Will the intensity scattered in the monostatic direction be directly proportional to the volume ensonified?" Experimental measurements were made for different geometrical conditions, which were controlled by combinations of pulse length and direction of the source from the scattering volume. This experiment also provided volume-scattering profiles from two areas in the Atlantic.

THEORY

The analysis for this experiment is based on the isotropic scattering model by Eckart et al.,* except following Urick† the concept of scattering strength is used rather than scattering coefficient. This is stated by

$$dI_s = S_v I_i \, dV \tag{1}$$

where dI_s is the elemental scattered intensity at unit distance from element of scattering volume, I_i is the incident intensity on the scattering volume, S_v is the volume scattering strength, and dV is the element of scattering volume.

Figure 1 illustrates the general geometry for volume scattering. From Eq. (1),

$$I_s = \int_V S_v I_i \, dV . \tag{2}$$

When the characteristics of the source, located a distance r_s from the elemental volume, are included, assuming spherical spreading over r_s with the energy distributed according to the source beam function, and the absorption is taken into account, I_s becomes

$$I_s = p \int_V \frac{S_v A(r_s) b_s(\theta, \phi)}{r_s^2} \, dV , \tag{3}$$

*C. Eckart, ed., "Principles of Underwater Sound," NDRC Summary Technical Reports, Division 6, Vol. 7, 1946.

†R. J. Urick, "The Backscattering of Sound from a Harbor Bottom," J. Acoust. Soc. Am. 26:231 (1954).

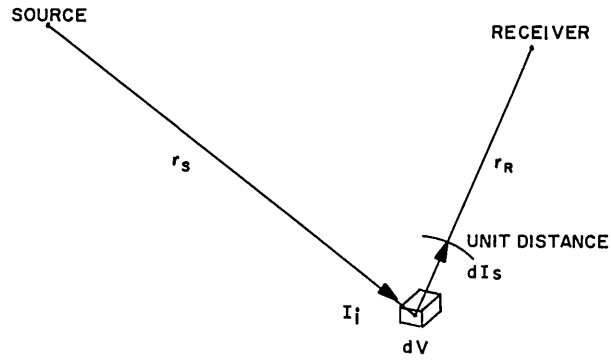

Fig. 1 - General geometry for volume scattering

where p is the source level (which can be considered a constant), $b_s(\theta,\phi)$ is the beam function, and $A(r_s)$ is the absorption over the path r_s.

When the scattered intensity is accounted for at the receiving point, it is further selected by the receiver beam function and decreased by spherical spreading and absorption losses over the distance r_R. The scattered intensity at the receiver is

$$I_R = pq \int_V S_v A(r_s) A(r_R) \frac{b_s(\theta,\phi)}{r_s^2} \frac{b_R(\theta,\phi)}{r_R^2} dV, \tag{4}$$

where q is the sensitivity of the receiver and $b_R(\theta,\phi)$ the receiving beam function.

At this point the following restrictions are made:

1. The monostatic case is considered, i.e., the source and receiving points are coincident; $r_s = r_R = r$.

2. The source and receiver beam functions are identical, i.e., $b_s(\theta,\phi) = b_R(\theta,\phi) = b(\theta,\phi)$.

3. The beam function possesses circular symmetry about its axis, i.e., is independent of θ.

It is assumed that S_v is a constant over volume V and that differential absorption over the volume can be neglected. These assumptions require that the contributing volume be kept small by employing a narrow beamwidth and short pulses. When the above restrictions and assumptions are made

$$I_r = pq\, S_v\, e^{-2k\bar{r}} \int_V \frac{b^2(\phi)\, dV}{r^4}, \tag{5}$$

where k is the absorption coefficient for intensity and $\bar{r}$ is the distance from the source-receiving point to the midpoint of the volume. Figure 2 indicates the volume of integration. Therefore, in polar coordinates,

$$I_r = pq\, S_v\, e^{-2k\bar{r}} \int_0^{2\pi} \int_{r_1}^{r_2} \int_0^{\pi} \frac{b^2(\phi)\, r^2 \sin\phi\, d\phi dr d\theta}{r^4}. \tag{6}$$

