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Reverberation in the Sea*

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The apparatus used to measure ocean reverberation at 24 kc consists essentially of a sound projector which sends a signal of adjustable duration into the water; a hydrophone which translates the backward scattered sound into electrical voltage; an amplifier which increases this voltage; a cathode-ray oscillograph which converts voltage fluctuations into spot movements; and finally a camera which records the movements on a moving film. Simple reverberation theory indicates (i) that reverberation level increases 10 db with a tenfold increase of pulse length; (ii) that volume reverberation level decreases 20 db for a tenfold increase in range; and (iii) that surface reverberation level decreases 30 db for a tenfold increase in range. At certain times and under certain conditions, presumably when ocean conditions are those postulated by theory, observed reverberation levels agree with theoretical values. Such agreement, however, is relatively uncommon. Under most conditions, deep scattering layers cause volume rever-

beration levels to depart markedly from simple theory; also, a combination of refraction, wind, and other factors causes a decrease in surface reverberation level with range which is too rapid to be in agreement with simple theory. When a sound beam is projected horizontally in deep water, both surface and volume reverberation might be expected. Under a rough sea and for ranges less than 500 yards, surface reverberation predominates over volume reverberation. Beyond 1000 yards, even under a rough sea, volume reverberation usually overshadows surface reverberation. Also, for such long ranges, attenuation enters as an important factor and causes the reverberation level to fall off more rapidly than the rate predicted by simple scattering. In shallow water, bottom reverberation (which depends for its intensity on whether the bottom is rock, sand, mud and sand, or mud) is the dominant part of the observed reverberation.

INTRODUCTION

IN most rooms one may hear a persistence of sound after the sound source is cut off. This so-called reverberation usually decreases rapidly in intensity, for the sound energy is dissipated at the surfaces, etc., where reflection takes place. As the sound drops in intensity, distinct echoes are

usually not heard, yet the reverberation may be considered as a blending of a large number of echoes. Similarly, when a sound beam is projected into the ocean from a sound projector, a persistence of sound is observed either when the projector serves also as a hydrophone, or when a separate hydrophone is used. But since the ocean is really not a closed volume like a room, the explanation of ocean reverberation and room reverberation must be different.

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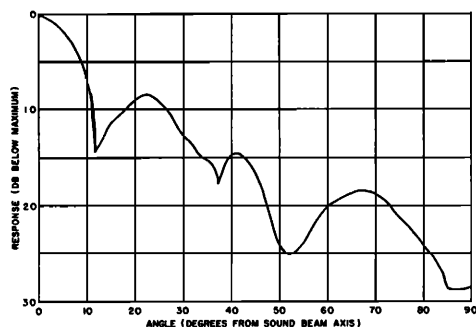


FIG. 1. Beam pattern of the M-S units measured in the plane parallel to the long dimension and perpendicular to the diaphragm.

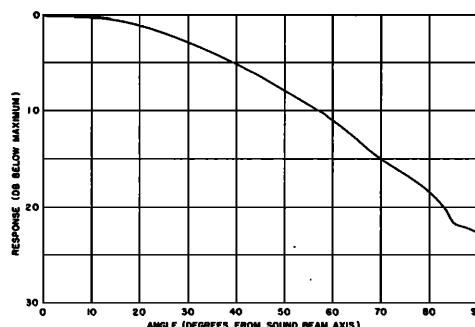


FIG. 2. Beam pattern of the M-S units measured in the plane parallel to the short dimension and perpendicular to the diaphragm.

A sea with a perfectly flat surface and bottom and free from internal "targets" which might reflect sound could not in general return sound to the hydrophone. Thus no reverberation would be observed. But roughen the surface and the bottom of the ocean, introduce into the water air bubbles, suspended solid matter and organic matter such as plankton and the fish which feed on it, permit the thermal structure of the sea to contain minute inhomogeneities, and these "targets" might be expected to scatter back to the hydrophone a large number of weak echoes which would be observed as reverberation.

Such scattered sound is actually observed. The individual echoes overlap, and, although marked fluctuations of sound intensity are recorded, the individual echoes are rarely observed as such. If long signals or pings (200 milliseconds) of constant frequency sound are emitted by the projector, the reverberation, if rendered audible by heterodyne reception, has a musical tone; if shorter pings are projected, the tone heard becomes rough and grating. In general, however, reverberation in the sea is easily distinguished from extraneous noise.

This paper is a report of a study of the scattering of 24-kc sound in the sea conducted off San Diego during 1941 and 1942—first a description of the equipment and apparatus and then a presentation of theory and experimental results.

EQUIPMENT

Floating Laboratory

The experimental work was conducted aboard a converted yacht, the U.S.S. Jasper, which was

operated by Navy officers and men. This ship, having a displacement of approximately 300 tons, provided ample laboratory space and a large, free area on the adjoining open fantail deck.

Projectors and Hydrophones

Two types of electroacoustic transducers served as projectors and hydrophones. The earlier phases of the work were conducted with an identical pair of magnetostriction (M-S) units, one used as projector, the other as hydrophone. In later work, a piezoelectric (R-S) unit built of a mosaic of 45-degree, x cut rochelle salt crystals was used both as projector and as hydrophone—an automatic switching system accomplished the transfer from the driving amplifier output to the receiving amplifier input and back again.

The active diaphragm of the M-S unit is rectangular in shape with the length about 3.5 times the width. The sound beam directivity pattern in the plane parallel to the long dimen-

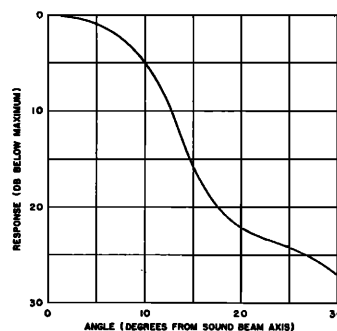


FIG. 3. Beam pattern of the R-S unit.

sion and perpendicular to the diaphragm is shown in Fig. 1. The pattern in the plane parallel to the short dimension and perpendicular to the diaphragm is shown in Fig. 2. These units are mounted either with the long or the short dimension horizontal, and the mounting provides separate adjustments for angles of tilt and of azimuth. The tilts of the projector and hydrophone are usually set at the same angle so that the two beam patterns approximately coincide in space.

