Acoustic Ambient Noise in the Ocean: Spectra and Sources

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The results of recent ambient-noise investigations, after appropriate processing, are compared on the basis of pressure spectra in the frequency band 1 cps to 20 kc. Several possible sources are discussed to determine the most probable origin of the observed noise. It is concluded that, in general, the ambient noise is a composite of at least three overlapping components: *turbulent-pressure fluctuations* effective in the band 1 cps to 100 cps; wind-dependent *noise from bubbles and spray* resulting, primarily, from surface agitation, 50 cps to 20 kc; and, in many areas, *oceanic traffic*, 10 cps to 1000 cps. Spectrum characteristics of each component and of the composite are shown. Additional sources, including those of intermittent and local effects, are also discussed. Guidelines for the estimation of noise levels are given.

INTRODUCTION

THE summary work of Knudsen, Alford, and Emling[1,2] discussed the nature of underwater acoustic ambient noise in the frequency range from 100 cps to 25 kc. While a few results from remote open-ocean areas were available, a large part of the source data for their study was taken in off-shore areas, and in the vicinity of ports and harbors. Three main sources of underwater ambient noise were identified: water motion, including also the effects of surf, rain, hail, and tides; manmade sources, including ships; and marine life. The "Knudsen" curves showing the dependence of the noise from water motion on wind force and sea state are well known. Increased levels due to nearby shipping and industrial activity have been observed. For several marine-life sources,[3–6] e.g., snapping shrimp and croakers, the noise characteristics and the times and places of occurrence have been indicated.

A number of ambient-noise studies has been made since 1945, including some investigation of the frequency range below 100 cps and some additional measurements in deep-water open-ocean areas. A great deal of the underwater ambient-noise information is the result of investigations conducted by U. S. Navy Laboratories, and by university and commercial laboratories operating under contract with government agencies, usually with the Office of Naval Research.

While most of the later results have been in general agreement with the Knudsen *et al.* data, there appear to be some significant differences from the earlier summary data and among the recent data. For example, as will be shown, in several studies it was observed that, at frequencies below 500 cps, the dependence of the underwater ambient-noise levels on wind speed and sea state decreased as the frequency decreased, and at 100 cps and below, little or no dependence was seen; while other observers have reported a substantial wind-speed dependence extending to frequencies as low as 50 cps.

As might be expected, differing procedures have been used in obtaining and processing data, and in defining results. Data from the various sources cannot always be compared directly but must be given additional treatment in many cases.

This review is designed to bring together for comparison, after being appropriately processed, the results of recent investigations; to show that many of the observed differences as well as similarities can be explained by certain plausible assumptions as to source and source characteristics; and to indicate how to apply this information in estimating the ambient-noise levels for a given situation.

1. AMBIENT-NOISE SPECTRA

The main purpose of this paper is to discuss the more widespread and prevailing characteristics of ambient noise in the ocean. Obvious noise from marine life, nearby ships, and other sources of intermittent and local noise is not included in the data considered in this section.

As has been shown,[1,2] in the absence of sounds from ships and marine life, underwater ambient-noise levels are dependent on wind force and sea state, at least at frequencies between 100 cps and 25 kc. Therefore, wind dependence was made the starting point for the analysis of the results of recent investigations.

The processing of data reported in differing terms included the following: conversion of levels to dB *re* 0.0002 dyn/cm^2 and a 1-cps bandwidth; estimation of wind force from stated sea states (see Table I); the derivation of spectra corresponding to the means of the Beaufort-scale wind-speed ranges, from given equations or graphs relating level to wind speed at various frequencies; and the computation of average spectrum levels corresponding to Beaufort-scale groupings. When the sampling was small, graphical smoothing and interpolation were often employed.

Each datum point used in determining the ambient-

[1] V. O. Knudsen, R. S. Alford, and J. W. Emling, "Survey of Underwater Sound, Report No. 3, Ambient Noise," 6.1–NDRC-1848 (September 26, 1944) (P B 31021).
[2] V. O. Knudsen, R. S. Alford, and J. W. Emling, J. Marine Research **7**, 410 (1948).
[3] E. O. Hulburt, J. Acoust. Soc. Am. **14**, 173 (1943).
[4] D. P. Loye and D. A. Proudfoot, J. Acoust. Soc. Am. **18**, 446 (1946).
[5] M. W. Johnson, F. A. Everest, and R. W. Young, Biol. Bull. **93**, 122 (1947).
[6] F. A. Everest, R. W. Young, and M. W. Johnson, J. Acoust. Soc. Am. **20**, 137 (1948).

TABLE I. Approximate relation between scales of wind speed, wave height, and sea state.

Sea criteria	Beaufort scale	Wind speed: Range knots (m/sec)	Wind speed: Mean knots (m/sec)	12-h wind: Wave height[a,b] ft (m)	Fully arisen sea: Wave height[a,b] ft (m)	Fully arisen sea: Duration[b,c] h	Fully arisen sea: Fetch[b,c] naut. miles (km)	Sea-state scale
Mirror-like	0	<1 (<0.5)						0
Ripples	1	1–3 (0.5–1.7)	2 (1.1)					½
Small wavelets	2	4–6 (1.8–3.3)	5 (2.5)	<1 (<0.30)	<1 (<0.30)			1
Large wavelets, scattered whitecaps	3	7–10 (3.4–5.4)	8½ (4.4)	1–2 (0.30–0.61)	1–2 (0.30–0.61)	<2.5	<10 (<19)	2
Small waves, frequent whitecaps	4	11–16 (5.5–8.4)	13½ (6.9)	2–5 (0.61–1.5)	2–6 (0.61 1.8)	2.5 6.5	10–40 (19–74)	3
Moderate waves, many whitecaps	5	17–21 (8.5–11.1)	19 (9.8)	5–8 (1.5–2.4)	6–10 (1.8 3.0)	6.5–11	40–100 (74–185)	4
Large waves, whitecaps everywhere, spray	6	22–27 (11.2–14.1)	24½ (12.6)	8–12 (2.4–3.7)	10–17 (3.0–5.2)	11 18	100–200 (185–370)	5
Heaped-up sea, blown spray, streaks	7	28–33 (14.2–17.2)	30½ (15.7)	12–17 (3.7 5.2)	17–26 (5.2–7.9)	18–29	200–400 (370–740)	6
Moderately high, long waves, spindrift	8	34–40 (17.3–20.8)	37 (19.0)	17–24 (5.2–7.3)	26–39 (7.9–11.9)	29–42	400–700 (740–1300)	7

[a] The average height of the highest one-third of the waves (significant wave height).
[b] Estimated from data given in U. S. Navy Hydrographic Office (Washington, D. C.) publications HO 604 (1951) and HO 603 (1955).
[c] The minimum fetch and duration of the wind needed to generate a fully arisen sea.

noise spectra is an average of several samples from a single locality. In many cases, shipborne systems were used and usually only a very few samples were obtained at each of several stations in the same general area. The mean spectra derived from such measurements comprise average values of data from all stations in the same general area.

[1.1] 20 cps to 10^4 cps

The spectra[7] resulting from measurements made in five different shallow-water areas are shown in Fig. 1. [Shallow water is defined as water less than 100 fathoms (183 m) in depth.] Deep-water ambient-noise spectra from five different areas are presented in Fig. 2. It is evident that spectra corresponding to the same scale of wind speed or sea state can exhibit considerable differences in spectrum shape and level. However, as is indicated by the arrangement of the figures, groupings can be made within which the spectra are roughly the same, and between which distinct differences are evident.

The wind-dependent spectra at the left in Fig. 1 [parts (a), (c), and (e)] are characterized by broad maxima, the highest value occurring at a frequency between 400 and 800 cps. None of the other spectra demonstrates this spectrum shape clearly, although there are suggestions of it in some, being indicated by a flattening between 200 and 1000 cps. The maxima appearing in Figs. 1(b) and 1(d) and Figs. 2(b) and 2(d) occur at frequencies 100 cps and below, and the levels in the neighborhood of the spectrum maximum are not wind-dependent.

The wind-dependent aspects of the ambient noise appear to be greatly influenced by non-wind-dependent components. In the spectra at the right in each figure, little wind dependence is evident below about 200 cps and the levels of the non-wind-dependent noise are as high as or higher than the levels shown for the highest wind speeds in the left-hand graphs in each figure. The levels of this non-wind-dependent noise decrease rapidly, 8 to 10 dB per octave, at frequencies above 100 cps.

In the areas associated with Figs. 1(a) and 1(c), a relatively high residual noise limits wind dependence to wind speeds more than 5 to 10 knots (Beaufort 2 to 3), depending on frequency.

At frequencies above 500 cps, where the noise levels show wind dependence in nearly every case, the spectra have the same general shape and approach a spectrum slope of about −6 dB per octave above 1000 cps.

[7] Unless otherwise indicated, all spectra are given in terms of pressure-spectrum level in dB *re* 0.0002 dyn/cm², the reference bandwidth being 1 cps as included in the definition of the term "spectrum level" in Sec. 2.8, American Standard Acoustical Terminology, ASA-S1.1-1960 (American Standards Association, May 25, 1960).

