Infrasonic ambient ocean noise measurements: Eleuthera

R. H. Nichols[a]

Bell Laboratories, Whippany, New Jersey 07981
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Measurements of ambient ocean noise in the frequency range 0.02 to 20 Hz were made with three hydrophones bottomed off Eleuthera Island, at depths of 13, 300, and 1200 m, respectively, over a period of about six weeks in June, July, and August. The results are compared with reported results of other experimenters and with results of some published theories of infrasonic noise generation in the ocean. Comparisons with published data in the frequency range from 0.1 to 20 Hz show reasonable agreement. There do not appear to be published data in the region below 0.1 Hz for comparison. Comparisons with theories do not allow conclusive identification of generating mechanisms, but it appears that nonlinear interaction of surface waves and/or ocean turbulence are likely candidates in the frequency range 0.1 to 10 Hz. Below 0.1 Hz no specific mechanism is postulated to account for the steep rise in noise level with decreasing frequency observed in the Eleuthera data.

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INTRODUCTION

The measurements reported in this paper are part of a set which may have been the earliest series of deep-water ocean ambient noise measurements made. Their publication at the present date is prompted by the observation that, even now, reported ambient acoustic noise data at frequencies below 10 Hz are sparse, below 1 Hz are very sparse, and below 0.1 Hz appear to be nonexistent. In view of the increasing interest in infrasonic ocean noise, the Eleuthera data are presented herewith and comparisons are made with experimental and theoretical results of subsequent studies by other authors.

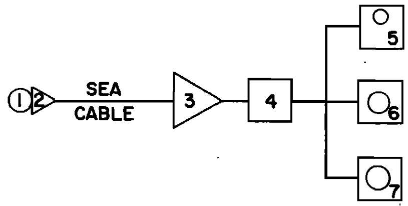
The total set of data taken at Eleuthera covers the frequency range from 0.02 to 1600 Hz. Inasmuch as the character of ocean ambient noise at higher frequencies has been well documented by this laboratory and others, discussion in the present paper is concentrated on the frequency range below 20 Hz.

I. INSTRUMENTATION AND PROCEDURE

Three laboratory-built barium titanate hydrophones were installed on the bottom of the Atlantic Ocean off the island of Eleuthera at depths of 13, 300, and 1200 m, respectively. An underwater pre-amplifier was directly associated with each hydrophone, and was connected by cable to a shore laboratory. There the signals from the hydrophones were further amplified and passed through contiguous octave bandpass filters to the measuring instruments, which comprised an electronic voltmeter, a laboratory-built full-wave rectifier meter and a cathode-ray oscilloscope. A block diagram is shown in Fig. 1. The overall response of the system, from sound-pressure level input at the hydrophones to the voltage output to the meters, was flat within half a dB from 1600 down to 5 Hz, and within 2 dB down to about 0.3 Hz (Fig. 2). Below that frequency, the response rolled off at a rate that largely tended to compensate for the rising ocean ambient noise levels with decreasing frequency.

The hydrophone pre-amplifiers were powered by current fed down the cable from batteries on shore; the shore amplifiers were also battery-powered for quiet operation. Provision was made for checking the gain of each underwater pre-amplifier periodically by sending ac calibrating signals of known voltage down the cable to a small resistor in series with the hydrophone at the pre-amplifier input and measuring the output voltage. Due to careful design of the amplifiers and selection of their components, the frequency characteristics of response, overload, and circuit noise were such that valid ocean ambient noise level measurements could be, and were made over the frequency range from 0.02 to 1600 Hz. The effects of pressure and temperature on the underwater equipment were accounted for in the calibrations.

Each hydrophone and pre-amplifier, which occupied a cylindrical casing about 2 in. in diameter and 15 in. long, was elastically mounted in a protective free-flooding housing, both for mechanical protection and for minimization of flow noise. Each housing was of the general form of a pocket-watch case, constructed from two "dishes" of $\frac{7}{16}$-in. steel, 48 in. in diameter, bolted together at the edges (Fig. 3). To allow acoustic access to the hydrophones, 73 holes $\frac{11}{16}$-in. in diameter were drilled in each face of the housing. In order to prevent marine life, sediment, etc., from entering through the holes, they were plugged with rubber which had the same specific acoustic impedance as sea water.



1 HYDROPHONE
2 PRE-AMPLIFIER
3 SHORE AMPLIFIER
4 OCTAVE BANDPASS FILTERS
5 OSCILLOSCOPE
6 VTVM
7 RECTIFIER METER

FIG. 1. Block diagram of instrumentation.

[a] Present address: Butler Service Group, 16 Main Street, Madison, NJ 07940.