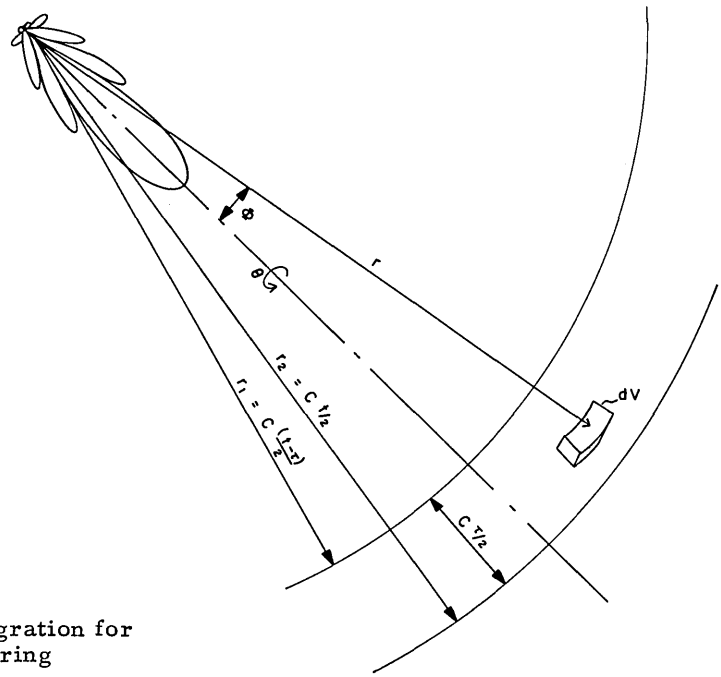

Fig. 2 - Volume of integration for monostatic scattering

Integration over θ and r gives

$$I_r = pq\,S_v\,e^{-2k\bar{r}}\left[\frac{1}{r_1}-\frac{1}{r_2}\right]\,[2\pi]\int_0^{\pi} b^2(\phi)\,\sin\phi\,d\phi\,. \tag{7}$$

For an ideal piston transducer whose beam function is a Bessel function of the first kind divided by its argument, $(J_1(\Psi))/\Psi$, a rigorous solution of the above integral can be obtained.* In solving the integral for a transducer beam function that is employed in obtaining experimental data, it is most often found that the measured function is not exactly analytic; thus a numerical integration is more appropriate. In this analysis a numerical integration of the square of the measured beam function was used. Letting

$$b = 2\pi\int_0^{\pi} b^2(\phi)\,\sin\phi\,d\phi \tag{8}$$

Eq. (7) becomes

$$I_r = pqb\,S_v\,e^{-2k\bar{r}}\left[\frac{1}{r_1}-\frac{1}{r_2}\right]. \tag{9}$$

In practice it is more convenient to write the variable in terms of time t of reception at the receiving point, with the initiation of the transmitted signal being $t_0 = 0$ and the pulse length or duration being τ. Then

$$\bar{r} = \frac{C}{2}\left[t-\frac{\tau}{2}\right], \tag{10}$$

*H. W. McLachlan, "Loud Speakers," Oxford:Clarendon Press, 1934.

$$r_1 = \frac{C}{2}(t - \tau) , \tag{11}$$

and

$$r_2 = \frac{C}{2} t , \tag{12}$$

where C is the sound speed.

Substituting Eqs. (10), (11), and (12) into Eq. (9) gives

$$I_t = pqb\, S_v \left[\frac{2\tau}{Ct(t-\tau)}\right] e^{-kC[t-(\tau/2)]} . \tag{13}$$

Equation (13) expresses the variation of received intensity with time for a nonrefractive medium, the pulse length being a parameter and the instrumentation parameters constant.

EXPERIMENTAL MEASUREMENTS

Data for the experiment were obtained in two areas of the Atlantic, the first in the Blake Plateau (30°10'N, 78°20'W) about 150 miles east of Jacksonville, Florida, and the second about 90 miles southeast of Cape Hatteras (33°57.5'N, 74°45'W).

