AD NUMBER
AD039544

CLASSIFICATION CHANGES	
TO:	unclassified
FROM:	confidential

LIMITATION CHANGES

TO:

Approved for public release, distribution unlimited

FROM:

Distribution: Controlled: All requests to Office of Naval Research, Washington, DC.

AUTHORITY

ONR ltr. Ser 93/057, 20 Jan 1998; ONR ltr. Ser 93/057, 20 Jan 1998

AD 39544

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION ALEXANDRIA, VIRGINIA

A SUMMARY OF UNDERWATER ACOUSTIC DATA

PART IV
REVERBERATION

by

R. J. Urick
Naval Research Laboratory

and

A. W. Pryce
Office of Naval Research

February 1954

Office of Naval Research
Department of the Navy
Washington, D. C.

CONFIDENTIAL

SECURITY

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Sections 793 and 794. The transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

Further distribution or reproduction of this document in whole or in part is prohibited except with permission of Code 411, Office of Naval Research.

PREFACE

This report is the fourth of a series which attempts to summarize existing knowledge about the parameters which appear in the sonar equations. These relationships, which find application in many problems involving underwater sound, are stated for reference in Part I of this series. As outlined in Part I, the objective of the summary is to provide a condensation of some of the basic data in underwater sound for use by practical sonar scientists. The present report deals with the scattering of sound in the ocean in its relation to the prediction of reverberation levels. Material which could not be included in these confidential reports will appear in a Secret Supplement to the series.

The complete series of reports is listed below:

Part I - Introduction (July 1953)
Part II - Target Strength (December 1953)
Part III - Recognition Differential (December 1953)
Part IV - Reverberation (February 1954)
Part V - Background Noise
Part VI - Source Level
Part VII - Transmission Loss

Manuscript received 2[illegible] January 1954.

CONTENTS

A SUMMARY OF UNDERWATER ACOUSTIC DATA

PART IV - REVERBERATION

INTRODUCTION

In underwater sound, "reverberation" means the sound scattered back toward the source by inhomogeneities of various kinds in the ocean. The most obvious inhomogeneities in the ocean are its surface and its bottom, which scatter sound back toward the source in the form of surface reverberation. The body of the ocean itself contains inhomogeneities of various kinds, such as biological organisms (fish, plankton, diatoms, shrimp, etc.) and thermal and turbulence microstructure. Such biological and physical scatterers in the volume of the ocean are believed to be the cause of volume reverberation.

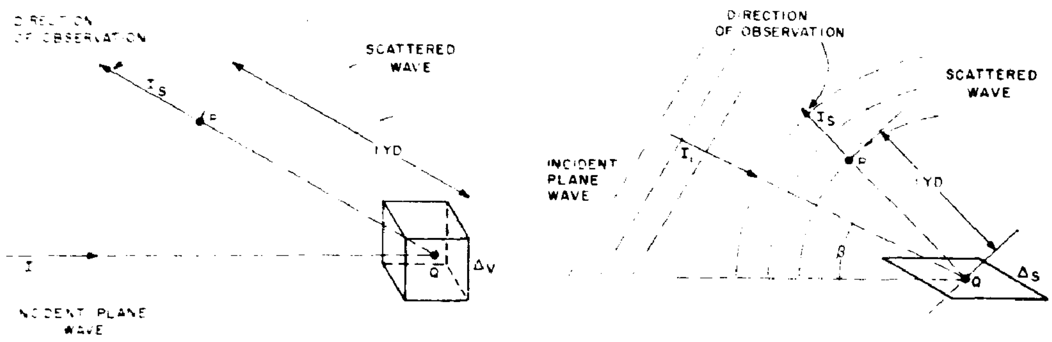
The importance of this back-scattered sound lies in the fact that it often forms the background in which a desired echo must be detected. In submarine search, reverberation often forms the limiting background interference when a high-power sonar set is used in shallow water; in mine hunting, bottom reverberation usually tends to obscure the mine echo. Whenever an active sonar system is employed, it is necessary to consider whether reverberation may mask the echo, and one must make some attempt at computing reverberation levels for simplified situations in dealing with problems in equipment design and performance prediction. It will be seen from what follows, however, that the computation of reverberation levels for realistic cases occurring in the ocean is, in the present state of knowledge, far from a simple matter.

The treatment of reverberation from a practical standpoint will begin with a statement of the definition of a scattering coefficient, followed by a summary of what appears to be known about it from the different scatterers in the ocean. In the sonar equations this parameter is associated with a special form of directivity index, called the directivity index for reverberation, to express the discrimination of a transducer against reverberation. Some practical expressions for the computation of this index will be given, and equations for the computation of reverberation levels for ideally simple situations will be derived. It will be seen that where simple conditions can be assumed to occur in the ocean, the prediction of reverberation levels is straightforward once a value of the reverberation coefficient is chosen. But for some practical problems of interest, such as the important one of long-range submarine search, it will appear that a reverberation computation is at present highly uncertain.

THE REVERBERATION PARAMETER

The amount of sound which is scattered in a given direction by a unit area or volume is specified by a scattering coefficient, 10 log m. This coefficient, unfortunately, has not yet been given a short name of its own, and in what follows, 10 log m will itself often be used to denote the coefficient. In order to identify the source of reverberation, subscripts will be employed, (10 log m_v, 10 log m_s, and 10 log m_b) denoting the scattering coefficient for volume, sea surface, and bottom reverberation, respectively.

10 log m is defined to be ten times the log of the power that would be scattered by unit area or volume, per unit intensity of an incident plane wave, if the scattering in all directions were equal to that in the direction of observation. By unit area is meant one square yard of surface or bottom; by unit volume is meant one cubic yard of ocean.



(a) Volume reverberation (b) Surface or bottom reverberation

Figure 1 - Diagrams illustrating the definition of 10 log m. (The reference point P is located one yard from the center of the elemental volume or area in the direction toward the observer.)

For volume reverberation the definition may be illustrated by reference to Fig. 1a. A plane wave of intensity I_i is incident upon a small volume Δ_v centered at Q. Let I_s be intensity of the scattered sound at a point P distant one yard from Q in the direction of observation. Then if the scattering is isotropic, the total power scattered by the volume Δ_v will be $4\pi I_s$ and the scattering coefficient is therefore given by

$$10 \log m_v = 10 \log \frac{4\pi I_s}{\Delta_v I_i} .$$

The coefficients for surface and bottom reverberation may be illustrated in a similar manner, as shown in Fig. 1b. Consider a plane wave of intensity I_i incident at some grazing angle β upon a small area Δ_s of surface or bottom centered at Q. If I_s is the intensity of the scattered sound at a point P, the total power scattered by the area Δ_s would be $2\pi I_s$ if the scattering were the same in all directions and there were no penetration into the surface or bottom. The scattering coefficient is therefore given by

$$10 \log m_{s,b} = 10 \log \frac{2\pi I_s}{\Delta_s I_i} .$$

In analogy with the target strength of sonar targets, 10 log $\frac{m_v}{4\pi}$ and 10 log $\frac{m_{s,b}}{2\pi}$ may be called the target strength of unit volume or area. In fact the quantity 10 log $\frac{m_b}{2\pi}$ for bottom reverberation has been called the scattering strength of a unit area of bottom in analogy with target strength, and is a coefficient which appears to be conceptually easier to utilize than the ordinary scattering coefficient in problems like acoustic mine-hunting (1). Indeed there is no essential difference between the reflection and scattering from targets and the scattering from scatterers in the ocean and its boundaries, and both could well be specified by a parameter of the same name and definition.

In general, the scattering coefficients may be expected to vary with the direction of observation. [illegible] scattering by the surface, bottom, and volume of the ocean has been studied only [illegible] back toward the source, this direction will be implied hereafter in this report. [illegible] a good deal of [illegible] literature in the field of scattering of light in other [illegible] surfaces (2). Such oblique scattering would be of importance in attempt- [illegible] systems employing separated sending and receiving [illegible].

VOLUME REVERBERATION

Causes of Volume Scattering

Volume reverberation originates in the body of the ocean, and is to be distinguished from the scattering produced by its boundaries. Because a perfectly homogeneous uniform ocean cannot scatter sound, the existence of volume reverberation must mean that there are scattering discontinuities of some kind in the ocean. The nature of these discontinuities has been the subject of considerable speculation and even theoretical investigation throughout the years, but is still one of the outstanding fundamental problems in underwater sound.

One cause of volume scattering that has received repeated attention is the velocity microstructure of the sea, which may be in the form of small-scale thermal or salinity gradients. However, a combination of theoretical study (3,4) and field measurements (5) seems to indicate that the reverberation which could be produced by thermal microstructure is too small, by several orders of magnitude, to account for the reverberation actually observed. Yet, the possibility exists that other physical discontinuities, such as a smaller microstructure not yet observed or the small bubbles that may be present in the mixed layer, may play some appreciable part in producing reverberation.

A more likely cause of reverberation is marine life. Various kinds of marine animals, such as shrimp and fish, are known to be responsible for the layer of enhanced scattering known as the "deep-scattering layer." The nature of this layer, as shown by acoustic data and by net hauls, has received a great deal of attention from oceanographers. Its properties are the subject of an enormous body of literature (6). One recent study (7) concluded that "the scattering layer is in reality a complex strata of organisms; it is probable that the upper scatterers are primarily euphausids and smaller crustacea, whereas the lower, heavier scatterers are primarily fish and forms of shrimp." Certainly the layer has a complex and variable faunal population. Laboratory measurements of the scattering coefficient of individual fish, squid, and a known number of shrimp (8), together with data about the population density of these organisms in the scattering layer as found by net hauls (9), indicate that the scattering which would be produced by such a population is of the same order of magnitude as that returned from the scattering layer. The scattering organisms, or those on which they feed, appear to be photosensitive, for the layer is known to move up during the night and down during the day, with the amount of vertical migration tending to keep the light intensity in the layer roughly constant (10).

The use of very short ping lengths also has yielded some knowledge of the distribution of the acoustic cross sections of the scatterers in the deep-scattering layer (11,12). Yet the relationship between acoustic size and physical size of the scatterers is uncertain, and marine biologists are not yet in complete agreement as to which organisms are principally responsible for the acoustic properties of the layer. It seems reasonably certain that these organisms are different in different areas and seasons.

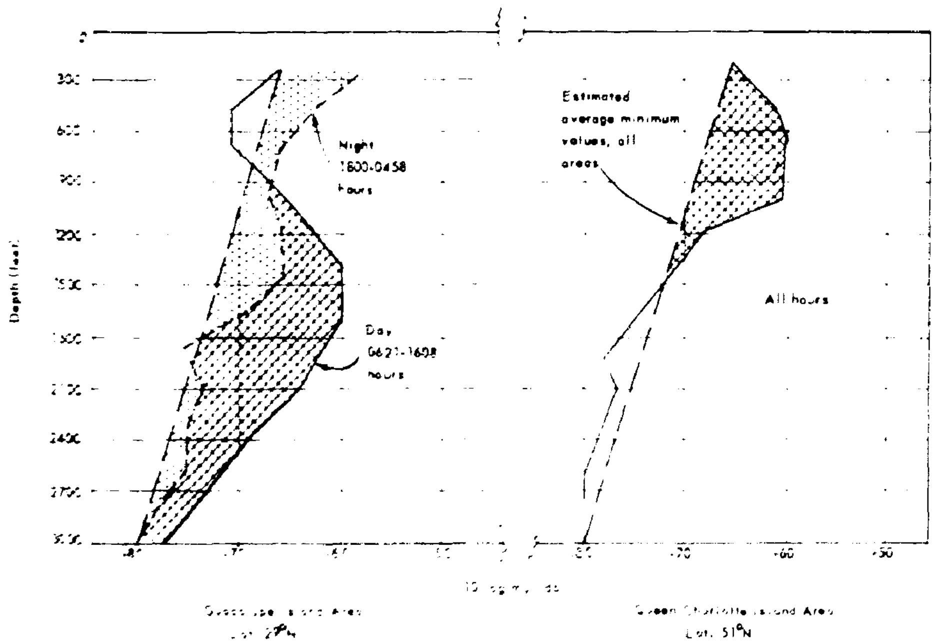
Unfortunately, there seems to be no observations of the nature of the scatterers above or below the deep-scattering layer. This is due in part to the sparse population of scatterers outside of the layer and the resulting relatively low amounts of scattering produced. Perhaps one might infer that the scatterers outside the layer are the same as those within it. Still, there is no assurance that such is the case, and there are as yet no observations which pertain directly to the source of scattering in the great volume of the deep ocean which produces the volume reverberation observed at long ranges. A very important zone in which the nature of scatterers is essentially unknown is within the surface sound-channel.

Variation with Depth

Much of our knowledge of volume scattering has been obtained with transducers directed vertically downward. Such measurements of reverberation yield 10 log m_v directly as a function of depth. Recently, a novel attempt was made to deduce the depth distribution of 10 log m_v from the reverberation observed from an explosive charge, but the reduction of the data proved so complex that few conclusions could be drawn (13,14).

The most extensive study of the depth distribution of 10 log m_v has been made recently by the Naval Electronics Laboratory (9). Measurements were made at two locations in the North Pacific, and some wartime data obtained at a location near San Diego was reanalyzed. The essential features of the variation of scattering coefficient with depth are shown in Fig. 2, which has been plotted from the data in Ref. 9. It is seen that 10 log m_v falls off with increasing depth, except for the broad increase in scattering near the depth of the scattering layer. That is to say, superposed on a uniform decrease of 10 log m_v with depth is the added scattering, shown cross-hatched, produced by the scattering layer. By day, the zone of enhanced scattering lies at a depth of about 1500 feet in the Guadalupe Island area; by night, it lies near the surface. This diurnal migration in depth of the layer causes the depth distribution of 10 log m_v to have the typical forms shown on the left in Figure 2. In the more northern area (Queen Charlotte Islands), the depth migration was found to be small or nonexistent. Above and below the layer, measured values of 10 log m_v tend to become smaller uniformly with depth, as shown by the dashed lines in Figure 2.