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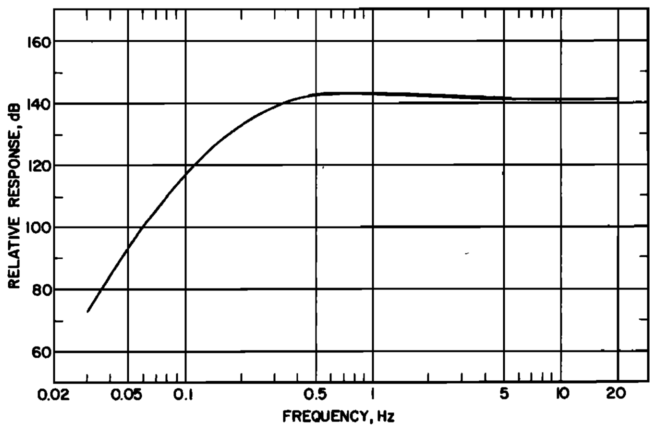

FIG. 2. Relative response of measurement system for constant acoustic input.

Measurements of sound transmission through the housings to the hydrophones, made both in the laboratory and at sea at frequencies from 0.1 to 100 Hz, indicated that the transmission loss due to the housings was zero ±2 dB over that range.

II. MEASUREMENT SCHEDULE

During a period of about six weeks, a measurement of ambient noise level was made on each hydrophone once every two or three days. The data were taken in contiguous octaves from the 0.02–0.04-Hz band to the 16–32-Hz band, except that above the 0.32–0.64-Hz band, octaves of 0.5 Hz were used. The sample lengths over which noise levels were averaged ranged from about 20 s at the highest frequency to 20 min. at the lowest.

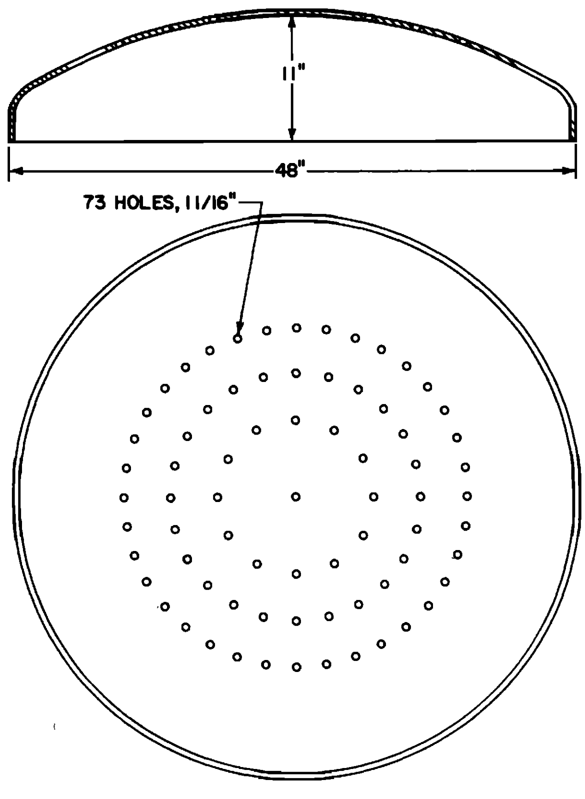

FIG. 3. Hydrophone housing; one-half is shown.

The ambient noise levels reported in this paper are equivalent sound pressure spectrum levels (per Hertz), reduced from the measured octave-band levels. The number of samples from each hydrophone at each frequency range from 12 to 21, and was 16 to 18 in most cases.

III. SEA STATE

The six weeks of measurements included the last days of June, all of July, and the first days of August. During this time the sea state was generally SS3 (occasional whitecaps) to SS4 (frequent whitecaps). Data-taking periods were about equally divided between the sea states. Occasional brief rain showers occurred, but appeared to have no effect on ambient noise in the infrasonic frequency range. With little exception, the wind was from the NE direction (on-shore) during the entire period.

IV. RESULTS

A. Difference with depth

The average spectrum levels of ambient noise from 0.02 to 20 Hz over the six-week period at the 13-, 300-, and 1200-m depths are plotted together in Fig. 4 to facilitate comparison. The standard deviations are plotted to the same scale in Fig. 5.

The characters of the spectra make it fairly natural to compare them in each of three frequency bands: roughly, 0.02 to 0.1 Hz, 0.1 to 1 Hz, and 1 to 10 Hz.

0.02-0.1 Hz

In the lowest-frequency band the slopes are steep, around 12 dB per octave at 13 m, and 20 dB per octave at 300 and 1200 m. The spectrum levels at the two deeper hydrophones are within a few dB of each other, but the shallow noise levels are 50 to 60 dB above them.