The instrumentation consisted of a special sonar operating at 19.5 kHz. Special features of the sonar included a piston transducer mounted in the bow of a submarine that could be directed throughout the forward hemisphere. Its beamwidth is approximately 8° to the half-power point with all side lobes being down 17 dB or more. Figure 3 illustrates the square of the beam function plotted in the interval between the axis and the second side lobe. The square of the function $b^2(\phi)$ is shown because the same function is employed in both transmission and reception as indicated in the previous section. Constant-amplitude sinusoidal pulses were transmitted with the pulse length controlled by a digital programmer in 1-ms increments. Pulse lengths from 2 to 3000 ms were available. The instrumentation also provided for recording the volume scattered returns with time base and amplitude calibration. Details of the instrumentation system are contained in another report.*

A series of runs was made for a range of depression and elevation angles, pulse lengths, and speeds. All parameters were held constant for a particular run while recordings of 20 to 100 returns of the scattered signal were made. Environmental data were taken periodically during the experiment to enable the evaluation of the refractive effect of the medium.

ANALYSIS OF MEASURED DATA

The amplitude envelope of the volume-scattered signal as a function of time was recorded in analog form (on a dB scale) for each return. The data were then incremented in 10 to 25 ms steps throughout the duration of the return and converted to digital form with the aid of a data reader. Care was taken to retain the time of each reading from t_0, the leading edge of the transmitted pulse. The power ratio e_i^2 of each value read was averaged over the number of returns recorded for each time increment throughout the return; i.e.,

*H.U. Criss, K.D. Flowers, B.G. Hurdle, R.M. Lee, and K.P. Thompson, "Procedures for a Series of Experiments in Acoustic Scattering from the Ocean Bottom and Volume in the Blake Plateau Area," NRL Memorandum Report 1767, April 17, 1967.

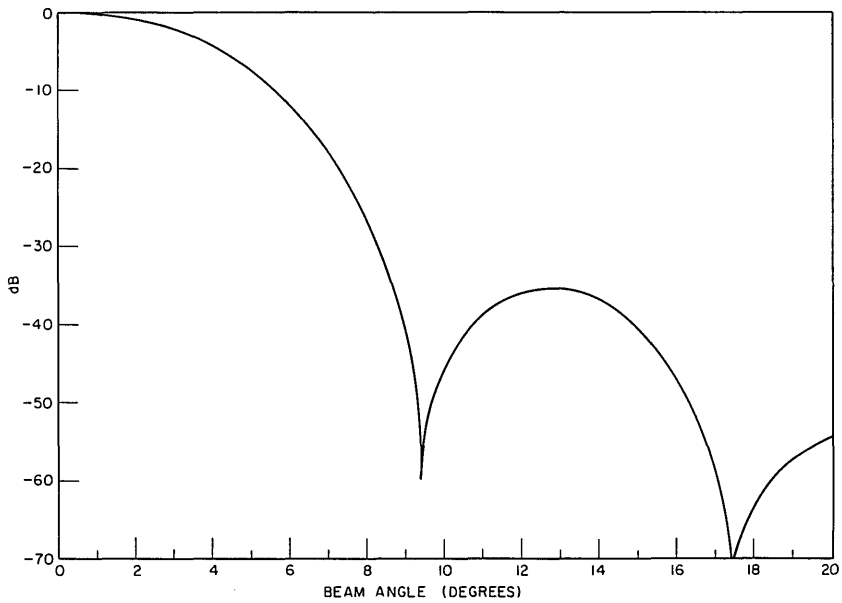

Fig. 3 - Measured beam function squared, 19.5 kHz

$$E_i = 10 \log e_i^2 \tag{14}$$

and

$$\langle e^2 \rangle = \frac{1}{n} \sum_{i=1}^{n} e_i^2 \Big|_{t=c} \tag{15}$$

where n is the number of returns and c is a constant.

