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Ambient Sea Noise: A Review of the Literature

WAYNE W. CROUCH
Technical Information Center

17 February 1972

NAVAL UNDERWATER SYSTEMS CENTER

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ADMINISTRATIVE INFORMATION

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The Technical Reviewers for this report were N. B. Stahmer (Code LA13) and A. J. Perrone (Code TA1).

REVIEWED AND APPROVED: 17 February 1972

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ABSTRACT

Knowledge about ambient sea noise between 10 Hz and 10 kHz is summarized. Information is included on several characteristics of ambient noise (variation of spectrum levels, directionality, and correlative properties) and two sources (surface agitation and rain). Other summaries are recommended that cover the prediction of spectrum levels associated with additional sources (distant shipping, biological, thermal, and seismic).

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FOREWORD

This report is the result of an extensive study of the literature on ambient sea noise. I have tried to obtain and review all reports and articles on the subject. Nearly 600 references are listed in two bibliographic source books published prior to this writing.* This report is a summary of the current knowledge on much of the unclassified material concerned with ambient sea noise. A classified report contains additional information on the prediction of noise spectrum levels.†

All the information reviewed in this report was taken from published material. Often the published data were difficult to compare because of varying formats or because of different experimental and analytical techniques. One of the main contributions of a state-of-the-art survey such as this is that comparisons can be made. In addition, previous research results can be screened and summarized. Only the most valuable work is included here, and then only in summary form. The briefness is an advantage to the reader, but should be viewed with caution. Whenever there is any question about the applicability of the material presented here, the original report or article should be consulted.

*W. W. Crouch, A Bibliographic Source Book on Ambient Sea Noise (U), NUSL Report No. 1030, 10 November 1969 (CONFIDENTIAL); A Bibliographic Source Book on Ambient Sea Noise: May 1968 – December 1969 (U), NUSC Report No. 4029, 29 December 1970 (CONFIDENTIAL).

†W. W. Crouch, Ambient Noise Spectrum Level Prediction: The State of the Art (U), NUSC Report No. 4251, in preparation (CONFIDENTIAL).

AMBIENT SEA NOISE: A REVIEW OF THE LITERATURE

INTRODUCTION

In the last few years it has been shown that under most circumstances there are two primary sources of ambient noise in the frequency range from 10 Hz to 10 kHz: surface agitation and distant shipping. Their relative importance varies from situation to situation and under some conditions, such as heavy rain or high biological noise levels, additional sources must be considered.

Surface agitation is highly wind dependent, and the noise it generates arrives at the measuring devices from vertical and nearly vertical angles. On the other hand, shipping noise is not wind dependent and arrives from nearly horizontal angles. The frequency of distant shipping noise is lower than that of surface noise.

Available information[1,2,3] about the characteristics of ambient sea noise (i.e., spectrum levels, directionality, and correlative properties) is almost always relevant only when the primary sources are dominant. Special consideration must be given to any other sources that make a significant contribution.

A thorough discussion of how one should approach the subject of ambient sea noise is given in the bibliographic source book.[1] The essence of that discussion is that the most important things to know about ambient noise are the characteristics of the noise at some time and place. The following characteristics have proven to be important:

a. Spectrum levels

b. Directionality

c. Correlative properties

d. Amplitude statistics

Spectrum levels, directionality, and correlative properties are discussed here. Evaluation of available research on amplitude statistics depends on the use that is to be made of the results, and relevant reports are indexed in the bibliographies.

Since sources can frequently be identified, their study is a very effective way to predict and understand noise characteristics. Besides surface agitation and distant ship traffic, the following noise sources are important under certain conditions:

a. Precipitation

b. Biological

c. Thermal

d. Seismic

Surface agitation and precipitation are discussed in detail here. The other noise sources are covered in referenced articles.

Other summaries have been published, and an analysis of them is available in the bibliographies. One thorough summary[4] published in 1964 by Wenz can be used in conjunction with this report to obtain a complete and up-to-date summary of current knowledge about ambient sea noise.

As is implied above, the reader should keep four documents at hand for general information about ambient sea noise: this report, the summary by Wenz, and the two bibliographic source books. For information on noise from biological sources, a summary by Tavolga is also recommended.[5]

CHARACTERISTICS OF AMBIENT SEA NOISE

SPECTRUM LEVELS

Prediction of Spectrum Levels

Only if extensive measurements of ambient noise have been made in an ocean area can one confidently predict future levels. Since this is seldom the case, predictions are almost always made on the basis of data averaged over long periods of time and large geographic areas. Knudsen was the first to publish such averages.[6] His very simple linear relationships (Fig. 1) show a change in ambient noise level with wind speed. Although all the averaged data were derived from shallow water measurements, the values above 1 kHz are in good agreement with later studies. Below 1 kHz the levels are higher than those of recent studies. These high levels appear to have occurred because much of Knudsen's data was obtained near ports and harbors where low-frequency shipping noise is high.

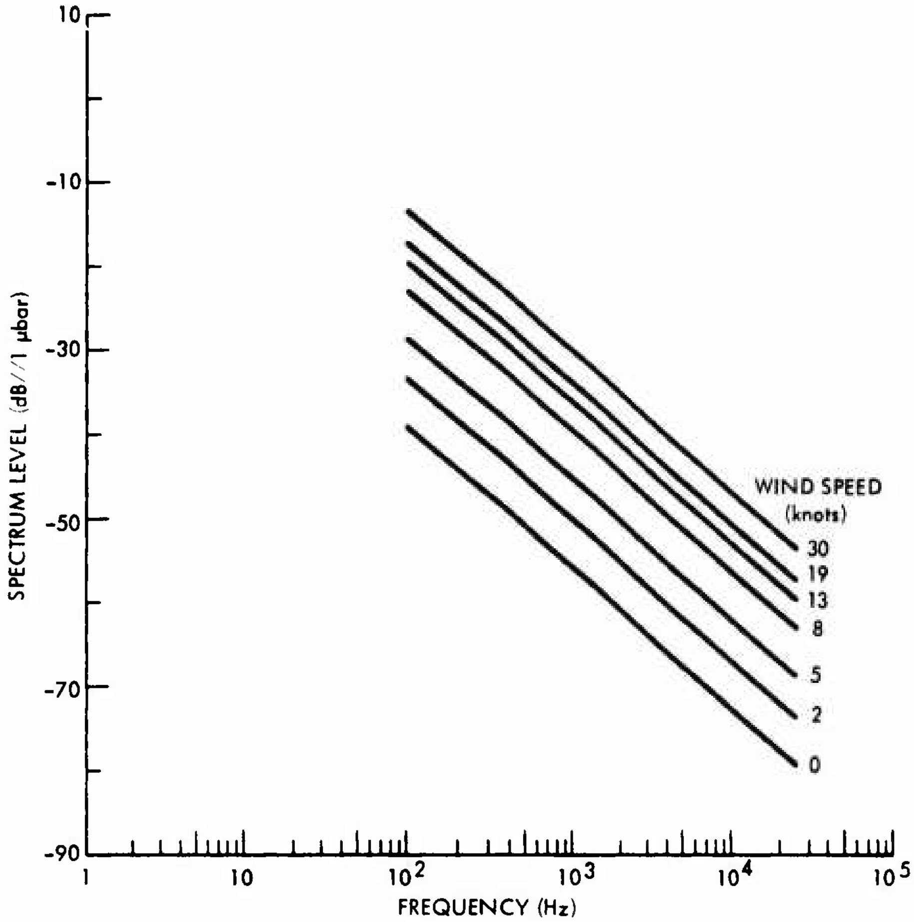

Fig. 1. Average Ambient Noise Spectrum Levels by Knudsen

Wenz has published a thorough study of ambient noise in many ocean areas.[4] He compiled average ambient noise levels due to various sources, and his results are shown in Fig. 2. This work is the best available in the open literature. Additional refinements of predictions for surface agitation and shipping have been published in confidential documents and a review of the classified literature on this subject is available in another report.[3]

Variation of Spectrum Levels

Very little has been done to determine expected variations in ambient noise levels. More needs to be known. Operational analyses based on mean levels alone can be misleading.