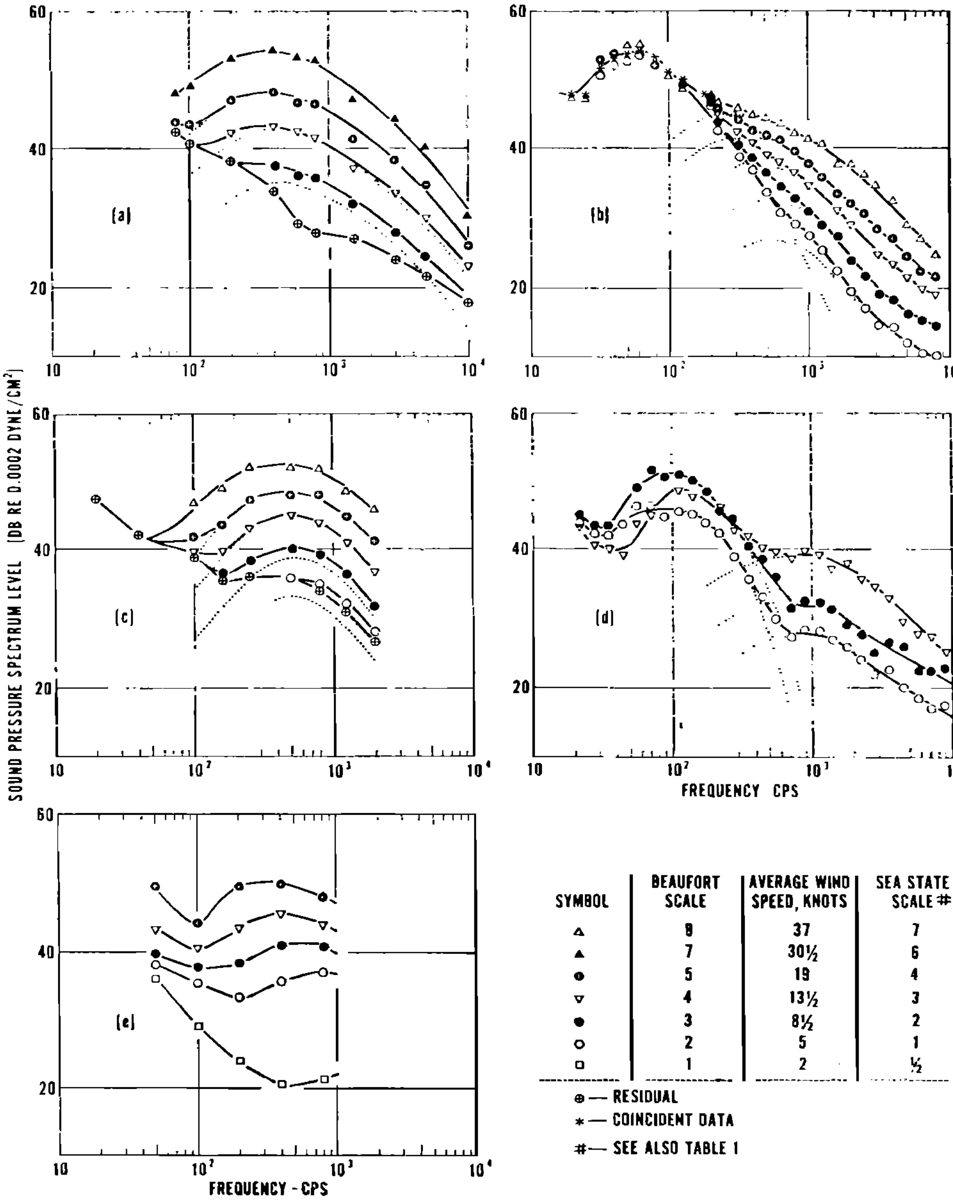


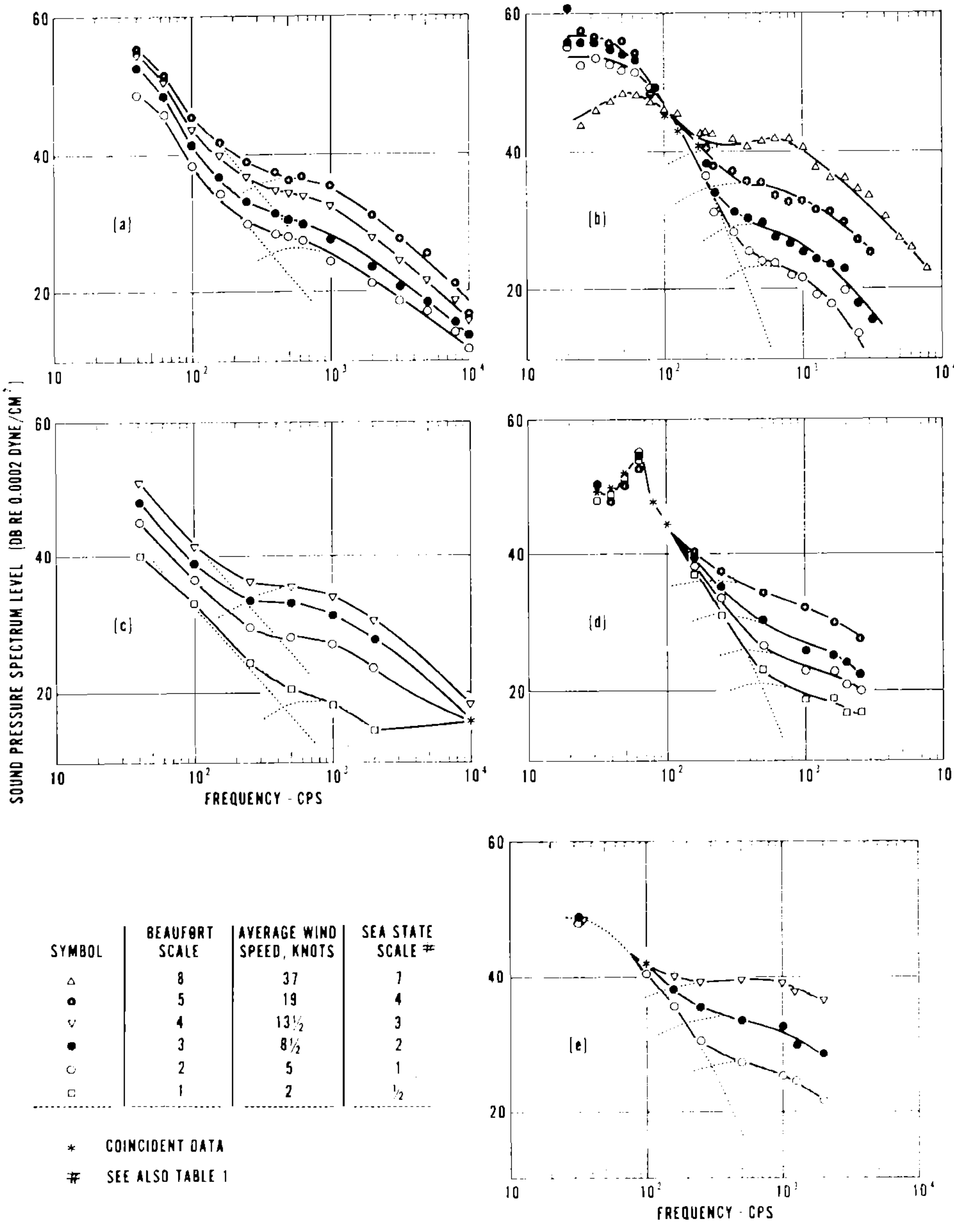
FIG. 1. Shallow-water ambient-noise spectra, showing average spectrum levels for each of several Beaufort-scale wind-speed groupings, as measured in five different areas. The dotted curves define component spectra according to an analytical interpretation of the observed spectra.

However, the shallow-water levels (Fig. 1) are in general about 5 dB higher than the corresponding deep-water levels (Fig. 2) at the same frequency and wind speed. The figures show average values. The variability is such that the higher deep-water levels for a given condition are about the same as the lower shallow-water levels; that is, the distributions overlap.

For frequencies between 20 cps and 10 kc, the range of the data in Figs. 1 and 2, the diverse ambient-noise spectra can be explained by assuming various combinations of a wind-dependent component and a non-wind-dependent component. The application of this interpretation is demonstrated in Figs. 1 and 2 by dotted curves which indicate the probable spectra of the components which have combined in each case to produce the observed spectrum. The wind-dependent component is assumed to have a spectrum with a broad maximum between 100 cps and 1000 cps, like those in Figs. 1(a), 1(c), and 1(e). In general, the spectrum of the non-wind-dependent component is assumed to peak at 100 cps or lower, and to fall off steeply above 100 cps, as seen in Figs. 1(b), 1(d), 2(b), 2(d),[8] and 2(e). As the figures illustrate, quite reasonable combinations of such spectra result in spectra like the observed spectra.

In Figs. 1(a) and 1(c), the spectrum of the residual noise does not decrease rapidly with frequency, and the wind dependence is altered at the higher frequencies as well as at low frequencies. In this case the observed

[8] The peak near 60 cps in Fig. 2(d) is not caused by a self-noise "hum" component from system-power sources. The maximum appears to be real but may be accentuated by variations in the response of the measurement system not revealed by the calibration data.



SYMBOL	BEAUFORT SCALE	AVERAGE WIND SPEED, KNOTS	SEA STATE SCALE #
△	8	37	7
◉	5	19	4
▽	4	13½	3
●	3	8½	2
○	2	5	1
□	1	2	½

* COINCIDENT DATA

SEE ALSO TABLE 1

FIG. 2. Deep-water ambient-noise spectra, showing average spectrum levels for each of several Beaufort-scale wind-speed groupings, as measured in five different areas. The dotted curves define component spectra according to an analytical interpretation of the observed spectra.

spectra are a combination of the wind-dependent spectra with the spectrum of a residual-noise component which prevails at the lower wind speeds.

In Figs. 1(e), 2(a), and 2(c), wind dependence appears to be universal. Also, minima or inflection points appear in the spectra between 100 and 500 cps. This spectrum shape suggests the possibility, at least, of two different wind-dependent sources or mechanisms. In the system used for the measurements from which the data in Figs. 2(a) and 2(c) were obtained, the hydrophones were not well isolated from the effects of surface fluctuations, and there is a strong possibility that the low-frequency wind-dependent noise is a form of system self-noise. This does not apply to the data in Fig. 1(e), however.

When measured in the same area, or even in the same place with the same system and at the same wind speed, there is often considerable variation in the observed levels of the wind-dependent noise as measured at different times. Such differences are illustrated in Fig. 3, which shows spectra comprising levels averaged over two different time periods at each of two different locations. While the spectra are of the same general shape, for the same wind speeds, the wind-dependent September levels in Fig. 3(a) run about 8 dB below those for January in Fig. 3(b), and the wind-dependent June–July levels in Fig. 3(c) are about 5 dB below those for September–October in Fig. 3(d). If it is assumed that the source of the wind-dependent noise is in the surface agitation resulting from the effects of the wind,

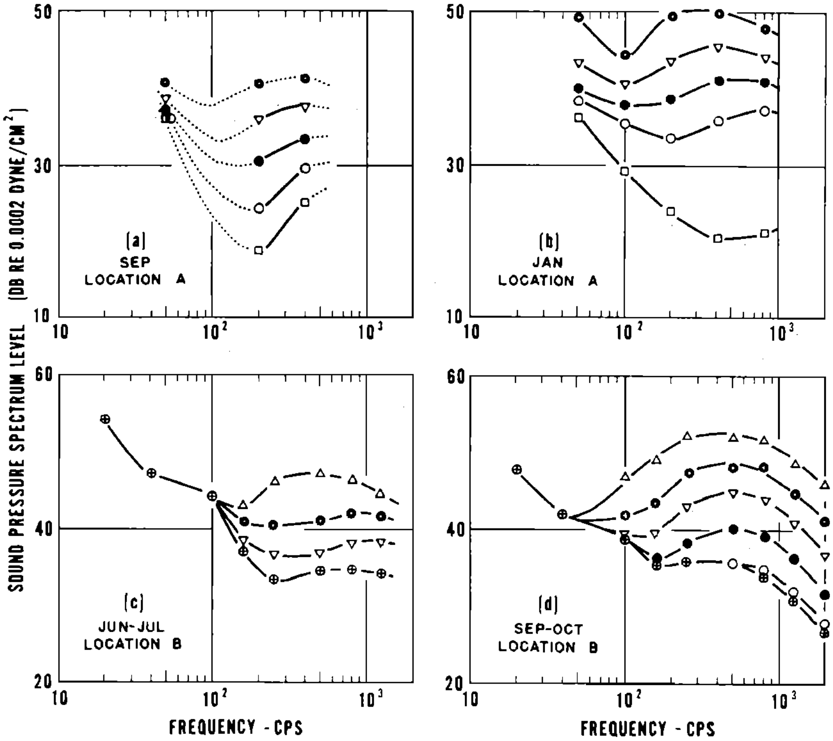


Fig. 3. Ambient-noise spectra, illustrating differences in the averages of levels measured in the same area and at the same wind speeds, but during different periods of time.

SYMBOL	BEAUFORT SCALE	AVERAGE WIND SPEED, KNOTS	SEA STATE SCALE #
△	8	37	7
⊙	5	19	4
▽	4	13½	3
●	3	8½	2
○	2	5	1
□	1	2	½

⊕ — RESIDUAL

— SEE ALSO TABLE 1

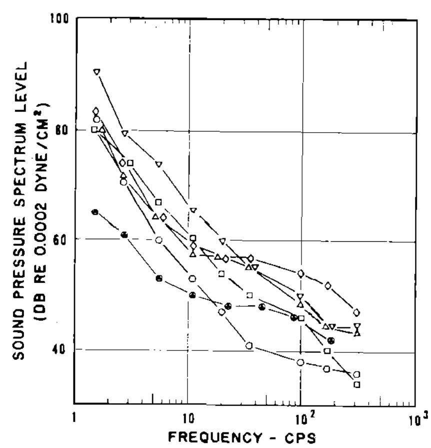


Fig. 4. Low-frequency ambient-noise spectra, comparing the averages of a number of measurements made in each of five different areas. The open triangles and the inverted triangles represent data taken in the same general area but at different depths.

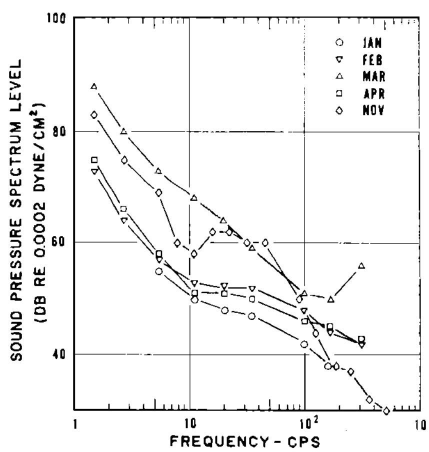


Fig. 5. Low-frequency ambient-noise spectra, comparing the averages of levels measured during different months of the year at the same location.