The mean value of the power ratio was then converted to db by

$$\langle E \rangle = 10 \log \langle e^2 \rangle . \tag{16}$$

This makes $\langle E \rangle \propto \langle I \rangle$ assuming that the intensity is proportional to pressure squared. Since the data are obtained as a function of time, $\langle E \rangle$ at each instant represents the return from a volume situated about a particular point in range. Figure 4 illustrates a single return of the volume scatter signal in which the relative intensity is plotted as a function of time. Also shown, by the dashed curve, is the mean intensity for 30 returns. The individual return is included in the mean of 30 returns. Employing Eq. (13) from the previous section and making the conventional conversion to the dB form gives

$$\begin{aligned} E(t) &= L + 20 \log i - D + M + G - D + B + \delta_v(t) \\ &\quad - KC\left(t - \frac{\tau}{2}\right) + 10 \log \left[\frac{2\tau}{Ct(t-\tau)}\right] , \end{aligned} \tag{17}$$

where

$$10 \log p = L + 20 \log i - D$$

and

$$10 \log q = M + G - D$$

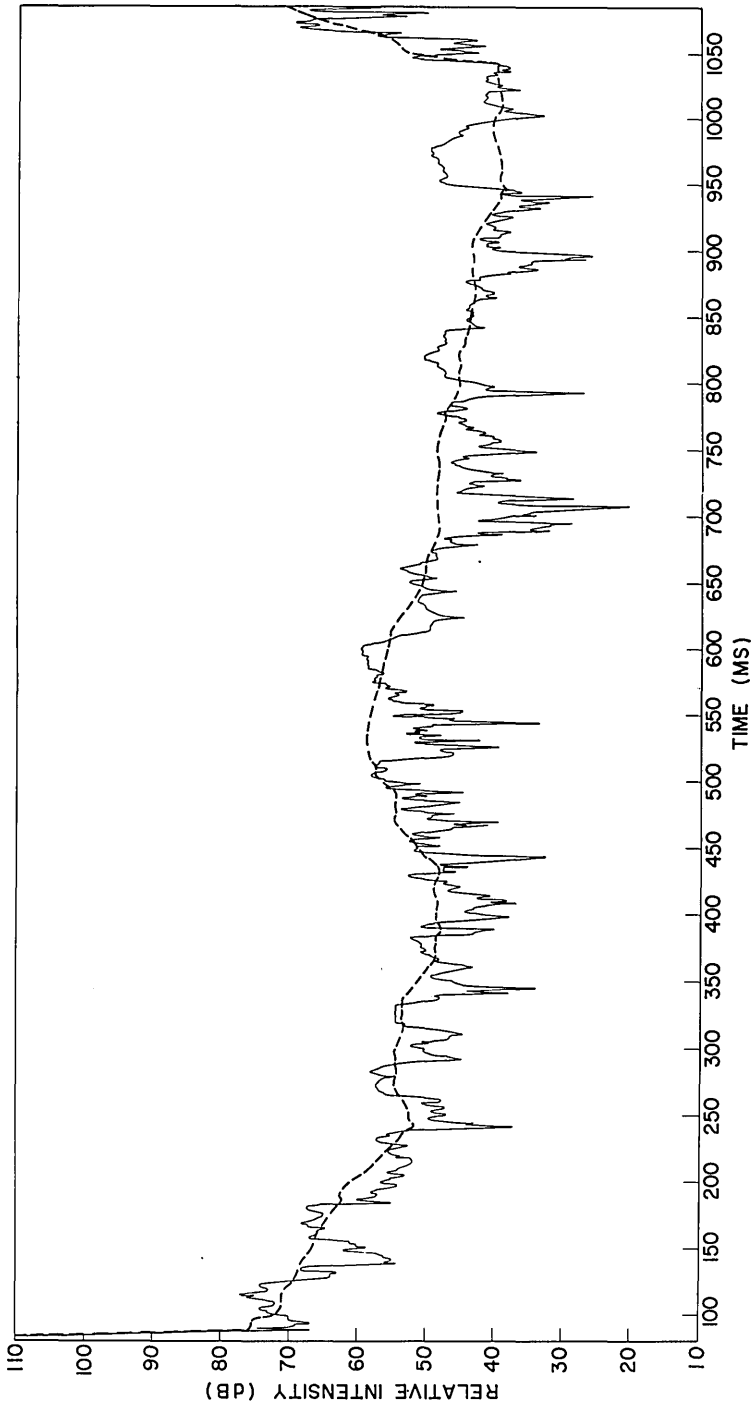

Fig. 4 - Received intensity as a function of time

or in terms of scattering strength,

$$S_v(t) = \langle E(t)\rangle - M - G - L - 20 \log i - B + 2D + KC\left(t - \frac{\tau}{2}\right) - 10 \log\left[\frac{2\tau}{Ct(t-\tau)}\right], \quad (18)$$

where $S_v(t)$ is the scattering strength at time t, L is the transmitting response of the transducer, i is the source current, D is the dome loss, M is the receiving sensitivity of the transducer, G is the receiver gain (fixed), K is the absorption coefficient, B is $10 \log b$, and $\langle E(t)\rangle$ is the average of the received signal at time t.