The quantitative aspects of the depth distribution are somewhat as follows. In the absence of, or above and below, the deep scattering layer, 10 log m_v decreases at the rate of about 0.5 db per hundred feet, having a value of -66 db at a depth of 300 feet and -80 db at 3000 feet. Within the scattering layer, increases of 5 to 15 db are to be expected. The layer may be as much as 2000 feet or more in thickness, and tends to become shallow at night and to become deeper during the day. Thus, during the night, 10 log m_v may fall off much faster with depth because of the presence of the layer at or near the surface. In addition, sometimes more than

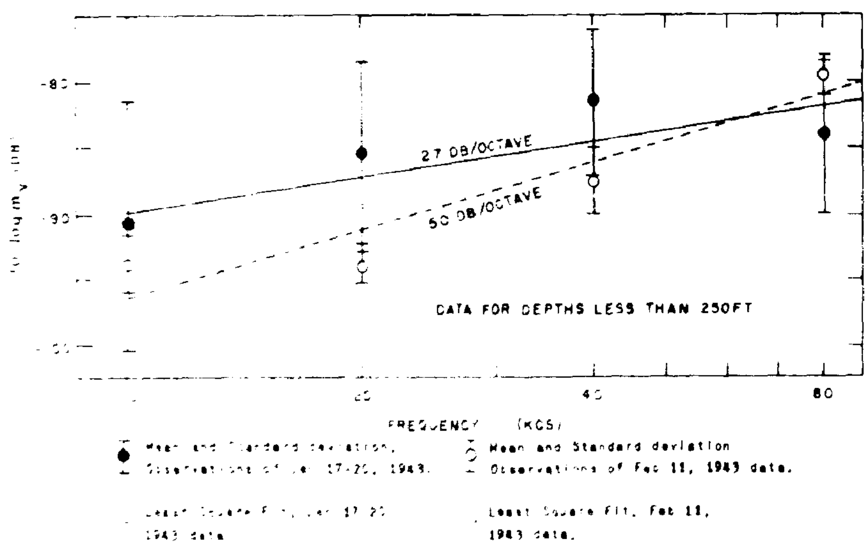


one scattering layer is observed. At depths shallower than 300 feet, it is likely that considerably higher coefficients may be found. Unfortunately there are no direct determinations of 10 log m_v at shallow depths nor within the mixed-layer sound channel. It appears, however, from wartime measurements of reverberation at 24 kc out to about 3000 yards made with horizontally directed transducers, that -60 db is a typical value for 10 log m_v under those conditions (15,p 305), which must represent an average value for the near-surface ocean down to perhaps 1200 feet in depth. Considerable variations from this value, however, are required to fit individual observations; from all the wartime data "we may conclude that the backward volume-scattering coefficient for horizontally projected 24-kc beams varies from 10^{-6} (-60 db) to 10^{-8} (-80 db), with 10^{-6} (-60 db) the typical value" (15,p 306).

Dependence upon Frequency

This subject was studied at considerable length by UCDWR during the early part of the war, and the results of this study still remain the most useful information for practical purposes (16). Reverberation was measured with downward-directed transducers at 10, 20, 40, and 80 kc in several areas south of San Diego. The values of 10 log m_v obtained at the various areas and at the various frequencies were irregular but, on the whole, showed a tendency to rise with increasing frequency. Fig. 3 shows mean and extreme values of 10 log m_v obtained at the above frequencies.* The average rate of increase with frequency is much less than the 12 db per octave to be expected from the fourth-power law of Rayleigh scattering, which applies to fixed, rigid obstacles smaller in size than a wavelength. However, there is no reason to expect Rayleigh scattering from the obstacles probably occurring in the sea, since they are certainly deformable and free to move in the sound field. Also, it is likely that, when all depths are averaged together, the scattering arises from different types of organisms, many of which are of the same size as the wavelength or larger.

More recently, knowledge of the frequency dependence of reverberation has been gained through detailed studies of the acoustic properties of the deep-scattering layer. In one



... of 10 log m_v with frequency

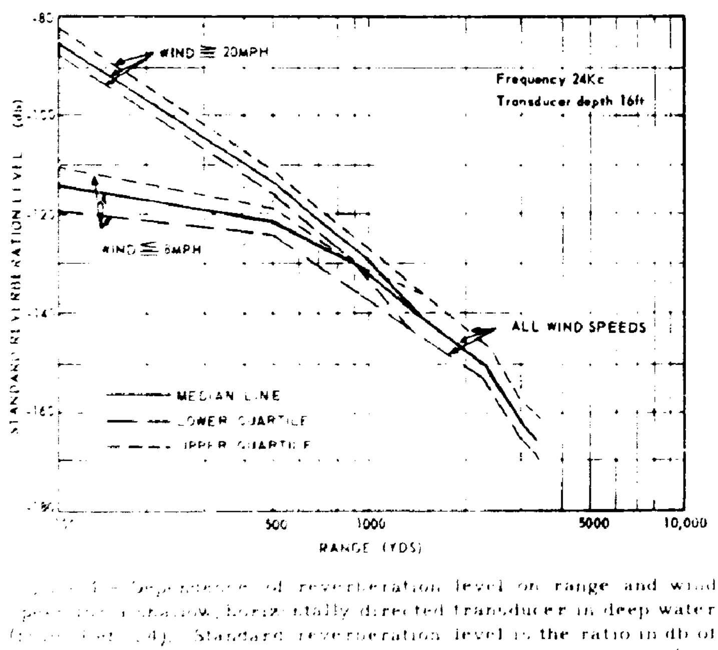
*These ... unknown reason

investigation, the scattered return from explosive shots was analyzed with narrowband filters between 2 and 19.6 kc (17). It was found that, at and above 5 kc, there were peaks in the scattering which varied with different depths. In one instance there was a considerable return at 15 kc at a depth of 450 feet, which did not appear at any lower frequency; at 5 kc on this same record, a much broader and deeper peak was found; and at 2 kc there was no evidence of peaking at all. This peculiar behavior must indicate a different faunal population in different parts of the layer, and in different areas. The matter of peaks and "holes" in the reverberation spectrum is of obvious importance in sonar echo-ranging, but for practical purposes, where comparatively large volumes of ocean return sound at any one instant, there has not yet been demonstrated any greatly increased or decreased reverberation at one frequency than another (18). The subject, however, deserves systematic study of a survey type for different parts of the sea.

The ultimate in a detailed study of scattering from different scatterers in situ has been achieved by lowering a spark sound source down to the layer, and recording the return from individual scatterers lying close to the source (12). This has permitted a study of the "echo" from single scatterers as a function of frequency, and has enabled individual scattering cross sections to be determined. But the method has not yet been used extensively enough to yield data of operational usefulness, although it has proved to be another tool for studying the source of volume scattering in the ocean.

SEA-SURFACE REVERBERATION

The surface of the sea is a type of inhomogeneity in the ocean which can, and does, scatter sound back toward the source. The obvious cause of this reverberation is the scattering



[illegible] - Dependence of reverberation level on range and wind speed for a shallow, horizontally directed transducer in deep water ([illegible] 4). Standard reverberation level is the ratio in db of the reverberation level for a standard pinglength of 80 yards (100 [illegible]) to the level of the outgoing ping at a distance of one [illegible] from the transducer.

investigation, the scattered return from explosive shots was analyzed with narrowband filters between 2 and 19.6 kc (17). It was found that, at and above 5 kc, there were peaks in the scattering which varied with different depths. In one instance there was a considerable return at 15 kc at a depth of 450 feet, which did not appear at any lower frequency; at 5 kc on this same record, a much broader and deeper peak was found; and at 2 kc there was no evidence of peaking at all. This peculiar behavior must indicate a different faunal population in different parts of the layer, and in different areas. The matter of peaks and "holes" in the reverberation spectrum is of obvious importance in sonar echo-ranging, but for practical purposes, where comparatively large volumes of ocean return sound at any one instant, there has not yet been demonstrated any greatly increased or decreased reverberation at one frequency than another (18). The subject, however, deserves systematic study of a survey type for different parts of the sea.

The ultimate in a detailed study of scattering from different scatterers in situ has been achieved by lowering a spark sound source down to the layer, and recording the return from individual scatterers lying close to the source (12). This has permitted a study of the "echo" from single scatterers as a function of frequency, and has enabled individual scattering cross sections to be determined. But the method has not yet been used extensively enough to yield data of operational usefulness, although it has proved to be another tool for studying the source of volume scattering in the ocean.

SEA-SURFACE REVERBERATION

The surface of the sea is a type of inhomogeneity in the ocean which can, and does, scatter sound back toward the source. The obvious cause of this reverberation is the scattering

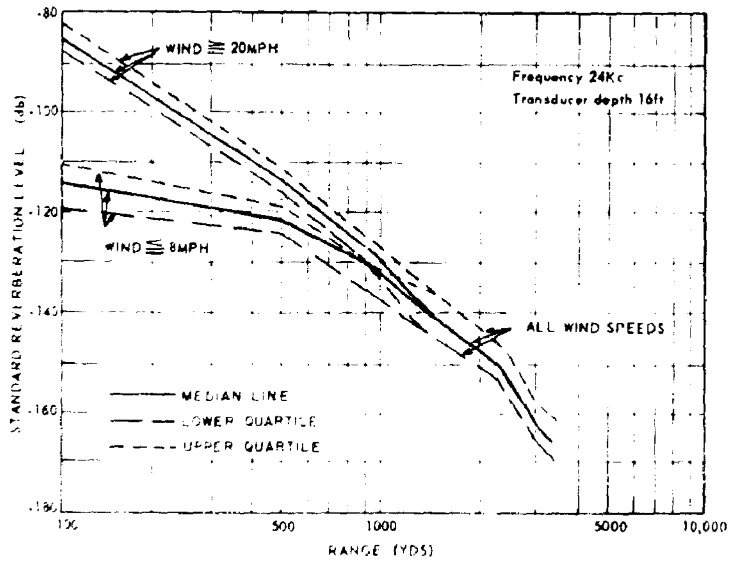


Figure 4 - Dependence of reverberation level on range and wind speed for a shallow, horizontally-directed transducer in deep water (from Ref. 24). Standard reverberation level is the ratio in db of the reverberation level for a standard pinglength of 80 yards (100 [illegible]) to the level of the outgoing ping at a distance of one [illegible]

produced by irregularities such as waves, ripples, and whitecaps, which exist whenever the sea is not perfectly calm. A more subtle cause of sea-surface scattering is the air entrapped near the surface. This air content, in the form of bubbles, represents the effect of whitecaps and sea roughness in mixing air into the upper surface layers of the ocean.

Little is known quantitatively about either of these sources of back-scattering. Even though ocean waves have been studied qualitatively for many years, the statistical shape of the sea surface has been entirely unknown until recently for any but the simplest type of ocean swell (19,20). Further, even if the shape of the surface were specified statistically, the back-scattering produced by it could not be foretold until the theory of scattering from rough surfaces is more advanced (21). The existence of air bubbles in the near-surface ocean water has recently been demonstrated by means of an upward-directed fathometer which at times failed to obtain an echo from the surface in moderate and high seas, apparently because of clouds of air bubbles entrapped beneath the surface (22). A possible effect of air bubbles has also been indicated by tests of a sound-velocity meter which showed a lower sound velocity near the surface after a storm (23). At any rate, although the presence of near-surface air bubbles are in all likelihood a concomitant of whitecaps on the surface, their comparative importance in producing surface reverberation is not known.

Both of these causes of scattering would become more effective the higher the sea state, and one would expect 10 log m_s to increase with increasing sea state or wind force.

During World War II, an analysis of much 24-kc reverberation data obtained with a shallow horizontally directed transducer in deep water revealed a marked dependence of reverberation level at short ranges on surface roughness (24). No such dependence was observed at long ranges (Fig. 4). This indicates that at the shorter ranges surface reverberation predominates over volume reverberation. On this basis, reverberation levels at a range of 100 yd given in the report of this wartime work* have been used to derive values of 10 log m_s by applying the reported equipment parameters. Values of 10 log m_s derived in this manner are given in Fig. 5 as a function of wind force. Since the transducer depth used was 16 ft, the grazing angle at 100 yards was 3°. 10 log m_s is seen to increase up to a wind speed of 20 mph, beyond which it is constant. This levelling-off of reverberation at high wind speeds perhaps may be attributed to the increased attenuation of bubbles whipped into the sea at high wind speeds, and to the shielding effect of the troughs of the waves. From the date presented in Fig. 5, 10 log m_s also appears to be independent of wind force at low wind speeds, below the speed at which whitecaps appear (8 mph). It is probable, however, that at low wind speeds the reverberation level is primarily due to volume reverberation, for if the reported reverberation levels for low wind speeds are used to compute values of 10 log m_v, values of -55 to -80 db are found, in approximate agreement with the values obtained from other data.

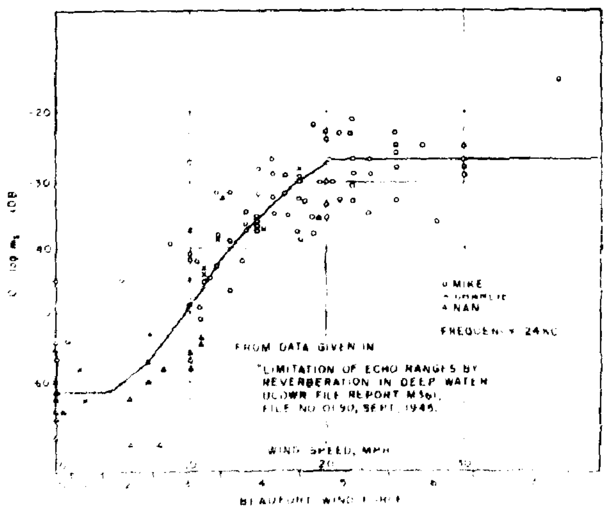


Figure 5 - Surface reverberation. Variation of 10 log m_s with wind force.