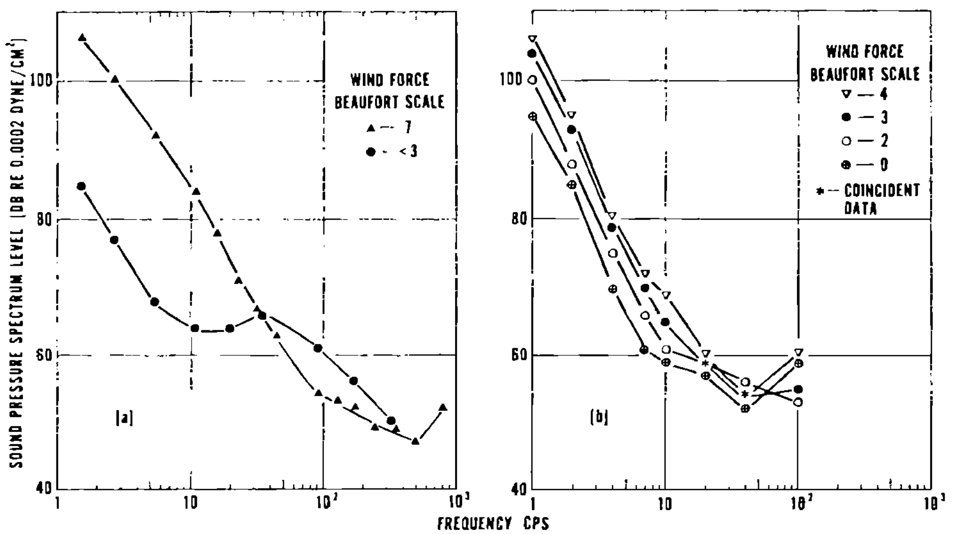


FIG. 6. Low-frequency ambient-noise spectra showing wind-dependence in very shallow water (less than 25 fathoms or 46 m) at two widely separated locations.

variations of this nature are not entirely unexpected. Wind speed alone is only a crude and incomplete measure of the surface agitation which depends also on such factors as the duration, fetch, and constancy of the wind, and its direction in relation to local conditions of swell, current, and, in near-shore areas, topography. Subjective estimates of sea state are not necessarily an improvement over wind speed as a measure of the pertinent surface agitation.

[1.2] 1 cps to 100 cps

The amount of data available from measurements at very low frequencies is relatively small. No consistent wind dependence has been reported, except for very shallow water. Some obvious effects from nearby shipping have been observed. Exclusive of these obvious effects, rather wide variations in the very low-frequency noise levels have been experienced.

In Fig. 4, the individual curves compare the averages of a number of measurements made in each of five different areas. All of the data in Fig. 5 were obtained at the same location, the different curves showing averages of data taken during different months of the year. Wind dependence in very shallow water (less than 25 fathoms or 46 m) at two widely separated locations is demonstrated in Fig. 6.

Some generalizations can be made about the results shown in Figs. 4–6. The very low-frequency noise may differ in level by 20 to 25 dB from one place to another, and from one time to another. The spectrum shape below 10 cps is nearly always the same, and has a slope of −8 to −10 dB per octave. Between 10 cps and 100 cps, the spectrum often flattens and may even show a broad maximum, but in some instances the spectrum slope shows little or no change from the slope below 10 cps.

1.3 Minimum Levels

The lowest levels encountered in the data available to the author are shown in Fig. 7. The solid symbols represent measurements made in an inland lake. The remainder of the data pertains to measurements in the ocean. Data from the same set of measurements are connected by dashed lines. Symbols shown with downward-pointing arrows designate equivalent system-noise levels which mark an upper limit to the ambient-noise levels existing at the time of the measurement. The solid curve defines levels which will almost always be exceeded by observed levels.

As indicated by the individual sets of measurements, it is unlikely that the very low levels will be encountered in every part of the spectrum at the same time. This may

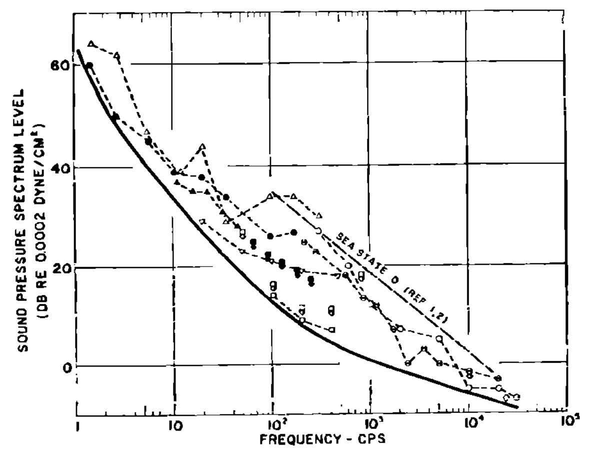


FIG. 7. The empirical lower limit of ambient-noise spectra (solid curve), as determined by the lowest of observed levels. The solid symbols refer to measurements made in an inland lake, the open symbols to those in the ocean. Symbols with downward-pointing arrows designate equivalent system-noise levels which mark an upper limit to the ambient-noise level existing at the time of the measurement. The sea state 0 curve from references 1 and 2 is shown for comparison.

be interpreted as an indication that the different regions of the spectrum are dominated by different components which combine to produce the observed spectra, but which are not all at a minimum at the same time.

The solid curve is an estimate of the minimum levels existing in the ocean. This estimate is probably high since the curve is to some extent an indication of the state of the measurement art. In the results of one investigation, it was stated that during a period of measurement covering 44 h of data, 40% of the time the noise levels at 200 cps were too low to measure. The limiting equivalent system-noise spectrum level at 200 cps was 10 dB *re* 0.0002 dyn/cm². The data represented by the symbols with downward-pointing arrows are also an indication of the need for improved measurement techniques.

1.4 Interpretation

In the absence of noise from marine life and nearby ships, the underwater ambient-noise spectrum between 1 cps and 10 kc may be resolved into several overlapping subspectra: A *low-frequency spectrum* with a −8 dB to −10 dB per octave spectrum-level slope, in the range 1 to 100 cps; a *"non-wind-dependent" spectrum* in the range 10 cps to 1000 cps with a maximum between 20 and 100 cps and falling off rapidly above 100 cps (sometimes not observed); and a *wind-dependent spectrum* in the range 50 cps to 10 kc with a broad maximum between 100 cps and 1000 cps and a −5-dB- or −6-dB-per-octave slope above 1000 cps.

At low frequencies, the ambient noise is dominated by the component, or components, characterized by a −8-dB- to −10-dB-per-octave slope, which extends in some cases to frequencies as high as 100 cps. Above 500 cps, wind-dependent noise nearly always prevails. The frequency band between 10 cps and 1000 cps, being the region of overlap, is a highly variable one in which each observed spectrum depends on a combination of the three overlapping component spectra, each of which may vary independently with time and place.

Minimum levels are determined in some cases, mostly in shallow water, by local residual-noise components, such as those illustrated in Figs. 1(a) and 1(c), whose levels exceed the levels of the more general limiting noise indicated in Fig. 7.

2. SOURCES OF NOISE IN THE OCEAN

2.1 Thermal Agitation

The effects from the thermal agitation of a medium determine a minimum noise level for that medium. For the ocean, the equivalent thermal-noise sound-pressure level is given, for ordinary temperatures between 0° and 30°C, by the relation[9]:

$$L_t \approx -101+20\log f, \tag{1}$$

where L_t is the thermal-noise level in dB *re* 0.0002 dyn/cm² for a 1-cps bandwidth, and f is the frequency in cps. According to Eq. (1), the thermal-noise spectrum has a slope of +6 dB/octave and a level of −10 dB at 35 kc. At the upper frequency limit of the ambient-noise data shown in Fig. 7, around 20 or 30 kc, the minimum ambient-noise levels are about the same as the thermal-noise levels. It is obvious from Fig. 7, however, that, at frequencies below 10 kc, even the lowest of the observed ambient-noise levels are well above the thermal-noise limit, and other noise sources must be found to explain the observed spectra.

2.2 Hydrodynamic Sources

A wide variety of hydrodynamic processes is continually taking place in the ocean, even at zero sea state. It is known that the radiation of sound often results from these processes.

2.2.1 Bubbles

An oscillating bubble is an effective sound source. Both free and forced oscillations of bubbles occur in the ocean, particularly in the surface agitation resulting from the effects of wind.

Pertinent information concerning the radiation of sound by air bubbles in water has been given by Strasberg.[10,11] The sound pressures associated with the higher modes of oscillation of the bubbles are negligible so that only simple volume pulsations (zeroth mode) need be considered. In the case of forced oscillations, the sound energy tends to be concentrated at the natural frequency of oscillation of the zeroth mode also, but this tendency may be altered if the frequencies associated with the environmental pressure fluctuations are much below the natural frequency of oscillation of the bubbles.

The natural frequency of oscillation for the zeroth mode is

$$f_0=(3\gamma p_s\rho^{-1})^{\frac{1}{2}}(2\pi R_0)^{-1}, \tag{2}$$

where γ is the ratio of specific heats for the gas in the bubble, p_s is the static pressure, ρ the density of the liquid, and R_0 is the mean radius of the bubble. The amplitude of the radiated sound pressure at a distance d from the center of the bubble is

$$p_0=3\gamma p_s r_0 d^{-1}, \tag{3}$$

r_0 being the amplitude of the zeroth mode of oscillation. It is assumed that the amplitude of the bubble oscillation is relatively small so that the various modes are independent of each other.

The natural frequency is inversely proportional to the bubble size, and the radiated sound-pressure amplitude is directly proportional to the bubble-oscillation amplitude. There is a practical limit to bubble size, and it is quite probable, also, that in many cases there would be a predominance of bubbles of nearly one size only. It is

[9] R. H. Mellen, J. Acoust. Soc. Am. 24, 478 (1952).

[10] M. Strasberg, J. Acoust. Soc. Am. 28, 20 (1956).

[11] H. M. Fitzpatrick and M. Strasberg, David Taylor Model Basin Rept. 1269 (January 1959).

to be expected, therefore, that in general the spectrum has a maximum at some frequency associated with either a predominant bubble size or a maximum bubble size, the exact shape depending on the distribution of bubble sizes and amplitudes of oscillation.

Franz[12] has measured the sound energy radiated by air bubbles formed when air is entrained in the water following the impact of water droplets on the surface of the water. His results are given in the form of one-half-octave-band sound-energy spectra which exhibit maxima. The decline toward lower frequencies is sharp (8 to 12 dB per octave, in terms of energy-spectrum level) and is attributed to an almost complete absence of bubbles larger than a certain size. A more gradual decline toward higher frequencies (-6 dB to -8 dB per octave) was found and was interpreted as being the result of a decrease in the radiated sound energy per bubble rather than a decrease in the prevalence of bubbles.

Data on bubble size and environmental conditions are not available in sufficient detail for making exact predictions concerning the bubble noise in the ocean. However, a rough appraisal can be made. According to Eqs. (2) and (3), a spherical air bubble of mean radius 0.33 cm, in water at atmospheric pressure, oscillating with an amplitude one-tenth the mean radius ($r_0=0.1R_0$), has a simple source-pressure level[13] referred to 1 m, of about 133 dB above 0.0002 dyn/cm^2 at a frequency of approximately 1000 cps. For a frequency of 500 cps, the mean-bubble radius is about 0.66 cm, and, for the same amplitude-to-size ratio, the source level is 6 dB higher.

These source levels are some 75 to 100 dB above the observed ambient-noise spectrum levels at these frequencies. The noise from such bubble sources could be observed at a considerable distance. The maxima in the observed wind-dependent ambient-noise spectra (see preceding Sec. 1.1 and Figs. 1 and 2) occur at frequencies between 300 cps and 1000 cps, which correspond to bubble sizes of 1.1 cm to 0.33 cm in mean radius, a reasonable order of magnitude.

The characteristic broadness of the maxima in the wind-dependent ambient-noise spectra can be explained by the reasonable assumption that in the surface agitation the bubble size and energy distributions are not sharply concentrated around the averages. The ambient-noise high-frequency spectrum slope above the maximum, approximately -6 dB octave, agrees with that of the bubble noise.

The nature of cavitation noise has been described by Fitzpatrick and Strasberg.[11] According to the acoustic theory, the sound-pressure spectra have maxima at frequencies corresponding approximately to the reciprocal of the time required for growth and collapse of the vapor cavities. At low frequencies the predicted spectrum slope is 12 dB per octave, but at high frequencies the spectrum is determined by details of very rapid changes in sound pressure which are not given correctly by the acoustic theory.

The noise produced by a stirring rod 2 in. long and $\frac{1}{16}$ in. in diameter rotating at 4300 rpm in the Thames River (New London, Connecticut) was measured by Mellen.[14] His results are given in the form of a sound-pressure spectrum which shows a maximum near 1000 cps and slope of approximately -6 dB per octave at higher frequencies. The spectra of noise from cavitating submerged water jets as reported by Jorgensen[15,16] show a slope of approximately 12 dB per octave at low frequencies, in agreement with the acoustic theory, and a slope of about -6 dB per octave at high frequencies, in agreement with Mellen's data. Observed spectra of noise radiated by submarines exhibit characteristics which are in general agreement with these data and which have been attributed to cavitation effects.[17]

The spectrum shape of cavitation noise is similar to that of the air-bubble noise, which, as has been pointed out, resembles the spectrum shape of the wind-dependent ambient noise (see Figs. 1 and 2). For cavities of comparable size one would expect higher noise levels from cavitation than from the simple volume pulsations of gas bubbles since the amplitude of oscillation is usually greater.