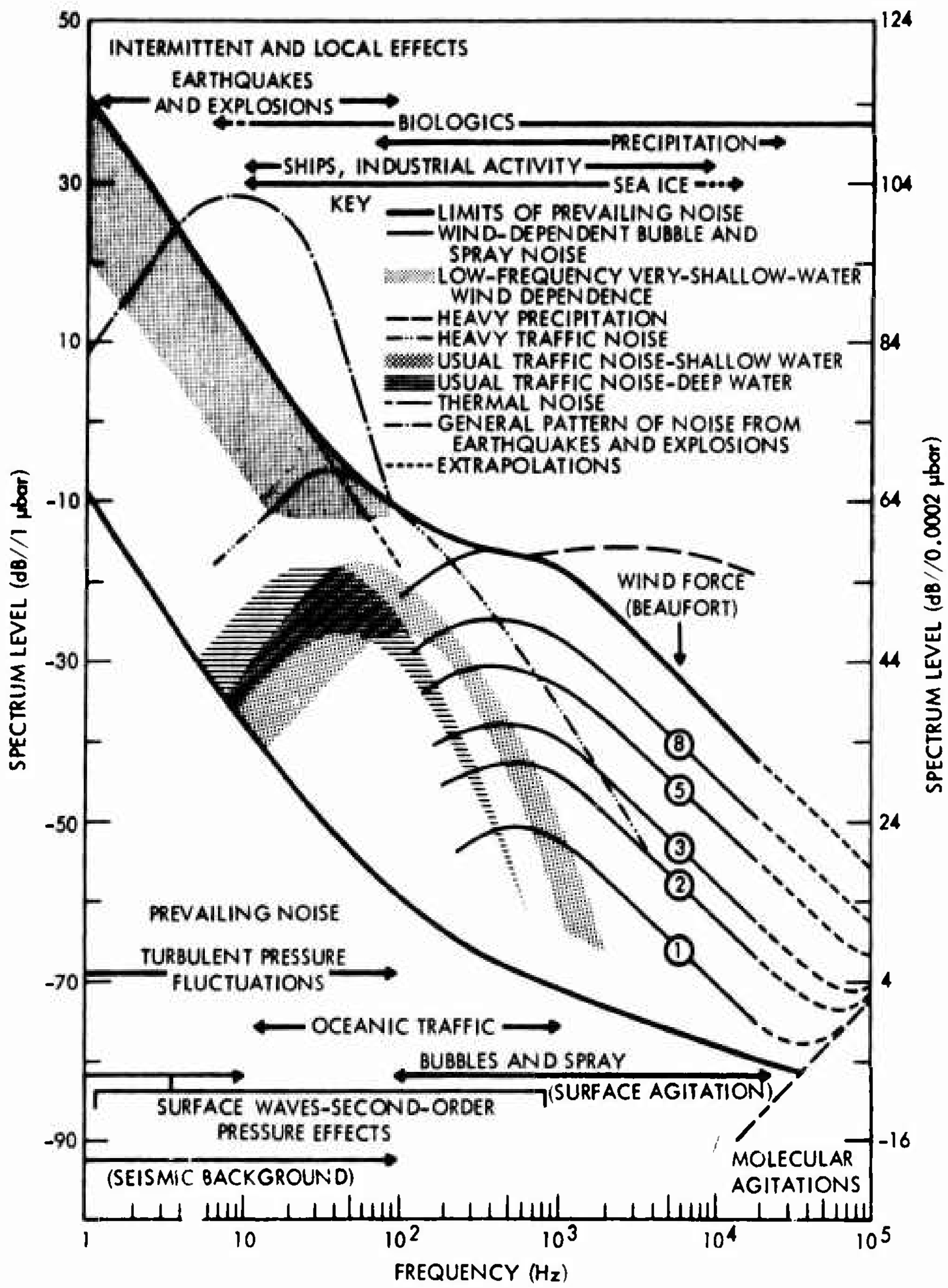

Fig. 2. Average Ambient Noise Spectrum Levels by Wenz (From Wenz, Reference 4)

Wenz studied the variation about mean levels along the West Coast of the U. S.[7] His results for each month of the year and for the entire 2-year period are shown in Fig. 3. The large discrepancy between the two time periods around 20 Hz is due to a variation with a period of about 6 months. Little other data on variations about the mean are available, and these results should be applied to other situations with caution.

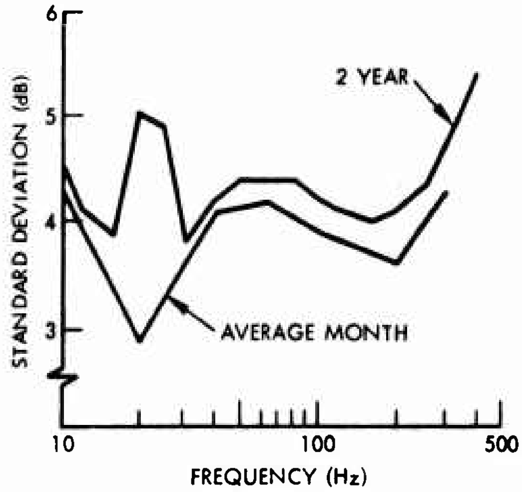

Fig. 3. Standard Deviation as a Function of Frequency for Two Periods of Time from Wenz

Hopefully, researchers will begin reporting on variations about the mean for various periods of time so that studies can be compared. The following time periods have been suggested: 1-day average, each month of the year, 1-month average, each season of the year, and 1-year average.[8] These time periods are frequently chosen for systems analysis and performance prediction.