*[illegible] reverberation was [illegible] standard reverberation [illegible] of reverberation [illegible] pulse length of 80 yards [illegible] the [illegible] one yard distance

In contrast to the situation at short ranges, no dependence of reverberation level on wind speed was observed at long ranges in these wartime experiments (24). This was attributed, probably correctly, to the fact that volume reverberation should be predominant at ranges beyond a few hundred yards under the conditions of depth, transducer directivity, and frequency of World War II echo-ranging sonar. A factor which contributes to the unimportance of surface reverberation under these conditions is the fact that 10 log m_s may vary with grazing angle between a sound ray and the mean surface, becoming less as the angle decreases in somewhat the same way as bottom reverberation will be seen to do.

In fact, a variation of 10 log m_s with grazing angle is indicated by the great change of 10 log m_s with wind speed at 100 yards (Fig. 5), together with the lack of dependence of reverberation level on wind speed at long ranges—say 1500 yards (Fig. 4). If volume reverberation is strong enough at 1500 yards to mask surface reverberation and the effect of wind on its level, it should be strong enough at 100 yards to prevent the change of 33 db due to the effect of wind speed on surface reverberation from taking place. It must be concluded therefore, that 10 log m_s is range-dependent or, more properly, that it is a function of the grazing angle at the sea surface. If the sea surface acts like a perfectly rough surface, this variation would be like the square of the sine of the grazing angle (Lambert's Law); if air bubbles extending below the surface for a certain distance play any great part in the scattering process, the scattering would be more nearly isotropic, and 10 log m_s would tend to become independent of the angle at the surface.

There are, however, no systematic measurements of this variation, although an experiment with a transducer tiltable in the vertical plane would be simple to carry out. Such a study would throw light on the scattering processes operating at the sea surface and indicate accurately the manner in which surface reverberation falls off with time. Surface reverberation has not been systematically studied at all in this country since the war, even though the development of sonars utilizing the mixed-layer sound channel, and of active homing torpedoes, would make such a study imperative. Indeed, nothing at all appears to be known about the variation of surface reverberation with frequency.

The British have recently made some measurements of 10 log m_s in shallow and in deep water (25). In this work, the quantity (10 log m_s - M_R) was measured, where M_R is the recognition differential. Unfortunately, M_R was not determined, but was estimated to be 0 ± 2 db for the equipment used (26). For deep water, it was concluded that (10 log m_s - M_R) was -30 ± 5 db for a wind force of 3 to 4 and that this value was constant over the range 300 to 800 yards. If it is assumed that M_R = 0 for the British equipment, this value is in good agreement with Fig. 4 for the range of 100 yards. In coastal waters where the depth was between 30 and 100 fathoms, the following values of (10 log m_s - M_R) were found:

No. of Observations	Mean Depth (Fathoms)	Range (Yards)			
		150	330	500	800
10	49	-31.0	--	-37.0	-34.6
7	49	--	-30.0	-32.6	-32.5
5	52	-29.0	-34.4	-36.8	-35.7

The higher values at the shortest range (150 yards) were believed significant, and perhaps are the effect of an increasing grazing angle at the surface. When the data was broken down as to sea state, the following values were found for ranges of 500 to 800 yards:

Sea State	Mean Depth (Fathoms)	No. of Observations	Mean Value (10 log m_s - M_R)
1	52	6	-31.9
2	59	4	-26.5
3	41	12	-35.8
4	50	2	-41.5

The falling-off of (10 log m_S - M_R) beyond sea state 2 was believed to be real, and to be due to an increasing aeration of the surface water with increasing sea state. This would result in absorption rather than scattering of sound, with a consequent reduction of reverberation level. In water 10-30 fathoms deep, higher values, averaging -26 db at 800 yards for (10 log m_s - M_R), were found, presumably because of the presence of bottom reverberation from the sea bed. These British results, obtained at a frequency of 50 kc, have been quoted at some length because they appear to be the only quantitative postwar data on surface scattering available at this time.

BOTTOM REVERBERATION

The bottom of the sea, or of a river or harbor, may scatter sound back toward the source by one or both of two processes. The predominant cause of bottom reverberation is probably the roughness of natural bottoms. This roughness may be the ripple marks produced by surface waves and currents; for rocky bottoms, the roughness may be the jagged, irregular bottom topography. Each element of roughness gives rise to an element of back-scattered sound. Such roughness-caused scattering arises in somewhat the same way that an optically rough surface scatters light. In addition, even a perfectly smooth bottom produces reverberation to some extent because of the fact that it consists of sedimentary particles, each of which scatters sound. This particle-caused scattering from smooth sand surfaces has been studied extensively in the laboratory (at frequencies between 0.4 and 1.0 megacycles) (27). However, it is not yet entirely clear how much of the reverberation observed in the field is due to particulate scattering and how much is due to surface roughness, although there is good evidence to show that the latter is often the more important (28).

The first measurements of 10 log m_b were obtained during the war in studying the reverberation observed in shallow water with World War II sonar sets. Since the war, the impetus to obtaining a knowledge of bottom back-scattering has been given by acoustic mine-hunting for bottomed mines, since back-scattering usually forms the background in which the mine echo must be detected. In response to this need, one field experiment aimed at evaluating 10 log m_b has been carried out in this country (1), and the British have given considerable attention to the subject, both in the field and in the laboratory, during the past two years (29, 30,31).

Variation with Grazing Angle

It is now well established that 10 log m_b increases with the angle between the incident sound ray and the bottom. This dependence on grazing angle plays an important part in determining the rate of fall-off of bottom reverberation with range. Figure 6 shows the results of three determinations of the variation of 10 log m_b with grazing angle, based on data obtained by UCDWR during the war (15, p.316), and recently by the Naval Research Laboratory (1), and UDE (30). The UDE data was originally reported in terms of reverberation level as a function of range, together with the level of the echo from a sphere of known diameter (18 inches). By using stated equipment parameters and converting range to grazing angle, the plotted values of 10 log m_b have been obtained. The values shown for the various determinations of 10 log m_b are not all mean or average values of this quantity. The UDE values are perhaps 6 db higher than the mean because of the use of a transducer having a broad beam in the vertical plane which permitted surface-reflected paths to add to the simple bottom reverberation; the UCDWR values at 10° are high for the same reason; the NRL values were stated to be about 5 db higher than mean because of the method of measurement. Nevertheless, it would appear that the NDRC data, obtained at 24 kc with horizontally directed transducers, are distinctly smaller than the two more recent and probably more reliable determinations.

A major source of discrepancy in measurements of this type is the unsatisfactory nature of sedimentary nomenclature based on particle size (sand, mud) as a criterion of acoustic

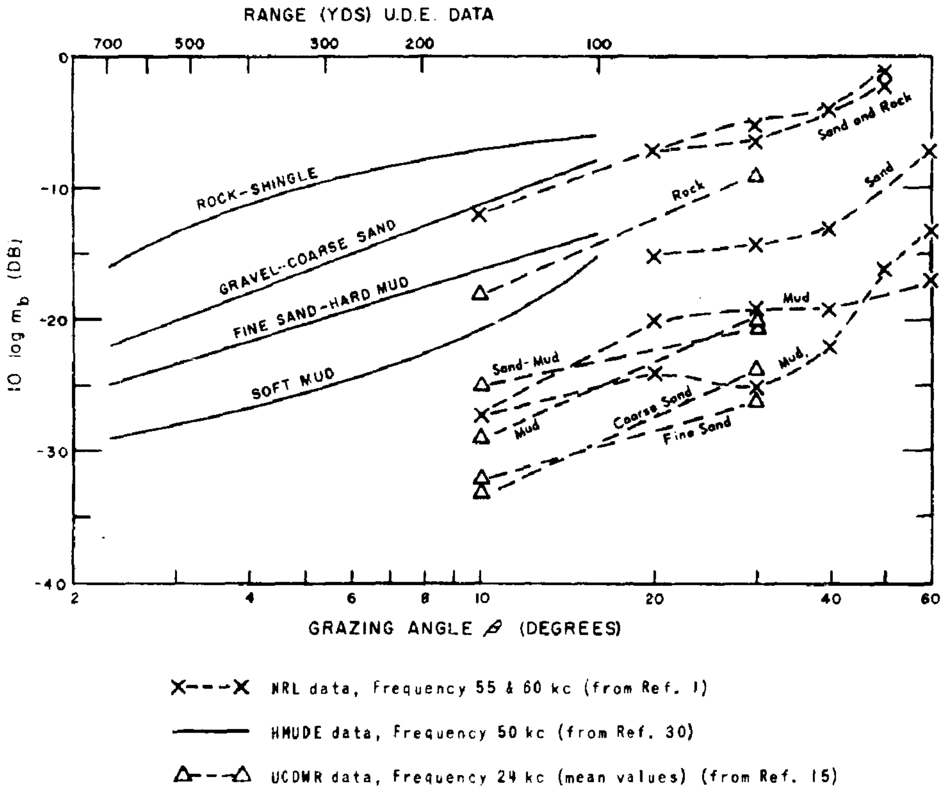


Figure 6 - Bottom reverberation. Variation of 10 log m_b with grazing angle and its dependence on bottom type.

scattering. If roughness is the principal cause of scattering, particle size will be at best only an indirect indication of reverberation. Indeed, the scattering from what seems to be the same type of bottom is known to vary by 20 db or more (32). Also, a small area of bottom may scatter differently for different directions in which it is viewed. In one experiment, the reverberation from a portion of a natural muddy bottom estimated to be about 9 square yards in area was found to vary by 10 to 15 db on training the projector around in azimuth (33).

Yet, the data of Fig. 6 are concordant in showing that m_b varies with grazing angle as the first or second power, so that 10 log m_b increases with grazing angle at the rate of between 3 and 6 db per angle doubled. A value of 4.5 db per angle doubled, corresponding to a 1.5 power variation with angle, is a reasonable average. This corresponds to a decay of reverberation with range as the minus 4.5 power of the range in isovelocity water. This variation in angle has been verified in the laboratory at 100 kc up to an angle of 25° through the use of a tiltable projector and a small tray of sedimentary material (29).

Variation with Frequency

The variation of 10 log m_b with frequency is of basic importance to acoustic mine hunting. Together with other parameters, it determines the optimum frequency for a mine-hunting sonar set.

The subject was first studied by UCDWR during the War for a rocky bottom at frequencies of 10, 20, 40, and 80 kc (15, p.318). The results showed no evidence of any systematic frequency dependence in this frequency range at a grazing angle of 30°. The essentially frequency-independent nature of 10 log m_b was also indicated more recently by NRL for other types of bottom as well in the range 10-60 kc (1). However, some recent British measurements at 7.5, 50, and 300 kc have shown a strong change of 10 log m_b with frequency, amounting to a decrease of about 13 db between 7.5 and 300 kc (29). The values obtained are shown in the following table:

Grazing Angle	7.5 kc	50 kc	300 kc
7.2°	-8.7	-16.7	-23.7
3.6°	-12.0	-22.7	-23.7
1.8°	-13.7	-26.7	--

The bottom in the area of these measurements consisted of 3 to 4 feet of soft mud overlying a harder material. The decrease of 10 log m_b with increasing frequency is believed to have been due to absorption in the mud, with the scattering arising principally from the harder layer below.

In summary, it may be said that there is no conclusive evidence as yet of a frequency variation of 10 log m_b. The subject deserves further study, however, for not only is it necessary to rational equipment design, but the frequency dependence of bottom reverberation throws light on the basic scattering processes operating at the bottom of the sea.

DEPENDENCE OF REVERBERATION ON PINGLENGTH

It has long been known that, as a general rule, the level of reverberation of all types is proportional to the length of the emitted ping. This pinglength dependence is reasonable, for the pinglength determines the extension in range of the reverberating area or volume. Thus, doubling the pinglength should increase the reverberation level by 3 db. That this actually takes place was observed during the War (15, p.302) and has been subsequently confirmed on many occasions (1,9).

There are, however, some instances where reverberation would not be expected to be proportional to pinglength. When bottom reverberation is observed with highly directional transducers at high angles of tilt, it is possible for the observed reverberation to be independent of pinglength when the reverberating area on the bottom is limited by the transducer beamwidth instead of the pinglength (1). Again, for extremely short pinglengths and extremely narrow beams, reverberation need not be proportional to pinglength when the reverberating area or volume is so small that it no longer contains many scatterers. However, an effect of this kind has never been observed, probably because of the extremely short pinglengths required to make it evident. At the other extreme, very long pinglengths produce less reverberation than would be expected from the linear law because of the effect of absorption in reducing the scattering from the more distant parts of the reverberating area or volume. An effect of this kind has been reported at an unstated frequency in a Russian paper (34). Figure 7 shows that the reverberation for long pinglengths is less than the linear law requires. Nevertheless, in spite of these exceptions, one can feel reasonably sure in applying the linear relationship in nearly all practical problems encountered at the present time.