From the foregoing, it is concluded that air bubbles and cavitation produced at or near the surface, as a result of the action of the wind, could very well be a source of the wind-dependent ambient noise at frequencies between 50 cps and 10 kc.

Bubbles are present in the sea (or lakes) even when the wind speeds are below that at which whitecaps are produced. Bubbles are created, not only by breaking waves, but also by decaying matter, fish belchings, and gas seepage from the sea floor. Furthermore, there is evidence of the existence of invisible microbubbles in the sea, and of the occurrence of gas supersaturation of varying degree near the surface. These conditions provide a favorable environment for the growth of microbubble nuclei into bubbles as a result of temperature increases, pressure decreases, and turbulence associated with currents and internal waves, as well as with surface waves.[18–20] As the bubbles rise to the surface, growing in size (because of the decreasing hydrostatic pressure), they are subjected to transient pressures which induce the oscillations which generate the noise. Even on quiet

[12] G. J. Franz, J. Acoust. Soc. Am. 31, 1080 (1959).

[13] Source-pressure level is defined as the sound-pressure level at a specified reference distance in a specified direction from the effective acoustic center of the source.

[14] R. H. Mellen, J. Acoust. Soc. Am. 26, 356 (1954).

[15] D. W. Jorgensen, David Taylor Model Basin Rept. 1126 (November 1958).

[16] D. W. Jorgensen, J. Acoust. Soc. Am. 33, 1334 (1961).

[17] NDRC Summary Tech. Repts. Div. 6, Vol. 7, Principles of Underwater Sound, Sec. 12.4.5. (Distributed by Research Analysis Group, Committee on Undersea Warfare, National Research Council.)

[18] E. C. LaFond and P. V. Bhavanarayana, J. Marine Biol. Assoc. India 1, 228 (1959).

[19] W. L. Ramsey, Limnology and Oceanography 7, 1 (1962).

[20] E. C. LaFond and R. F. Dill, NEL TM-259 (1957) (unpublished technical memorandum).

days and in the absence of wind, bubbles have been seen to emerge from the water, sometimes persisting for a time as foam, and then to burst. These oceanographic data support the hypothesis that bubble noise may still be an important component of underwater ambient noise, even when there is little or no surface agitation from the wind.

Thus, there is evidence of the presence of bubbles in the ocean both when winds are high and when winds are low, or even during a calm. Oscillating and collapsing bubbles are efficient and relatively high-level noise sources. Both the level and shape of the observed wind-dependent ambient noise can be explained by the characteristics of bubble noise and cavitation noise.

2.2.2 *Water Droplets*

The underwater noise radiated by a spray of water droplets at the surface of the water has been investigated by Franz.[12] The noise from such splashes appears to be made up of noise from the impact and passage of the droplet through the free surface. In many cases, air bubbles are entrained so that the total noise includes contribution from the bubble oscillations as well. The sound-energy spectrum has a broad maximum near a frequency equal to twice the ratio of the impact velocity to the radius of the droplets. Towards lower frequencies, the spectrum density decreases gradually at a rate of 1 or 2 dB per octave. At frequencies above the maximum, the slope approaches −5 or −6 dB per octave. The impact part of the radiated sound energy increases with increase in droplet size and impact velocity. The relation is modified somewhat by the bubble noise, particularly at intermediate velocities.

Franz estimated the sound-pressure spectrum levels to be expected from the impact of rain upon the surface of the water. He concluded that rain exceeding a rate of 0.1 in./h would be expected to raise ambient-noise levels and flatten the spectrum at frequencies above 1000 cps under sea-state-1 conditions. The measurements of ambient sea noise made by Heindsmann *et al.*[21] during periods of rainfall are in fair agreement with the estimates made by Franz.

The noise from splashes of rigid bodies, such as from hail or sleet, is in general similar to that from water droplets, but is modified by the effects of resonant vibrations of the bodies.

In addition to the effects of precipitation, there is the possibility that noticeable contribution to the ambient sea noise may come from spray and spindrift, especially at the higher wind speeds.

2.2.3 *Surface Waves*

The fluctuations in the elevation of the surface of a body of water cause subsurface pressure fluctuations which, whether controlled by compressibility or not, affect the transducer of an underwater system.

[21] T. E. Heindsmann, R. H. Smith, and A. D. Arneson, J. Acoust. Soc. Am. 27, 378 (1955).

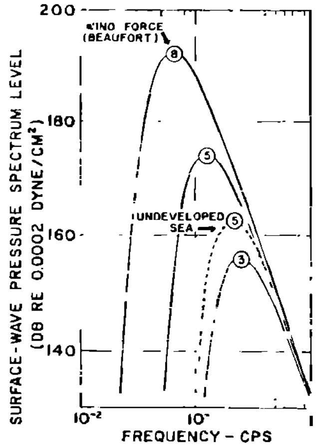


FIG. 8. Surface-wave pressure-level spectra, derived from Neumann–Pierson surface-wave elevation spectra (see references 22 and 23).

The spectra of surface waves, that is, the spectrum densities of the time variation of the surface elevation at a fixed point, according to Neumann[22] and Pierson,[23] are represented by the relation

$$\bar{h}^2(\omega) = C\omega^{-6}\exp(-2g^2\omega^{-2}v^{-2}), \qquad (4)$$

where $\bar{h}^2(\omega)$ is the mean-square elevation of the surface per unit bandwidth at the angular frequency ω, g is the acceleration of gravity, and v is the wind speed. In cgs units the constant C, determined from empirical data, is equal to 4.8×10^4 cm² sec⁻⁵.

Surface-wave elevation spectra for winds of force 3, 5, and 8 (about 5, 10, and 20 m/sec) were computed using Eq. (4). The spectra shown in Fig. 8 are in terms of the pressure-spectrum levels corresponding to the mean square of the variation in the surface elevation in reference to a 1-cps bandwidth. The maximum of spectrum energy occurs at frequencies below 0.5 cps, and the band of maximum energy moves to lower frequencies as wind speed increases.

Equation (4) applies to a fully developed sea. When the sea is not fully developed, the high-frequency part of the spectrum is unchanged, but the larger low-frequency waves have not yet been produced, and the spectrum is cut off at the lower end as roughly exemplified by the dashed curve in Fig. 8. The cutoff frequency depends on the duration and fetch of the wind.

For frequencies above 1 cps, the value of the exponential function in Eq. (4) is very nearly unity, and the spectrum densities decrease as f^{-6} (−18 dB per octave). However, the relation was derived from measurements of the larger waves of frequencies below 0.5 cps, and extrapolation to frequencies above 0.5 cps is not certain.

The higher frequency surface fluctuations are in the form of small gravity waves and capillaries. Phillips[24] discusses an equilibrium region for the small gravity waves for which the spectrum is given by the relation

$$\bar{h}^2(\omega) \sim 7.4\times10^{-3}g^2\omega^{-5}. \qquad (5)$$

[22] G. Neumann, Department of the Army, Corps of Engineers, Beach Erosion Board Tech. Mem. No. 43 (December 1953).
[23] Willard J. Pierson, Jr., Advances in Geophysics 2, 93 (1955).
[24] O. M. Phillips, J. Marine Research 16, 231 (1957–1958).

According to Eq. (5), the pressure level corresponding to $\bar{h}^2(2\pi)$ (frequency 1 cps) is 132.6 dB, essentially the same as the corresponding values derived from Eq. (4) (see Fig. 8). A relation is given for capillaries[25] in which the surface-displacement spectrum is proportional to $\omega^{-7/3}$. Details of the capillary-gravity wave system are not known, although Cox[26] has presented evidence from wave-slope observations which suggests that capillary waves become important only for wind speeds above 6 m/sec (11 to 12 knots).

Kinsman[27] has summarized a number of surface-wave spectrum measurements and his results indicate that the slope is between −13.5 and −16.5 dB per octave in the frequency band from 0.7 to 2.1 cps.

The first-order pressure fluctuations induced by the surface waves are attenuated with depth, the attenuation being frequency-dependent.[28–30] The characteristics of the "depth filter" are shown in Fig. 9. The depth filter is a low-pass filter with a sharp cutoff and generally limits significant first-order pressure effects from surface waves to frequencies below 0.2 to 0.3 cps, and to depths less than a few hundred feet.

In Fig. 10 low-frequency pressure spectra obtained from "ocean-wave" measurements are compared with spectra resulting from shallow-water "ambient-noise" measurements. The ocean-wave spectra were derived from data reported by Munk *et al.*[31] The ambient-noise spectra were selected from the sources for Fig. 6 (of this paper). The effect of the depth filter is indicated by the ocean-wave spectra. Considering the difference in measurement methods and the variety of environmental conditions involved, the two sets of data merge remarkably well.

Because of the steep negative slope of the surface-wave spectra, and because of the steep cutoff of the depth filter, it is doubtful that the ambient noise at frequencies above 1 cps includes any significant contribution from the first-order pressure fluctuations induced by surface waves. At frequencies below 0.3 cps, approximately, these pressure fluctuations will very likely comprise a large part of the "ambient noise" observed *at very shallow depths* (<300 ft or 100 m) with pressure transducers.

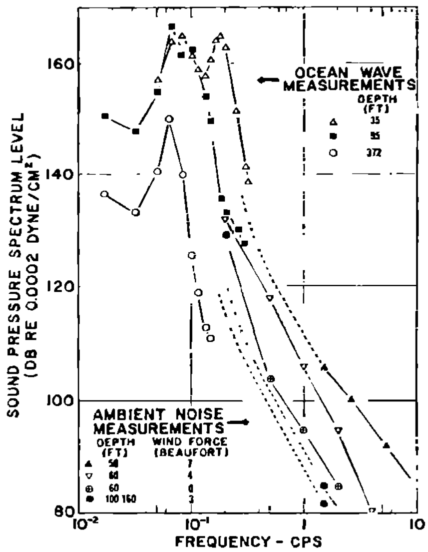


FIG. 10. Pressure-level spectra comparing results of ocean-wave measurements (derived from reference 31) and ambient-noise measurements. The dashed curves are extrapolations.

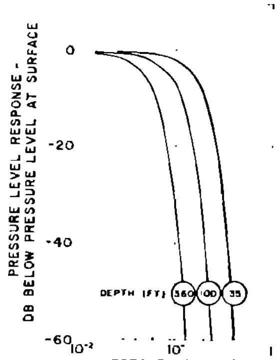


FIG. 9. Depth-filter characteristics, showing the attenuation of first-order pressure fluctuations as a function of frequency at three selected depths.

Longuet-Higgins[32] has called attention to a second-order pressure variation which is not attenuated with depth. These second-order pressure variations occur when the wave trains of the same wavelength travel in opposite directions. The resulting pressure variation is of twice the frequency of the two waves with an amplitude proportional to the product of the amplitudes of the two waves. When the depth is of the same order as, or greater than, the length of the compression wave, compression waves are generated.

The conditions for the Longuet-Higgins effect are met in the open ocean where the winds associated with a cyclonic depression produce waves travelling in opposite directions. Opposing waves occur when waves are reflected from the shore. The vagaries of local winds may also produce the required patterns in the high-frequency capillary-gravity wave system, which, though short-lived, may be numerous and frequent.

One may postulate that surface waves are a source of low-frequency ambient noise by way of these second-order pressure variations. A comparison of the observed ambient-noise levels in Fig. 10 with the estimated surface-wave spectrum levels in Fig. 8 indicates that the pressure variations are of sufficient magnitude. The observed ambient-noise low-frequency spectrum slope

[25] O. M. Phillips, J. Marine Research 16, 229 (1957–1958).
[26] Charles S. Cox, J. Marine Research 16, 244 (1957–1958).
[27] Blair Kinsman, J. Geophys. Research 66, 2411 (1961).
[28] S. Rauch, University of Calif. Department of Engineering, Fluid Mechanics Lab. Tech. Rept. HE-116-191 (November 29, 1945).
[29] R. L. Wiegel, University of Calif. Department of Engineering, Fluid Mechanics Lab. Mem. HE 116-108 (September 8, 1948).
[30] W. H. Munk, F. E. Snodgrass, and M. J. Tucker, Bull. Scripps Inst. of Oceanog. Univ. Calif. 7, 283 (1959), Fig. 5.
[31] Reference 30, charts 2.1, 4.1, and 5.1.

[32] M. S. Longuet-Higgins, Phil. Trans. Roy. Soc. (London) A243, 1 (1950).

of -8 to -10 dB per octave could be accounted for by the assumption of a suitable combination of the capillary and gravity waves in the wave system for the frequency range 0.3 to 10 cps.