Perrone has published standard deviations as a function of wind speed for data taken during the month of January near Bermuda.[9] Figure 4 shows his results. He summarizes his findings as follows:

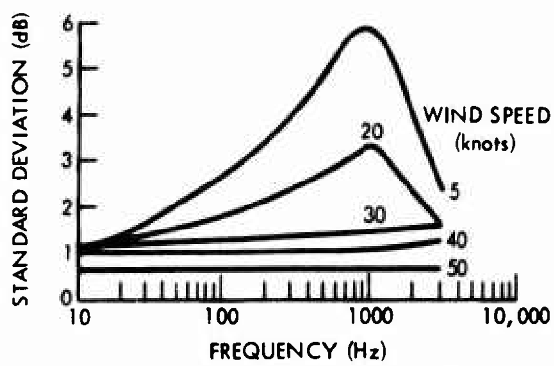

Fig. 4. Standard Deviation as a Function of Frequency and Wind Speed for the Month of January (From Perrone, Reference 9)

> The results shown for the low-wind speed group (2.5 to 7.5 knots) suggest that the total variance in the spectrum levels as a function of frequency may result from the summation of two noise sources, one due to wind and the other due to shipping. The part of the variance attributed to the wind-dependent source is believed to be small and relatively invariant over the entire frequency range. The part due to shipping is not constant and, at any particular frequency, it depends on the amount and type of ship traffic noise. This effect results in a varying spectrum, with the largest variations occurring at the higher frequencies. The decreasing values of the standard deviation above 1000 Hz suggest that the non-wind-dependent source has less influence on the wind-generated ambient-noise spectra at these frequencies.

An inconsistency which he does not discuss is that, because of the technique used for smoothing the data, the standard deviation was found to be wind dependent at frequencies where no wind dependence was found in the spectrum levels (approximately 20 to 100 Hz). A mathematical description of the variation resulting from two Gaussian noise sources has been developed,[10] and it agrees fairly well with Perrone's results except for the inconsistency in wind dependence.[11] The usefulness of that mathematical description is not yet clear. Again caution must be suggested in estimating the variation of ambient noise levels. Perrone's and Wenz's figures represent currently available knowledge on the subject.

Depth Dependence

Two meaningful studies are available on ambient noise as a function of depth. Perrone studied ambient noise at four depths from 2400 to 15,000 ft for frequencies from 11 to 1414 Hz.[11] Above 14,400 ft the results can be summarized by looking at the results in three frequency bands (Fig. 5). From 11 to 89 Hz the levels were lower near the surface. At 11 Hz, the noise at 2400 ft was about 12 dB less than the noise at 14,400 ft. This difference decreased to nearly zero at 89 Hz. In this frequency band, wind speed did not affect the ambient noise levels since the curves have the same slope for wind speeds from 0 to 50 knots.

In the band from 89 to 177 Hz there was essentially no difference in level between 2400 and 14,400 ft. However, between 177 and 1414 Hz the levels were higher near the surface. The level difference increased from 0 to 4 dB for small wind speeds and from 0 to 8 dB for high wind speeds. This can be seen best in the data for 1414 Hz. The difference at 50 knots is noticeably greater than the difference at 0 knots. In general, for this highest band the level difference is greater for higher frequencies and higher wind speeds.

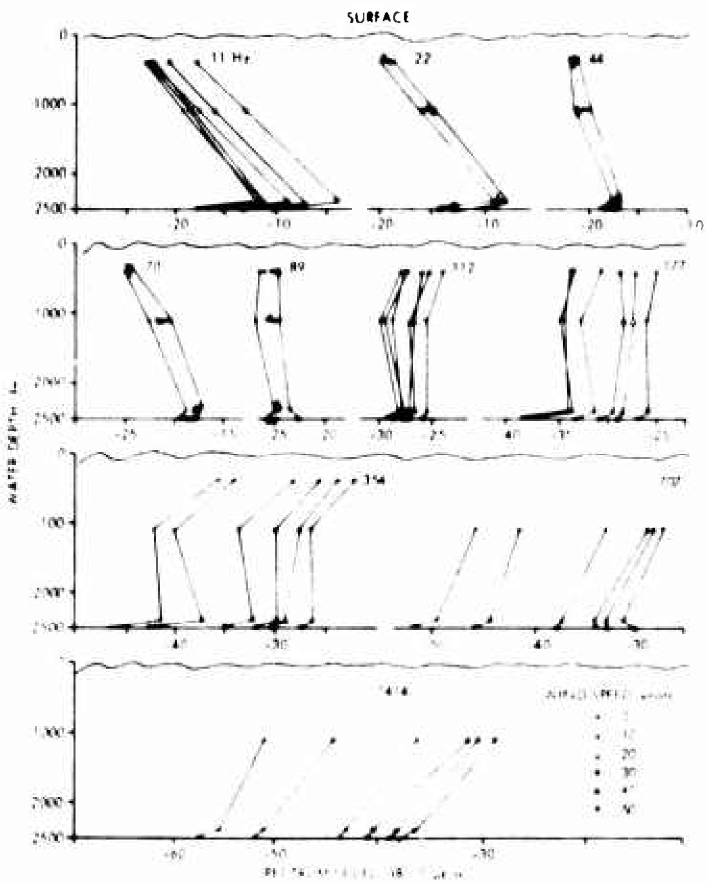

Fig. 5. Ambient Noise Levels versus Water Depth for Ten Frequencies at Six Wind Speeds: Data Grouped by Frequency (After Perrone, Reference 11)

Noise levels at the 15,000-ft hydrophone were within 2 dB of those at the 14,400-ft hydrophone for the high frequencies and high wind speeds. However, at lower frequencies and lower wind speeds there was as much as a 6 dB difference. A smaller difference at the high frequencies and wind speeds is reasonable since most of the noise is from surface agitation and the additional attenuation to the lower hydrophone would not be great. Also, a larger difference at lower frequencies and lower wind speeds could be attributed to propagation conditions (as Perrone did). In this hypothesis, the noise arrives at the hydrophones via RSR, RRR, and bottom bounce paths. Since "the 15,000-ft hydrophone is on the ocean floor and thus beyond the direct path field, signals reaching it are mainly bottom limited.[11]

Lomask and Frassetto, using the bathyscaph Trieste, conducted a series of experiments in the Tyrrhenian Sea where the noise from shipping was found to be relatively low.[12] They found wind-speed dependence in the frequency range from 18 to 100 Hz, whereas in Perrone's study nc wind dependence was observed. Consequently, it appears that the ambient noise spectrum levels vary as a function of water depth and are dependent on the area and the balance between surface agitation and distant shipping sources.

DIRECTIONALITY

Axelrod, Schoomer, and Von Winkle,[13] and Fox[14] have reported on studies of the directionality of ambient sea noise in deep water, and Becken[15] has reported on studies with an array suspended near the surface. Theoretical works have been published by Liggett and Jacobson[16] and Talham.[17]

Von Winkle[13] and Fox[14] used the same array to take their data, and the dates of their experiments overlapped. This section compares those results, summarizes the works by Becken, Liggett, and Talham, and includes comparisons of the theoretical models with experimental results.

Von Winkle took data during the winter and summer of 1963; Fox took data during the winter only of the same year. Both used the same array near Bermuda. Von Winkle studied seven frequencies; he used logit bandpass filters centered at 112, 178, 355, 562, 891, 1122, and 1414 Hz. Fox studied four frequencies; he used 10-percent bandpass filters centered at 200, 400, 750, and 1500 Hz. For each frequency, Von Winkle grouped his data according to the ambient level at 891 Hz and assigned a Beaufort Wind Force number to each group; for each frequency, Fox divided his data into three groups according to wind speed and assigned Sea State 1, 3, or 5 to them.