FLUCTUATION AND FREQUENCY SPREAD OF REVERBERATION

So far, we have been concerned with average reverberation levels and their dependence on various parameters. However, the reverberation from an emitted ping is not a smoothly decaying sound, but occurs in "blobs" of about the same duration as the emitted ping. Also,

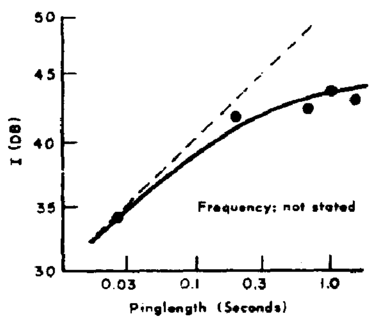


Figure 7 - A Russian observation of the lesser rise in volume reverberation for long pinglengths (from Ref. 34).

the envelope of reverberation never repeats itself from ping to ping, but exhibits an irregular fluctuation in level at any particular instant following the initial ping. This fluctuation is probably due to the motion of the scatterers relative to each other and to the sound source, so that the vector sum of the individual scattering amplitudes of variable phase fluctuates in amplitude. This should result in a cumulative Rayleigh distribution of reverberation amplitudes defined by $P(x) = \exp(-x^2/a^2)$, where P(x) is the probability that any reverberation amplitude exceeds x and a is the rms amplitude. This expression indicates that the instantaneous reverberation amplitude will be greater than its mean or rms value 37% of the time, and less 63% of time; it will be 10 db less than its rms value 10% of the time and 10 db greater than its rms value only 0.005% of the time. The validity of this Rayleigh distribution for the instantaneous reverberation amplitude at a particular interval after the ping was demonstrated by lengthy wartime studies (15,p.324).

The frequency spread of reverberation has not been given intensive study, even though it is of manifest importance in the design of reverberation filters. There are several factors which contribute to the frequency spread of reverberation. One is the own-ship Doppler, which, in addition to the obvious Doppler shift of the mean reverberation frequency, causes a spread in frequency because of the finite beamwidth of a directional transducer. Another source of frequency spread is the finite duration of the emitted ping, which itself has a spread in frequency between the half-power points of approximately $1/\tau_0$ cycles, where τ_0 is the pinglength in seconds. A third source of frequency spread lies in the nature of the scatterers themselves; if they are in random motion, as surface and volume scatterers probably are, a broadening of the reverberation spectrum will occur.

The frequency spread of reverberation was studied to some extent during the War with a device called the periodmeter (15,p.330), which provided a display on a cathode-ray tube showing the interval between successive zeros of an alternating signal recorded against time. The frequency spread of reverberation, heterodyned down to an audio frequency, was found to vary as the inverse one-fourth power of the pinglength and as the three-fourths power of the audio output frequency. These surprising results are not understandable until a satisfactory theory for the periodmeter, which would yield the relation between periodmeter readings and the reverberation spectrum, has been developed. The periodmeter has recently been used to study the frequency characteristics of reverberation from frequency-modulated pings (35), but no quantitative information appears to have been obtained.

A more direct investigation of the frequency spread of reverberation has been made recently, using cw, in connection with the development of an active cw homing torpedo (36). A typical cw reverberation spectrum for a moving transducer (15) is shown in Fig. 8 for a frequency of 60 kc. Some of the results of this study were: (1) the maximum of the normalized spectrum occurs at a frequency shift of 0.55 to 0.63 cps/kc/knot, in good agreement with the predicted Doppler shift; (2) the average spectrum width at half voltage (6 db down) is 0.06 cps/kc/knot, with variations from 0.03 to 0.18; (3) observed spectra are asymmetrical about the Doppler-shift frequency, with more reverberation at the smaller Doppler shifts than at the higher (Fig. 8) (this off-peak reverberation, however, is 30 to 40 db down from the peak); and (4) the normalized spectra do not change significantly with transducer speed, indicating that (in this data) the beamwidth effect on frequency spread is small. In these experiments much or all of the reverberation is probably surface reverberation, as evidenced by the fact that the reverberation level was observed to increase with sea state and to decrease with increasing transducer depth below the surface.

THE REVERBERATION EQUATIONS

Equations by which the reverberation level at any instant of time can be computed were developed during the War (15). The formulation of equations for volume and surface reverberation was obtained mathematically in terms of two parameters, J_v and J_s, which express the discrimination of the transducer against reverberation. Instead of giving a mathematical treatment, however, we shall deal with reverberation from a geometrical viewpoint in a way that may make the derivation easier to understand and the expressions easier to apply to practical problems. This will be done through the concept of an ideal, searchlight-type transducer having a uniform transmitting and receiving (or "composite") response within a certain angle, and none beyond.

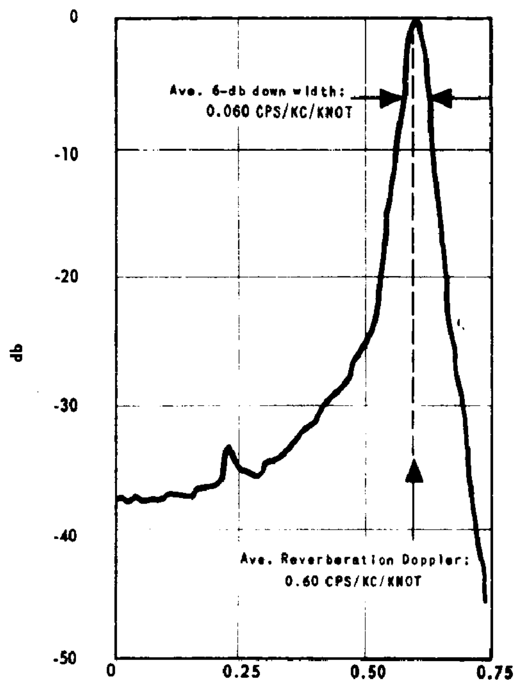


Figure 8 - Typical normalized reverberation spectrum for a moving transducer (redrawn from Ref. 36).

Volume Reverberation

Let us assume that we are echo-ranging in an unbounded ocean with such a transducer, which has uniform sensitivity within a certain solid angle ψ, (Fig. 9). Later on we will see how an equivalent solid angle, ψ, can be found for any transducer for which the composite response is known, and how ψ is related to J_V. Thus, while the derivation will be given in terms of the ideal transducer, it will apply to any transducer once its equivalent angle ψ is known. At some range, r, the reverberating volume which scatters sound toward the source will be approximately $\psi r^2 \tau$, where τ is the pinglength in yards, equal to $(c\tau_0)/2$ where τ_0 is the time duration of the emitted pulse and c the velocity of sound.* If L is the source level of the transducer and H_R the transmission loss for reverberation (discussed below), the intensity reaching the reverberating volume is $L - H_R$. From the definition of scattering coefficient, the intensity, at one yard, of the back-scattering from each cubic yard of the reverberating volume is 10 log $(m_V/4\pi)$ for unit incident intensity. The scattering intensity for the whole volume, if measured at unit distance, is $L - H_R + 10 \log \psi r^2\tau + 10 \log m_V/4\pi$. Back at the source the intensity of reverberation will, therefore, be

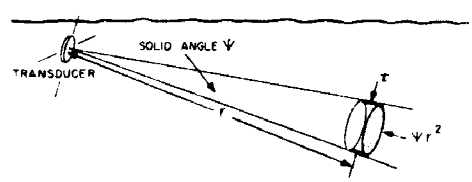


Figure 9 - Geometry of volume reverberation for an ideal searchlight-type transducer.

$$R = L - 2H_R - 10 \log \psi + 20 \log r + 10 \log \tau + 10 \log \frac{m_v}{4\pi}$$

*In these reports, the terms "pinglength" and "pulselength" are used synonamously when referring to the time duration of a pulse. But when a distance is meant, "pinglength" means the extension in range of the reverberating area or volume, while "trainlength" refers to the extension in range of the insonified area or volume, hence pinglength is one-half the trainlength (37, p. 87).

This is the volume reverberation equation in terms of the solid angle ψ.

For any transducer, whether used in the same manner or not for transmitting and receiving, we can define an equivalent value of ψ such that the total composite response of the actual and fictitious transducers is the same. If $q(\theta,\varphi)$ and $q'(\theta,\varphi)$ are the transmitting and receiving sensitivities in the direction (θ,φ), and $d\Omega = \cos\theta d\theta d\varphi$ is a small solid angle in the direction (θ,φ), the actual transducer* has the composite response

$$\int_{4\pi} qq'd\Omega = \int_0^{2\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} q(\theta,\varphi)q'(\theta,\varphi) \cos\theta d\theta d\varphi$$

The fictitious, ideal transducer has the response

$$\int_0^{\psi} 1\cdot 1 \, d\Omega = \psi$$

Hence we find

$$\psi = \int_0^{2\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} q(\theta,\varphi)q'(\theta,\varphi) \cos\theta d\theta d\varphi$$

Surface Reverberation

For surface reverberation (including bottom reverberation), we shall characterize the ideal transducer beam by a plane angle, Φ, and proceed in a similar manner as shown in Fig. 10.

At the instant of time when the intersection of the axis of the beam and the surface lies at the center of the reverberating area, the reverberation level is a maximum and the reverberating area is then $\Phi r\tau$ for small inclination angles β. The intensity of back-scattering from each square yard of this area (per unit incident intensity) is $10 \log (m_b/2\pi)$, measured at the unit distance of one yard. Hence, in the same manner as for volume reverberation, we obtain for the surface reverberation level

$$R = L - 2H_R + 10 \log \Phi + 10 \log r + 10 \log \tau + 10 \log \frac{m_b}{2\pi}$$

For most instances involving surface reverberation, the axis of the transducer is horizontal, or nearly so, and the reverberation arises from a nearly horizontal surface (the sea-surface or bottom). In these instances, only the horizontal directivity of the transducer is effective, and the appropriate responses are the transmitting and receiving responses in the horizontal plane, $q(0,\varphi)$ and $q'(0,\varphi)$. Proceeding as before, we equate the composite response of the actual transducer to that of the ideal transducer in order to obtain an expression for the equivalent ideal beamwidth

$$\int_0^{2\pi} q(0,\varphi)q'(0,\varphi)d\varphi = \int_{-\Phi/2}^{\Phi/2} 1\cdot 1 \, d\varphi = \Phi$$

*In an infinite baffle.

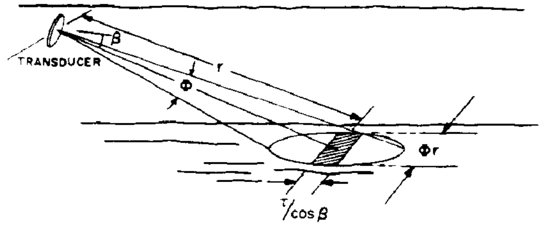


Figure 10 - Geometry of bottom reverberation for an ideal searchlight-type transducer inclined at a small angle from the horizontal.

As has been noted above, two parameters, J_V and J_S, were introduced into sonar usage during the war to express the degree of discrimination of transducers against reverberation (15,chap.12;38), in much the same manner as the ordinary receiving directivity index, D, expresses the discrimination against isotropic or nondirectional noise. One essential difference between the reverberation indices and D is that the former involve the two-way or composite beam pattern of the transducer, whereas D is determined by the receiving pattern alone. Table 1 gives expressions for J_V and J_S in terms of the wavelength vs. transducer-size ratio, the angle y in degrees between the axis and the 6-db-down points of the composite pattern, and the receiving directivity index. The first line of Table 1 shows the integral expressions for J_V and J_S. It will be observed that J_V and J_S differ from ψ and Φ as used above by factors of 4π and 2π, respectively:

$$J_v = -10 \log \frac{\psi}{4\pi}$$

$$J_s = -10 \log \frac{\Phi}{2\pi}$$

Writing the reverberation equation in terms of these quantities we obtain

$$R_{volume} = L - 2H_R + 10 \log m_v - J_v + 10 \log \tau + 20 \log r$$

$$R_{surface} = L - 2H_R + 10 \log m_s - J_s + 10 \log \tau + 10 \log r$$

These are the basic equations from which reverberation can be computed in simple cases. In many complicated cases occurring in practice, great care must be exercised in selecting values for H_R and 10 log m for the range at which the reverberation level is desired, and in adding up all the sources of reverberation that may be present. Some of the considerations which must be borne in mind in using the equations in actual cases are given in the following discussion.

DISCUSSION OF THE REVERBERATION EQUATIONS

The preceding equations contain the quantity H_R—called the transmission loss for reverberation—which requires discussion. We have derived the equations on the assumption of straight-line paths. In this simple case, H_R is the same as the ordinary transmission loss, due to spreading and absorption, between the transducer and the reverberating area or volume. If we write for this case of straight-line paths and spherical spreading $H_R = 20 \log r + \alpha r$, where the first term is the loss due to spreading, and the second the loss due to absorption and scattering, we then obtain for volume reverberation

$$R_{vol} = L - 20 \log r - 2\alpha r + 10 \log m_v - J_v + 10 \log \tau$$

and for surface reverberation

$$R_{sur} = L - 30 \log r - 2\alpha r + 10 \log m_s - J_s + 10 \log \tau$$

TABLE 1

Expressions for the Ordinary and the Reverberation Directivity Indices in Terms of the Transducer Dimensions, Wavelength, and Composite Beam Pattern (Largely based on Ref. 38)

Receiving Directivity Index, D	Volume Reverberation Index, J_v	Surface Reverberation Index, J_s
Integral Expressions		
$D = -10 \log \frac{1}{4\pi} \int_0^{2\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} q'(\theta,\varphi) \cos \theta d\theta d\varphi$	$J_v = -10 \log \frac{1}{4\pi} \int_0^{2\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} q(\theta,\varphi) q'(\theta,\varphi) \cos \theta d\theta d\varphi$	$J_s = -10 \log \frac{1}{2\pi} \int_0^{2\pi} q(0,\varphi) q'(0,\varphi) d\varphi$
Circular Piston of radius $a > 2\lambda$ in an infinite baffle		
$D = -10 \log \left(\frac{\lambda}{2\pi a}\right)^2$	$J_v = -10 \log \left(\frac{\lambda}{2\pi a}\right)^2 + 3.3$	$J_s = -10 \log \frac{\lambda}{2\pi a} + 4.1$
$= -20 \log y + 39.3$	$= -20 \log y + 42.6$	$= -10 \log y + 23.8$
	$= D + 3.3$	$= D/2 + 4.1$
Rectangular Piston with side a horizontal and b vertical, in an infinite baffle		
$D = -10 \log \frac{\lambda^2}{4\pi ab}$	$J_v = -10 \log \frac{\lambda^2}{4\pi ab} + 3.6$	$J_s = -10 \log \frac{\lambda}{2\pi a} + 1.8$
$= -10 \log y_a y_b + 39.3$	$= -10 \log y_a y_b + 42.6$	$= -10 \log y_a + 23.6$
	$= D + 3.3$	
Horizontal Line of length ℓ in an infinite baffle		
$D = -10 \log \frac{\lambda}{2\ell}$	$J_v = -10 \log \frac{\lambda}{2\pi\ell} + 1.8$	$J_s = -10 \log \frac{\lambda}{2\pi\ell} + 1.8$
$= -10 \log y - 17.0$	$= -10 \log y + 23.8 = J_s$	$= -10 \log y + 23.8 = J_v$
	$= D + 6.8$	$= D + 6.8$
Point Source		
$D = 0$	$J_v = 0$	$J_s = 0$

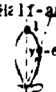
SYMBOLS:

$q(\theta,\varphi)$: Transmitting intensity in direction θ,φ relative to Unity Intensity in direction 0,0.