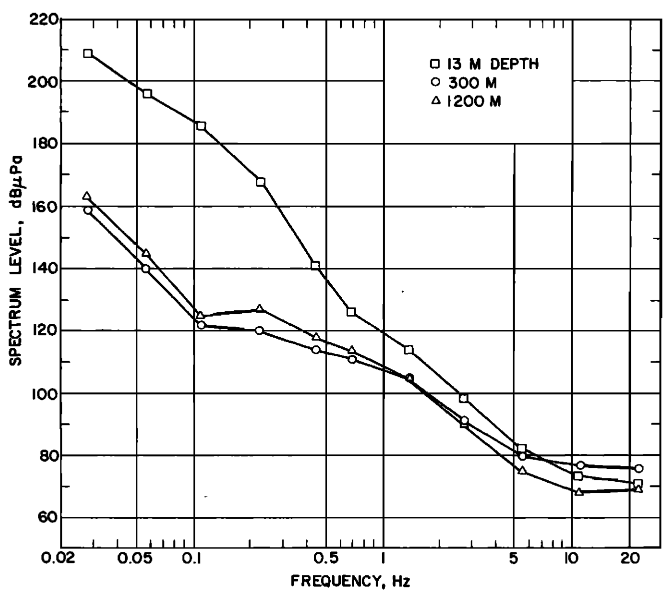

FIG. 4. Spectrum levels of Eleuthera ambient noise at three depths, averaged over six weeks of data.

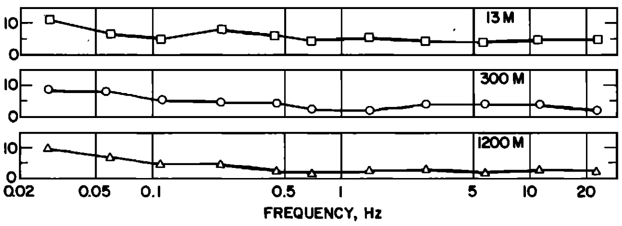

FIG. 5. Standard deviations of Eleuthera ambient noise spectrum levels at the three depths.

0.1-1 Hz

In the intermediate-frequency band, the noise levels are very similar for the two deeper units and the slopes for both spectra have leveled off sharply at 0.1 Hz to roughly 6 to 8 dB per octave. The sharp break at 0.1 Hz is a particularly intriguing feature. The shallow noise level continues to fall at an average of very roughly 20 dB per octave.

1-10 Hz

In the highest of the three frequency bands, the levels at the two deeper hydrophones are again generally comparable, and the average slopes are about 10 to 12 dB per octave. The spectrum at the 13-m depth has decreased in slope to around 14 dB per octave, with the result that at 10 Hz the spectrum levels at all three depths lie within a range of 8 dB. From 10 to 20 Hz, the spectra are approximately flat.

B. Differences with sea state

Comparison of the means of the data for SS3 with those for SS4 showed differences of only a decibel or two. These differences are too small to be statistically significant in view of the magnitudes of the variances. This is not surprising, since the range of sea states was small and not sharply definable.

V. COMPARISON WITH OTHER EXPERIMENTS

Experimental acoustical data for the frequency range from 1 to 20 Hz have been reported by a number of observers,[1-7] and for the range from 0.1 to 1 Hz by a few.[8,9]

There does exist a quantity of seismic data in the range from 0.1 to 1 or 2 Hz characterizing the amplitude, velocity or acceleration of the sea bottom,[10-15] which, as Urick has pointed out, might well be closely related to sound pressure at the bottom.[16] The existence of a close relationship is supported by the work of Sutton *et al.*,[17,18] and of Latham and Nowroozi.[19] The latter, for example, report that in their measurements, "...coherence between vertical particle motion and pressure is greater than 0.95 in all cases." In one case where simultaneous data were taken on both a hydrophone and a seismometer,[8] the spectrum of sound-pressure levels computed from the seismometer data agreed closely with the measured hydrophone data for one set of measurements, but was nearly 10 dB different from the measured spectrum of the second set.

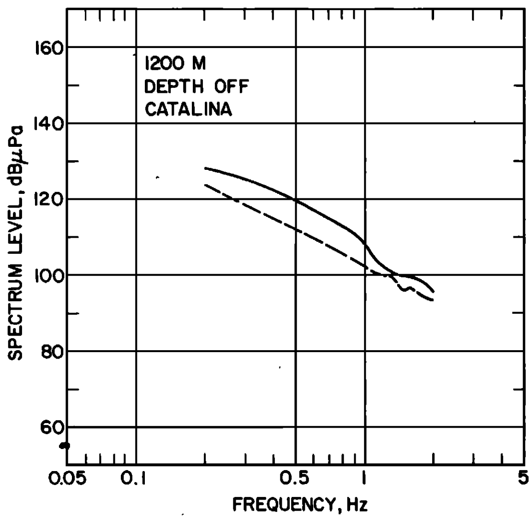

FIG. 6. Ambient noise levels at the ocean bottom, 1200-m deep, off Catalina (Schneider and Backus,[8] two data sets).

However, it appears quite possible, according to a conversation with W. A. Schneider, that this one example of a seemingly large discrepancy may have been due to an error in printing of the ordinate numbers on the plot of the second set of data. Bradner[20] has indicated the possibility that some reported seismic records may have been contaminated with effects due to water motion past the instruments. Of course, this is also a possibility for measurements using hydrophones, as discussed by McGrath.[21] In any case, the inference drawn is that use of vertical seismic measurements to compute equivalent ambient noise-pressure levels may be reasonably reliable in many cases.