The R-S unit is designed to have a conical pattern of circular cross section. Its beam pattern is shown in Fig. 3.

Driving Systems

The driving system for the earlier M-S projector unit consisted of a simple self-excited oscillator followed by a single class "C" stage of

amplification giving a nominal output of 200 watts. The system was pulsed by making and breaking the cathode return of the oscillator.

In later work the driving system consisted of a 100-watt Class "A" amplifier. Excitation was by means of an external signal generator; keying of this input to the power amplifier provided the signal control.

Receiving System

The hydrophone was connected to a high gain, low self-noise, tuned amplifier with an over-all electrical Q of about 20. The resonant frequency, 23.5 kc, was chosen to coincide with the natural resonant frequency of the M-S transducers. This frequency also worked well for the R-S unit which possessed a broad frequency response encompassing 23.5 kc.

After the reception of the scattered sound

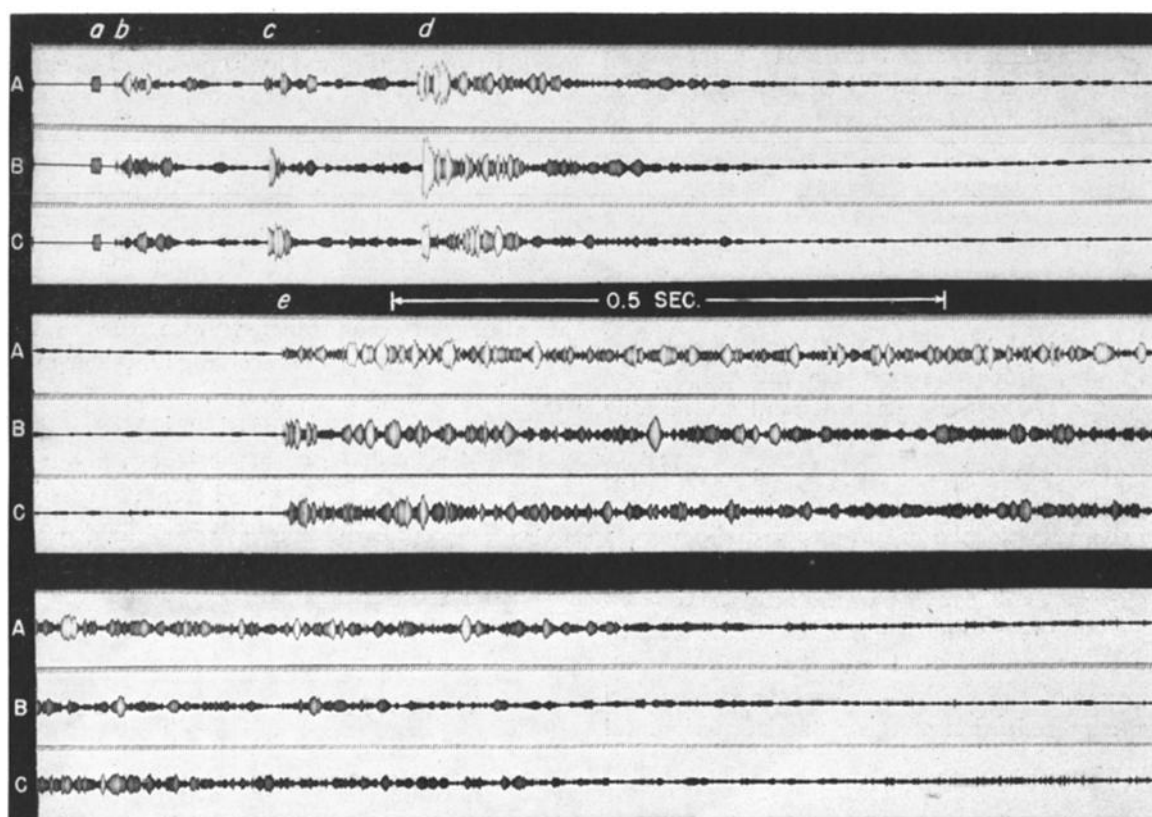


FIG. 4. Three typical reverberation records, *A*, *B*, and *C*, taken in rapid succession. The transmitted signal is shown at *a*. At point *b* the transducer is connected to the receiver; at *c*, *d*, and *e* increases in gain are effected. Attention is called to the marked fluctuation of the reverberation amplitude in a given record and to the amplitude variation from record to record.

begins, the gain of the amplifier is automatically increased in three steps which are manually preselected for both magnitude and sequence interval. The gain change is accomplished by successive removal of shorts from sections of the grid resistor of the second stage (pentode). The maximum possible gain change for all steps is about 85 db. Usually a 20- to 25-db change per step is the maximum desired when a linear voltage amplifier is used and a recording is made on a cathode-ray screen.

All switching is accomplished by a motor-driven system of adjustable cams, the cams operating micro switches in control circuits. Separate cam sections control: (i) the duration of the emitted signal; (ii) switching of transducer from "transmit" to "receive" circuits and back again; (iii) the three steps of gain change.

The amplified electrical signal from the hydrophone is applied to one pair of deflecting plates of the cathode-ray tube and the resulting deflections are recorded on 35-mm film running at constant speed. A fork-controlled strobotron flashing system with an optical arrangement provides timing lines on the film for the accurate determination of time intervals (Fig. 4).

PROCEDURES AT SEA

While reverberation measurements are being made, the ship's propulsion machinery is stopped. The transducer(s), with pre-set angles of downward tilt, are lowered overside to a chosen depth, usually between ten and twenty feet. The lowering is accomplished with a supporting manila line, a ship's boom, and a winch. The azimuth steering is accomplished by the use of two manila lines attached, respectively, to the two ends of the wooden beam which carries the transducer mountings. The roll of the ship causes some vertical rise and fall of the transducer(s) in the water with consequent small deviations in both azimuth and tilt angles. However, the period of roll is long in comparison with the length of the average reverberation record; thus the errors produced by the vertical surging motions are negligible.

When the transducer is in position, pulse signals are emitted and the amplifier gain steps are adjusted in magnitude and sequence interval by visually monitoring the amplitude response

on the cathode-ray screen. With gain changes properly set, a number of photographic records are made in rapid succession in order to provide a statistical sample with essentially constant physical conditions (Fig. 4).