Since the Beaufort Numbers and Sea States were not assigned in the same way, not one of Von Winkle's curves can be compared with one of Fox's. However, families of curves for the same frequency can be compared if Von Winkle's results for 200, 400, 750, and 1500 Hz are found by interpolation and extrapolation. This has been done,[18] and Fig. 6 shows the superposition of Fox's and Von Winkle's families of curves for the four frequencies. Although not shown here, Von Winkle's article shows the results for all seven frequencies studied.

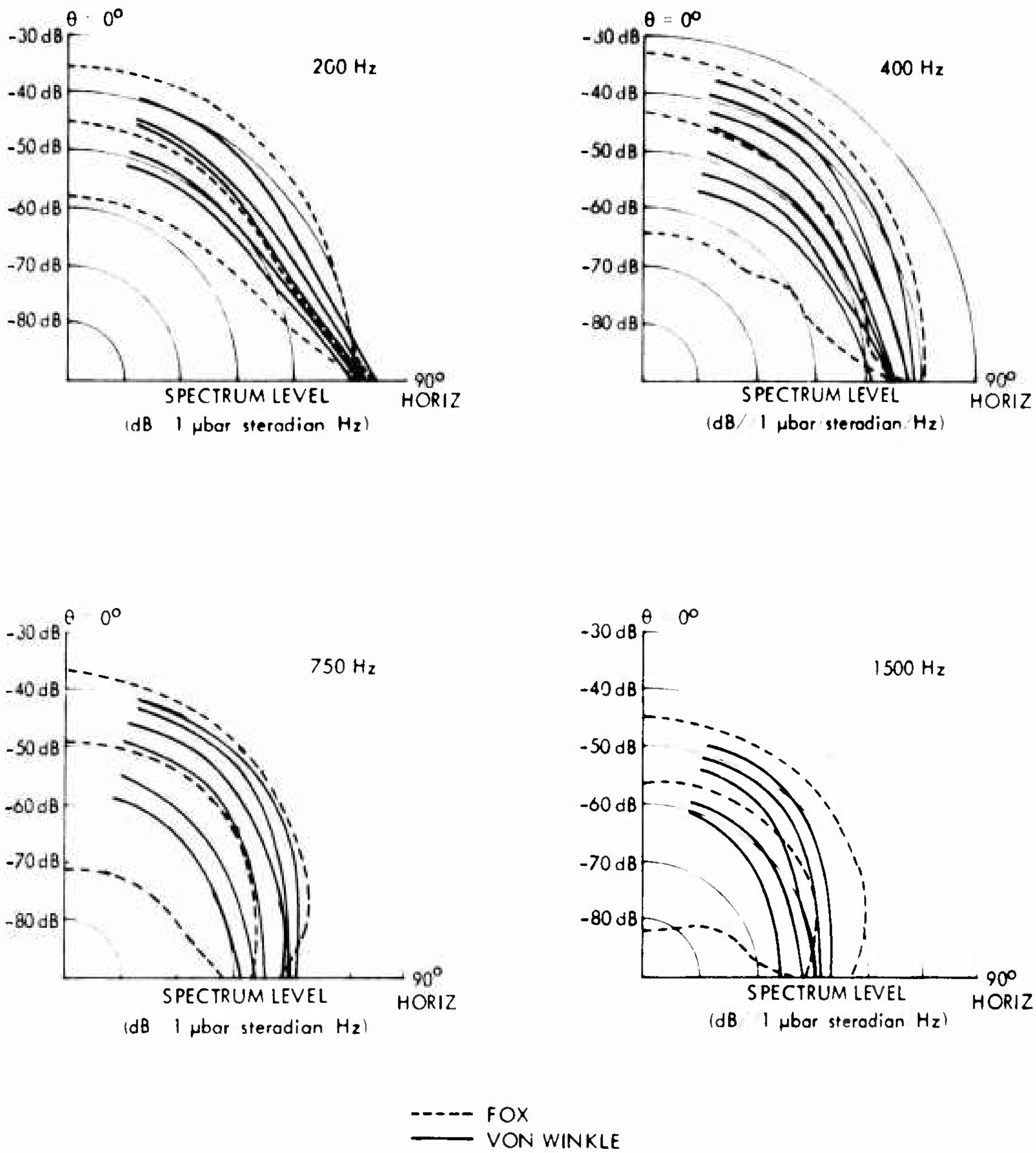

Fig. 6. Superposition of Von Winkle's and Fox's Results for the Vertical Directionality of Ambient Sea Noise

In most cases, the results agree. Both authors make the same qualitative evaluation of the results. Von Winkle stated the following:

> Qualitatively, this sort of directionality is what one should expect. Noise emanating from distant sources arrives at the array at near the horizontal, its high-frequency components having been strongly attenuated in transit. On the other hand, noise incident from the vertical originated from sources nearly above the array and, because of the much shorter path lengths involved is subject to much less attenuation.
>
> This interpretation is consistent also with the especially strong "sea state" dependence of noise from near the vertical. Horizontal noise, originating in distant shipping, should exhibit little "sea-state" dependence; this expectation is borne out by the results.

A quantitative comparison can be made by normalizing each of Fox's curves to the nearest of Von Winkle's curves near the vertical ($\theta \approx 15°$). The curves differ at other values of θ by varying amounts. For moderate and high sea states the amount of the difference varies from 0 to 5 dB; for low sea states it varies from 8 to 20 dB. Von Winkle excluded any data taken during periods when line components could be detected by narrow-band spectral analysis. Fox excluded data "when noise due to local shipping seemed to be predominant." Thus, one would expect Von Winkle to have excluded data that Fox kept. Consequently, at low sea states Fox's data should have higher horizontal noise levels caused by moderately distant shipping. Note that in Fig. 6 Fox's curves for Sea State 1 show a relatively larger amount of horizontal noise than do Von Winkle's.

Fox's data also show a greater spread in levels between the lowest and the highest curves. The difference may be attributable to different sorting techniques. It could also be due to seasonal effects since Von Winkle's results represent an average over winter and summer, wheras Fox's results apply only to winter.

Thus, the significant differences between comparable results of the two studies might be attributed to differences in the experimental and analytical procedures, but, of course a physical explanation can not be excluded at this time. Further research may clarify the differences.

Figures 7 and 8 show the results of Becken's study in a 750- to 1500-Hz frequency band. Data were taken in 6000 to 12,000 ft of water with the array suspended 130 to 1000 ft below the surface.[15] In evaluating the results on vertical directionality presented in Fig. 7, Becken made the following statement:

> Sea state effects are apparent with maximum to minimum differences for a given condition varying from less than 1 decibel for sea state one-half to 6 decibels for the highest sea state. Less significance can be attributed to differences in anisotropy magnitude as a function of array depth because of uncertainty in the constancy of sea state during the recording period.

Figure 8 shows azimuthal directionality. The maximum levels are consistently aligned with the wavefronts of the ocean surface and the minimum levels are consistently perpendicular to the wavefronts. The effect is more pronounced for angles of θ more nearly vertical (where θ is the angle from the vertical looking upward toward the surface). Becken continued as follows:

> This fact suggests a nonuniform radiation pattern of the white cap or wavelet source, transmission in directions normal to the wavefront is impeded by the troughs, with lateral transmission along the ridges being less affected.