It is concluded that the *second-order pressure variations* resulting from surface waves may sometimes be a significant part of the ambient noise at frequencies below 10 cps (see Sec. 1.2 and Figs. 4–6).

2.2.4 *Turbulence*

The state of turbulence is mainly one of unsteady flow with respect to *both* time and space coordinates. When the fluid motion is "turbulent," irregularities exist relative to a point moving with the fluid, as well as relative to a fixed point outside the flow.

Turbulence may occur in a fluid as a result of current flow along a solid boundary and also when layers of the fluid with different velocities flow past or over one another. Turbulence may be expected in the ocean at the water ocean-floor boundary, particularly in coastal areas, straits, and harbors; at the sea surface because of the movement and agitation of the surface; and within the medium as a result of the horizontal and vertical water movements, such as advection, convection, and density currents.

Noise resulting from turbulence created by relative motion between the water and the transducer is considered to be self-noise of the system rather than ambient noise in the medium.

Much of the energy input into the ocean occurs at frequencies too low to be of direct consequence to the ambient noise at frequencies above 1 cps. In the processes of turbulence,[33] the largest-scale eddies and the lowest wavenumbers correspond to the region of energy input. The largest eddies break up into smaller and smaller eddies, some of the energy being transferred to higher and higher frequencies. This is precisely the kind of mechanism which could transfer low-frequency energy in the ocean to higher frequencies.

However, the generation and radiation of noise from turbulence are a very inefficient process. Radiated noise levels derived from the relations formulated by Lighthill,[34] using values of turbulent-velocity fluctuations and dissipation rates estimated by Pochapsky,[35] for the ocean are many orders of magnitude below the observed ambient-noise levels. The levels corresponding to experimental values found for regions of strong currents in an inland passage by Grant *et al.*[36] are also low by many orders of magnitude. Even when there is comparatively violent turbulence, such as the case of a turbulent jet,[37] the level of the radiated pressure fluctuations is low compared to ambient-noise levels. It is concluded that the *radiated noise* from turbulence does not contribute to the observed ambient noise, except possibly under specific local conditions.

The pressure fluctuations of the turbulence itself are of much greater magnitude than those of the radiated noise.[38] A pressure-sensitive hydrophone[39] in the turbulent region responds to these pressure fluctuations as it does to any pressure fluctuations, whether they are those of propagated sound energy or not.

According to experimental results and the generally accepted theory of turbulence,[33] the following relations may be used for rough estimates of the turbulent velocity and pressure fluctuations:

$$\tilde{u} \approx 0.05\,\bar{U}, \tag{6}$$

$$\tilde{u}^2(k) \propto k^4 \quad (k \ll 0.01\ \text{cm}^{-1}), \tag{7a}$$

$$\tilde{u}^2(k) \propto k \quad (k < 0.01), \tag{7b}$$

$$\tilde{u}^2(k) \approx \text{maximum} \quad (0.01 < k < 0.1), \tag{7c}$$

$$\tilde{u}^2(k) \propto k^{-5/3} \quad (k > 0.1), \tag{7d}$$

$$\tilde{u}^2(k) \propto k^7 \quad (k \gg 0.1), \tag{7e}$$

$$f = k\bar{U}(2\pi)^{-1}, \tag{8}$$

$$\tilde{p} \approx \rho\tilde{u}^2. \tag{9}$$

The first of these relations states that, if and when turbulence exists, the rms turbulent velocity $\tilde{u}$ is on the average about five percent of the mean-flow velocity $\bar{U}$. The general features of the turbulent-velocity spectra are indicated by the set (7a)–(7e), showing the approximate dependence of the turbulent-velocity spectrum density function $\tilde{u}^2(k)$ on the wavenumber k in different parts of the wavenumber range. Equation (8) for the frequency f is a reminder that it is the ***mean-flow velocity*** that relates wavenumber and frequency in this case. An estimate of the rms turbulent-pressure fluctuation may be derived from the mean-square turbulent velocity according to expression (9) in which ρ is the density of the fluid.

Pochapsky[35] has estimated that the magnitude of $\tilde{u}$ is no more than 2 cm/sec for the horizontal velocity components of the "ambient" oceanic turbulence. By Eq. (6), the corresponding current speed is 40 cm/sec (0.8 knot). These estimates are indicative of an upper limit to the background turbulence. Flow rates of as much as 200 cm/sec (3.9 knot) are observed in the swifter ocean currents, and of 600 cm/sec (11.7 knot) or more in straits and passages where very strong tidal

[33] Several of the classical papers may be found in the book, *Turbulence*, edited by S. K. Friedlander and L. Topper (Interscience Publishers, Inc., New York, 1961). More recent experimental and theoretical results are included in the book, J. O. Hinze, in *Turbulence* (McGraw-Hill Book Company, Inc., New York, 1959).

[34] M. J. Lighthill, Proc. Roy. Soc. (London) A222, 1 (1954).

[35] T. E. Pochapsky, Columbia University Hudson Laboratories Tech. Rept. 67 (March 1, 1959).

[36] H. L. Grant, R. W. Stewart, and A. Moilliet, Pacific Naval Laboratory, Esquimalt, B. C., Canada Rept. 60–8 (1960).

[37] Reference 11, p. 268.

[38] The possible significance of the pressure fluctuations near and within the turbulent regions was suggested to the author by Paul O. Laitinen.

[39] The so-called "velocity" transducer is not excepted since such devices are sensitive to pressure gradients and will respond to the pressure gradients of the turbulence.

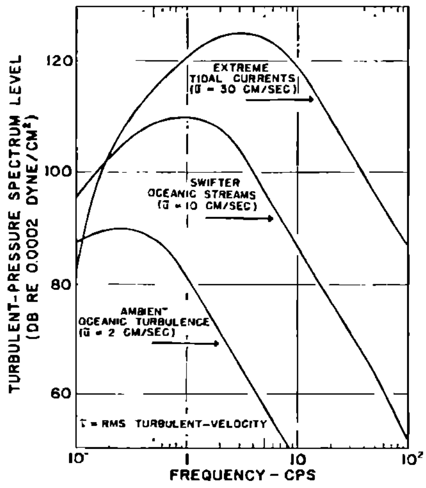


FIG. 11. Turbulent-pressure-level spectra, derived from theoretical and experimental relations [see Eqs. (6) through (9)].

currents are experienced. Corresponding rms turbulent velocities are 10 cm/sec and 30 cm/sec.

Equations (6) through (9) were used to derive turbulent-pressure spectra for each of the three flow conditions mentioned in the preceding paragraph. These spectra are shown in Fig. 11 in terms of turbulent-pressure spectrum levels. The estimates are rough and variations of at least one order of magnitude are probable. A comparison with the spectra in Figs. 4–6 reveals that the estimated oceanic turbulent-pressure spectra agree quite well in both slope and level with the ambient-noise spectra below 10 cps, and between 10 and 100 cps in some instances.

For a hydrophone to respond to the turbulent-pressure fluctuations it must be in the region of turbulence. There is evidence that the movement of the water masses in the ocean is mostly chaotic and turbulent.[40] The dimensions of flow are nearly always large so that turbulent conditions may prevail, even though the flow velocity is often small. Turbulence is spread out and maintained in the ocean volume by a continual source of turbulent energy at the boundaries, particularly the sea-surface boundary. There is reason to believe that there exists in the ocean an essentially universal "ambient" turbulence which varies widely in intensity with both time and place.

According to the "elementar" current theory,[41] which assumes a homogenous ocean, the variation of velocity with depth depends on the mutual effect of wind-induced "drift currents" and "gradient currents" which result from the pressure differences produced by sea-surface slopes. The magnitude of the pure gradient current is constant with depth, except near the bottom boundary where frictional forces decrease the magnitude logarithmically to zero. The speed of the drift current decreases with depth and becomes negligible at a depth, dependent on the surface velocity, of the order of 45 to 200 m (25 to 110 fathoms). The speed of the elementar current, therefore, does not change greatly with depth except near the surface and the bottom, and in shallow water, where the bottom is near the surface. The characteristics of the elementar current are modified by the effects of density currents resulting from internal forces.[42] Vertical circulatory patterns may occur which produce velocity maxima and minima between the surface and the bottom.[43]

The theoretical and conjectural aspects of the preceding discussion have experimental support. For example, measurements[44] made in water 45 m (25 fathoms) in depth showed a logarithmic decrease of velocity with depth from about 40 cm/sec to 10 cm/sec between 160 cm and 20 cm above the bottom, and conditions of turbulence were found to exist. Recent deep-water measurements[45–47] made with the Swallow neutrally buoyant float indicate that deep currents are faster and more variable than was anticipated, with no evidence for a decrease in speed with depth. Average speeds of 6 cm/sec were observed at 2000-m depth (approximately 1100 fathoms), while at 4000-m depth (2200 fathoms) the average was 12 cm/sec, with as much as 42 cm/sec being observed in two cases.[47] The existence of eddies with a typical diameter of as much as 185 km (100 nautical miles) was implied by the observed fluctuations of the deep currents.

From Eqs. (6) and (9), one would ordinarily expect the turbulent-pressure levels to increase and decrease as the flow velocities increase and decrease. In the limited amount of low-frequency ambient-noise data available, there is no evidence of consistent depth dependence. This could be explained in part by the probable variety of patterns in the vertical velocity structure of the currents. Since the speed of the drift current decreases with depth, a decrease in turbulent-pressure level with depth should be observed in shallow water and at shallow depths in deep water, except when strong density or local currents are present.

The characteristics of the "drift" current, which is wind-dependent, could quite reasonably explain the wind dependence of the ambient noise in very shallow water, which is illustrated in Fig. 6, and also, possibly, the wind dependence at frequencies below 100 cps in Fig. 1(e).

Whenever local boundaries are involved, particularly if there are sharp edges and rough surfaces, the local scales of motion are generally small, but the velocities of

[40] Albert Defant, *Physical Oceanography* (Pergamon Press, New York, 1961), in particular Vol. I, part II.
[41] Reference 40, Vol. I, p. 413.
[42] Reference 40, Vol. I, Chap. XV.
[43] Reference 40, Vol. I, Chaps. XVI and XXI.
[44] R. M. Lesser, Trans. Am. Geophys. Union 32, 207 (1951).
[45] J. C. Swallow, Deep Sea Research 4, 93 (1957).
[46] J. C. Swallow and L. V. Worthington, Nature (London) 179, 1183 (1957).
[47] M. Swallow, Oceanus (Woods Hole Oceanographic Institution) VII (3), 2 (1961).

the local turbulence may be large, and the local effects may be intense.

A great deal of the low-frequency ambient-noise data has been acquired using systems employing fixed bottom-mounted hydrophones. With such systems it is sometimes difficult to separate the self-noise produced by turbulence resulting from water motion past the stationary transducer from noise which is characteristic of the medium. Similar considerations apply to ship-borne systems when differential drift between the ship and the hydrophone causes the hydrophone to be towed by the ship, or when any forces, such as buoyancy and gravity, produce relative motion between the hydrophone and the water.

On the basis of spectrum shape and level, there is good support for the hypothesis that one component of low-frequency ambient noise is turbulent-pressure fluctuations. There is good reason to believe that turbulence of varying degree is a general circumstance throughout the ocean. By the mechanisms of turbulence, a portion of the energy which is introduced into the ocean at very low frequencies (large eddies, low wavenumbers) is transferred to range of higher frequencies, which, according to the curves of Fig. 11, extends above 1 cps. Some aspects of depth and wind dependence (and the lack of it) are explained by the hypothesis, but the data are inconclusive.

The conclusion is that, while noise *radiated* by turbulence does not greatly influence the ambient noise, the turbulent-pressure fluctuations are probably an important component of the noise below 10 cps, and sometimes in the range from 10 to 100 cps.

2.3 Oceanic Traffic

The ambient noise may include significant contributions from two types of noise[48] from ships. *Ship noise* is discussed briefly in Sec. 2.6. *Traffic noise* is the subject of this section.

The degree to which traffic noise influences the ambient noise depends on the particular combination of *transmission loss*, *number of ships*, and the *distribution of ships* pertaining to a given situation. For instance, a significant contribution could result from widely scattered ships if the average transmission loss per unit distance were relatively small such as might be the case at a deep-water location in an open-ocean area crossed by transoceanic shipping lanes. A significant contribution could also result even when transmission losses per unit distance are high if there were a comparatively large concentration of ships at relatively close range, such as might be the case in shallow water near a harbor and coastal shipping lanes. The traffic-noise characteristics are determined by the mutual effect of the three factors.