$q'(\theta,\varphi)$: Receiving response from direction θ,φ relative to Unity Response from direction 0,0.

θ,φ : Polar angles, θ being taken in the vertical plane, φ in the horizontal.

y : Half-angle in degrees between the two directions of the composite or product beam pattern in which the response is 6db down from the axial response, $q(y)q'(y) = 0.25$. [y_a, y_b for the rectangular piston are taken in the horizontal and vertical planes, respectively; y for the horizontal line, in the horizontal plane.]



λ : Wavelength.

Whenever the ray paths are curved, however, complications arise because of the concomitant effect of ray bending upon the size of the reverberating area and upon the transmission loss. For example, in the case of volume reverberation, ray convergence will decrease the transmission loss and the size of the reverberating volume in equal amounts. Ray-bending may be visualized accordingly as affecting only the return trip of the emitted sound. Hence, if H is the transmission loss between the transducer and the reverberating volume—suitably averaged over the latter if it is large—and H_R is the transmission loss for reverberation, then $2\,H_R = 2H\text{-}A$, where A is that part of the transmission loss due to ray bending or refraction. For surface and bottom reverberation, the effect of refraction in the vertical plane is negligible because both the horizontal width, φ, and the radial extent, τ, of the reverberating area are sensibly unaffected by bending if the grazing angle at the surface is small. Therefore, for surface and bottom reverberation, the ordinary transmission loss and the transmission loss for reverberation are usually the same.

In general, it also is necessary to distinguish between the transmission loss for reverberation, H_R, and the transmission loss for the echo, H_E, in computing echo-to-reverberation ratios, because the target may not be located at the same place in the ocean as the major part of the reverberating area or volume. For example, a surface target may be masked by reverberation originating deep in the body of the ocean. In general, then, H_E and H_R are different; they are equal only when the target echo and the reverberation originate approximately at the same range and depth in the ocean.

In computing volume reverberation, care should be exercised to use the appropriate value of m_V. Whenever downward ray-bending exists, the depth from which volume reverberation is received is a function of range, and it is necessary to allow for the depth variation of 10 log m_V in choosing a value for this parameter. Because of the fact that 10 log m_V has been found to decrease with depth below the deep-scattering layer, the volume reverberation observed with a transducer with a downward tilt, or one located in a negative gradient, will decrease faster with time than the inverse second power, which would hold with a constant 10 log m_V. In a computation it will generally be necessary to draw a rough ray diagram in order to determine from what depth the reverberation is coming at any instant, so as to be able to estimate a value of 10 log m_V.

At short ranges, up to a few hundred yards, it is probable that multiply-scattered sound does not contribute appreciably to the observed volume reverberation and that only once-scattered sound need be considered (15,p.269). This has been indicated by observing the reverberation received on turning a transducer quickly away after emitting a ping, when it was found that in deep water the reverberation was 20 to 30 db less than its normal level (34), thus demonstrating the unimportance of multiple scattering. However, at the longer ranges now of interest in submarine search it is possible that sound scattered in the ocean and its boundaries two or more times forms an appreciable part of the observed reverberation. There are no observations on this matter, and the subject of multiple scattering at long ranges is one for future study.

We have seen from Fig. 4 that when using horizontally directed 24-kc transducers at shallow depths there is a wind-force variation of reverberation at short but not at long ranges, indicating that surface reverberation masks volume reverberation at short ranges but that at long ranges volume reverberation predominates. This illustrates the fact that reverberation may have different origins at different ranges. Unless an individual case clearly indicates a single origin, each source of reverberation must be computed from the ray diagram, together with the appropriate equations, and the contributions of each added together to give the total reverberation.

A ray diagram is also useful in estimating bottom reverberation, and is necessary whenever velocity gradients may change the grazing angle of a ray at the bottom. The effect of downward refraction, for example, is to give a greater grazing angle and to produce enhanced reverberation. Even in isovelocity water, we have seen that bottom reverberation falls off

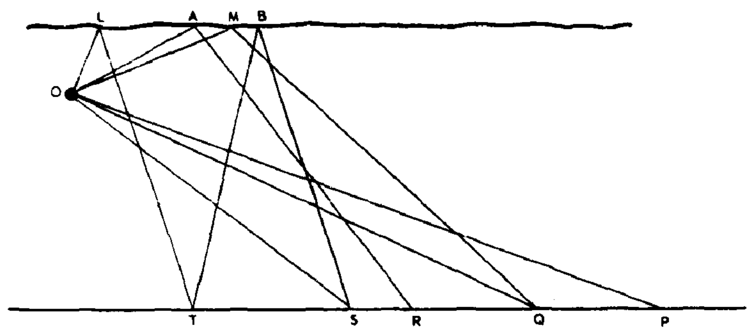


Figure 11 - Multiple paths contributing to bottom reverberation in shallow water. (All paths shown are assumed to be the same length, so that reverberation from different parts of the bottom is received simultaneously.)

faster than the inverse third power of the range because of the fact that the grazing angle becomes smaller with increasing range.

An additional complication must be considered in most cases of bottom reverberation—the effect of the surface in producing additional paths by which bottom-scattered sound can reach the transducer. In Fig. 11, let a transducer with a wide beam in the vertical plane be located at O. In addition to the reverberation received from the bottom at P, reverberation is received at that same instant from other points Q, R, S, via surface reflected paths such as OMQO or OARAO. Thus, the effective reverberation level is increased because of the finite transducer beam width and the presence of the reflecting sea surface nearby. Narrowing the vertical beamwidth should, therefore, result in lowered reverberation levels. That this actually occurs has been shown by British experiments in which the reverberation in shallow water was compared for transducers with different horizontal and vertical beamwidths (29). Although it was found that the reverberation decreased linearly with <u>horizontal</u> beamwidth (31), as it should, a strong dependence on <u>vertical</u> beamwidth was observed, as shown in Fig. 12. Narrowing the beamwidth, however, may not improve the echo-to-reverberation ratio for a target lying on the bottom. Thus, from the British experiments, it is concluded (29) that multiple paths contribute 6 db to both reverberation and echo, except when the pinglength is so short that the surface echo is completely separate in time from the direct-path echo and does not reinforce it. The multiple paths due to surface reflections are believed to enhance volume reverberation as well whenever the transducer beam is not sufficiently directive to exclude the reflected paths (15,p.271).

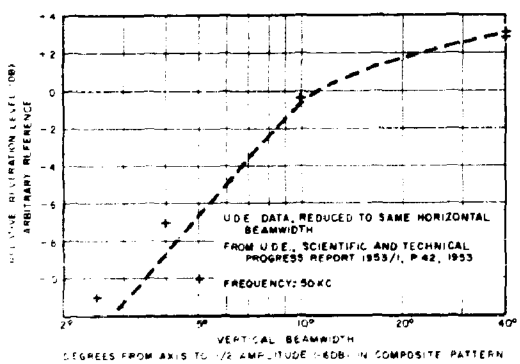


Figure 12 - Effect of the vertical beamwidth of a horizontally directed transducer on bottom reverberation level.

A practical matter that makes accurate prediction of bottom reverberation difficult is the fact that what appears to be the same type of bottom often varies in scattering coefficient by 20 db or more. The slope and shape of the bottom are important, and

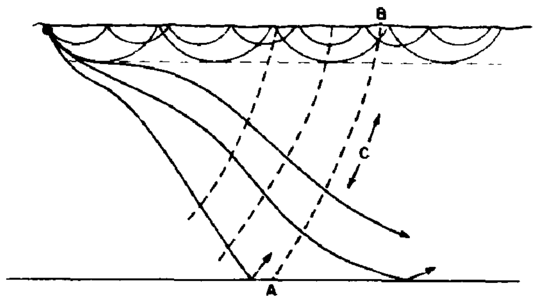


Figure 13 - Multiple origin of reverberation in deep water at long ranges.

even the echo from an 18-inch spherical target placed on the bottom has been observed to vary considerably in the course of a few hours, apparently with the tide (29).

It will be apparent from the foregoing discussion that there are many cases which are too complex to be treated in the simple manner described by the reverberation equations. Complex situations can be handled only by first drawing on a ray diagram the wave front for some instant of time and then adding up all the reverberation contributions from each part of the wave front, taking into account the composite beam pattern of the transducer. Fig. 13, for example, shows a wave front AB at a long range in deep water. Reverberation may arise from: (1) the bottom at A, (2) the surface B via sound channel paths, and (3) the volume C throughout the body of the ocean. In order to find the reverberation level for this case it would be necessary to add up the contributions from A, B, and the several portions of C, by assigning to each a transmission loss, a value of 10 log m, and a factor depending upon the composite beam pattern of the transducer. The simple equations can be used only when it is possible to choose —a priori—a value of 10 log m which applies effectively to the entire reverberating volume or area. Otherwise, one must proceed in the difficult stepwise manner of summing up all the sources of reverberation.

Considering these difficulties in making a reverberation prediction for the long ranges of current interest in active submarine detection, it will be apparent that the formal, logical approach to reverberation prediction indicated by the reverberation equations is at present impractical. For this problem we shall have to be content for the immediate future with empirical predictions based on long-range reverberation measurements. Obtaining long-range reverberation data in shallow and deep water is thus an urgent necessity at the present time.

* * *

REFERENCES

1. R. J. Urick, "The Back-Scattering of Sound from a Harbor Bottom and Its Application to Acoustic Mine Hunting " (Confidential), NRL Report 4195, July 1953.

2. V. G. W. Harrison, "Definition and Measurement of Gloss-A Survey of Published Literature," Printing and Allied Trades Research Association, London, 1945.

3. C. L. Pekeris, "Note on the Scattering of Radiation in an Inhomogeneous Medium," Phys. Rev. 71, 268-269, Feb. 1947.

4. NDRC Summary Technical Report, Div. 6, Vol. 8, "Part IV: Acoustic Properties of Wakes," p. 482, 1946.

5. R. J. Urick and C. W. Searfoss, "The Microthermal Structure of the Ocean Near Key West, Florida, Part II," NRL Report S-3444, 1949.

6. R. H. Backus, "A Bibliography Pertaining to the Deep Scattering Layer and the Fishery Applications of Echo Sounding and Ranging," WHOI Reference No. 53-42, May 1953.

7. G. H. Tucker, "Relation of Fishes and Other Organisms to the Scattering of Underwater Sound," NEL Report 179, 1951. (Reprinted from Journal of Marine Research, Vol. 10, No. 2, pp. 215-238, 1951).

8. P. F. Smith, "Measurements of the Sound Scattering Properties of Several Forms of Marine Life," WHOI Reference 51-68, 1951.

9. W. E. Batzler and E. C. Westerfield, "Sonar Studies of the Deep Scattering Layer in the North Pacific," NEL Report 334, Jan. 1953.

10. H. B. Moore, "Scattering Layer Observations, Scientific Report No. 3 on 'Atlantis' Cruise 151," WHOI Reference 49-2, 1949.

11. R. W. Raitt, "Sound Scatterers in the Sea," Journal of Marine Research 7, 393-409, 1948.

12. V. C. Anderson, "Wide Band Sound Scattering in the Deep Scattering Layer," SIO Reference 53-36, 1953.

13. S. Machlup, "Interpretation of Echoes from Stratified Scatterers," WHOI Reference 51-66, 1951.

14. S. Machlup and G. W. Wheeler, "Analysis of Explosive Echoes from Scattering Layers," WHOI Reference 51-80, 1951.

15. NDRC Summary Technical Report, Div. 6, Vol. 8, "Part II: Reverberation," 1946.

16. "Volume Reverberation - Scattering and Attenuation vs. Frequency," UCDWR No. U 50, OSRD 1555, 1943.

17. J. B. Hersey, H. R. Johnson, and L. C. Davis, "Recent Findings about the Deep Scattering Layer," Journal of Marine Research XI, pp. 1-9, July 1952.

18. A. G. Pieper and R. J. Urick, "A Method for Measuring Small Volume Reverberation in the Ocean," USNJUA 1, No. 1, 16-20, Jan. 1951.

19. C. Cox and W. Munk, "The Measurement of the Roughness of the Sea Surface from Photographs of the Sun's Glitter," SIO Reference 52-61, 1952.

20. A. H. Schooley, "A Simple Optical Method for Measuring the Statistical Distribution of Water Surface Slopes," J. Opt. Soc. Am. 44, No. 1, p. 38, Jan. 1954.

21. C. Eckart, "The Scattering of Sound from the Sea Surface," Acous. Soc. Am. J. 25, 566, 1953; see also -- Discussion of this paper by D. Mintzer. Acous. Soc. Am. J. 25. 1015. 1953.