Liggett proposed a simple directivity function that agrees with Von Winkle's and Fox's results. It is used to study the covariance for the case of vertical receiving points. The function is

$$N(\theta) = A\, e^{A\cos\theta} / [2\pi(e^{A} - 1)] \quad .$$

where

θ is the angle from the vertical

A is a function of frequency, sea state, and other environmental factors.

Figure 9 shows N for various values of the parameter A, and it also shows another directivity function,

$$N' = \frac{1}{\pi}\cos\theta \quad .$$

Figure 10 shows comparisons between the analytical approximation for various values of A and experimental results.[16] The 112- and 355-Hz curves are from Von Winkle, and the 750-Hz curves are from Fox.

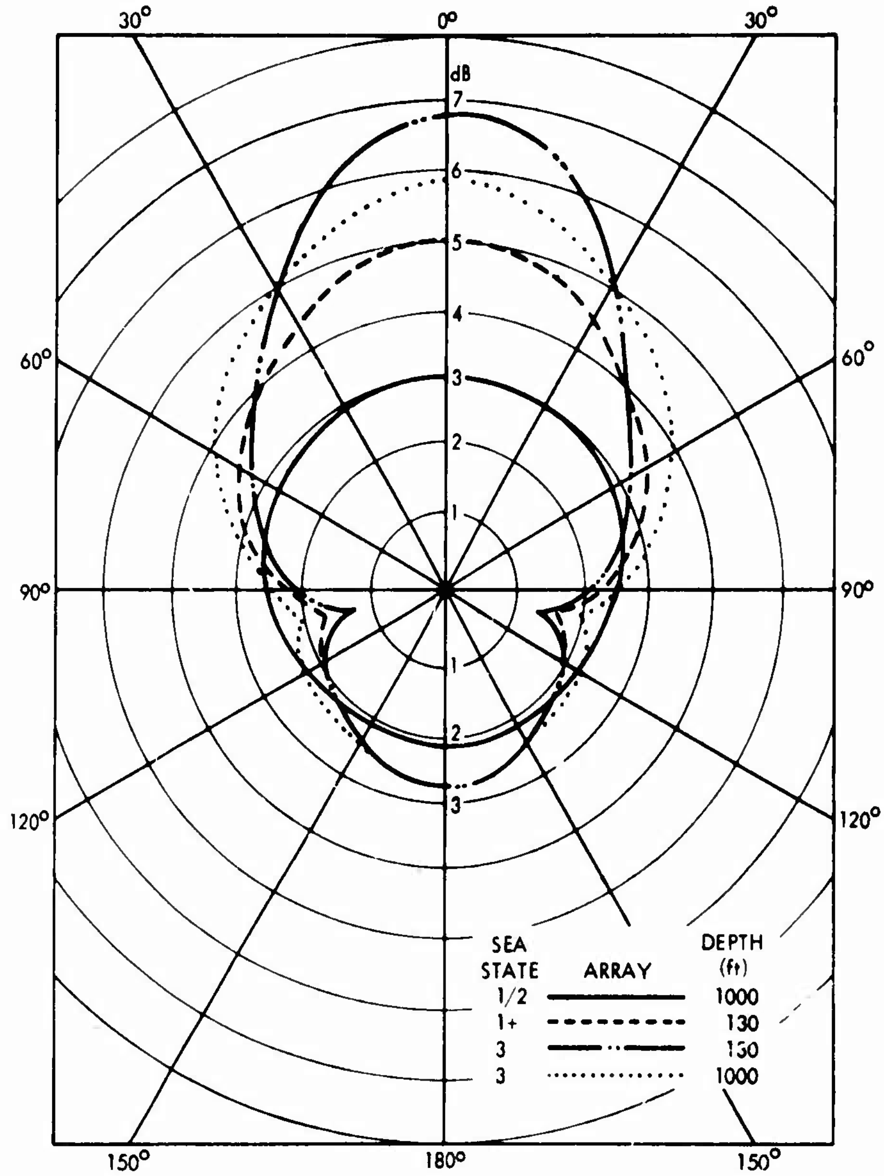

Fig. 7. Becken's Results for the Vertical Directionality (in Relative dB's) of Ambient Noise in a 750- to 1500-Hz Band Studied with an Array Near the Surface (After Becken, Reference 15)

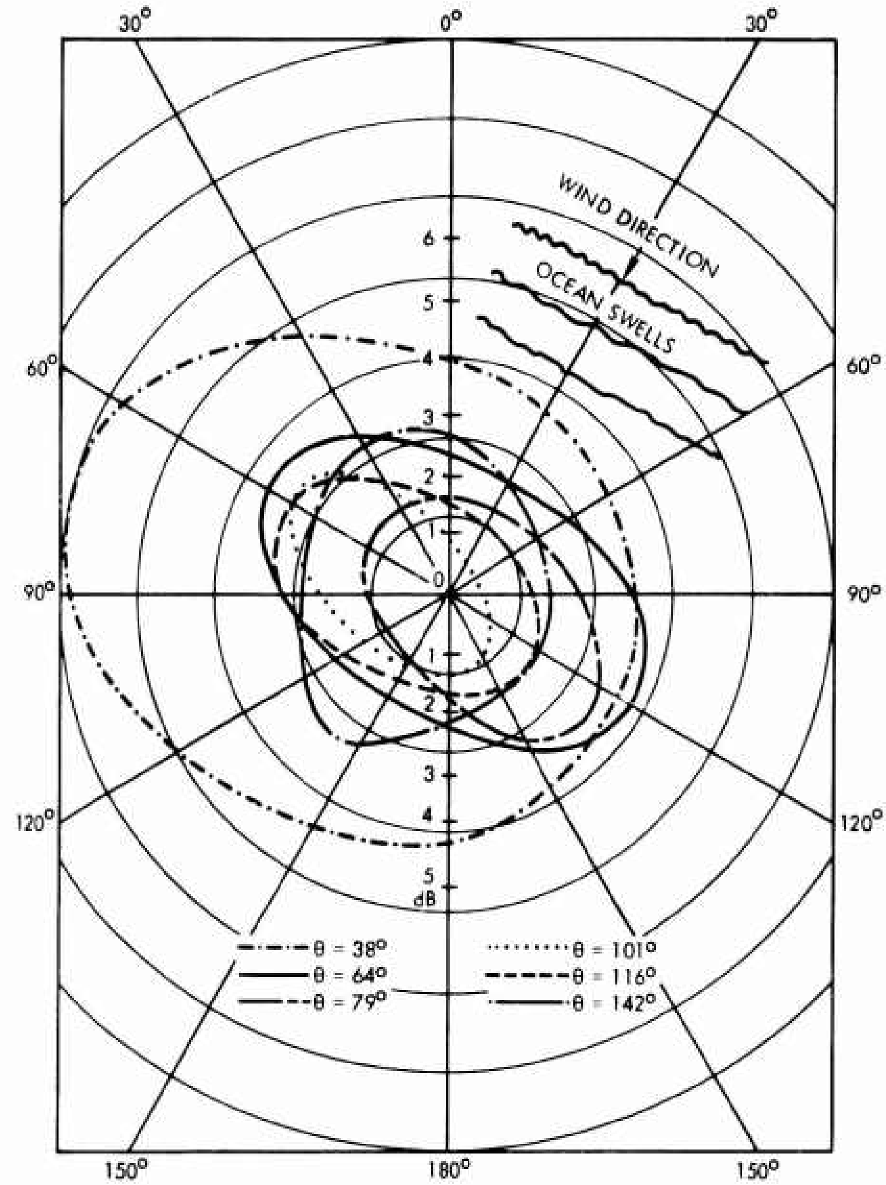

Fig. 8. Becken's Results for Azimuthal Dependence of Ambient Noise in a 750- to 1500-Hz Band Studied with an Array Near the Surface (After Becken, Reference 15)