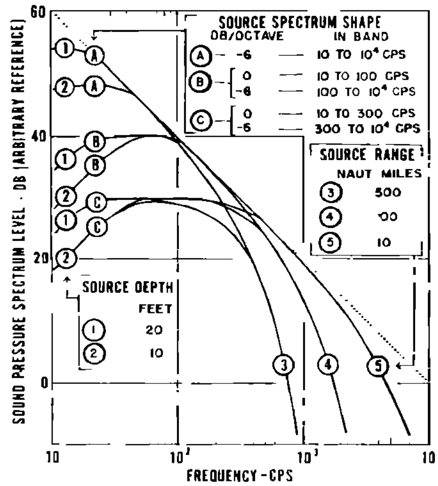


FIG. 12. Traffic-noise spectra deduced from ship-noise source characteristics and attenuation effects. Several variations are shown. For example, the curve 1B4 defines the expected spectrum shape at 100 nautical miles (185 km) from a source whose noise spectrum is flat up to 100 cps and decreases −6 dB per octave above 100 cps, the effective source depth being 20 ft (6m).

Traffic-noise characteristics also depend on the kinds of ships involved, that is, upon the nature of the source. In general the base is broad so that individual differences blend into an average source characteristic.

A study of the noise from surface ships[49] indicates that on the average, when measured at distances of about 20 yards, the sound-pressure-level spectra have a slope of about −6 dB per octave. The spectrum is highly variable at frequencies below 1000 cps, and, under some circumstances, the slope tends to flatten in the neighborhood of 100 cps. This source-spectrum shape is altered in transmission by the frequency-dependent attenuation part of the transmission loss. According to Sheehy and Halley,[50] the attenuation is 0.033 $f^{\frac{3}{2}}$ dB per kiloyard or 0.066 $f^{\frac{3}{2}}$ dB per nautical mile, where f is the frequency in kc. At long ranges, the attenuation increases rapidly with frequency above 500 cps.

For most surface ships, the effective source of the radiated noise is between ten and thirty feet below the surface. Up to frequencies of about 50 cps, the source and its image from surface reflection operate as an acoustic doublet radiating noise with a spectrum slope of +6 dB per octave relative to the spectrum of the simple source.

To obtain some notion of the probable shape of traffic-noise spectra, the foregoing information was used in deriving the curves shown in Fig. 12. Variations in

[48] *Ship noise* is the noise from one or more ships at close range. It may be identified by short-term variations in the ambient-noise characteristics, such as the temporary appearance of narrow-band components and a comparatively rapid rise and fall in noise level. Ship noise is usually obvious and therefore generally can be and is deleted from ambient-noise data.

Traffic noise is noise resulting from the combined effect of all ship traffic, excepting the immediate effects of ship noise as defined in the preceding paragraph. Traffic noise is usually not obvious as such.

[49] M. T. Dow, J. W. Emling, and V. O. Knudsen, "Survey of Underwater Sound, Report No. 4, Sounds from Surface Ships," 6.1–NDRC–2124 (1945).

[50] M. J. Sheehy and R. Halley, J. Acoust. Soc. Am. 29, 464 (1957).

the spectra caused by differences in source depth, differences in the shape of the source-noise spectrum, and differences in the attenuation at different ranges are indicated by the composite set of curves. The effect of the source depth at low frequencies is shown by the curves numbered (1) for a depth of 20 ft, and (2) for 10 ft. The choices of source-noise spectrum shape, based on the data reported by Dow,[49] are described in terms of the slopes of the sound-pressure-level spectra, and the resulting curves are identified as follows: (A) −6 dB per octave; (B) 0 dB per octave up to 100 cps and −6 dB per octave above 100 cps; and (C) 0 dB per octave up to 300 cps and −6 dB per octave above 300 cps. The change in spectrum shape as the range varies, a consequence of attenuation, is shown by curve (3) representing a range of 500 miles (926 km), curve (4) a range of 100 miles (185 km), and curve (5) a range of 10 miles (185 km). The spectrum corresponding to a particular set of conditions may be found by following the curves identified by the relevant numbers and letter. For example, the curve 1B4 is the spectrum form which would be observed at 100 miles from a source located at a depth of 20 ft, and whose noise spectrum is flat up to 100 cps and decreases at 6 dB per octave above 100 cps.

There is a remarkable similarity between the synthetic traffic-noise spectra of Fig. 12 and the spectra of the non-wind-dependent component of the observed ambient noise, which are discussed in Sec. 1.1. In each case, the maximum is in the vicinity of 100 cps, and the spectrum falls off steeply above 100 cps.

The high-frequency "cutoff" occurs at lower frequencies in the deep-water spectra of Figs. 2(b), 2(d), and 2(e) than in the shallow-water spectra of Figs. 1(b) and 1(d). This effect can be explained, or even anticipated, by assuming that the average range of the effective traffic-noise sources is generally less for shallow- than for deep-water locations.

Measurements of the noise radiated by surface ships have been reported by Dow *et al.*[49] Corresponding to these data, for surface ships the equivalent simple source-pressure levels in a 1-cps band at 100 cps at a distance of 1 yard are between 125 dB and 145 dB (*re* 0.0002 dyn cm^2) in most cases. Hale[51] has shown that experimental results from long-range transmission in deep water do not fit the free-field, spherical divergence law very well, and that better agreement with experiment does result if boundaries and sound-velocity structure are taken into account. According to this theory and experiment, 105 dB is a reasonable estimate of the average transmission loss at 100 cps for a range of 500 miles. Accordingly, the spectrum level (*re* 0.0002 dyn cm^2) at 100 cps from one "average" ship source at 500 miles is 20 to 40 dB; from 10 "average" ships all at 500 miles, 30 to 50 dB (assuming power addition); and from 100 ships, 40 to 60 dB. At a range of 1000 miles the levels would be only 3 to 6 dB lower. The spectrum levels at 100 cps of the aforementioned non-wind-dependent component of the ambient noise are between 40 and 55 dB, according to Figs. 1(b), 1(d), 2(b), 2(d), and 2(e).

[51] F. E. Hale, J. Acoust. Soc. Am. 33, 456 (1961).

It is apparent from this evaluation that the effective distance for traffic-noise sources in the deep-open ocean can be as much as 1000 miles or more.

The spectra in Figs. 1 and 2 were arranged originally on the basis of spectrum shape. A similar arrangement would result from traffic-noise considerations. At the locations for Figs. 1(a) and 1(e), some ship noise is encountered (deleted from the data when detected), but usual transmission ranges are too short for the composite effect of traffic noise. Figure 1(c) pertains to an isolated area where ship noise is infrequent. The data in Figs. 1(b) and 1(d) were obtained in the midst of both coastal and transoceanic shipping lanes, and illustrate the case of a comparatively large concentration of sources at relatively close range. While Figs. 2(a) and 2(c) represent measurements in deep water, i.e., greater than 100 fathoms in depth, the locations were not in the open ocean in the sense of being open to long-range transmission. The spectra shown in Figs. 2(b), 2(d), and 2(e) were derived from measurements made in the deep ocean open to long-range transmission and crossed by transoceanic shipping lanes.

The evidence is strong that the non-wind-dependent component of the ambient noise at frequencies between 10 cps and 1000 cps is traffic noise. It is concluded that, while there are many places which are isolated from this noise, in a large proportion of the ocean, traffic noise is a significant element of the observed ambient noise and often dominates the spectra between 20 and 500 cps.

2.4 Seismic Sources

As a result of volcanic and tectonic action, waves are set up in the earth. Even when the point of origin is distant from the ocean boundary, appreciable amounts of the energy may find their way into the ocean and be propagated as compressional waves in the water (T phase).[52–55] (Similar effects often result from artificial causes such as manmade explosions.)

When observed at close range, waterborne noise of seismic (volcanic) origin has been reported[56] as including observable energy at frequencies up to at least 500 cps. The spectrum characteristics depend on the magnitude of the seismic activity, the range, and details of the propagation path, including any land or sea-floor segments. Experimental data[57,58] indicate that in

[52] I. Tolstoy, M. Ewing, and F. Press, Columbia University Geophysical Lab. Tech. Rept. 1 (1949), or Bull. Seismol. Soc. Am. 40, 25 (1950).

[53] R. S. Dietz and M. J. Sheehy, Bull. Geol. Soc. Am. 65, 1941 (1954).

[54] D. H. Shurbet, Bull. Seismol. Soc. Am. 45, 23 (1955).

[55] D. H. Shurbet and Maurice Ewing, Bull. Seismol. Soc. Am. 47, 251 (1957).

[56] J. M. Snodgrass and A. F. Richards, Trans. Am. Geophys. Union 37, 97 (1956).

[57] Allen R. Milne, Bull. Seismol. Soc. Am. 49, 317 (1959).

[58] J. Northrop, M. Blaik, and I. Tolstoy, J. Geophys. Research 65, 4223 (1960).

general the spectrum has a maximum between 2 and 20 cps and that noticeable waterborne noise from earthquakes may be expected at frequencies from 1 to 100 cps. The noise is manifest as a single transient, or a series of transients, of relatively short duration and infrequent occurrence. However, in some areas and during some periods of time the frequency of occurrence may be as often as several times an hour.

A seismic background of continuous disturbance of varying strength is also observed, being attributed to the aftereffects of the more transient events, and to the effects of storms, and of waves and swell at the coastal boundary, with local contributions from winds, waterfalls, traffic, and machinery. The spectrum of the vertical ground-particle displacements of the background noise as observed on land (and excluding noise from obvious local and transient sources) has a maximum between 0.1 and 0.2 cps, with amplitudes from 2×10^{-2} to 20 μ.[59,60] The amplitudes decrease approximately in inverse proportion to frequency between 1 and 100 cps. At 1 cps, the amplitudes range from 10^{-3} to $10^{-1}\,\mu$, and at 100 cps from 10^{-6} to $10^{-3}\,\mu$. Vertical and horizontal velocity spectra show maxima at the same frequencies as the displacement spectra.[61] In the neighborhood of 0.5 cps, the upper frequency limit of the data, the velocity spectra begin to flatten, suggesting a flat velocity spectrum above 1 cps, as might be expected from the inverse frequency dependence of the displacement spectra.

A crude estimate of noise in the ocean associated with the continuous seismic disturbances may be obtained by assuming, in the absence of specific data, that the seismic spectrum characteristics on the sea floor are about the same as those on land and that the vertical components of the particle displacements and velocities of the water at the boundary are the same as those of the sea floor. For such conditions, the pressure-level spectrum is essentially flat between 1 and 100 cps, varying in level between 45 and 95 dB *re* 0.0002 dyn/cm^2. The peak levels between 0.1 and 0.2 cps are from 65 to 120 dB. The spectrum shape does not agree with the observed ambient-noise spectra (see Sec. 1), but the levels are of sufficient magnitude to suggest the possibility that some of the variability in ambient-noise spectra may be a consequence of the seismic background activity.

Measurements at frequencies between 4 and 400 cps directly comparing background seismic velocity components and waterborne sound pressures as measured at the sea bottom in shallow water[62,63] show order-of-magnitude agreement when continuity across the interface is assumed. The velocities which were measured fall within the range of the results of seismic measurements made on land,[59–61] which were mentioned in the preceding discussion. However, the sea-floor velocity spectra showed a slope of -5 or -6 dB per octave.

The experimental data indicate a close relation between the seismic background and the nearby pressure fluctuations in the water. A pertinent question is: Which is the cause and which the effect? Possibly some equilibrium process exists, the direction of net energy transfer depending on the relative energy levels existing in the two media in a particular situation.

From this brief survey, it is concluded that noise from earthquakes does dominate the ambient noise at frequencies between 1 and 100 cps, but such effects are transient and highly dependent on time and location. Significant noise from lesser, but more or less continuous, seismic disturbances is possible particularly when current velocities and turbulence are at a minimum, but additional data are needed for a more definite evaluation.

The seismic disturbances may have a direct effect on bottom-mounted transducers. For this reason, the vibration sensitivities of the transducer should be known and taken into consideration in the design of such a system, and in the interpretation of results.

2.5 Biological Sources

Many species of marine life have been identified as noise producers. Noise of biological origin has been observed at all frequencies within the limits of the systems used, which, in aggregate, have covered from 10 cps to above 100 kc.[1–6,64,65] The individual sounds are usually of short duration, but often frequently repeated, and include a wide variety of distinctive types such as cries, barks, grunts, "awesome moans," mewings, chirps, whistles, taps, cracklings, clicks, etc. Pulse-type sounds which change in repetition rate, sometimes very quickly, have been identified with echo location by porpoise.[66–68] Repetitive pulse sounds have also been attributed to whales. Continuous (in time) biological noise is frequently encountered in some areas when the sounds of many individuals blend into a potpourri, such as the crackling of shrimp and the croaker chorus.[1–6]

The contribution of biological noise to the ambient noise in the ocean varies with frequency, with time, and with location, so that it is difficult to generalize. In some cases diurnal, seasonal, and geographical patterns may be predicted[1,2,5] from experimental data, or from the habits and habitats, if known, of known noisemakers.