The data log includes entries which might have a bearing on the results: wind velocity, visual estimate of the state of the sea, bathythermogram showing temperature distribution with depth, navigation position fix, time of day, water depth, signal intensity as indicated by the driving voltage or current, receiver amplifier gain settings, and transducer orientations. All film processing and data treatment are handled ashore at the laboratory.

DEFINITION OF REVERBERATION LEVEL RL

Reverberation level, RL , as reported in this paper has the definition,

$$RL = 10 \log(P/Wd^2), \quad (1)$$

where P is the electrical power generated in the hydrophone circuit by the reverberation sound and W is the power in the hydrophone circuit when the hydrophone faces the projector driven at operating level at a distance of separation, d . In an actual determination of W the distance d might be chosen unity but for the fact that the radiation field is probably not well established at so short a distance from the projector. Consequently, the measurement of W was made with d equal to four yards, a distance which places the hydrophone well into the radiation field.

When a single transducer serves as both projector and hydrophone, W is obtained by using an additional pair of transducers, neither of which need be calibrated, or by using a single additional transducer calibrated as both source and receiver.

TREATMENT OF DATA

Reverberation levels are determined from the experimental records obtained at sea, by use of a modified definition of RL . The amplitudes recorded on the 35-mm films, when corrected to the standard gain setting of the amplifier, are proportional to the square root of the electric power generated in the hydrophone. This permits the replacement of the power ratio by the square

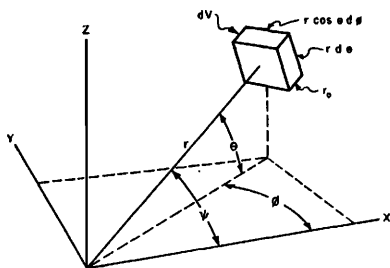


FIG. 5. The geometry of volume scattering.

of an amplitude ratio.

$$RL = 10 \log(P/Wd^2) = 10 \log(a/A)^2 \\ = 20 \log(a/A), \quad (2)$$

where a is the amplitude corresponding to the reverberation power P and A the amplitude corresponding to the reference power Wd^2 .

Examination of the film records shows a random type of amplitude fluctuation superimposed upon a general trend of amplitude decay (Fig. 4). The time positions of the fluctuation maxima and minima change from one record to the next, even though the two records are made within seconds of each other. Thus, the determination of reverberation level must be statistical, requiring a number of records made in rapid succession to insure essentially the same set of physical conditions. Ten successive records usually constitute the statistical sample here used to establish reverberation amplitude.

The jagged amplitude envelope poses difficulties in reading. To meet the problem the "point" and "band" methods were tried. In the "point" method, the amplitude of each of the ten records is read at a specific time after emission of the ping. The arithmetical mean of the ten amplitudes is used to determine the RL for that specific time. In the "band" method the largest amplitude in a time interval equal to three times the emitted ping duration is read. This is taken as a measure of the reverberation amplitude at the center of the interval. The arithmetical mean of these maxima is used to determine the RL for the center of the interval chosen. A number of comparisons of the two methods established the fact that the band method gives values which average about 6 db higher than the point method. Because of the greater ease of reading amplitudes from the

records, the band method is generally adopted except for short range reverberation. The mean values obtained by the band method are all reduced by 6 db.

VOLUME REVERBERATION

Theory of Idealized Situation

Let a projector, located far beneath the ocean surface and far from the ocean floor, send out a sound pulse of duration t_0 into a homogeneous medium with speed of sound the same in all directions and with many identical scatterers uniformly distributed. Also assume that the emitted sound intensity is constant over the time t_0 , which is fairly short.

The geometry of volume scattering is illustrated in Fig. 5. The transducer (projector) is located at the origin of the coordinates with the sound beam axis directed in the x direction. At a time t , measured from the mid instant of the emitted signal, echoes will be received at the transducer (hydrophone) from scatterers found within a spherical shell of radii $r \pm r_0/2$, where $r = ct/2$, $r_0 = ct_0/2$ and c is the velocity of sound.

A small volume element, dV , of this shell is depicted in Fig. 5. Assuming random phase distribution, the average intensity of the echo received from this volume element will equal the sum of the intensities of the echoes from the scatterers contained within the volume element. In other words, the acoustic scattering cross section of the element will equal the sum of the cross sections of the scatterers within the element.

Neglecting the absorption and scattering loss in the medium between the transducer and the volume element, the intensity dI_r of the reverberation received at the hydrophone from dV will equal

$$dI_r = ImdV/4\pi r^2, \quad (3)$$

where I is the incident intensity at dV and m is the specific scattering cross section of the medium for backward scattering. The specific scattering coefficient m is usually expressed in units of square yards per cubic yard. The incident intensity I is

$$I = I_1 q(\theta, \phi) r^2, \quad (4)$$

where I_1 is the transmitted sound intensity on the

sound beam axis of the projector at unit distance from the source and $q(\theta, \phi)$ is a directionality factor. The latter function, $q(\theta, \phi)$, is unity on the sound beam axis ($\theta = \phi = 0$).

The electrical power, dP , developed in the hydrophone circuit by the reverberation dI_r , will also depend on the hydrophone directivity. If the hydrophone unit differs from the projector unit, its directivity will also differ and may be designated by $q'(\theta, \phi)$. At once it follows that

$$dP = Kq'(\theta, \phi)dI_r, \tag{5}$$

where K is an instrumental constant describing the hydrophone sensitivity. Combining Eqs. (3)–(5),

$$dP = KI_1mq(\theta, \phi)q'(\theta, \phi)dV/4\pi r^4. \tag{6}$$

Or, since $dV = r^2r_0 \cos\theta d\theta d\phi$,

$$dP = (KI_1mr_0/4\pi r^2)q(\theta, \phi)q'(\theta, \phi) \cos\theta d\theta d\phi. \tag{7}$$

The total power received is obtained by integrating Eq. (7) over all angles θ and ϕ . Finally

$$P = (KI_1mr_0/4\pi r^2) \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \times q(\theta, \phi)q'(\theta, \phi) \cos\theta d\theta d\phi. \tag{8}$$

The quantity KI_1 equals Wd^2 of Eq. (1). Hence the quantity, $10 \log(P/KI_1)$, is equal to the reverberation level RL previously defined (Eq. (1)). For convenience let

$$J_v = 10 \log \left\{ (1/4\pi) \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \times q(\theta, \phi)q'(\theta, \phi) \cos\theta d\theta d\phi \right\}. \tag{9}$$

J_v is called the volume reverberation index. It is inherently negative in sign and equals zero for

completely non-directional transducers. With these definitions, the idealized theory of volume reverberation gives the volume reverberation level (in db) as,

$$(RL)_v = 10 \log m + 10 \log r_0 + J_v - 20 \log r. \tag{10}$$

If absorption in the medium is present, it can be allowed for by subtracting the quantity $2\alpha r$ from the right side of the equation. α is the attenuation coefficient in db per unit distance.