22. "Sonar Research Conducted During the Period Jan. 1 - Mar. 31, 1953" (Confidential), WHOI Reference No. 53-46, pp. 10-11, 1953.

23. "Research and Development of an Improved Bathymeter" (Confidential), Contract No. Nonr-08601, Cook Project No. P-342, Cook Research Labs. Addendum No. 3 to Final Report PR 6-2.

24. "Limitation of Echo Ranges by Reverberation (Deep Water)" (Confidential), UCDWR File Report M361, File No. 01.90, Sept. 1945.

25. C. A. Teer, "Factors Concerning the Design of a Asdic Set" (Secret), Great Britain UDE Report 111, 1953.

26. C. A. Teer, Informal Communication, UDE, April 1953.

27. Defense Research Laboratory, University of Texas, Monthly Progress Reports, Dec. 1951 - Sept. 1953, BuShips Contract Nobsr-52267 (Confidential).

28. W. K. Grimley, Informal Communication, Nov. 1953.

29. Great Britain HMUDE Scientific & Technical Progress Report, 1953/1 (Secret), 1953.

30. Great Britain HMUDE Scientific & Technical Progress Report, 1952/1 (Secret), 1952.

31. R. Hall, "The Influence of Directivity on Reverberation Level at 19 kc," UDE Pamphlet 148, 1952.

32. Great Britain HMUDE Scientific & Technical Progress Report, 1951/2 (Secret), 1951.

33. R. Hall, Informal Communication, UDE, April 1953.

34. Yu M. Suklarevski, "Some Characteristics of Reverberation Observed in the Sea," Translation by Sci. Information Centre, DRB, Canada, of Article in Dok. Akad, Nauk. 60, 7, 1161-1164, 1948.

35. E. C. Westerfield and N. S. Young, "Periodmeter Studies of Underwater Acoustic Reverberation from Frequency-Modulated Pings "(Confidential), NEL Report 398, Dec. 1953.

36. P. Conley and G. Klotzbaugh, "The Spectra of C-W Reverberation" (Secret), Westinghouse Research Laboratories Report SR-487, estimated date, 1952.

37. NDRC Summary Tech. Report, Div. 6, Vol. 7, "Principles of Underwater Sound" (Confidential), pp. 67-88, 1946.

38. "The Discrimination of Transducers Against Reverberation," UCDWR No. U75, File 01.40. NDRC. Sec. 6.1-5530-968, May 1943.

* * *

REVERBERATION

An Addendum to Part IV of the Summary of Underwater Acoustic Data

R. J. Urick*
Ordnance Research Laboratory
The Pennsylvania State University
University Park, Pennsylvania

and

A. W. Pryce

Office of Naval Research (Code 411)
Washington 25, D. C.

(Received November 16, 1959)

INTRODUCTION

Much increased attention has been given to the subject of reverberation since the appearance of Part IV, Reverberation, of the Summary of Underwater Acoustic Data in 1954 (1).† Torpedo homing interests in particular have provided the motivation for its investigation under the Bureau of Ordnance's Acoustics of the Medium program (2) and have clarified many problems associated with sea-surface reverberation at the higher frequencies. Interest in bottom mine hunting, largely responsible for the information on bottom reverberation reported earlier, has provided additional knowledge and understanding. Growing interest in long-range active sonar has pointedly emphasized the urgent need for knowledge and understanding of reverberation from long ranges. Here the LORAD program has provided valuable information (3-7).

VOLUME REVERBERATION

Only a relatively small amount of additional data on volume reverberation has been obtained in recent years. NOTS (8) has reported values for the volume scattering strength‡ as measured

---

*Now at U. S. Navy Mine Defense Laboratory, Panama City, Florida.

†References appear on pp. 31-33.

‡Scattering strength, analogous to target strength, is the ratio, expressed in decibels, of the scattered intensity at a distance of one yard from unit volume (1 cubic yard) or unit area (1 square yard) to the incident intensity.

$$S = 10 \log \frac{I_s}{I_i}$$

where I_s is the scattered intensity at one yard and I_i is the incident intensity. It should be noted that the volume scattering strength S_v is related to the scattering coefficient $10 \log m_v$ as follows

$$S_v = 10 \log \frac{m_v}{4\pi},$$

and the surface or bottom scattering strength $S_{s,b}$ to the surface or bottom scattering coefficient $10 \log m_{s,b}$ by the equation,

$$S_{s,b} = 10 \log \frac{m_{s,b}}{2\pi}.$$

PRECEDING PAGE BLANK NOT FILMED

at depths between 50 and 1300 feet off Long Beach, California, for both a 60-kc c-w pulse and for a "noise" pulse a few kilocycles wide centered at this frequency. No significant difference in scattering strength was found for those two types of transmission, although in both cases a strong increase with depth was observed, presumably because of a deep scattering layer. The following table gives measured coefficients at 60 kc for two runs (runs 8 and 10) at a number of different depths:

Run No.	Depth (ft)	Measured Scattering Strength (db)
10	347	-82
10	347	-81
8	423	-93
8	595	-95
10	595	-79
10	595	-82
8	1114	-78
10	1335	-65
10	1335	-67

Essentially similar ORL measurements (9), though at shallower depths ranging from 60 to 250 ft, gave values lying in the range -79 to -69 db, with an average value close to -70 db. Measurements were obtained at 25 kc and 60 kc, but no difference in scattering strength between these two frequencies could be established.

The so-called deep-scattering layer has long been thought to be the dominant source of volume scattering in the areas where it occurs. This layer has recently been restudied (10) by means of an echo sounder lowered into the sea in order to observe the sound scatterers at short ranges. Individual scatterers were made visible in this way. On one occasion individual scatterers, presumably fish, were observed to rise at a rate of about 15 ft per minute and to have an estimated density of one scatterer for each 650 cubic meters within the layer. A camera also was used along with the echo sounder to obtain simultaneous acoustic and photographic records; this experiment showed a correlation between pictures of individual fish and the occurrence of strong echoes. A layer of scatterers, presumably biological, has also been observed in the North Sea, just at the top of a strong thermocline at a depth of 15 fathoms (11). The existence of a strong scattering layer near the thermocline has also been indicated in LORAD reverberation studies conducted in the Pacific during periods of severe convergent zone reverberation (7). It is of interest to note a suggested correlation of the variation of reverberation level observed from the convergent zone with biological activity or specific diatom productivity (6).

The most thorough recent investigation of volume reverberation appears to have been made by Westinghouse (12, 13, 14) by means of two transducers mounted on the bow of a submarine. The use of short pulse lengths (0.3 ms at 60 kc) and the recording and subsequent analysis of the back return permitted a detailed study of the back scattering within a small distance immediately in front of the submarine (within 30 ft from the bow). Individual discrete echoes within this volume were found to comprise the bulk of the reverberation. These individual scatterers had target strengths ranging from -58 to -82 db, with a mean value of -63 db, and had a density of 0.45 scatterer per cubic yard for scatterers within this range of size. The target strength per scatterer was observed to increase with depth down to 380 ft by factors of 2 to 8, while the density of scatterers decreased with depth by factors of 5 to 25 between 80 and 380 ft. The product of these two factors, determining the reverberation power, tended to decrease with depth, although considerable variations from a mean value were observed at any one depth. Apparently at least some of the scatterers were fish since their acoustic size agrees roughly with the target strengths measured by others for single fish, and because many of them had a proper motion of their own of the order of 0.1 knot.

SURFACE REVERBERATION

Only inconclusive data taken during World War II could be included in the summary at its original writing (1). Since that time much quantitative information on sea-surface scattering has been obtained. Extensive measurements at kilocycle frequencies were made by the three laboratories (NOTS, APL, and ORL) participating in the Acoustics of the Medium program (2). Both NOTS and ORL employed a tiltable pair of transducers (one transmitting, the other receiving) so as to observe the return of a short pulse from the surface as a function of the angle between the incident direction and the horizontal, while APL used nondirectional transducers which gave a variation of angle during each ping.

Possibly the most systematic measurements of sea-surface back-scattering strength as a function of angle are those of ORL, made off Key West, Fla. (15, 16). Figure 1 shows smooth curves of the variation of scattering strength with grazing angle at 60 kc for a number of wind speeds, together with the data points from which the curves were drawn. Although considerable scatter is evident in the data of this figure, the average deviation from the curves of a data point involving 10 or more pings was only 3 db. The peculiar shape of these curves suggests that there are different processes causing scattering in different ranges of grazing angle. It has been suggested (17) that near normal incidence specular reflection from wave facets is the dominant source of back scattering, while at intermediate angles, roughness irregularities are important. At low angles, a layer of scatters just beneath the surface was proposed as an important cause of back scattering at moderate and high wind speeds. Evidence in favor of this latter hypothesis was provided by observations of the acoustic return at normal incidence; oscilloscope photographs of surface-reflected pulses showed a "forerunner" arriving ahead of the main surface return whenever the wind speed was 10 knots or more (18).

An essentially similar type of measurement was made by NOTS (8) in Pacific Ocean coastal waters. Figure 2 is a summary of a large number of NOTS measurements of surface scatterings plotted against wind speed in knots. Each plotted point is an average of all 60-kc measurements at angles between 15 and 50 degrees plotted at the average wind speed of the group. Although this data, together with that of the previous figure, show an increase of scattering with wind speed, the results for the same wind speed are not entirely concordant, possibly because of the different ocean areas involved. Finally, APL has investigated the dependence of scattering on the roughness of the surface in Dabob Bay in Puget Sound, Washington (19), with the result shown in Fig. 3.

In order to determine the dependence of sea-surface scattering on frequency, NOTS has made measurements (8-20) at frequencies of 31.5, 60, and 100 kc, while ORL (9) compared those at 25 kc and 60 kc. The NOTS data indicated no significant difference in scattering strength for these three frequencies; on the other hand, the ORL results suggested that the scattering strength at 60 kc is 4.5 db higher than at 25 kc. Again the discrepancy may not be entirely observational, but may represent different sea-surface conditions at the time and place the observations are made.

One final variable affecting sea-surface reverberation is the direction relative to the wind. By analogy with the "sea-clutter" of radar, one would expect to find higher scattering looking against the wind than looking with the wind. However, neither the NOTS nor the ORL investigations were able to confirm an effect of this kind; under the conditions prevailing for these measurements, no appreciable difference in scattering in directions with and against the wind could be established. Thus, although the acoustic measurements involved wavelengths closely similar to those used in radar, there appear (18) to be only general similarities between sonar reverberation and radar sea clutter at the same wavelength, probably because of essential differences in the scattering processes in the two cases.

The instantaneous amplitude of reverberation has long been known from theory and experiment to be Rayleigh-distributed (1, 21, 22), and a number of recent findings tend to confirm this result. In the NOTS work briefly described above (8), the reverberation amplitude at an arbitrary instant after the emission of the ping was found to fit a Rayleigh distribution reasonably well for groups of 50 pure-tone pings for all three types of reverberation (surface, bottom, and volume); however, the fit to a Rayleigh distribution for the "noise" pings was not as good. In other measurements by NOL (23), an approximate agreement with a Rayleigh distribution also was observed for surface back-scattering at normal incidence by means of bottom-mounted transducers at 55, 110, 270, and 470 kc. However, the occurrence of large amplitudes was found to be less frequent than expected—an effect which was said to indicate the presence of only a small number of effective surface scatterers. Similarly, for bottom reverberation, an

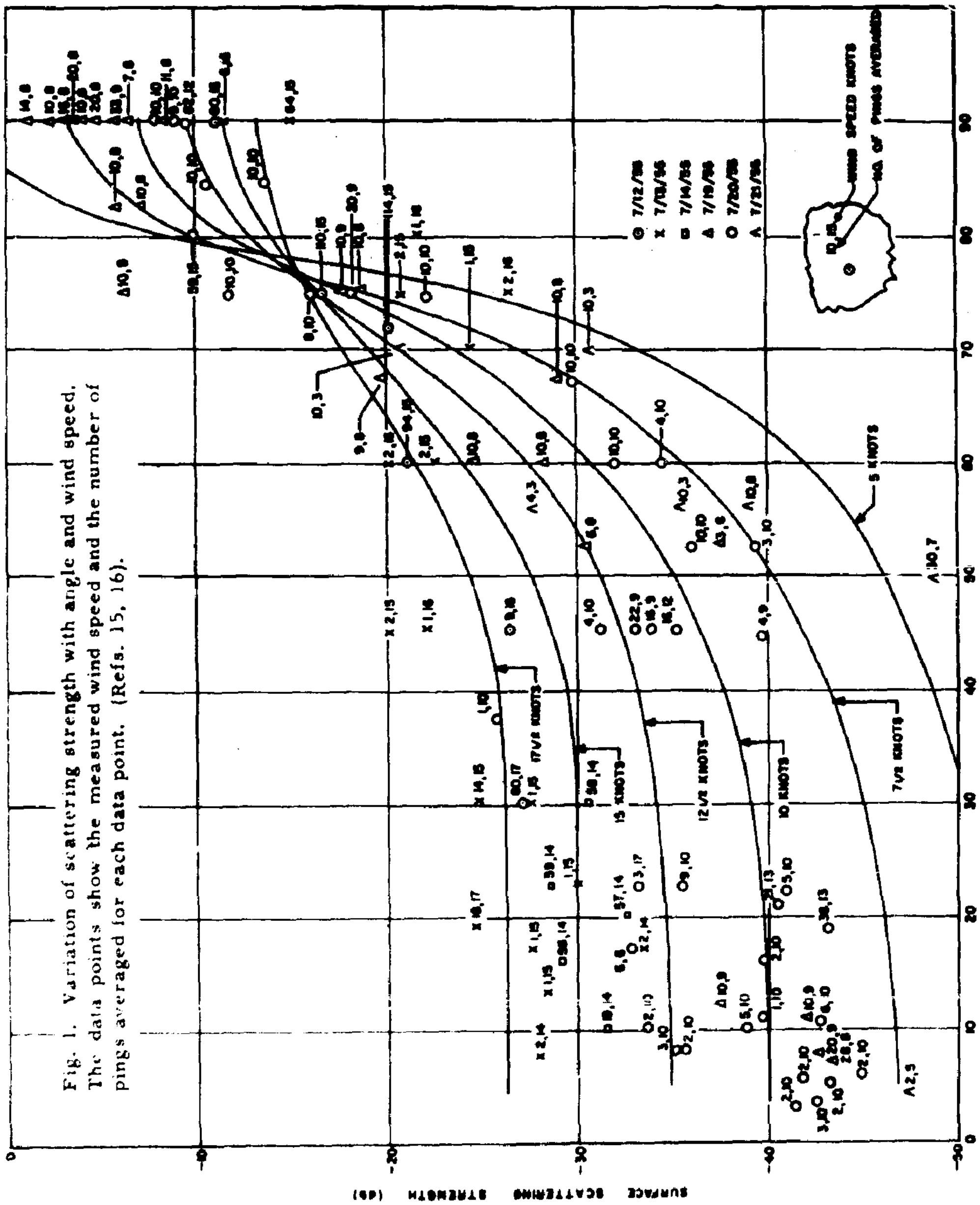


Fig. 1. Variation of scattering strength with angle and wind speed. The data points show the measured wind speed and the number of pings averaged for each data point. (Refs. 15, 16).