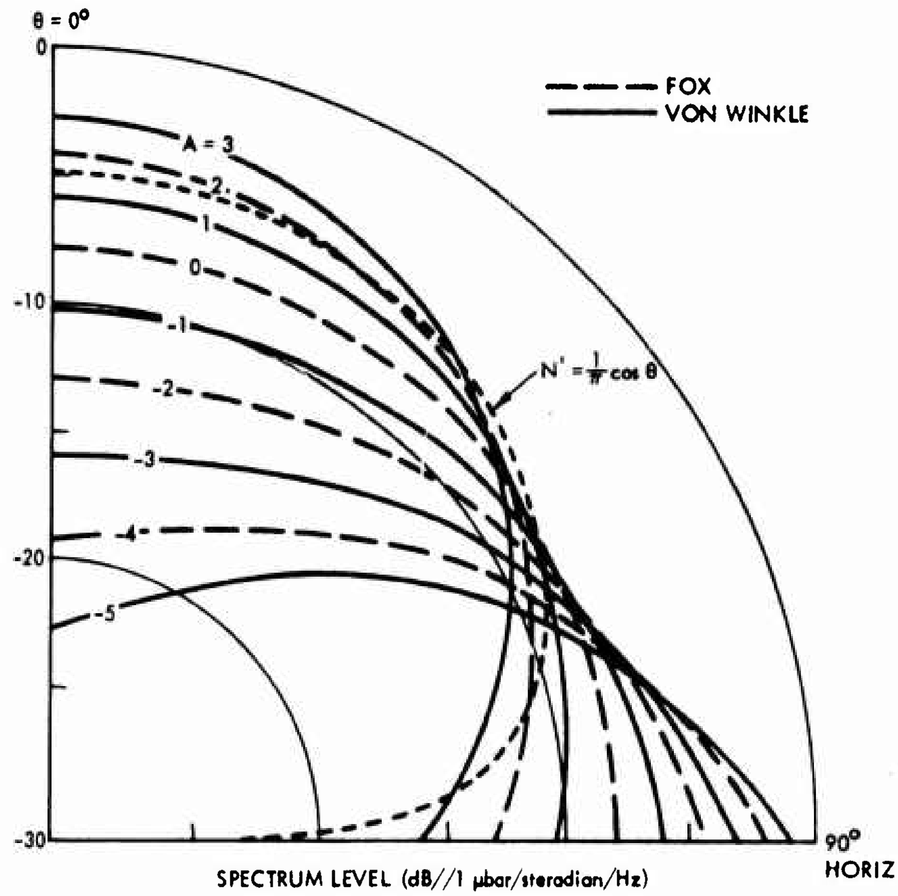

Fig. 9. Liggett's Theoretical Noise Directivity Function for Several Directivity Parameter Values (After Liggett, Reference 16)

Talham also derived a directivity function[17] :

$$N(\theta) = [DPW\, g(\theta')\, \exp(-2ar)]\, [\cos(\theta')]^{-1}\, [1 - \beta\gamma \exp(-4ar)]^{-1} \quad ,$$

where

$N(\theta)$ = spectrum level (dB//1 μbar^2)/steradian (Hz)

θ = angle from the vertical

D = surface density of source elements

P = power emitted by an isotropic point source (watts/solid angle)

W = $[\sin(\theta)/\sin(\theta)]^2$

$g(\theta')$ = amplitude directionality function

θ' = angle between source element and observation point

a = attenuation constant (nepers/kiloyard)

r = actual path length (kiloyards) between source and observer

β = bottom reflection coefficient

γ = coefficient of surface scattering loss.

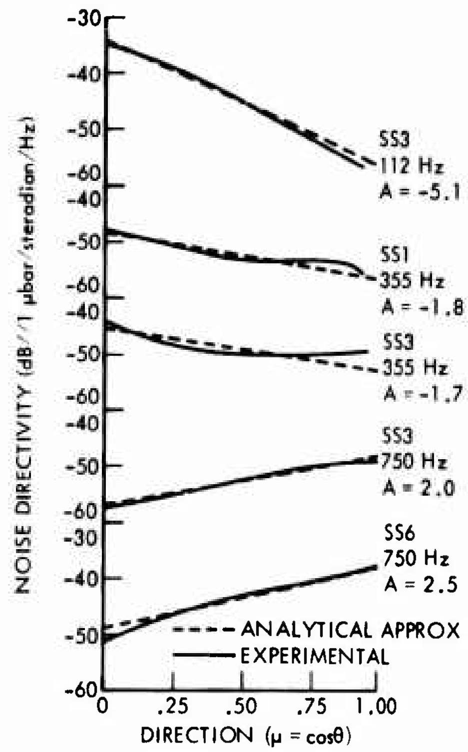

Fig. 10. Comparison of Liggett's Theoretical Noise Directivities with Experimental Results (After Liggett, Reference 16)

By assuming a simple source, $\cos\theta$ source, $\cos^2\theta$ source, and Becken-type source, Arase in Fig. 11 showed that Talham's model had the following relationship to Fox's data. Taking agreement within 3 dB to be a good fit, Arase stated:

> ...the assumption of a simple source fits the data at 200, 400, and possibly at 750 cps. At sea state 5, the assumption of $\cos^2\theta$ sources fits the data at 200, 400, 1500 cps. At sea state 3, each of the four frequencies requires its own type of radiator, none of which fit too well, indicating the complex character of the noise at this intermediate sea state.

In summary, available data on directivity are limited, but what is available is shown in Figs. 6, 7, and 8. Theoretical models seem promising, but more verification is needed.