To obtain the scattering strength profile, i.e., the scattering strength as a function of depth for a nonrefractive medium, the center of the scattering volume (Fig. 5) is positioned in depth by

$$d = d_0 + \frac{Ct \sin \beta}{2} \quad (19)$$

where d is the depth, d_0 is the depth of the source-receiver, and β is the depression angle (the sign of β is plus for depression and minus for elevation).

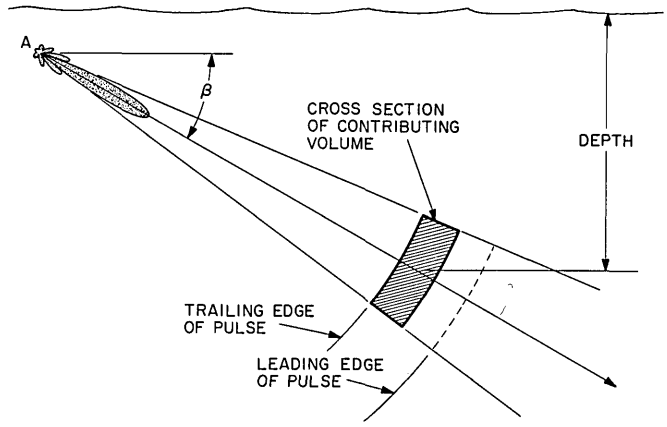

Fig. 5 - Location of scatter volume

SCATTERING STRENGTH PROFILE

Figure 6 is a typical scattering strength profile. Depth is in yards along the ordinate and scattering strength in dB, increasing along the abscissa. This profile was made with the transducer at a depth of 25 yards and directed downward at an angle of 45° with respect to the horizontal. The measurements were made in the early morning between 0200 and 0300. Note the steep decrease of scattering strength between the 100 and 200 yard depths, the minimum in the region just below 200 yards, and the scattering layer at about 500 yards.

The effects of refraction on the scattering strength profile were investigated and found to be negligible for the parameters employed, with the exception of sound speed. The average sound speed over the path, obtained from the computation of propagation factors in another report,* was employed.

*H.U. Criss, K.D. Flowers, B.G. Hurdle, R.M. Lee, and K.P. Thompson, "Procedures for a Series of Experiments in Acoustic Scattering from the Ocean Bottom and Volume in the Blake Plateau Area," NRL Memorandum Report 1767, April 17, 1967.