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60 G. E. Frantti, D. E. Willis, and J. T. Wilson, Bull. Seismol. Soc. Am. 52, 113 (1962).

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62 E. G. McLeroy (unpublished data).

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64 W. N. Kellog, R. Kohler, and H. N. Morris, Science 117, 239 (1953).

65 M. P. Fish, University of Rhode Island, Narragansett Marine Lab., Kingston, Rhode Island Reference 58-8 (1958).

66 W. N. Kellog, Science 128, 982 (1958).

67 W. N. Kellog, J. Acoust. Soc. Am. 31, 1 (1959).

68 K. S. Norris, J. H. Prescott, P. V. Asa-dorian, and Paul Perkins, Biol. Bull. 120, 163 (1961).

Noises having the distinctive nature of biological sounds are readily detected in the ambient noise, but the biological source is not always certain.

The data presented in Sec. 1 exclude noise of known or suspected biological origin.

2.6 Additional Sources

Various other sources of intermittent and local effects include ships, industrial activity, explosions, precipitation, and sea ice.

Ship noise is the noise from one or more ships at close range, and, as used here, is differentiated from traffic noise.[45] Ship noise causes short-term variations in the ambient noise characterized by the temporary appearance of narrow-band components at frequencies below 1000 cps, and broad-band cavitation noise extending well into the kilocycle region, often with low-frequency modulation patterns.

Industrial activity on shore, such as pile driving, hammering, riveting, and mechanical activity of many kinds, can generate waterborne noise. The characteristics of the noise depend on the particular situation. Noise from industrial activity may predominate at times in particular near-shore areas.

Noise from *explosions* is very much like that from earthquakes (see Sec. 2.4). At close range, the effects cover a wide range of frequencies, but at longer range the spectrum has been modified by propagation, and the larger part of the energy is usually at frequencies below 100 cps.

Precipitation noise is basically noise from a spray of water droplets (rain) and rigid bodies (hail) (see Sec. 2.2.2). The effects of precipitation are most noticeable at frequencies above 500 cps, but may extend to as low as 100 cps if heavy precipitation occurs when wind speeds are low.

The various kinds of *sea-ice* movements are a source of noise which at times covers a wide range of frequencies at high level. The noise originates in the straining and cracking of the ice from thermal effects, and in the grinding, sliding, crunching, and bumping of floes and bergs.

It is difficult to generalize on the characteristics of the various kinds of intermittent and local noise, since such noise is dependent to a great degree on the particular time and place of concern.

3. COLLIGATION

The experimental and theoretical data which have been presented in the foregoing lead to the conclusion that the general spectrum characteristics of the prevailing ambient noise in the ocean are determined by the combined effect of several components, which, though of widespread and continual occurrence, vary each in its own way with time and location. A composite picture is given in Fig. 13, which summarizes the characteristics and probable causes in the various parts of the spectrum between 1 cps and 100 kc.

On the basis of spectrum characteristics, the principal components of the prevailing ambient noise in the ocean are:

(a) a low-frequency component characterized by a spectrum-level slope of approximately −10 dB per octave and wind dependence in very shallow water, the most probable source being ambient turbulence (turbulent-pressure fluctuations);

(b) a high-frequency component characterized by wind dependence, a broad maximum between 100 and 1000 cps and a slope of approximately −6 dB per octave at frequencies above the maximum, with levels, on the average, some 5 dB less in deep water than in shallow (most probable source—bubbles and spray from surface agitation);

(c) a medium-frequency component characterized by a broad maximum between 10 and 200 cps, and a steep negative slope at frequencies above the maximum band (most probable source oceanic traffic); and

(d) a thermal noise component characterized by a +6 dB per octave slope.

Component (a) nearly always predominates at frequencies below 10 cps, and its influence may be evident up to frequencies as high as 100 cps in the absence of component (c). Component (b) nearly always predominates at frequencies above 500 cps. Component (c) frequently predominates in the band from 20 to 200 cps, but is not observed in isolated[69] areas. Component (d) is a factor at frequencies above 20 kc.

The general similarity between the observed levels and the spectrum shape of the ambient noise and of the spectra estimated for the turbulent-pressure fluctuations leads to the conclusion that the low-frequency ambient noise, component (a), consists primarily of the turbulent-pressure fluctuations (which are much greater in magnitude than the radiated sound pressures generated by turbulence). It may be said further that turbulence is a process by which some of the energy introduced into, or originating in, the ocean at very low frequencies is transformed into energy of consequence to the ambient noise at frequencies above 1 cps. The not unreasonable assumption of a widespread ambient turbulence in the ocean is required. (See Sec. 2.2.4.)

A small amount of low-frequency data taken in very shallow water indicates a dependence of level, but not of spectrum slope, on wind speed (see Fig. 6). This wind dependence is explained by the influence of wind-caused drift currents on the turbulence. The data are not of sufficient quantity to establish even a tentative quantitative relationship between level and windspeed; so none is shown in Fig. 13.

Components of the seismic background noise in the

[69] "Isolated" either because of geographic location or because of propagation conditions, or both.

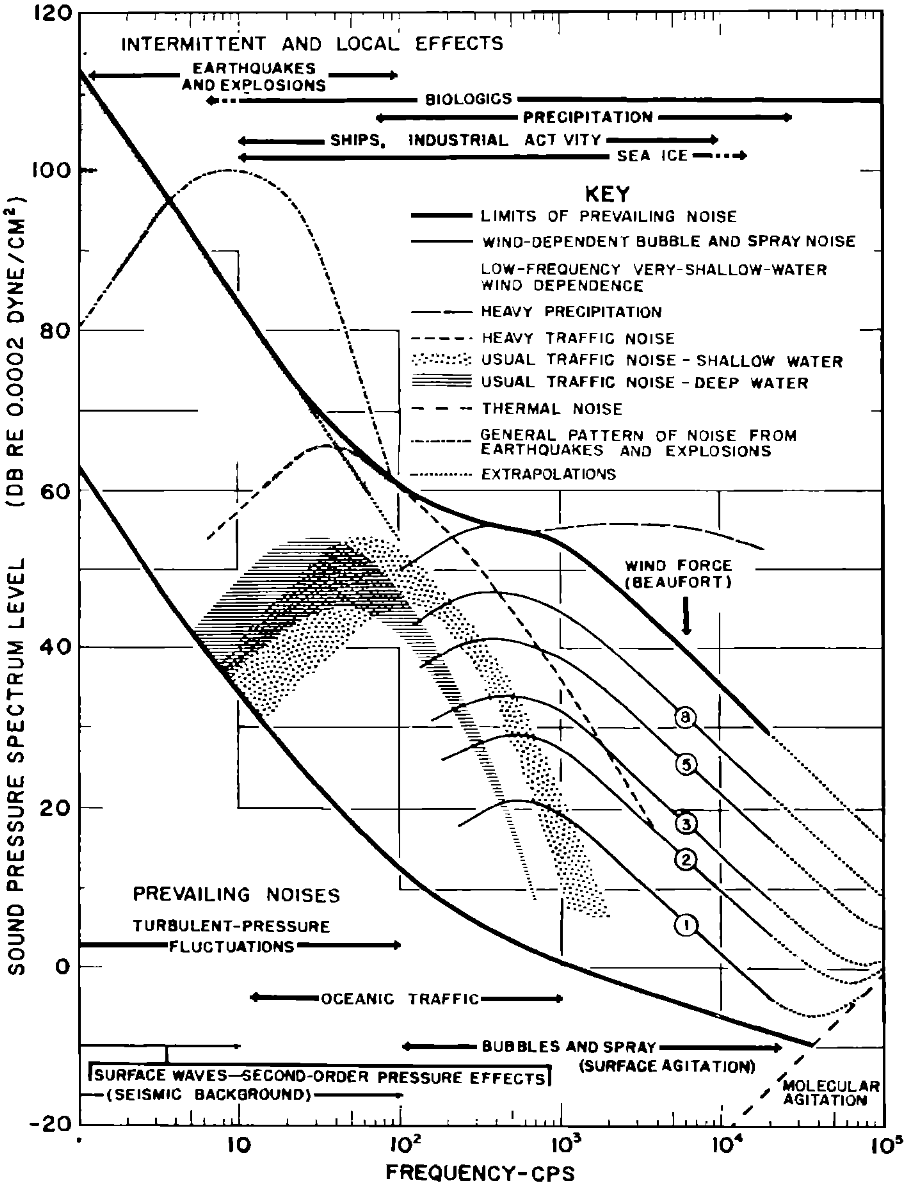

FIG. 13. A composite of ambient-noise spectra, summarizing results and conclusions concerning spectrum shape and level and probable sources and mechanisms of the ambient noise in various parts of the spectrum between 1 cps and 100 kc. The key identifies component spectra. Horizontal arrows show the approximate frequency band of influence of the various sources. An estimate of the ambient noise to be expected in a particular situation can be made by selecting and combining the pertinent component spectra.

earth, including the sea floor, are often attributed to the effects of pressure fluctuations in the ocean rather than vice versa. There is probably some sort of a give-and-take process by which in some areas the seismic waves are produced by waterborne pressure fluctuations, such as the Longuet–Higgins second-order pressure effects from surface-wave trains, while in other areas the seismic activity causes waterborne pressure fluctuations. Such a process would allow hydrodynamic pressure effects to be transmitted from one place to another via seismic processes. The estimated noise from seismic background activity differs in spectrum shape from that of the low-frequency component (a), but seismic noise could account for some of the variability observed at low frequencies and could become significant where current velocities and turbulence are at a minimum. (See Sec. 2.4.)

Because of the steep negative slope of surface-wave spectra, and because of the rapid attenuation with depth, it is doubtful that the first-order pressure effects from surface waves are of much significance to the ambient noise at frequencies above 1 cps. However, it is probable that the Longuet–Higgins second-order effects contribute to the noise at frequencies up to 10 cps, particularly in or near storm areas and certain coastal areas. (See Sec. 2.2.3.)

The wind dependence and the "on-the-average" −5 to −6 dB per octave slope of the high-frequency component (b) are well established. The high-frequency wind-dependent curves shown in Fig. 13 represent over-all averages, including both deep- and shallow-water data. (The comparable shallow-water averages are 2 to 3 dB higher than the over-all averages, the deep-water averages 2 to 3 dB lower.) The hypothesis that gas bubbles, cavitation, and spray in the surface agitation are the sources of the high-frequency wind-dependent component (b) is well supported by the observed spectrum levels, spectrum shape, and band of maximum levels. (See Secs. 2.2.1 and 2.2.2.)

The assumption that the medium-frequency component (c) is the result of the combined effect of many ships at relatively long range is shown to be a reasonable one by the general agreement between the observed spectra and the spectra estimated for traffic noise (see Sec. 2.3). The high-frequency "cutoff" begins at lower frequencies in deep water, as compared to shallow according to the observed data (Sec. 1). This effect is to be expected from the curves in Fig. 12, if one assumes that, while in both cases the ranges are comparatively long, the average range of the effective noise sources is greater for deep water than for shallow.

The shape of the lower-limit curve in Figs. 7 and 13 is not greatly different from that which would result from a combination of a turbulent-pressure spectrum (Sec. 2.2.4), a low-level bubble-noise spectrum due to a remanent distribution of bubbles (which, as was shown in Sec. 2.2.1, may exist even at zero sea state), and the thermal noise spectrum. It is quite likely that the empirical lower-limit curve is, to some degree, an indication of the state of the art of measuring very low-pressure levels in the ocean. With a sensitive system, one might expect to encounter even lower levels, particularly at low frequencies in a region of minimum current and turbulence, where the probable source of residual noise is seismic background activity.

The relatively high residual or threshold noise observed in some shallow-water locations [Figs. 1(a) and 1(b)] apparently arises from local conditions. The shape of the residual spectra suggests that the noise is a combination of the average effects from such sources as local turbulence and cavitation (particularly if rough boundaries and high currents are involved), industrial activity, marginal traffic noise, and the more subtle types of self-noise, such as that which may result from relative motion between the hydrophone and the water.