Example of Nearly Ideal Case

In order to insure that only volume reverberation is being picked up, a relatively narrow sound beam is directed down in the sea in water deep enough to avoid bottom effects, precautions thus being taken to avoid scattering which might be received from the sea surface and bottom. Even with such precautions, the observations rarely fit the simple Eq. (10). An example of one of the few cases in which results approximate this equation is shown in Fig. 6.

This example represents observations made on June 3, 1942, with the M-S transducers tilted downwards 60 degrees from the horizontal and placed at a depth of 60 feet. The signal length was 10 ms. Twenty records were filmed, measured, and averaged to give the points shown as solid circles. The solid line on the graph represents Eq. (10) for a value of the scattering coefficient, m , equal to 10^{-7} yd.^{-1} . The points give a fair fit to the calculated line.

Typical Situations—Deep Scattering Layers

Although the reverberation records present such a large variety of forms that one has difficulty in selecting representative samples, certain features are found in practically all records

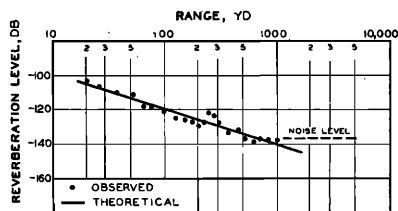


FIG. 6. Volume Reverberation. Sound beam directed 60 degrees downwards. An example of an ideal case; the straight line represents an inverse square dependence of reverberation intensity on range.

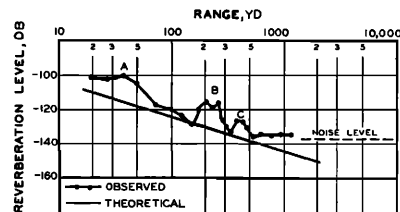


FIG. 7. Volume Reverberation. Sound beam directed 60 degrees downwards. Peaks A, B, and C are produced by horizontal layers of high scattering power. The straight line represents an inverse square dependence of reverberation intensity on range.

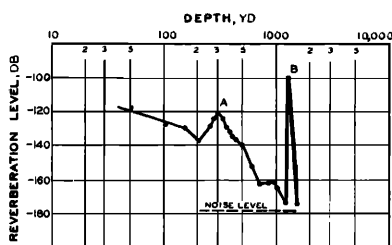


FIG. 8. *Volume Reverberation*. Sound beam directed vertically downward. Peak *A* is produced by a single scattering layer at a depth of approximately 300 yards; *B*, by reflection from the bottom.

when the projector beam is directed down into the sea and these are depicted in Figs. 7 and 8.

Figure 7 represents observations made on June 8, 1942, with the M-S transducers directed down 60 degrees from the horizontal at a depth of 60 feet. The signal length was 8 ms. Ten successive records were averaged and the data obtained are plotted as solid circles. The straight line depicts Eq. (10) for a scattering coefficient m of 5×10^{-8} yd.^{-1} . Large departures from the simple theory of uniform distribution of scatterers are noted. These departures are caused by the fact that the scatterers in the ocean are not distributed uniformly throughout the medium but are stratified into horizontal layers of concentrations which vary with depth. In Fig. 7 three such layers are seen at *A*, *B*, and *C*.

Figure 8 is more representative than Fig. 7 of conditions usually observed during the daylight hours. It represents observations made on August 5, 1942, with the R-S transducer directed vertically downwards. The signal length is 12 ms. Ten successive records were averaged and the data obtained are plotted as solid points.

In this figure, the principal feature of volume scattering is the strong peak marked *A* at a depth of 300 yards. The peak *B* is due to sound reflected from the ocean bottom from a depth of 1300 yards. Although observations made from month to month or even from day to day rarely duplicate Fig. 8 in detail, the scattering layer, at a depth of about 300 yards, is the most persistent feature of daylight observations of volume scattering made off the California coast. Subsequent observations reported elsewhere¹

¹ C. E. Duvall and R. J. Christensen, "Stratification of sound scatterers in the ocean," *J. Acous. Soc. Am.* **18**, 254 (1946).

have shown that this layer migrates diurnally. The principal features of the migration are the movement upward toward the surface at sunset and the movement downward at sunrise.

Horizontally Directed Projector

Usually when a sound projector, located near the surface, is directed horizontally, scattering from the surface renders it difficult or impossible to separate the volume reverberation from surface reverberation. Occasionally, however, the surface is calm enough to render surface reverberation negligible. Such a situation is depicted in Fig. 9.

This figure depicts observations made on August 5, 1942, with the R-S transducer at a depth of 20 feet and its sound beam directed horizontally. The signal length was 11 ms. Reverberation level averages obtained from ten successive records are plotted as solid points. Even with a sound beam leaving the projector in a horizontal direction, the deep scattering layer *A* is observable on the record, not as prominently as with the downward directed projector, but still observable. The very rapid decrease of temperature with depth, which was found in the ocean on this date, caused a strong downward refraction of the "horizontal" sound beam, and thus the beam reached into the deep scattering layer. The thermal condition prevailing during these observations and the resultant ray diagram are shown.

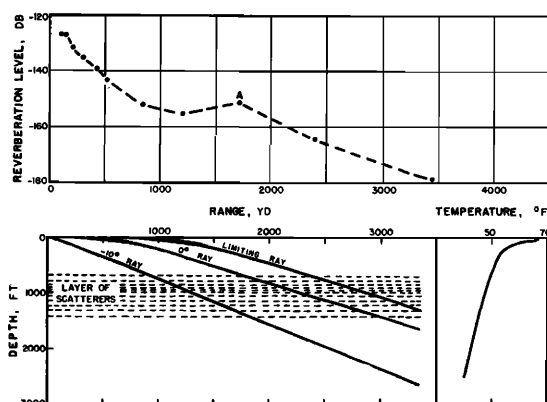


FIG. 9. *Volume Reverberation*. Sound beam directed horizontally. Ocean surface smooth enough to render surface reverberation negligible. Peak *A* produced by deep scattering layer. Temperature variation with depth and its effect on the sound rays are shown in the lower half of the figure.