There appear to be no published acoustical data on noise sound pressures in the frequency range below 0.1 Hz. Also, there appear to be no published data in the infrasonic range for water as shallow as 13 m, with the possible exception of Fig. 6 of Wenz.[1] However, he does not identify the depths beyond saying that they are

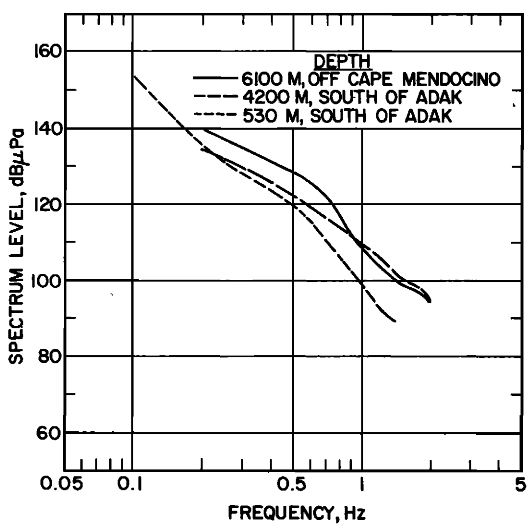

FIG. 7. Ambient noise levels at the deep ocean bottom (Schneider *et al.*[9]).

less than 46 m. The slopes of his two curves in that figure between 1 and 10 Hz are about half of the slope of the 13-m Eleuthera curve in Fig. 4.

A. 0.1 to 2 Hz

Ambient noise levels at the ocean bottom in deep water, measured by Schneider and Backus,[8] and by Schneider *et al.*,[9] in the 0.1- to 2-Hz range are plotted in Fig. 6 and 7, respectively. (These data, and those published by other authors and reproduced in this paper for comparison, were perforce often taken from small published plots, hence may be in error by 1 or 2 dB.) Each curve in Fig. 6 is for a noise sample 1 min. long. In Fig. 7, each curve is the average of four or five individual spectra taken about an hour apart; it is stated that, "the variance of the individual samples relative to the average is usually small."

There is considerable similarity in the slopes and levels of these spectra. With the exception of the data for the 530-m depth in Fig. 7, there appears to be a general increase in noise level with increasing depth. This may be happenstance, in view of the limited amount of data. The deep-water Eleuthera data similarly show some increase in noise level in this frequency region in going from 300- to 1200-m depth, but the differences are not statistically significant except for the 0.16–0.32-Hz band (plotted at 0.23 Hz).

In Fig. 8, the Eleuthera data for 300- and 1200-m depths are plotted along with the envelope of the five curves from Figs. 6 and 7, for comparison. The Eleuthera results lie within or close to the limits of the data from the other experiments, except in the 0.1- to 0.5-Hz region for the one curve.[9] For that one set of data the difference between it and the Eleuthera data at 1 Hz is large, of the order of 30 dB.

B. 1 to 20 Hz

Wenz shows six curves for noise levels in this frequency range, but does not identify depths or areas (his

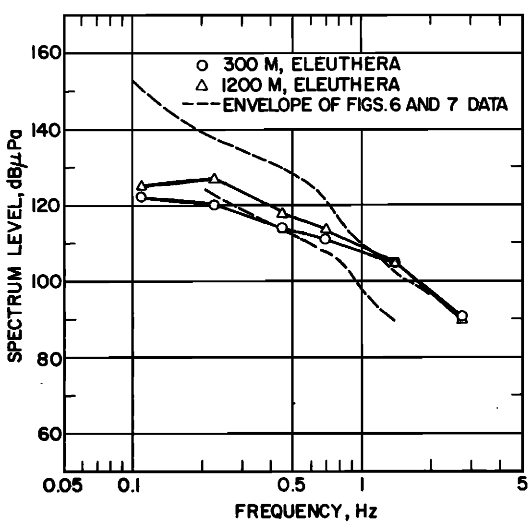

FIG. 8. Comparison of deep-water Eleuthera data with envelope of data in Figs. 8 and 9.

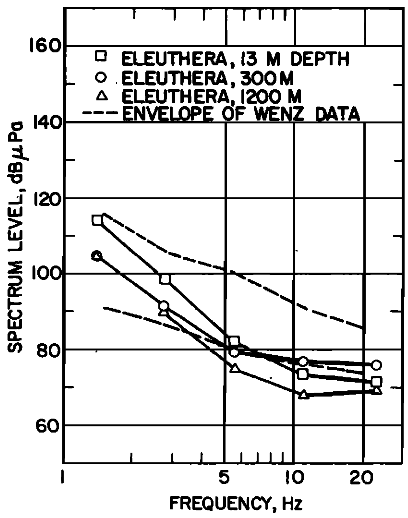

FIG. 9. Comparison of deep-water Eleuthera data with envelope of data of Wenz.[1]

Fig. 4). The Eleuthera noise spectra are plotted in Fig. 9 with the envelope of Wenz's data for comparison.