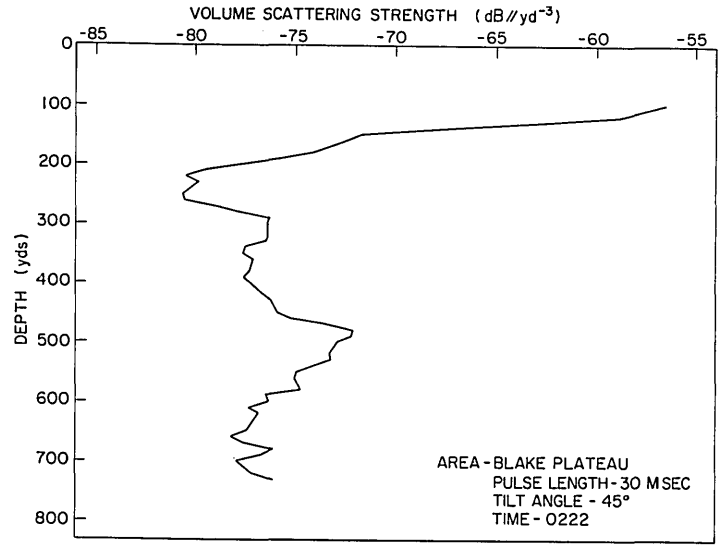

Fig. 6 - Typical scattering strength profile

SCATTERING STRENGTH AS A FUNCTION OF PULSE LENGTH

Figure 7 is a composite illustration of six scattering strength profiles including the 30 ms profile of Fig. 6. All of the profiles are made with a 45°-depression angle. The pulse lengths for the profiles are 15, 20, 30, 40, 50, and 60 ms. It is not intended that the reader resolve each of the profiles but rather observe the similarity of the profiles as the pulse length is varied by a factor of four to one. With the exception of the fine structure all of the profiles are the same.

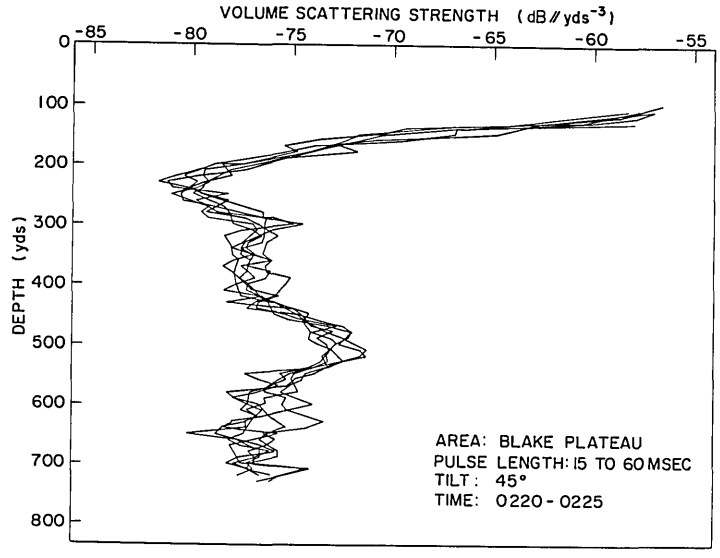

Fig. 7 - Composite of six scattering strength profiles

As mentioned earlier, one of the objectives of the experiment was a comparison of measured scattering from the volume with isotropic scattering theory. Specifically, is the received intensity directly proportional to the contributing volume, all other parameters being constant, or is the scattering strength constant for different magnitudes of the contributing volume?

Ideally an experimental situation would be chosen in which the scattering strength was uniform and constant throughout the medium. Since the ocean is not subject to this kind of control, the next best procedure is to find as large a region as possible over which the scattering strength is constant or substantially so. Then the ensonified volume is varied and the scattering strength examined for systematic variations.

In this experiment the volume was varied by the control of pulse length. When a short pulse was employed a region of constant scattering strength, to approximately ± 1 dB, was found between the 300-yard depth and the 425-yard depth of the scattering strength profiles of Fig. 7. As the ensonified volume was increased by increasing the pulse length, the scattering strength remained constant within approximately ± 1 dB. The size of the region restricted the maximum pulse length such that a variation in volume of only four to one was covered. Within the experimental error, the scattering strength was constant over the four-to-one variation.

SCATTERING STRENGTH AS A FUNCTION OF β

Scattering strength profile was constructed by holding the pulse length constant at 2 ms and varying the elevation of the beam from straight up to straight down in 10° increments. The transducer was located at a depth of 60 yards for this set of data.

The scattering strength versus time data (Eq. (18)) was positioned at the appropriate depth by Eq. (19) for each depression and elevation angle. This gave a number of scattering strengths for each depth. Since no systematic variation of scattering strength as a function of β could be detected, the data were averaged to provide a single profile. The resulting profile is illustrated by the dashed curve in Fig. 8. For comparison, the profiles of Fig. 7 were averaged and illustrated by the solid curve of Fig. 8. Both profiles were made from data taken in the same area of the Blake Plateau, the major difference being the time of day when the measurements were taken. The dashed curve was obtained between 1900 and 2000 in the evening, and the solid curve was obtained between 0200 and 0300 in the morning. The significant decrease of scattering strength from the dashed curve to the solid curve below the depth of 150 yards is attributed to a diurnal change of scatterers in this area. Unfortunately, data were not taken to complete the solid profile near the surface.