Volume Scattering Coefficients

From the above examples it is seen that volume reverberation is a variable phenomenon. Values of the specific scattering power m vary with depth at a given position and time and vary with time at a given position. At the scattering layer depth of about 300 yards the values observed during the daylight hours are usually greater than at other depths. Below the region of high scattering, a systematic decrease in m is observed. As a matter of fact, the smallest observed value of m was found well below the scattering layer. The magnitudes of observed values of m range between the rough limits of 10^{-9} yd.^{-1} to 10^{-5} yd.^{-1} .

Causes of Volume Reverberation

The work reported here had as its original objective the measurement of the scattering power and spatial distribution of the scatterers responsible for reverberation. Little or no effort was expended on the problem of the identification of the scatterers, and this question still remains largely unanswered. The diurnal movements of the scattering layer indicate strongly that the causes of scattering are to be found primarily in biological organisms, since many forms of life in the sea are known to exhibit diurnal movements. The determination of the particular life forms responsible for the scattering is a problem for future investigations.

SURFACE REVERBERATION

Separation of Surface and Volume Reverberations

While it is relatively easy to observe volume reverberation free from surface reverberation by directing the transducers down into the medium, the converse does not hold, for it is impossible to eliminate volume reverberation from surface reverberation measurements completely. The mitigating circumstance that permits the observation of surface reverberation is the fact that, under proper conditions, the scattering power of the surface is greater than that of the scatterers within the volume of the sea.

Observations illustrating the separation of surface and volume reverberation are shown in

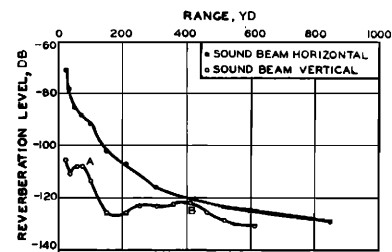


FIG. 10. *Surface and Volume Reverberation.* The short range surface reverberation obtained with the horizontal beam is approximately 20 db higher than the volume reverberation obtained with the beam directed vertically downward. Peaks at A and B represent scattering layers.

Fig. 10. They were made on July 9, 1942, with the M-S transducers when the sea's surface was liberally covered with whitecaps. The upper curve represents observations made with the transducers directed horizontally; the lower curve, observations made a short time later with the transducers directed vertically downward. At ranges less than about 300 yards, the upper curve is well above the lower one. Clearly the initial portion of the reverberation, resulting from the horizontally directed beam, originates at or close to the sea's surface. Therefore, it is of interest to investigate the type of reverberation decay which might be expected for scattering originating at the surface and then to compare theory with experiment.

Idealized Situation

The simple theory of surface reverberation follows a point of view similar to that adopted for volume reverberation. The difference in the type of reverberation is due only to the fact that in surface reverberation the scatterers are found not throughout the volume of the sea but in the ocean surface or in a shallow layer extending a short distance beneath the surface. The scattering power of the surface or surface layer is specified as the scattering cross section per unit area, a dimensionless quantity called n .

Using the coordinate system of Fig. 5, let the z axis be perpendicular to the sea's surface, and, as before, let the sound beam axis be directed in the x direction. Then, following the same development as for volume reverberation, the power dP delivered to the receiver by scattering from a surface element, dS , is

$$dP = KI_1 n q(\theta, \phi) q'(\theta, \phi) dS / 4\pi r^4. \quad (11)$$

It will be noted that for any given range θ is a constant, θ being defined by $\theta = \sin^{-1}(D/r)$ where D is the transducer depth. The surface element, dS , is that portion of the surface included between the concentric spheres of radii $r \pm r_0/2$ and the planes ϕ and $\phi + d\phi$. Its area is

$$dS = rr_0 d\phi. \quad (12)$$

Hence the total power, an expression analogous to Eq. (8), is

$$P = (KI_1 nr_0 / 4\pi r^3) \int_0^{2\pi} q(\theta, \phi) q'(\theta, \phi) d\phi. \quad (13)$$

The surface reverberation index is a function of θ and is designated $J_s(\theta)$, which has a value given by the expression

$$J_s(\theta) = 10 \log \left\{ (1/2\pi) \int_0^{2\pi} q(\theta, \phi) q'(\theta, \phi) d\phi \right\}. \quad (14)$$

The complete expression for surface reverberation level, analogous to Eq. (10), is

$$(RL)_s = 10 \log(n/2) + 10 \log r_0 + J_s(\theta) - 30 \log r. \quad (15)$$

Since θ is a function of range, the form of rever-

beration decay predicted by Eq. (15) depends on the nature of $J_s(\theta)$ and on the dependence of n on range. The simplest form assumes n to be constant; occasionally, observed surface reverberation is of this type.

Figures 11 and 12 illustrate two cases of this simple type. Both observations were made on May 8, 1942, with the M-S transducers placed at a depth of 20 feet. In obtaining the data of Fig. 11, the transducers were oriented with the broad portion of the beam in the vertical plane so that the directivity in the vertical plane was negligible for values of θ corresponding to the observed ranges. Under these conditions, $J_s(\theta)$ is constant and Eq. (15) has a very simple form, giving a 30-db drop in reverberation level for each tenfold increase in range. The solid line represents Eq. (15) for n equal to 3×10^{-4} . The plotted points represent averages of 36 successive records. The signal length is 8 ms.

In the observations of Fig. 12 the M-S transducers were turned so that the beam pattern showed high directivity in the vertical plane. Hence, $J_s(\theta)$ was dependent on range. The solid curve was calculated from Eq. (15), assuming $n = 5 \times 10^{-5}$. The plotted points represent averages of 30 successive records with signal lengths of 8 ms.