The prevailing features of the ambient noise are altered by intermittent and local effects. The noise from earthquakes and explosions perturbs the spectrum mostly at frequencies around 10 cps, the extent of the band of influence being determined, to a large degree, by the range. Disturbance from biological sources may show up at almost any frequency, often conforming to diurnal, seasonal, and geographic patterns, but with distinctive characteristics. The effects of precipitation are most apparent at frequencies above 500 cps, but may extend to lower frequencies when heavy precipitation occurs at low wind speeds. Major ship-noise effects occur at frequencies above 10 cps and often include narrow-band components below 1000 cps. Noise from industrial activity occurs in particular near-shore locations. Noise resulting from sea-ice movement is distinctive in character, covering a wide range in frequency, but is restricted to particular geographic areas.

4. APPLICATION NOTES

The provisional picture of ambient noise in the ocean which has been developed shows that the ambient noise depends on several variables, some of which, unfortunately, are as difficult to estimate or measure as the ambient noise itself. However, a few general guidelines can be given for estimating and predicting the ambient noise which prevails in the absence of intermittent and local effects.

[4.1] 500 cps to 20 kc

Estimates of the prevailing ambient-noise levels in the ocean at frequencies between 500 cps and 20 kc can be made from a knowledge of the wind speed. Estimates of wind speed can be obtained from the *Atlas of Climatic Charts of the Oceans* issued by the U. S. Weather Bureau (1938), if more specific information is lacking. Table I, or similar tables, may be used to estimate wind speed from wave-height or sea-state information. Knowing the wind speed, one may determine "on-the-average" levels by reference to the high-frequency wind-dependent curves in Fig. 13 (which, including the influence of more recent data, are 2 to 3 dB lower in level than the Knudsen[1,2] averages).

For example, a wind speed of 7 knots (3.6 m/sec) falls at the lower limit of the range for Beaufort wind force 3. According to the wind-force-3 curve in Fig. 13, the estimated spectrum level at 1 kc (to the nearest dB) is 32 dB (*re* 0.0002 dyn/cm²). The curves represent average levels and may be considered as corresponding to the mean of the Beaufort wind-speed grouping. Interpolations may be made for estimates of levels at other wind speeds. For the example of 7 knots, an interpolated level estimate at 1 kc is 30 dB. Similar interpolations may be made for wind speeds falling in the wind-force-4, -6, and -7 groups, for which curves are not shown in Fig. 13.

The curves in Fig. 13 are averages over both deep- and shallow-water data. For a closer deep-water estimate, the over-all average level should be lowered by 2 or 3 dB. Thus, for deep water and a wind speed of 7 knots, the estimated level at 1 kc is 27 or 28 dB. For shallow water, the over-all levels are raised by 2 or 3 dB. (The shallow-water estimates are about the same as those of the Knudsen curves, while the deep-water estimates are about 5 dB lower in level.)

As it happens, the wind-dependent spectra follow *approximately* an empirical "rule of fives," which is stated as follows:

> In the frequency band between 500 cps and 5 kc the ambient sea-noise spectrum levels decrease 5 dB per octave with increasing frequency, and increase 5 dB with each doubling of wind speed from 2.5 to 40 knots; the spectrum level at 1 kc in deep water is equal to 25 dB (5×5) *re* 0.0002 dyn/cm² when the wind speed is 5 knots, and is 5 dB higher in shallow water.

The "rule of fives" is fairly accurate up to a frequency of 20 kc.

To illustrate the use of the rule of fives: The estimated spectrum level at 4 kc in deep water when the wind speed is 20 knots (10.3 m/sec) is equal to 25 dB (1-kc level for 5 knots) plus 10 dB (wind speed doubled twice from 5 knots) minus 10 dB (2 octaves above 1 kc), which adds up to 25 dB. The corresponding shallow-water level is 30 dB, and the mean between the deep and shallow values is $27\frac{1}{2}$ dB. This value is about the same as the value indicated at 4 kc by the wind-force-5 curve in Fig. 13, showing that the rule-of-fives result agrees reasonably well with the average data.

It is believed that the procedures which have been given will lead to useful estimates of the ambient sea noise in the frequency band from 500 cps to 20 kc. But it should be remembered that considerable departure may sometimes be expected, since wind speed is not a precise measure of the actual surface agitation (see Sec. 1.1 and Fig. 3), nor are estimates of sea state. If information is known about duration, fetch, and topography, a judicious use of the kind of information given in Table I will improve the reliability of the estimate. Ideally, information is needed as to the details of the surface agitation, such as the relation between meteorological and oceanographic conditions and the distributions of the sizes of bubbles and droplets, and the degree of cavitation. At low wind speeds, the effects of other influences may be expected to increase the variability.

[4.2] 1 cps to 10 cps

An "on-the-average" spectrum-level slope of −8 to −10 dB per octave in the frequency range from 1 to 10 cps may be predicted with some assurance, since the observed data are quite consistent in this respect. This slope persists down to 0.05 cps, and perhaps to lower frequencies, except when the first-order effects of surface waves are encountered at shallow depths.

It is to be generally anticipated that the levels will fall between the lower-limit curve and the bottom of the shaded area (upper left) in Fig. 13. According to the conclusions reached in Sec. 2.2.4, the spread in the observed low-frequency ambient-noise levels is principally the result of the variation in the oceanic turbulent-pressure fluctuations, and the higher levels are to be expected in or near the major oceanic currents, or anywhere else where relatively high water motion is known to exist. One might also expect high levels to accompany high winds and storms because of a general increase in the turbulent energy, and because of the Longuet-Higgins second-order pressure effects.

When observations are made at very shallow depths, less than 25 fathoms (roughly 50 m), one should be prepared for high and wind-dependent levels, as indicated by the shaded (upper left) area in Fig. 13. The data are insufficient to establish a quantitative relation between level and wind speed which can be applied generally.

Although these qualitative approximations do not permit very definite predictions of the ambient noise at the low frequencies, they should be useful in defining specific areas for investigation.

[4.3] 10 to 500 cps

In the frequency band between 10 and 500 cps, the noise is influenced by at least three components. To predict the noise, one must know or assume the spectrum for a low-frequency component, a traffic-noise component, and a high-frequency wind-dependent component, and then combine the component spectra. The high-frequency wind-dependent component and the low-frequency component were discussed in Secs. 4.1 and 4.2, respectively.

The experimental data indicate that the traffic-noise levels usually fall within the medium-frequency shaded areas shown in Fig. 13. The difference between shallow-water levels (area shaded by large dots) and deep-water levels (area shaded by lines) is to be noted. The more extreme higher and lower traffic-noise levels correspond respectively to relatively nearby concentrations of shipping and to the more remote[69] areas. The classification as a "remote" area may be time-dependent, the result of daily, seasonal, or other variations in propagation or traffic patterns. As was brought out in Sec. 2.3, the effective distance for traffic-noise sources in the deep ocean can be as much as 1000 miles or more, and a rather widely observed traffic-noise component is to be expected. A comparison of the traffic-noise spectra with the other spectra in Fig. 13 indicates that the traffic-noise component generally predominates at frequencies between 20 and 200 cps.

In shallow-water areas isolated from general shipping activity in very remote deep-water areas, and in some deep-water areas which are isolated by underwater topography or oceanographic conditions, the effect of the traffic-noise component is very small, and levels should be estimated by combining only the appropriate low-frequency component and the high-frequency wind-dependent component.

4.4 Example

The guidelines suggested by the foregoing remarks were used to estimate three spectra, which are shown in Fig. 14, corresponding to three frequently encountered situations. The three spectra are: (1) that expected in

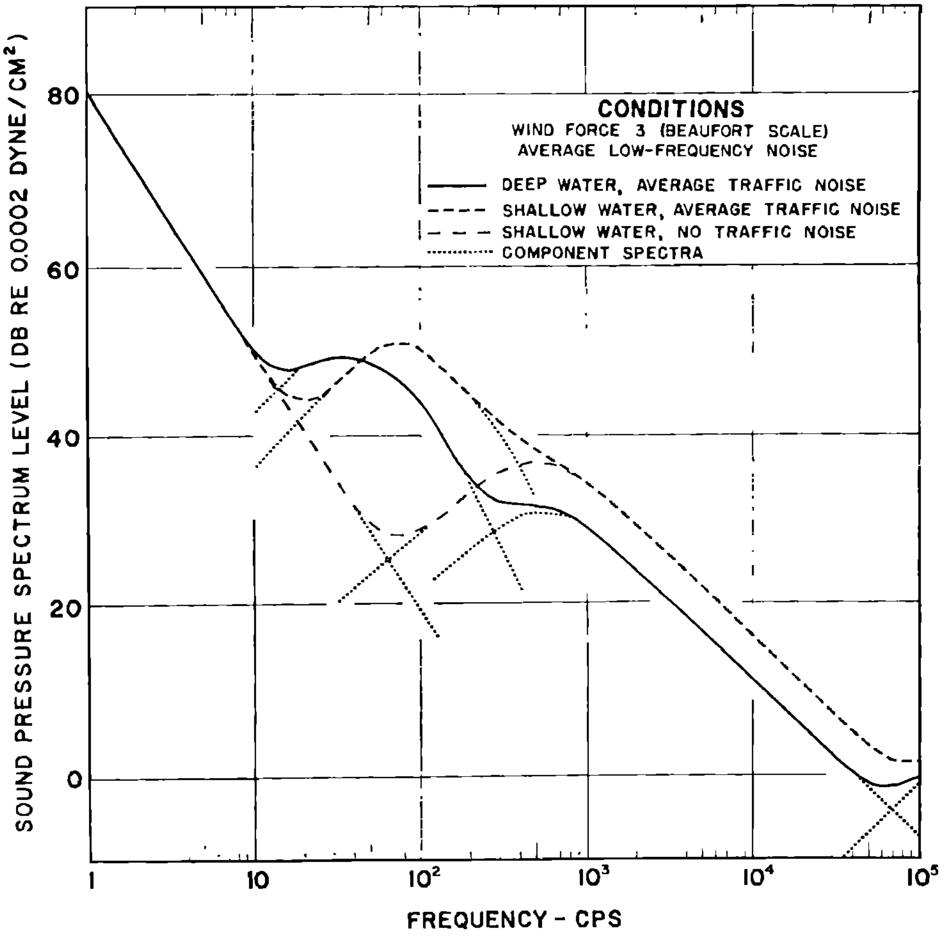

FIG. 14. Ambient-noise spectra estimated for three frequently encountered situations. The dotted-line extensions indicate, in the regions of overlap, the individual component spectra from which the estimated spectra were derived.

deep water with average traffic noise, (2) that expected in shallow water with average traffic noise, and (3) that expected in isolated shallow water (no traffic noise); when in each case average low-frequency noise conditions (average oceanic ambient turbulence) and force-3 winds prevail.

The shapes of the individual components, in the region of overlap before combination, are indicated by the dotted extensions. The low-frequency component,[70] in Fig. 14, is at a level approximately halfway between the lower-limit curve and the bottom of the low-frequency shaded area (upper left) in Fig. 13. The medium-frequency curves in Fig. 14 are the approximate medians of the deep- and shallow-water shaded traffic-noise areas in Fig. 13. The shallow-water high-frequency component is about $2\frac{1}{2}$ dB above the wind-force-3 curve shown in Fig. 13, the deep-water component $2\frac{1}{2}$ dB below.

These components were then combined by power addition. The resulting deep-water spectrum is shown by the solid curve, the two shallow-water spectra by the dashed lines.

5. CONCLUDING REMARKS

The scope of this review has been limited, primarily, to comparisons based on averaged spectrum characteristics. Other features, for which existing data are very meager, and which should be investigated further, include: temporal characteristics such as hourly, daily, seasonal, and like time patterns; spatial characteristics, such as the directional properties of the ambient-noise sound field; other statistical properties such as amplitude distributions; and the factors influencing such characteristics.

The accumulation of ambient noise data is not yet large in amount nor comprehensive in scope when considered in relation to the number and range of the variables. The generalizations which have been made are subject to further test. The discussion of sources and mechanisms has some verisimilitude, and patterns illustrated in Sec. 1 are frequently repeated. But more direct experimental data and more precise quantitative

[70] It is of interest to note that this approximation of the average low-frequency noise-level spectrum derived from observed ambient-noise data is almost identical to the turbulent-pressure-level spectrum estimated for ambient oceanic turbulence as shown in Fig. 11. This nearly exact agreement is fortuitous, but is a good indication of the similarity between observed ambient-noise spectra at the low frequencies and the probable oceanic turbulent-pressure-level spectra.

relationships are needed. The results and conclusions should be useful for immediate needs and for guidance in future investigations.

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