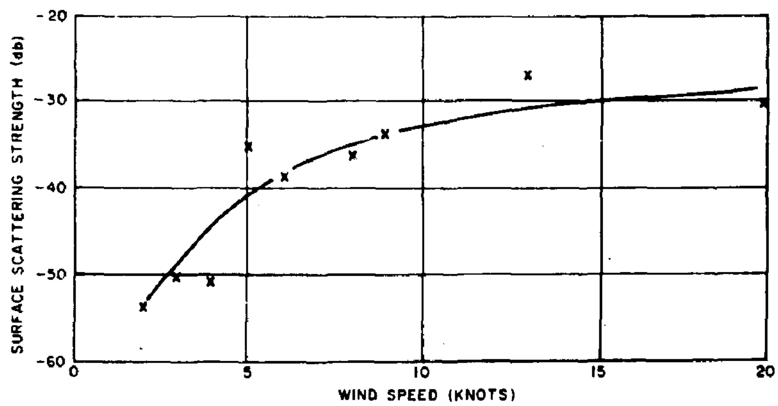


Fig. 2. Surface-scattering strength vs wind speed. Average values over grazing angles of 15 to 50 degrees. (NOTS data, Ref. 8)

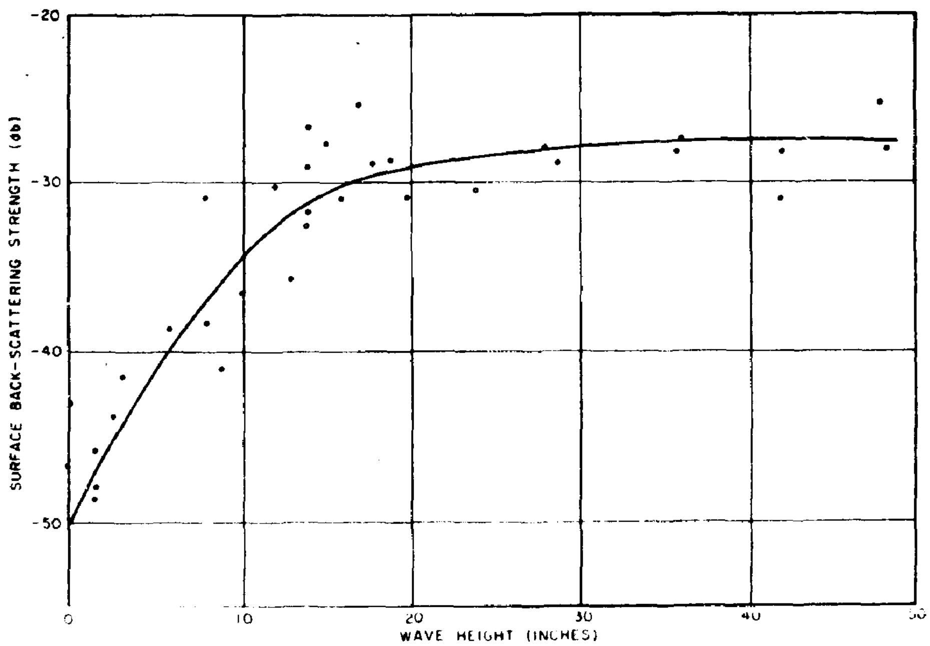


Fig. 3. Surface-scattering strength as a function of wave height in Dabob Bay in the range of grazing angles of 5 to 20 degrees. (APL data, Ref. 19)

NEL study (24) has demonstrated anew the validity of the Rayleigh distribution for the reverberation envelope and shown that the interval-maximum method of measuring reverberation—where the peak of the envelope is read within successive fixed intervals—is the easiest, least variable, and most realistic method of determining reverberation levels, inasmuch as conversion factors to reduce such readings to mean reverberation levels are available (25).

The practical interest in the back-scattering coefficient is that, together with certain instrumental parameters, it determines the shape and level of the surface reverberation to be expected in any specified situation. An actual computation of surface reverberation, however, turns out to be tediously difficult because of the complications created by transducer directionality in the vertical plane and by the refraction of the water medium. The latter effect has been the subject of a separate mathematical study leading to methods suitable for use on a large computer (26). However, for some needs an exact computation is unnecessary and may indeed be impractical. Here some simple methods for the computation of surface, bottom, and volume reverberation may be of value (27).

In high-power, low-frequency echo-ranging, surface reverberation might be expected to be the principal source of the return from the convergence zones although scattering layers and other phenomena can be important under certain conditions* (6, 7) and may account for some observed convergent zone reverberation levels which are 15 or 20 db above normal average values. Some measurements of convergence zone reverberation have been reported by NEL (4) at 530 and 1030 cps. The investigators used an essentially nondirectional sound projector for which the reverberating area can be considered to be a circular annulus approximately a mile in width and lying at a distance of about 30 miles from the source. Measurements of both the level and bandwidth of the reverberation from the convergence zone annulus were obtained. The reverberation spectrum for pings several seconds long was found to be only about 1 cps or less per kilocycle in a zero sea state and to widen with increasing sea state in a manner consistent with the belief that the velocity of the surface scatterers was the principal source of the spectral widening. The finite width of the convergence zone is reflected in the observation that the reverberation increases with pinglength only up to a pinglength of 4 seconds in sea state 4 and 1 second in sea state 2, with no increase beyond. The "standard" reverberation level (referred to the projector source level at 1 yard) was -123 db for sea state zero, with an increase of 2 db per unit of sea state; no significant difference between the levels at the two frequencies could be established (4).

BOTTOM REVERBERATION

A limited number of bottom-reverberation measurements were made in the Acoustics of the Medium program by the same techniques as those used for the study of surface scattering. Data on bottom scattering obtained by NOTS in this program (8) appear to be in disagreement with older data on the bottom-scattering coefficient, in that there is an absence of any dependence on angle between 5 and 55 degrees for bottoms of sand-clay and fine sand, while the values of scattering strength obtained (generally -30 to -40 db) are small. ORL data (9) on sand bottoms in the area of Newport, Rhode Island, and on coral rock and mud bottoms off Key West, Florida, appear to be essentially similar to data on similar bottoms summarized earlier (1). However, for a given type of bottom the scatter of reported data is such that it is not yet possible to estimate a reverberation or coefficient to much better than 10 db. One attempt to rationalize the various measurements that have been made in the past is shown in Fig. 4, where the regions containing most (though by no means all) the published data on scattering versus grazing angle are indicated for the three principal types of bottom (27). The scatter of the various available measurements confirms the belief that the bottom contour, or roughness, is a more important factor than bottom type in determining the back scattering of sound from the bottom.

The British have made extensive field and laboratory measurements that throw a great deal of light on the scattering behavior of bottom materials (28, 29). Figure 5 shows the results of measurements on smooth and rough sand and "shingle" in a laboratory tank in which a tiltable 35-kc transducer was used. The variation of back scattering is roughly as the square of the grazing angle, a behavior that had previously been observed at higher frequencies. Although the effect of roughening the surface was found to be small in the case of shingle, a roughened surface raised the scattering from sand by about 10 db. The scattering from a rough sand, a smooth shingle, and a rough shingle is approximately the same. These results lend credence to the view that the scattering process is a surface phenomenon without any penetration of the bottom material—as there was no difference in scattering from sand layers ranging from 0.5 to 3 inches in thickness.

*See section on Volume Reverberation.

Data on bottom back-scattering coefficient has also been obtained by DRL, University of Texas, at several locations (30, 31). In measurements off Panama City, Fla. (30), made at 12.5, 30, 69, 100, and 180 kc, with grazing angles from 5° to 60°, the variation with grazing angle was found to depend on the frequency. At the lowest frequency the back scattering coefficient was found to vary as the square of the sine of the grazing angle, as the 3/2 power at 69 and 100 kc, and as the first power at 180 kc. Surprisingly, at angles above 25°, the scattering coefficient decreased with increasing angle, especially at the two lowest frequencies. The coefficients themselves, at a grazing angle of 10°, in terms of back-scattering strength, ranged from a value of -49 db at 12.5 kc to a value of -33 db at 180 kc.

The DRL group has also conducted model studies of back-scattering from water-filled sands (32). They found that these, like other model studies of scattering, tend to predict lower scattering strengths than those observed in the field, undoubtedly because of the dominance of surface roughness as the scattering phenomena in the field. Again reviewing the available data, they concluded that the dependence of the scattering strength on frequency is smaller in the field than idealized laboratory experiments would predict, although the reason for this is not clear (32).

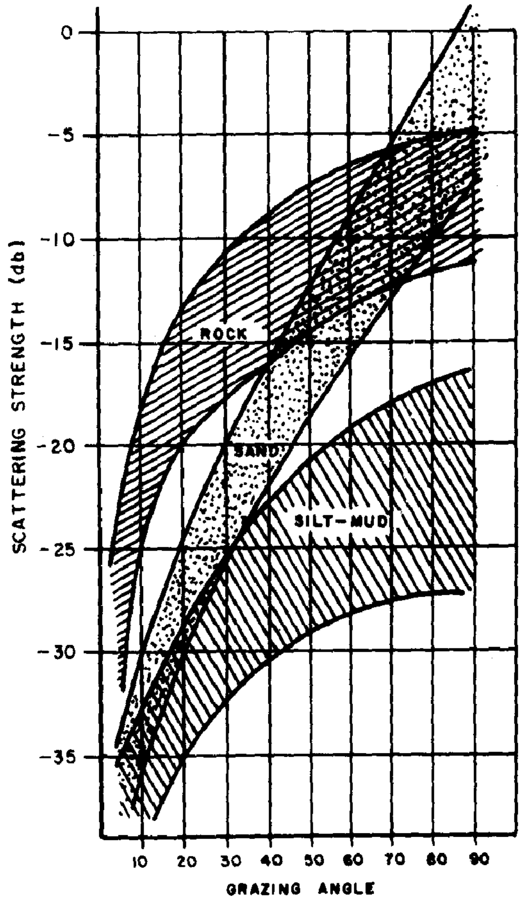


Fig. 4. Estimated approximate variation of bottom-scattering strength with grazing angle, based on various published data. (From Ref. 27)

Although most determinations of bottom coefficient have been made in shallow water, at least one measurement of the back scattering of the deep sea bottom has been published (5). By means of a nondirectional sound source and receiver at 530 and 1030 cps, the bottom reverberation coefficient in 2100-fathom water was found to be proportional to the square of the sine of the grazing angle (Lambert's law) and to show no significant difference between the two frequencies. If S_ψ is the scattering strength and ψ the grazing angle, the measured data for very soft mud over the range 30° to 90° were found to obey the relation,

$$S_\psi = -27 + 10 \log \sin^2 \psi ,$$

where -27 db is the scattering strength at normal incidence. Figure 6 copied from this report is a summary of a number of determinations of scattering strengths of muds, silts, and fine sands, reduced to normal incidence through assuming that the above relationship applies. Although considerable scatter still remains in the data, there is a suggestion that some degree of concordance to the miscellaneous measurements previously reported is achieved by reducing the data in this way.

The scattering of sound from the bottom in nonbackward directions—corresponding to nonreciprocal target strengths—has been investigated through the use of a separate source and

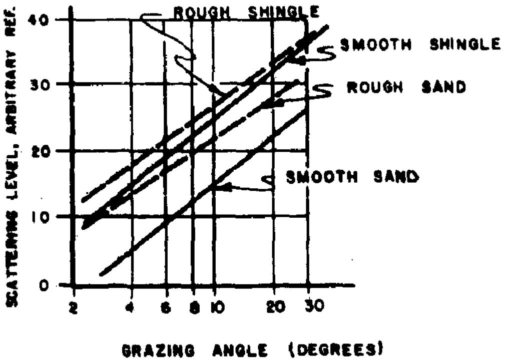


Fig. 5. Variation of back scattering at 35 kc from bottom materials with angle for 2 degrees of roughness. The "sand" particles had an average diameter of 0.06 cm; the "shingle" particles, 0.4 cm. The "rough" surfaces had roughnesses 2 to 2.5 inches deep spaced 7 to 14 inches apart. (Ref. 29)

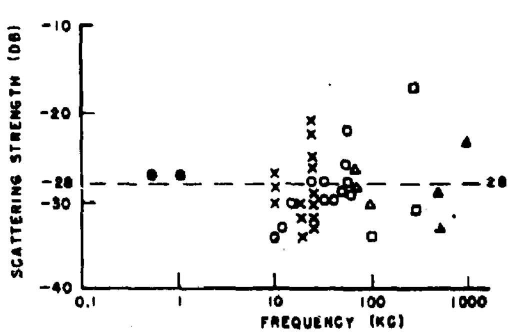


Fig. 6. Bottom back-scattering strength vs frequency as compiled in Ref. 5
NEL data (deep water)
British data, Ref. 28
NDRC data, Ref. 21, pp. 316, 319
NRL data, Ref. 33
DRL data, Ref. 34
NEL data, 1954, Ref. 35

receiver (36). At a frequency of 92 kc, no appreciable difference between the scattering in the direction back toward the source (0°) and the scattering in other directions (23° to 55° from this direction) could be established. Thus, at the particular location inside San Diego harbor, the bottom appeared in these measurements to be a substantially nondirectional isotropic scatterer of sound. However, other bottoms, especially those bearing regular ripple marks or sand waves, may be suspected to exhibit strong directional effects when viewed in different directions.