Prevalent Situations

Agreement of the observations of Figs. 11 and 12 with the simple theory is seen to be very good, but the quality of the agreement is exceptional rather than typical. In many cases the decay is much too rapid to agree with simple theory. The cause of this rapid decay is not clearly understood. It may be caused by a greater than inverse square transmission loss as the sound goes to the surface and back, or by a decrease in the scattering coefficient with a decreasing angle, θ .

a. *Effect of refraction.*—One possible cause of a rapid drop of reverberation level with range is downward refraction. When the temperature decreases rapidly with depth, the sound beam is bent downwards away from the surface. Figure 13 illustrates such a phenomenon. The thermal conditions at the surface and the sound ray of maximum range are shown in Fig. 13A. Figure 13B shows the reverberation observations; the arrow indicates the greatest range from which

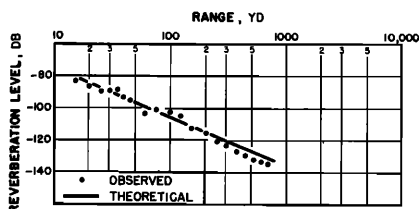


FIG. 11. *Surface Reverberation.* Comparison of observed and calculated surface reverberation. Measurements were made with the M-S transducers with the broad pattern in the vertical plane and with the beam directed horizontally.

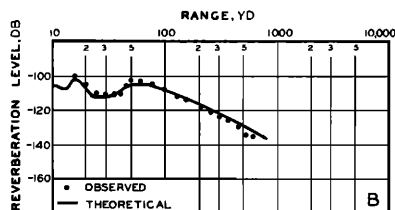


FIG. 12. *Surface Reverberation.* Comparison of observed and calculated surface reverberation. The data were taken on the same day as those illustrated in Fig. 11, but the horizontally directed transducers were oriented to give high directionality in the vertical plane. The theoretical line takes into account the beam pattern.

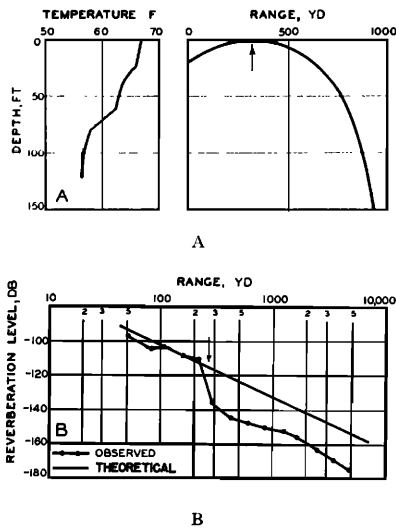


FIG. 13. *Surface Reverberation.* Effect of downward refraction on reverberation with beam directed horizontally: (A) bathythermogram and corresponding ray diagram; (B) comparison of observed results with those calculated from simple ray theory. The sharp drop, at the point designated by the arrow, corresponds to the range at which the limiting sound ray leaves the surface.

surface scattering is to be expected. The observed drop occurs close enough to the predicted drop to give reasonable assurance that this explanation is the correct one.

b. *Effect of wind speed.*—The effect of wind on surface reverberation is essentially a secondary effect. The primary effect is surface roughness, frequency of whitecaps, concentration of air bubbles, or some other property of the sea which is, in turn, dependent on wind speed. Because of this indirect relationship with the winds, the correlation between wind speed and reverberation is not expected to be very good, and this is indeed the case. However, the correlation, even though not very good, does suggest that there is a real dependence of surface reverberation upon wind speed.

Figure 14 presents the results of nine sets of observations at wind speeds varying from 6 to 18 miles per hour. They were made during July and August, 1942, with the R-S transducer directed horizontally at a depth of 20 feet and with a signal length of 10 ms. Reverberation level is plotted as a function of wind speed for selected ranges from 80 yards to 3200 yards.

It is seen that at ranges of 400 yards or less there is a significant increase of reverberation

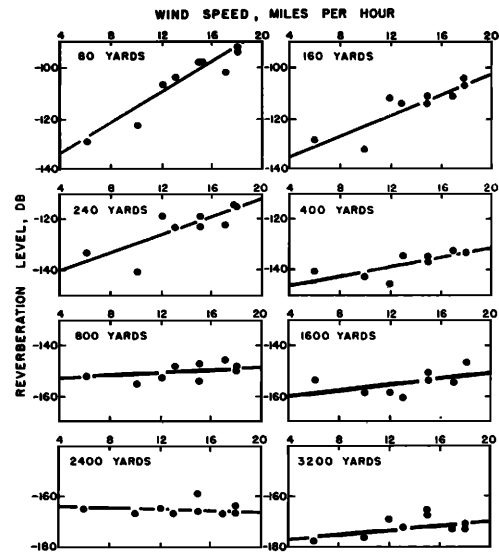


FIG. 14. *Surface Reverberation.* Levels as a function of wind speed at specified ranges.

level with wind speed. At ranges of 800 yards or more the change with wind speed is so small that it is hardly significant compared with the scatter of the observations themselves. Furthermore, the levels of these longer-range observations are of the order of magnitude of the levels expected from volume reverberation alone, and it is probable that surface scattering contributes very little if at all to the observed reverberation.

As already explained, each of the plots of Fig. 14 represents the dependence on wind speed of the reverberation level of scattered sound from a given range. The straight line in each plot has been fitted to the data by the method of least squares. The set of straight lines permits a plot of reverberation level and range for any desired wind speed up to 18 miles per hour. Three such curves are plotted in Fig. 15. They depict reverberation level decay at wind speeds of 6, 12, and 18 miles per hour. Since there is no reason to believe that the reverberation level for ranges of 800 yards and beyond is affected by the wind speed, no attempt is made to show such a dependence. Accordingly, the observations for such ranges are averaged together, and the three curves are united into one for ranges beyond 800 yards.

Surface Scattering Coefficients

Magnitudes of the surface scattering coefficient n can be calculated from the graphs of

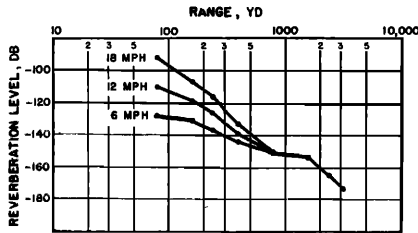


FIG. 15. *Surface Reverberation.* Level variation with range at wind speeds of 6, 12, and 18 miles per hour.