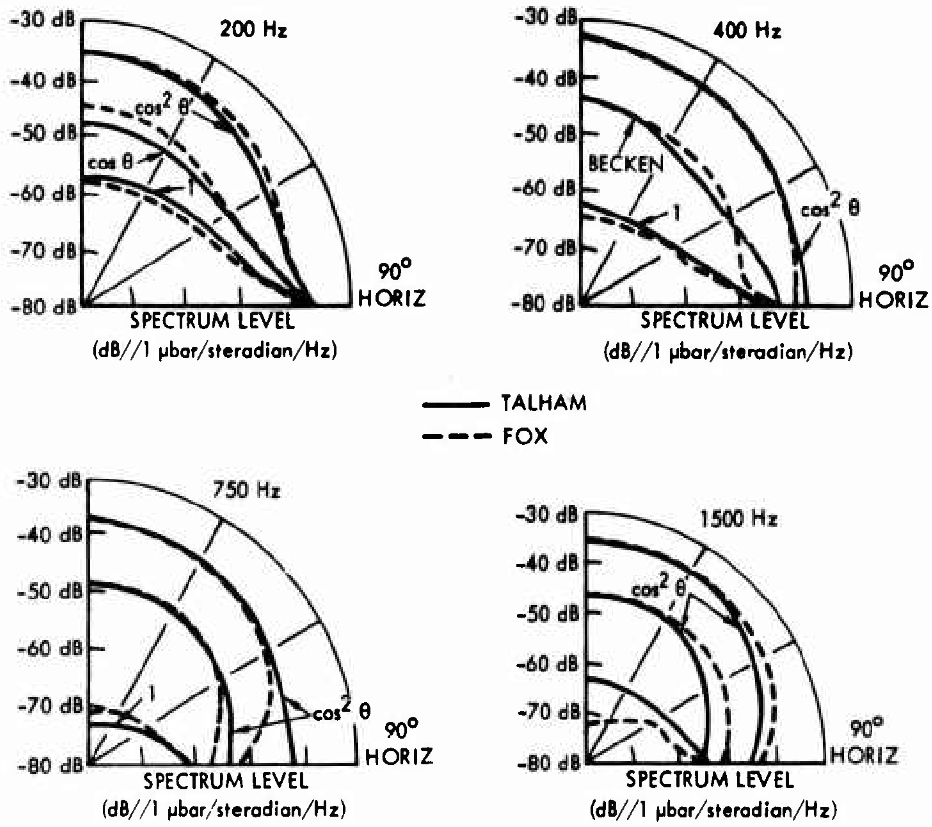

Fig. 11. Comparison of Talham's Theoretical Noise Directivities with Fox's Experimental Results (After Arase, Reference 19)

CORRELATIVE PROPERTIES*

Research in this area has relied on the concept of two sources. A very effective model is available for surface-generated noise, but noise from distant shipping has defied theoretical treatment.

The spatial correlation function can be calculated from the mean-square noise output of a two-hydrophone array and of one hydrophone alone. Following the notation of Cron and Sherman,[20] we see that

$$\rho(\mathbf{r}_1, \mathbf{r}_2, T_{12}) = \frac{\langle e^2 \rangle_2}{2 \langle e^2 \rangle_1} - 1 \quad ,$$

*This section was prepared jointly by the author and H. A. Hurwitz.

where $<e^2>_1$ and $<e^2>_2$ are the mean-square outputs of one receiver alone and of two receivers, respectively, and $\rho(\vec{x}_1, \vec{x}_2, T_{12})$ is the normalized spatial correlation function of the noise pressure at the two points $\vec{x}_1$ and $\vec{x}_2$ with T_{12} the delay time between the receivers at those points.

Non-Wind-Dependent Noise

Cron and Sherman[20] hypothesized that non-wind-dependent noise was due to a uniform volume distribution of identical noise sources and derived the associated correlation function. However, the observed horizontal directionality of this noise casts doubt on such a volume model and experimental results have failed to substantiate it. Thus, the equations are not included here. At present, there is no suitable model for the correlation function of non-wind-dependent noise.

Surface-Generated Noise

The model for surface-generated noise consists of identical noise sources distributed uniformly over the surface. The geometry for this model appears in Fig. 12. A vertical receiver orientation means that the line joining the receivers is perpendicular to the surface; a horizontal orientation indicates that

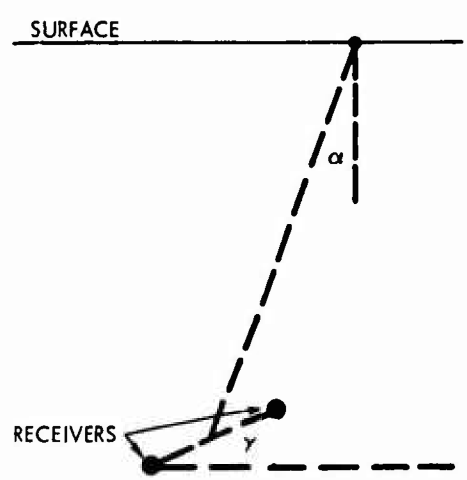

Fig. 12. Geometry for the Surface-Noise Model (γ is the angle the line connecting the receivers makes with the horizontal, and α is the angle between the line connecting the receivers to surface source and the vertical.)

the line joining the receivers is parallel to the surface. In order to simplify the mathematical analysis, the distance between the receivers and the surface is assumed to be much greater than the distance between receivers. Factors which affect the correlation function are receiver orientation, time delay, frequency, radiative characteristics of the surface sources, and boundaries. Table 1 lists the equations presented and the conditions under which they apply. The "Reference" column indicates the document in which the corresponding equation can be found.

Table 1

SURFACE-GENERATED NOISE EQUATIONS AND CONDITIONS

Reference	Equation	Receiver Orientation	Time Delay	Frequency	$g(\alpha)$	Boundaries
20	1	any	zero	single	any	none
21	2	any	any	single	any	none
22	3	vertical	any	spectrum	$\cos^n\alpha$	none
22	4	horizontal	any	spectrum	$\cos^n\alpha$	none
23	5	horizontal	any	spectrum	$\cos\alpha$	none
23	6	vertical	any	spectrum	$\cos\alpha$	none
24	7	horizontal	zero	single	$\cos^n\alpha$	yes
24	8	vertical	zero	single	$\cos^n\alpha$	yes

It is assumed that the ocean has a constant velocity profile. In addition, the following eight equations contain symbols defined as follows: $\lambda \equiv$ the wavelength, $K \equiv$ the wave number $(2\pi/\lambda)$, $d \equiv$ the distance between receivers, $c \equiv$ the velocity of sound, $w \equiv$ the angular frequency $(2\pi c/\lambda)$, $T \equiv$ the electrical time delay, $\sqrt{f_1 f_2} \equiv$ the geometric mean frequency of the flat bandwidth f_1 to f_2, $\lambda_g \equiv$ the geometric wavelength $(c/\sqrt{f_1 f_2})$, $x = d/\lambda_g$, $\psi = T\,c/d$, $b = \sqrt{f_2/f_1}$, $Si(x) = \int_0^x \sin u/u \; du$, $J_n \equiv$ the nth order Bessel function, $l \equiv$ the depth, and $g \equiv$ the amplitude directionality function.

For the simplest case of zero time delay and single frequency, Cron and Sherman[20] show that

$$\rho(d, \gamma, 0) = \frac{\int_0^{\pi/2} g^2(\alpha) \tan\alpha \cos(kd \sin\gamma \cos\alpha) \times J_o(kd \cos\gamma \sin\alpha)\, d\alpha}{\int_0^{\pi/2} g^2(\alpha) \tan\alpha\, d\alpha} . \qquad (1)$$

Figure 13 shows the spatial correlation function of Eq. (1) for the cases of horizontal receivers ($\gamma = 0$) and vertical receivers ($\gamma = \pi/2$). The noise radiates with a $g(\alpha) = \cos\alpha$ amplitude.