MISCELLANEOUS TOPICS

Concerning the important subject of the frequency spread of reverberation, a few additional studies of this matter have been made in recent years. An investigation of the spectrum of CW reverberation, previously conducted at 60 kc and mentioned on page 12 in the earlier summary (1), has been extended to frequencies of 85, 100, and 150 kc (37). In these experiments both the peak level and frequency spread were found to increase with frequency, with the peak level of the reverberation increasing at a rate of 5 db per octave and the spectral width at the 6-db down points increasing from 0.052 cps/kc/knot at 60 kc to 0.064 cps/kc/knots at 100 kc. The measurements were made aboard a submarine at various depths and over a range of speeds between 6 and 12 knots; the data represent a mixture of surface and volume reverberation. The reverberation at 150 kc was found, in these measurements, to be considerably lower than the reverberation at the lower frequencies, although this effect could not be positively established as being real. Some of the theory and results of this program of measurement of c-w reverberation have appeared in the unclassified literature (38, 39). However, this Westinghouse study of reverberation at short ranges immediately in front of a moving submarine (12) gave clear evidence that a submarine imparts a forward motion to the water just in front of its bow. A frequency analysis of the reverberation recorded immediately after the emission of a short (0.3-ms) ping showed that the motion imparted by a 5-knot submarine to the water in front of it was about 0.5 knot at a distance of three feet from the bow and extended out as far as 26 feet. Beyond this range, where the water and its included scatterers were unaffected by the submarine motion, the spread of the volume reverberation at a frequency of 60 kc was less than 5 cps at the 3-db down points. Inside this range, where the bulk of the reverberation in active c-w systems originates, the reverberation spectrum was found to be broader, with its peak shifted slightly downward in frequency. Because of this, the spectrum of the reverberation observed with such systems, illustrated in Fig. 8 of the earlier Reverberation summary (1), does not represent the spectrum of reverberation arising at a longer range.

It is clear of course that the reverberation spectrum is significant only for c-w transmission or for long pulses; for short pulses, the bandwidth inherent in the pulse dominates the spectral bandwidth of the reverberation itself. Under these conditions, which applied to some British experiments with a short pulse 100-kc Asdic (40), the frequency spectrum of the reverberation does not depart greatly from that of the pulse itself.

The interest in long-range echo ranging in recent years has resulted in a number of determinations of the fall-off, or decay, of reverberation with ranges or time under different conditions. For example, during tests of an NRL submarine-mounted 10-kc directional sonar (41), the reverberation decay in the surface sound channel was found to be 9 db per distance doubled, or like $-30 \log R$; at longer distances, the decay in the interval corresponding to the ranges R_1 and R_2 could be fitted by the expression

$$10 \log \frac{R_1}{R_2} + 2(\alpha_0 + \alpha_k)(R_1 - R_2),$$

where the first term represents cylindrical spreading and the second term represents the effects of absorption (α_0) plus a residual attenuation (α_k) probably due to leakage out of the channel. For three cases, α_k was measured to be 0.17, 0.21, and 0.22 when the pulse length was 1 second. Experiments by USL (42) have utilized explosive sources to provide information on reverberation as a function of time and frequency. Near 100 cps the decay of reverberation in the interval of 1 to 15 seconds was found to be approximately 6 db per time doubled in shallow water (less than 500 ft) and 12 db per time doubled in deep water, corresponding to cylindrical and spherical spreading, respectively. Near 10 kc, the corresponding figures were 15 and 13, respectively, representing the added attenuation produced by the presence of the bottom and by absorption. NEL experiments (5) showed that the reverberation from a ping in deep (2100-fathom) water at times immediately following the first return of sound from the bottom (between 5 and 10 seconds) could be fitted by an analytical expression based on simple geometrical considerations; in these experiments the effect of surface-image interference was plainly manifested by regular variations of a few db in the reverberation decay. For shallow water NEL has found a theory, based on ray methods for calculation of long-range bottom reverberation, which gives good agreement with experiment when a sine squared dependence of scattering strength (Lambert's Law) is assumed rather than omnidirectional scattering (43).

REFERENCES

1. R. J. Urick and A. W. Pryce, "A Summary of Underwater Acoustic Data, Part IV, Reverberation," ONR Survey of Naval Science No. 3, February 1954.

2. D. C. Whitmarsh, "Acoustics of the Medium Summary Report-A Joint Report," BuOrd Report Nord-16597-35, February 1958.

3. Naval Electronics Laboratory, "LORAD Summary Report," NEL Report 698, 1956.

4. K. V. Mackenzie, "Reverberation from Convergence Zones," JUA(USN) 5, 58-68 (1955).

5. K. V. Mackenzie, "Bottom Reverberation in 2100-Fathom Water," JUA(USN) 6, 24-36 (1956).

6. K. V. Mackenzie, "Seasonal Variation of LORAD Reverberation and a Possible Correlation with Phytoplankton Production," JUA(USN) 8, 413-416 (1958).

7. M. A. Pedersen and F. E. Hale, "LORAD Reverberation," JUA(USN) 9, 269-282 (1959).

8. L. Beck et al., "Reverberation Studies in the Acoustics of the Medium Program," NOTS 1569, NAVORD Report 5322, May 1956.

9. R. M. Hoover and F. E. Kaprocki, "Sound Back-Scattering in the Ocean at 25 and 60 kc," ORL Conf. External Report NOrd-16597-24, March 1957.

10. H. R. Johnson et al., "Suspended Echo-Sounder and Camera Studies of Midwater Sound Scatterers," WHOI Reference 56-58, 1956; also Deep Sea Research 3, 266-272 (1956).

11. D. E. Weston, "Observations of a Scattering Layer at the Thermocline," J. Royal Naval Scientific Service 12, No. 3 (1957).

12. D. S. Sims and D. D. Skinner, "Reverberation of Very Short Ranges - Part I," Westinghouse Research Laboratories, Research Report 100FF1042-R6-X, May 1957.

13. D. S. Sims and D. D. Skinner, "Distribution of Reverberation Scatterers in the Sea - Part II," Westinghouse Research Laboratories, Research Report 100FF1042-R4-X, May 1957; also JUA(USN) 8, 521-529 (1958).

14. D. S. Sims and D. D. Skinner, "Short-Range Reverberation Instrumentation - Part III," Westinghouse Research Laboratories, Research Report 100FF1042-R5-X, May 1957.

15. R. N. Hoover, "Measurement of the Back-Scattering of 60-kc Sound by the Ocean Surface," ORL Conf. External Report NOrd-16597-22, February 1957.

16. R. J. Urick and R. M. Hoover, "The Back Scattering of Sound from the Sea Surface: Its Measurement, Causes, and Application to the Prediction of Reverberation Levels," J. Acous. Soc. Am. 28, 1038-1042 (1956).

17. R. J. Urick, "Recent Acoustic Observations of a Near-Surface Layer of Scatterers in the Sea," ORL Conf. Tech. Memo. 7.3366-35, April 1956.

18. R. M. Hoover and R. J. Urick, "Sea Clutter in Radar and Sonar," IRE Convention Record, 1957.

19. University of Washington, Applied Physics Laboratory, "Reverberation Measurements at 60 kc in Dabob Bay," Report APL UW/TE/56-36, 1956.

20. L. Beck, L. Mittenthal, and Y. Igarashi, JUA(USN) 7, 175-186 (1957).

21. NDRC Div 6, "Physics of Sound in the Sea, Part II, Reverberation," Summary Technical Report, Vol. 8, 1946, p. 324.

22. B. F. Cron, "Theoretical Statistical Study of the Scattering of Sound," USL Research Report 352, May 1957.

23. G. E. Lund, "Characteristics of Ultrasonic Reflections from the Ocean Surface," NOL NAVORD Report 4194, 1956.

24. J. A. Whitney and W. E. Batzler, JUA(USN) 7, 187-200 (1957).

25. E. C. Westerfield and W. E. Batzler, "Interval-Maximum Method of Measurement for Underwater Reverberation and Noise," NEL Report 239, October 1952.

26. L. Mittenthal, "A Study of the Effects of Refraction on Reverberation," NOTS 1284, NAVORD Report 4962, 1955.

27. R. J. Urick, "Simple Methods for the Computation of Surface, Bottom, and Volume Reverberation," ORL Conf. External Report NOrd-16597-23, March 1957.

28. A. R. M. Noton and D. Byfleet, "Scattering from Sea Bottom Materials," Report No. 115, Underwater Detection Establishment (British), October 1953.

29. R. J. Donato and D. E. Byfleet, "Acoustic Scattering from Sand and Shingle Surfaces at 35 kc/s," Report 153, Underwater Detection Establishment (British), July 1955.

30. C. D. Anderson and N. B. Ward, "Acoustic Backward-Scattering Measurements, Panama City, Fla. - July 1956," DRL Report A-114, March 1957.

31. C. D. Anderson and F. T. Wyatt, "Report of Acoustic Backward-Scattering Measurements in Gulf of Mexico, Galveston, Texas - May 1957," DRL Acoustical Report 130, November 1957.

32. C. M. McKinney and J. F. Mifsud, JUA(USN) 9, 357-368 (1959).

33. R. J. Urick, "The Back Scattering of Sound by Harbor Bottoms with Application to Acoustic Minehunting," NRL Report 4195, July 1953.

34. University of Texas, Defense Research Laboratory, Monthly Progress Report, April 1953.

35. W. E. Batzler et al., "Sonar Echoes and Bottom-Reverberation Studies Related to the Mine Countermeasures Problem," NEL Report 554, November 1954.

36. W. E. Batzler et al., JUA(USN) 5, 248-255, 1955.

37. D. S. Sims, "CW Reverberation and Propagation at 85, 100, and 150 kc," Westinghouse Research Laboratories, Research Report 100FF809-R5-X, February 1955; also JUA(USN) 6, 175-183 (1956).

38. G. A. Klotsbaugh, J. Acous. Soc. Am. 27, 956-961 (1955).

39. P. Conley, J. Acous. Soc. Am. 27, 962-966 (1955).

40. J. W. R. Griffiths and A. W. Pryce, "The Spectrum of Reverberation and the Influence of Pulse Duration and Receiver Bandwidth on Signal/Reverberation Ratio," Royal Naval Scientific Service 10, No. 6 (1955).

41. H. L. Saxton et al., "10-kc Long-Range Search Sonar," NRL Report 4515, August 1955.

42. P. A. Barakos, "Shallow Water Reverberation, Cruise I-5," USL Tech Memo 1110-023-56, November 1956.

43. K. V. Mackenzie, JUA(USN) 8, 359-378 (1958).

CONFIDENTIAL

CONFIDENTIAL

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

IN REPLY REFER TO
5510/1
Ser 93/057
20 Jan 98

From: Chief of Naval Research
To: Commanding Officer, Naval Research Laboratory (1221.1)

Subj: DECLASSIFICATION OF DOCUMENTS

Ref: (a) NRL ltr 5510 Ser 1221.1/S0048 of 25 Feb 97
(b) NRL memo Ser 7103/713 of 29 Jan 97
(c) ONR Report "A Summary of Underwater Radiated Noise Data, March 1966"

Encl: (1) ONR Report "A Summary of Underwater Acoustic Data, Part I" AD-030 750
(2) ONR Report "A Summary of Underwater Acoustic Data, Part II" AD-039 542
(3) ONR Report "A Summary of Underwater Acoustic Data, Part III" AD-039 543
(4) ONR Report "A Summary of Underwater Acoustic Data, Part IV" AD-039 544
(5) ONR Report "A Summary of Underwater Acoustic Data, Part V" AD-105 841
(6) ONR Report "A Summary of Underwater Acoustic Data, Part VII" AD-115 204
(7) ONR Report "A Summary of Underwater Acoustic Data, Part VIII" AD-105 842

1. In response to reference (a), the following information is provided:

Enclosure (1) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (2) was downgraded to UNCLASSIFIED by NRL, 12/3/90;
Enclosure (3) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (4) was downgraded to UNCLASSIFIED by CNR, 7/29/74;
Enclosure (5) was downgraded to UNCLASSIFIED by NRL, 12/3/90;
Enclosure (6) was downgraded to UNCLASSIFIED by CNR, 7/29/74; and
Enclosure (7) was downgraded to UNCLASSIFIED by CNR, 7/29/74.

Enclosures (1) through (7) have been appropriately stamped with declassification information and, based on the recommendation contained in reference (b), Distribution Statement A has been assigned.

AD-396 737

2. To my knowledge, reference (c) has not been previously reviewed for declassification. Based on our discussions in April 1997, I am still holding it for Dr. Hurdle's comments.

3. Questions may be directed to the undersigned on (703) 696-4619.

Completed
18 Apr 2000
B.W.

PEGGY LAMBERT
By direction