Figs. 14 and 15. This has been done only for the shortest range, 80 yards. At greater ranges, the effects of refraction, mentioned above, may reduce, by an unknown amount, the apparent scattering coefficient below its true value. Since the transducer was at a depth of 20 feet, a range of 80 yards corresponds to a grazing angle, θ , of 4.8 degrees. Scattering coefficients calculated for this range and grazing angle vary from 10^{-6} at 6 miles per hour wind speed to 5×10^{-3} at 18 miles per hour.

BOTTOM REVERBERATION

Idealized Situation

Since bottom reverberation originates at the surface of the ocean bottom, it is qualitatively similar to surface reverberation. Hence, the theory developed in the preceding section would be expected to be directly applicable to bottom reverberation. While this is true in principle, there are important differences which usually make it easily possible to distinguish bottom reverberation from surface reverberation.

Reverberation is commonly observed with the transducer mounted just below the bottom of the ship and directed horizontally, and thus the range from which bottom reverberation is first returned is usually longer than that corresponding to surface reverberation.

Another distinguishing characteristic is scattering power—that of the bottom is usually greater. Consequently, when echo-ranging is done in shallow water, bottom reverberation usually dominates surface and volume reverberation, except for ranges less than that at which the lower edge of the sound beam strikes the bottom.

An example of an unusually simple case of bottom reverberation is illustrated in Fig. 16.

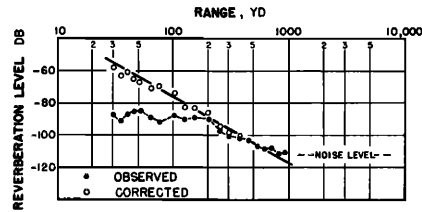


FIG. 16. *Bottom Reverberation.* A simple case in which the scattering, when corrected for beam pattern, shows an inverse fourth power dependence on range—the solid line. Here the scattering coefficient is proportional to the sine of the grazing angle.

Observations were made over an area with an ocean depth of 75 feet and with a flat, but rocky, bottom. The M-S transducers were oriented in their mounting so that their maximum directivity lay in the vertical plane and were then placed at a depth of 10 feet with the sound beam directed horizontally. Thirteen successive records were averaged to give the solid points plotted in the figure.

In the locality where these observations were made, the bottom was rough and the scattering was strong. It is safe to assume that all of the observed reverberation is due to bottom scattering, and therefore that the equation of surface reverberation is applicable.

In order to eliminate the effect of projector directivity on the decay curve and thereby to permit the focusing of attention on the scattering itself, the observed solid points were corrected by subtracting the quantity, $(J_s(\theta) - J_s(0))$, from the reverberation levels. These corrected points, shown as open circles in the plot, represent the reverberation levels that would have been observed with a transducer which is non-directional in the vertical plane and which has a reverberation index $J_s(0)$ in the horizontal plane. The angle θ used in making this correction is the grazing angle at the bottom and is given by

$$\theta = \sin^{-1}(D/r), \quad (16)$$

where D is the bottom depth and r is the range.

The corrected equation has the form

$$(RL)_s = 10 \log(n/2) + 10 \log r_0 + J_s(0) - 30 \log r, \quad (17)$$

which, for constant n , represents a 30-db drop for each tenfold increase in range. Actually the observations give a 40-db drop for this range

increase, thereby indicating that the scattering coefficient n decreased with increasing range and therefore with decreasing grazing angle. Good agreement with observations is obtained if it is assumed that n is directly proportional to the sine of the grazing angle θ , such that

$$n = n_0 \sin \theta. \tag{18}$$

This relation, combined with Eqs. (16) and (17), gives the equation

$$(RL)_s = 10 \log(n_0 D/2) + 10 \log r_0 + J_s(0) - 40 \log r, \tag{19}$$

which is shown as the solid line in Fig. 16. This theoretical line yields a value of n_0 equal to 0.2.

Other Examples of Bottom Reverberation

It should not be assumed that all cases of bottom reverberation are as simple as the example depicted in Fig. 16. Most observations are much more complicated, so much so that Eqs. (15) and (19) cannot be relied upon for quantitative predictions. Even so, these equations are useful when a qualitative picture of bottom reverberation is sought.

Examples of some of the ways in which complexity arises are shown in Figs. 17 and 18. These figures depict bottom reverberation recorded on July 29, 1942, in two localities: Fig. 17 represents recordings over a mud bottom and Fig. 18 over a sand-and-mud bottom. In both

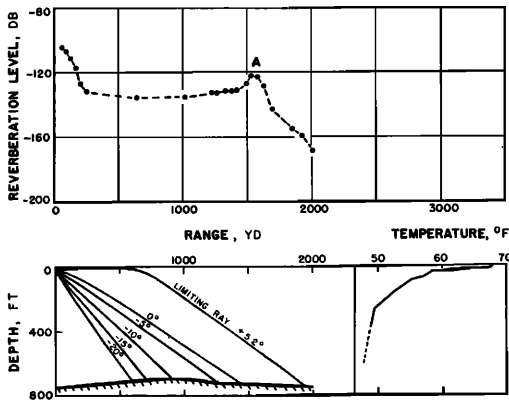


FIG. 17. *Bottom Reverberation.* A complex case. The bottom is mud; the thermal condition and the resulting ray diagram are shown in the lower half of the figure. The rapid decay beyond the peak at 1600 yards is due to low specular reflection from the mud.

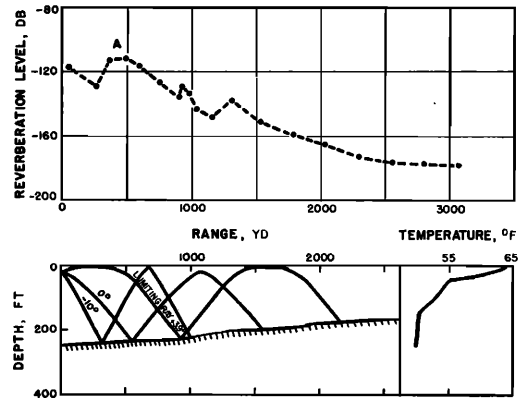


FIG. 18. *Bottom Reverberation.* Another complex case. The bottom is sand-and-mud. Appreciable reverberation from ranges beyond the peak at 500 yards is attributable to bottom reflections.

cases, the R-S transducer was directed horizontally at a depth of 20 feet.