Results of experiments by Perrone,[7] McGrath,[6] Bardyshev and Voronina,[4] Bardyshev *et al.*,[2] Masterov and Shorokhova,[5] and Furduev,[22] performed at various depths are plotted in Fig. 10. McGrath's results, at 2400-m depth, were obtained only in the range above 5 Hz and are indistinguishable there from Perrone's, hence are not plotted. Their experiments were similar in that both were at considerable depths, and both in regions of heavy ship traffic.

The data in Fig. 10 from the shallower sites show a great diversity in levels and slopes. The difference between Masterov and Shorokhova's results and Furduev's is attributed to the use of a bottomed hydrophone with a flow-noise shield in the former, whereas the latter were obtained with a ship-suspended hydrophone, subject to motion and current effects. It appears that current shields of various types can dramatically reduce

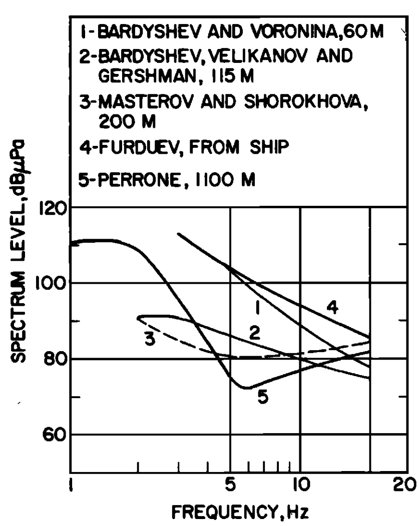

FIG. 10. Results of several observers at various depths and various sites. Curve 3 was obtained with a current-shielded hydrophone.

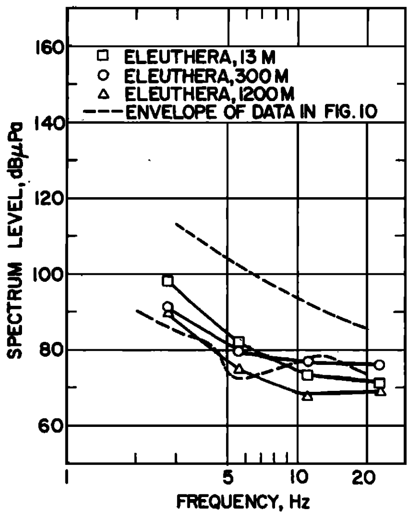

FIG. 11. Comparison of Eleuthera data with envelope of data in Fig. 10.

the infrasonic noise levels in areas of high ocean currents.[5] McGrath *et al.*,[21] have made laboratory measurements of flow noise with three particular configurations of hydrophones, and find that currents of 0.25 kn or greater can produce noise levels comparable with their measured sea noise levels. Strasberg[23] has postulated that noise due to current-hydrophone interaction may have been high enough in some reported data to mask the acoustic noise levels. While not clearly stated in their paper, it is possible that the low ambient levels plotted by Bardyshev *et al.*,[2] are also due to the effects of flow-noise shielding.

A plot (Fig. 11) of the Eleuthera data on the envelope of the curves of Fig. 10 shows that again, they fall within the range of other experimenters' results, but definitely on the low side. This may well be due either to the current-shielding effects of the large and more or less streamlined housing, which would reduce self-noise contamination, or the lack of high ocean currents at the sites, or both.

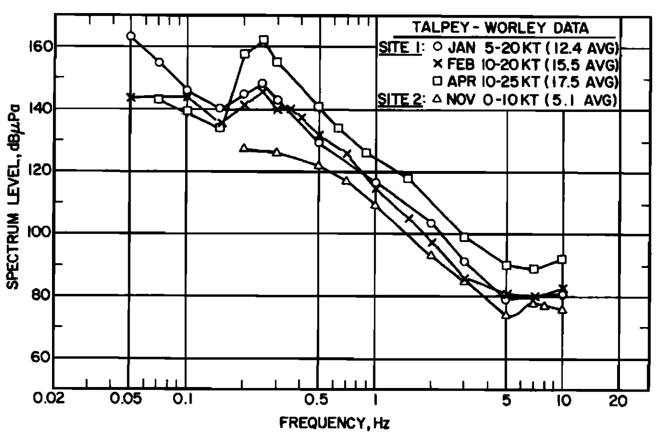

FIG. 12. Data of Talpey and Worley[24] from bottomed hydrophones off Bermuda. Site 1 and site 2 are about 25 nmi apart; site 1 is at 4300-m depth and site 2 is at 3500 m.