SCATTERING STRENGTH PROFILE IN THE CAPE HATTERAS AREA

Two additional scattering strength profiles were taken in an area about 90 nautical miles south-southeast of Cape Hatteras. They are illustrated in Fig. 9. The data for both profiles were taken with the transducer axis directed vertically downward. The solid curve data were obtained with a pulse length of 10 ms and the dashed curve data were obtained with a 100-ms pulse length. Both sets of data were obtained between 2300 and 2400. Here again, good agreement is found between profiles obtained with a factor of 10 difference in pulse length.

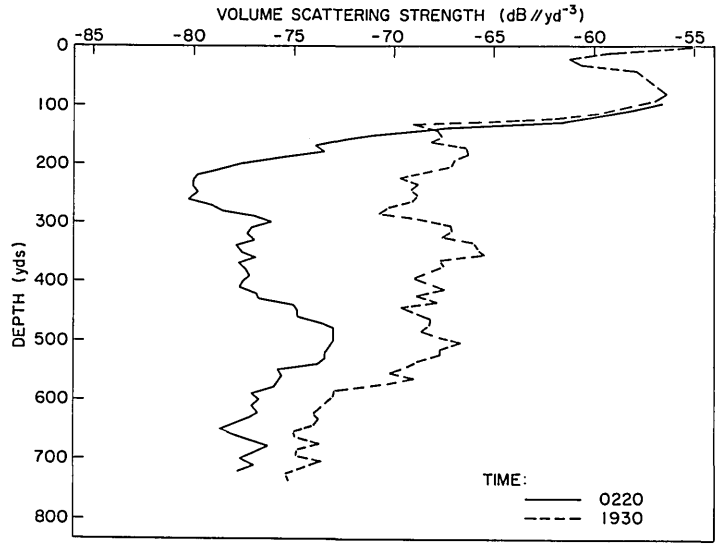

Fig. 8 - Comparison of two scattering strength profiles taken at different times of day -- Blake Plateau area

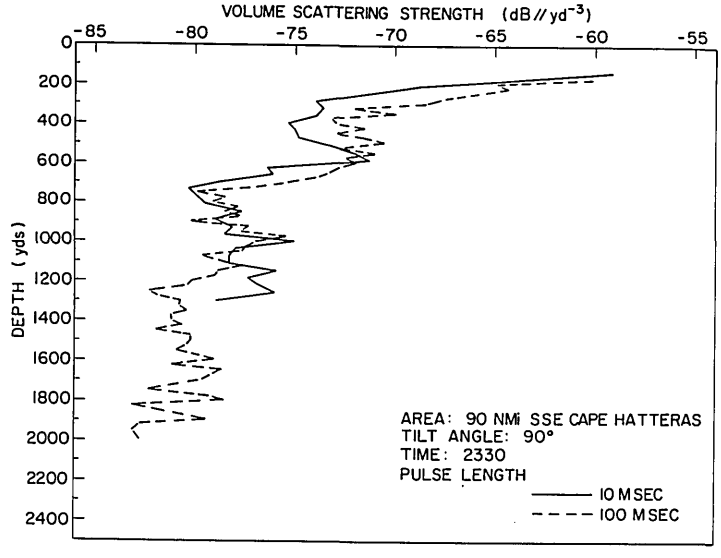

Fig. 9 - Scattering strength profiles in the Cape Hatteras area

SUMMARY AND CONCLUSIONS

An experiment has been conducted that indicates monostatic volume scattering strength in the ocean is independent of the magnitude of the ensonified volume, when the volume is changed by varying the pulse length by a four-to-one ratio. Thus, experimentally measured scattering in the ocean satisfies the isotropic scattering model under the conditions employed.

Appendix

SERVICES

Commander, Operational Test and Evaluation Force, has provided the following aid in the acquisition of data for the experimental portion of this report. The operations were conducted under Project D/S-34, during the period August 28, 1961, through September 14, 1961.

USS Grouper (AGSS-214) was available 18 days operating and in transit plus 10 days at the pier for installation and removal of instrumentation.

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13. ABSTRACT

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Scattered intensity						
Volume scattering strength						
Scattering strength profile						