Even though taken closely spaced in time, the data plotted on the two graphs show marked differences, differences whose major features can be understood by a study of bottom profiles and ray diagrams. The ray diagrams show the calculated paths of sound rays which leave the transducer at various angles measured from the horizontal.

Each of the reverberation graphs has a strong peak *A* approximately at the range where the beam axis strikes the bottom. This peak occurs at shorter range in Fig. 18 than in Fig. 17 because the depth is smaller. However, the most striking difference between the two curves is found in the portions following the major peaks *A*. In Fig. 17—observations taken over mud—the reverberation decays rapidly to a negligible level at ranges beyond the far edge of the sound beam. In Fig. 18—observations taken over mud-and-sand—the peak *A* is followed by two more peaks and then by a slow decay. Thus, reverberation is not cut off, as in the case of the mud bottom, beyond the range where the forward edge of the sound beam strikes the bottom. Sufficient sound, it seems, is reflected *forward* by the sand-and-mud surface to permit appreciable reverberation at long ranges. It is safe to assume that the forward reflected sound suffers several successive bottom reflections on its way from the transducer and, similarly, that the backward scattered sound also suffers reflections on its way

back to the transducer. These observations indicate that a mixture of sand and mud is a better reflector of sound than mud alone. However, mud, in its ability to scatter sound backward at the grazing angles corresponding to the peak level A , is as strong as, or perhaps somewhat stronger than, sand-and-mud.

Bottom Scattering Coefficients

From the above examples, it is apparent that the levels of bottom reverberation are affected by other factors than the specific scattering power of the bottom itself. Thus, the error of determination of the scattering coefficient is large under the normal conditions in which bottom reverberation is usually observed. The experiments reported here, which were made in order to establish the order of magnitude of reverberation levels under practical conditions, are not suitable for the detailed study of the scattering power of the ocean bottom. These experiments do establish, however, the fact that various types of bottom show large differences in backward scattering. The greatest scattering comes from rock bottoms; next, mud bottoms, curiously enough; and then sand bottoms. The order of magnitude of the scattering coefficient at grazing angles of 5 to 10 degrees is 10^{-2} for rock bottoms and 10^{-3} for sand bottoms.

The observations represented by Fig. 16 indicate that scattering coefficients depend on grazing angle. Because of refraction complications illustrated in Figs. 17 and 18, it is not possible to determine the nature of this dependence for these cases.

REVERBERATION AND PING LENGTH

Theory asserts that *reverberation intensity* should be directly proportional to ping length

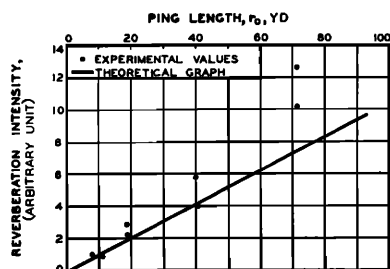


FIG. 19. Reverberation intensity as a function of ping length. The intensity is approximately proportional to ping length.

and that the *reverberation level* should increase 10 db for each tenfold increase of ping length (see Eqs. (8), (10), (13), and (15)). Using the band method of averaging, the reverberation intensity was measured as a function of time and ping length. At as many as ten different times during the reverberation decay, reverberation intensities and ping lengths were compared. Figure 19 depicts the theoretical relationship as a solid line. Experimental values follow the theoretical curve for ping lengths up to 40 yards.

The film records (e.g., Fig. 4) show a marked dependence of the *coherence* of the received reverberation on the emitted ping length. By coherence is meant the tendency for a high amplitude to be followed by a high amplitude. In general, the amplitude envelope appears to be a sequence of "blobs" which, on the average, have a length about that of the emitted signal. This presents evidence that the scattering properties of the bulk of the scatterers have not changed appreciably in a time equal to the pulse duration (up to 0.1 second in this study). Yet from record to record, taken one second apart, there appears to be no coherence. This latter effect may be caused by (i) a change in the scatterers during one second or (ii) movement of the source and receiver due to the ship's motion or (iii) a combination of (i) and (ii).

SUMMARY

Simple theory indicates (i) that reverberation intensity is directly proportional to the sound source intensity and to the ping length; (ii) that volume reverberation intensity varies inversely as the square of the range (the reverberation level decreases 20 db for a tenfold increase in range); and (iii) that surface reverberation intensity varies inversely as the third power of the range (the reverberation level decreases 30 db for a tenfold increase in range), except that if the range is too short, elaborate calculations are necessary and the dependence on range is somewhat changed. At certain times and under certain conditions, presumably when ocean conditions are those postulated by theory, observed reverberation levels agree with theoretical values. Such agreement, however, is relatively uncommon. Under most conditions, deep scattering layers—

the non-uniform distribution of scatterers—cause volume reverberation levels to depart markedly from the simple theory; also, a combination of refraction, wind, and other factors may cause a decrease in surface reverberation level with range which is too rapid to be in agreement with simple theory.

When the sound beam is projected horizontally in deep water, both surface and volume reverberation might be observed. At short ranges (less than 500 yards) and high wind speeds (great roughness of the sea surface), surface reverberation is strong and overshadows volume reverberation; at short ranges and low wind speeds, surface reverberation is negligible and is overshadowed by volume reverberation; and at long ranges (beyond 1000 yards) volume reverberation overshadows surface reverberation at all wind speeds and, in fact, is not affected by the wind. Also, for ranges beyond 1000 yards attenuation enters as an important factor, causing the reverberation level to fall off more rapidly than that predicted by simple scattering alone.

In shallow water, bottom reverberation may well be a dominant part of the observed reverberation. It is always combined with volume and surface reverberation if the sound beam is horizontally directed. Bottom reverberation levels depend on the character of the sea bottom, whether it be rock, sand, mud-and-sand, or mud.

Then too, the ocean surface, by reflecting scattered sound, is a means of increasing bottom reverberation.

Volume scattering coefficients are found between the rough limits of 10^{-9} yd.⁻¹ and 10^{-5} yd.⁻¹; surface scattering coefficients may vary from 10^{-6} at six miles per hour wind speed to 3×10^{-3} at 18 miles per hour; bottom scattering coefficients at grazing angles of from 5 to 10 degrees are found to be of the order of 10^{-2} for rock bottoms and of 10^{-3} for sand bottoms.

ACKNOWLEDGMENTS

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