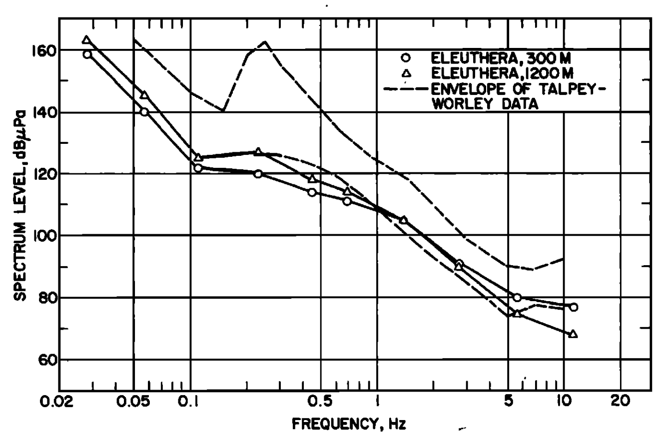

FIG. 13. Comparison of Eleuthera data with envelope of data of Fig. 12.

C. Talpey–Worley data, 0.05 to 10 Hz

Data taken by Talpey and Worley[24] on a hydrophone bottomed at 4300-m depth in an area south of Bermuda ("site 1") are plotted in Fig. 12. Three sets of data are shown, taken 1 or 2 months apart. Each point is the average of ten 4-min. samples; the frequency resolution of the data processing was 0.0043 Hz. Measurement system noise was more than 10 dB below the measured ocean ambient in all cases. Also shown in Fig. 12 is an ambient noise spectrum taken during November on a bottomed hydrophone in the same general area, but about 25 nmi away ("site 2") from site 1, at 3500-m depth.

In the light of evidence developed by DeVilbiss[25] through further measurements, it is believed that the rise in level and the growth in the peak at 0.25 Hz in going from the November data to the January–February data and then to the April data is associated with the increasing wind speed noted in Fig. 12. This belief is supported by the fact that, when the Eleuthera noise spectra, which were taken at low sea states, are plotted along with the envelope of the Bermuda data, they follow rather closely the lower bound (site 2 data) of the Talpey–Worley results, for which the sea state was comparable (Fig. 13). It is further supported by data taken at a nearby Bermuda site by Perrone,[26] which show a strong relationship between wind speed and the level of the overall spectrum in this frequency range.

VI. COMPARISON WITH THEORY

A. Surface-wave pressures

Wenz derives surface-wave pressure-level spectra for several wind forces (his Fig. 8) and also presents curves showing the spectral attenuation of these pressure levels with depth (his Fig. 9). Combining the appropriate spectra for the conditions of the Eleuthera experiment, it is clear that the effects of direct surface-wave pressures will not be observable at the 300- and 1200-m depths. In Fig. 14, the calculated surface-wave pressure spectrum for wind force 3 at a depth of about 13 m is compared with the measured data from the 13-m hydrophone. The calculated level is about the

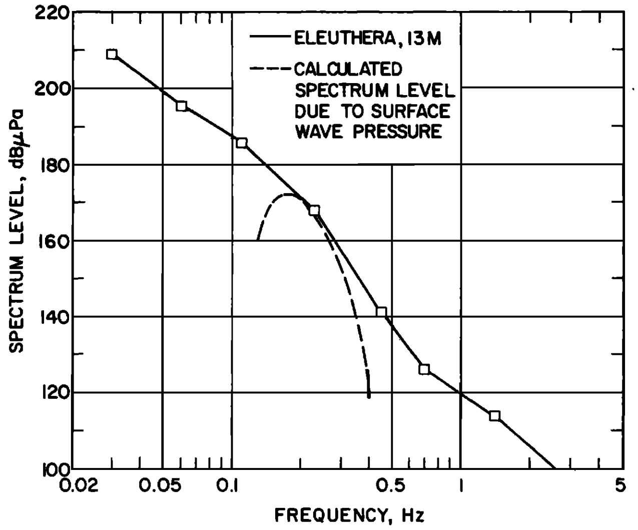

FIG. 14. Comparison of calculated surface-wave pressure spectrum level at 13-m depth (after Wenz[1]) with results at 13-m depth at Eleuthera.

same as the measured level in a very limited frequency range; it is possible that surface waves are contributing directly to the level at the shallow unit. However, the correspondence is so limited that one suspects that other factors are the main contributors, or else Wenz's theory is not appropriate.

Isakovich and Kur'yanov[27] have developed a theory to relate wind and surface waves to ambient noise levels at low frequencies. In their Fig. 5, the calculated spectrum levels from 1 to 100 Hz for deep water are shown for several "wind wave height" numbers ranging from 1 to 8. It is not clear how these numbers are related to wind speed or sea state, but it is perhaps reasonable to assume that an intermediate value such as 3 would correspond to sea state 3 or 4. On that assumption, their predicted spectrum is plotted in Fig. 15 with the deep-water Eleuthera spectra for comparison.

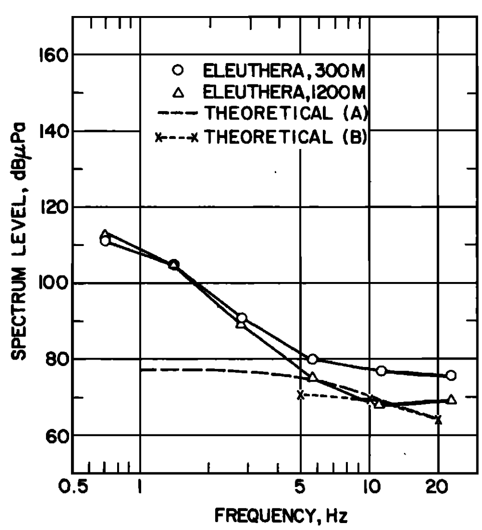

FIG. 15. Comparison of theoretical spectra by (A) Isakovich and Kur'yanov,[27] and (B) Wilson[28] with Eleuthera deep-water data.

While the predicted level in the 5 to 10 Hz region is similar to that of the measured data, the slope of the predicted spectrum below 5 Hz is far less than that of the measured spectra. Use of a different theoretical wind-wave-height-numbered curve from their paper would not improve the fit of the predicted to the measured spectra, since their theoretical spectra for different numbers are all essentially parallel to one another. J.H. Wilson[28] has recently modified the theory of Isakovich and Kur'yanov and has made use of newer wave-height spectra. In the range from 20 down to 10 Hz his theoretical curve for 26.5 kn wind speed appears to agree closely with Isakovich and Kur'yanov's. However, from 10 down to 5 Hz (the lowest frequency he plots), it appears to fall somewhat below theirs, and, hence somewhat farther below the Eleuthera data which were taken at lower wind speeds (Fig. 15).

B. Nonlinear surface wave interaction

The generation of very-low-frequency sound pressures due to nonlinear interaction of waves on the ocean surface was discovered by Miche[29] in a theoretical study. The distinctive features of these waves are that they are unattenuated by depth, and they occur at twice the surface wave frequency. The theory has been further developed and expanded by Longuet-Higgins,[30] Nanda,[31] Brekhovskikh,[32] Hughes,[33] and Harper and Simpkins.[34]

The spectrum of surface waves at the sea states prevailing during the Eleuthera measurements would be expected to peak in the vicinity of 0.12 Hz.[35] This is supported by the finding of Nichols and Young[36] that the spectrum of fluctuations of surface-reflected acoustic signals at other Eleuthera hydrophones also peaks at that frequency. In the deep-water Eleuthera noise spectra (Fig. 4), there is no obvious peak in the region of twice that frequency (0.25 Hz), but there is a bit of a bulge, particularly in the 1200-m plot. (The width of the filter bands used, one octave, would tend to obscure the existence of a sharp peak in the spectrum.) The Talpey and Worley measurements at site 1 off Bermuda, which were made with a very narrow analyzing band, (0.0043 Hz) do show a strong peak at 0.25 Hz, the magnitude of the peak and the level of the spectrum appearing to be related to wind velocity (Fig. 12). It seems reasonable to attribute the peaks to nonlinear surface wave interactions. This view is supported by the results of Latham and Nowroozi,[19] which show amplitude correspondence between surface waves and ocean-bottom microseisms at frequencies below 1 Hz, and exhibit a 2-to-1 ratio in their periods, as predicted by nonlinear interaction theory. They conclude that, "wave action in the vicinity of the ocean-bottom seismometer is the most likely mechanism for generation of the observed microseisms.... The Longuet-Higgins mechanism for generation of microseisms is supported by the results of this study." As discussed earlier, acoustic pressures appear to be closely related to microseisms.

Early theoretical estimates of nonlinearity-generated noise do not generally agree closely with measured values. For example, Brekhovskikh's predictions for the spectrum above 1 Hz, for windspeeds of 2 and 20 kn, as taken from Fig. 5 of Ref. 9, lie below the Eleuthera spectra (Fig. 16) although they have about the same slope. A theoretical estimate by Gonchorov,[37] based on interaction of surface waves and turbulence, is also plotted in Fig. 16. In this case the theoretical levels are higher, although again, the slope is similar to that of the measured data. More recently, Hughes,[33] working with newer information on surface-wave spectra, and taking into account multiple surface-bottom reflections, arrived at a prediction for 30-kn wind (SS5) also shown in Fig. 16. This lies above the measured results, as might be expected from the higher sea state used in the prediction; at the sea states of the Eleuthera measurements, his model might perhaps fit the data.

C. Ocean turbulence

Wenz postulates that ocean turbulence due to current flow past boundaries and movements of the water within the medium may be a strong contributor to infrasonic noise. In his Fig. 11 he plots the results of a theoretical examination of this postulate, with the aid of some experimental information. Three predicted spectra of turbulence-generated noise for the frequency range 0.1 to 100 Hz are presented there, for turbulent velocities of 0.04, 0.2, and 0.6 kn, which correspond to current flow velocities of 0.8, 4, and 12 kn, respectively. Strasberg[23] has raised some questions about Wenz's theory. Nevertheless, when Wenz's lowest-velocity curve is plotted for comparison with the deep-water data (Fig. 17) the resemblance of the theoretical spectrum for 0.04-kn turbulent velocity to the measured ones over the range from 0.2 or 0.3 to 10 Hz is remarkable. Unfortunately, data on current velocities at the Eleuthera site are not available; it is not known whether current velocities of as much as 0.8 kn (corresponding to a turbulent velocity of 0.04 kn according to Wenz), exist there.

VII. SUMMARY

Measurements of ambient ocean noise in the frequency range 0.02 to 20 Hz were made with bottomed hydrophones at three depths, 13, 300, and 1200 m over a period of six weeks.

The noise spectrum at the 13-m depth descends monotonically with frequency, having an average slope of about −18 dB per octave from 0.02 to 5 Hz, following which it changes rapidly to about −3 dB per octave.

The spectrum levels at the 300- and 1200-m depths are very nearly identical. They exhibit a steep drop with increasing frequency from 0.02 to 0.1 Hz, with a slope of −18 dB per octave. The average slope abruptly lessens to about 7 or 8 dB per octave between 0.1 and 1 Hz. From 1 to 10 Hz it is about −13 to −14 dB per octave and from 10 to 20 Hz, the spectrum is essentially flat.

Deep-water data in the region from 0.1 to 20 Hz reported by other experimenters show the same general spectral characteristics in that region, over a wide variety of geographical locations. The levels, also, are reasonably alike; considering the variety of sites and of potential generating mechanisms.

In the absence of detailed data on wind velocities, bottom ocean currents, etc., it is hardly possible to assign generation mechanisms for the noise. However, comparisons of the measured results at Eleuthera with values computed and published on the basis of various theories of noise generation indicate that, for the frequency region 0.1 to 10 Hz, nonlinear interaction of surface waves and/or ocean turbulence are likely mechanisms. This view is supported by the observations of a number of experimenters that noise levels increase with increasing wind speed. The nonlinear theory, in particular, is supported by the finding of peaks in the ambient noise spectra and in those of the associated ocean-bottom microseismic noise at twice the surface-wave frequency. Ocean turbulence may account for the noise at low wind speeds; its spectral shape, as derived by Wenz, fits the Eleuthera data very well.

The steep rise in noise level in going from 0.1 Hz downward in frequency is an intriguing phenomenon for which no mechanism is postulated. There appear to be no other published data in that frequency range. However, the existence of such a sudden change in slope is supported by the results of Talpey and Worley at Bermuda, which indicate a similar phenomenon in each of

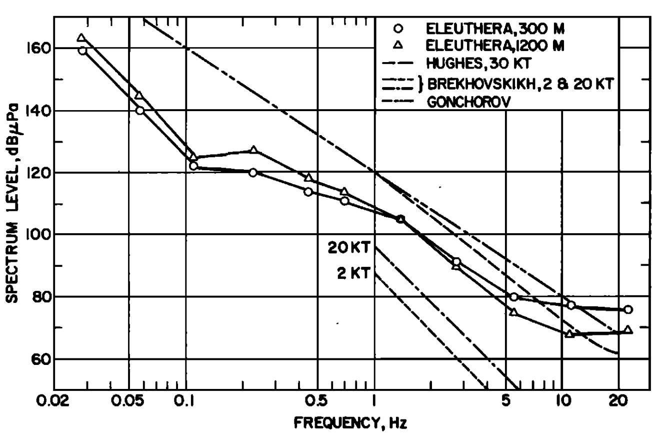

FIG. 16. Comparison of predicted spectra by Hughes[33] and by Brekhovskikh (from Isakovich and Kur'yanov[27]) with Eleuthera deep-water data.

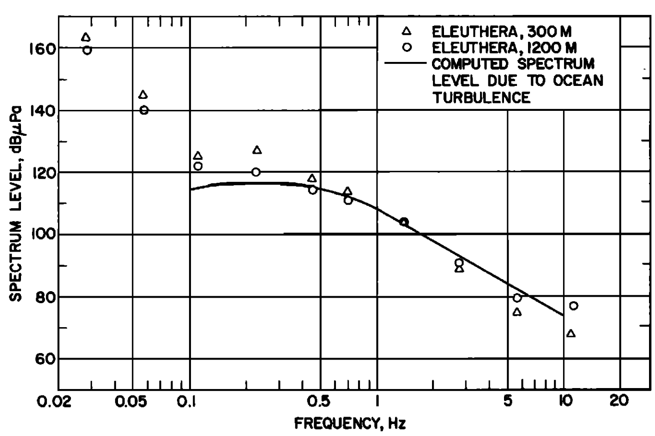

FIG. 17. Comparison of Eleuthera data with ocean turbulence noise spectrum computed by Wenz[1] for 0.8-kn flow velocity (0.04-kn turbulence velocity).

three sets of measurements made during three different months.

The high noise levels at the shallow (13-m) hydrophone below 1 Hz must presumably be associated with surface waves, with swells, and with high currents on the ocean floor. In listening to the output of this hydrophone with high-fidelity headphones, a great deal of miscellaneous noise was heard sounding like surf, rattling of pebbles and thumping of larger objects against the housing, etc. These noises were not heard on the two deep units. No attempt has been made to develop theoretical values for this location.

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