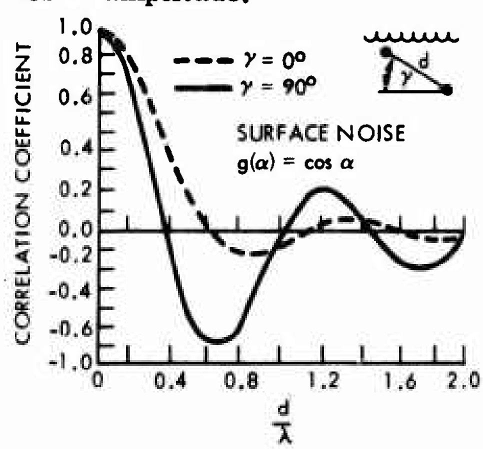

Fig. 13. Spatial Correlation Functions for Horizontal and Vertical Feceiver Orientations in the Surface-Noise Model with $g(\alpha) = \cos\alpha$ (From Cron, Reference 20)

Generalizing to any time delay gives

$$\rho(d, \gamma, T) = \rho(d, \gamma, 0) \cos\omega T + \left(\rho\ d, \gamma, \frac{\pi}{2\omega}\right) \sin\omega T \ , \qquad (2)$$

where

$$\rho\left(d, \gamma, \frac{\pi}{2\omega}\right) = \frac{\int_0^{\pi/2} g^2(\alpha) \tan\alpha \sin(kd \cos\alpha \sin\gamma) \times J_o(kd \cos\gamma \sin\alpha)\, d\alpha}{\int_0^{\pi/2} g^2(\alpha) \tan\alpha\, d\alpha} .$$

Equations (3) through (6), which were derived by Hassell[25] and Edie,[26] allow for a flat spectrum over a finite bandwidth. They integrate the product of the single-frequency correlation function and the power spectrum over the bandwidth. Only horizontal and vertical receiver orientations were considered:

$$
\begin{aligned}
\rho_n(d, T, b) = {} & \frac{n}{\pi\chi(b - 1/b)} \int_0^1 \frac{q^{2n-1}}{q - \psi} \\
& \times \Big\{ \sin\left[2\pi b\chi (q - \psi)\right] \\
& - \sin\left[\frac{2\pi\chi}{b}(q - \psi)\right] \Big\}\, dq
\end{aligned}
\tag{3}
$$

$$n \geq \frac{1}{2}, \quad \chi > 0$$

and

$$
\rho_n(d, T, b) = \frac{2^n n!}{2\pi\chi(b - 1/b)} \int_{2\pi\chi/b}^{2\pi b\chi} \frac{J_n(q)}{q^n} \cos q\psi \, dq
\tag{4}
$$

$$m = 0, \frac{1}{2}, 1, \frac{3}{2}, \ldots, \left(m + \frac{1}{2}\right)! = \sqrt{\pi}\,\frac{1 \cdot 3 \ldots (2m+1)}{2^{m+1}},$$

where q is the variable of integration, and n is an arbitrary constant to be empirically defined. The other symbols are as defined earlier. The following equations illustrate Eqs. (3) and (4) for $n = 1$:

$$
\rho(d, T, b) = \frac{2}{2\pi\chi(b - 1/b)} \int_{2\pi\chi/b}^{2\pi b\chi} \frac{J_1(q)}{q} \cos q\psi \, dq
\tag{5}
$$

and

$$
\begin{aligned}
\rho(d, T, b) = {} & \frac{1}{2\pi\chi(b - 1/b)} \Big\{ 2\, \frac{\cos(2\pi\chi/b) - 1}{2\pi\chi/b} \\
& \times [\cos(2\pi\chi\psi/b)] - 2\, \frac{\cos 2\pi b\chi - 1}{2\pi b\chi} \\
& \times (\cos 2\pi b\chi\psi) + 2\psi[\mathrm{Si}(2\pi b\chi\psi) \\
& - \mathrm{Si}(2\pi\chi\psi/b)] - \psi\{\mathrm{Si}[(1 + \psi)\, 2\pi b\chi] \\
& - \mathrm{Si}[(1 - \psi)\, 2\pi b\chi] - \mathrm{Si}[(1 + \psi)\, 2\pi\chi/b] \\
& + \mathrm{Si}[(1 - \psi)\, 2\pi\chi/b]\} \Big\} .
\end{aligned}
\tag{6}
$$

Allowing for boundaries and assuming a hard bottom and a receiver location near the bottom (l >> d), Cron and Sherman derived the following equations for horizontal and vertical receivers, respectively:

$$\rho(d, l) = \frac{\int_0^{\pi/2} J_0(kd \sin \alpha) \cos^2(kl \cos \alpha) \cos^{2n-1} \alpha \sin \alpha \, d\alpha}{\int_0^{\pi/2} \cos^2(kl \cos \alpha) \cos^{2n-1} \alpha \sin \alpha \, d\alpha} \tag{7}$$

and

$$\rho(d, l) = \frac{\int_0^{\pi/2} \cos\left[k\left(l - \frac{d}{2}\right)\cos\alpha\right] \cos\left[k\left(l + \frac{d}{2}\right)\cos\alpha\right] \cdot \cos^{2n-1}\alpha \sin\alpha \, d\alpha}{\left\{\int_0^{\pi/2} \cos^2\left[k\left(l - \frac{d}{2}\right)\cos\alpha\right] \cos^{2n-1}\alpha \sin\alpha \, d\alpha \cdot \int_0^{\pi/2} \cos^2\left[k\left(l + \frac{d}{2}\right)\cos\alpha\right] \cos^{2n-1}\alpha \sin\alpha \, d\alpha\right\}^{1/2}} . \tag{8}$$

For $l = 0$, or $l \to \infty$, Equation (7) reduces to the no-boundary case given in Fig. 1. Cron and Sherman drew the following conclusions from their investigation of the effects of boundaries: (1) boundaries do affect spatial correlation if the center of the line joining the two receivers is within two wavelengths of the boundary, (2) for the case of surface noise and vertical receivers, if the center of the receiver-receiver line is at a distance of two wavelengths or more from the boundary, there is very little change in the spatial correlation as compared with the no-boundary case, and (3) for the case of surface noise and horizontal receivers, there is a very slight change in the spatial correlation as compared with the no-boundary case if the receivers are at a distance of five wavelengths or more from the boundary.

Experimental Verification

Several studies have been conducted to experimentally verify the above theoretical models. Linnette and Thompson[27] showed that, in a frequency range of 500 to 1500 Hz, a surface noise model could indeed explain the data. In the directionality of amplitude function, $\cos^{n}\alpha$, m was approximately two or three for wind speeds of 10 to 15 knots and approached unity for speeds between 2 and 5 knots.

Cron, Hassell, and Keltonic[23] performed experiments in Bermuda with 12 elements of a 40-element array and concluded that reasonable agreement between experiment and theory was obtained in the 400- to 1000-Hz frequency band when a cos α amplitude was assumed. In a 200- to 400-Hz band, their data did not agree with the model for any value of n. This is not surprising since non-wind-dependent noise is expected to dominate at those frequencies. In addition, the data did not agree with the volume-noise model. This lack of agreement supports the hypothesis that non-wind-dependent noise is due to distant shipping and arrives from horizontal directions.

Figures 14, 15A, 15B, and 16 exhibit graphs derived from the work of Cron et al. Figure 14 portrays plots of the spatial correlation functions for the volume-noise model (isotropic noise model) and the surface-noise model for $g(\alpha) = \cos^m \alpha$, m = 1, 2, and 3, in the 400- to 600-Hz frequency range.[20]

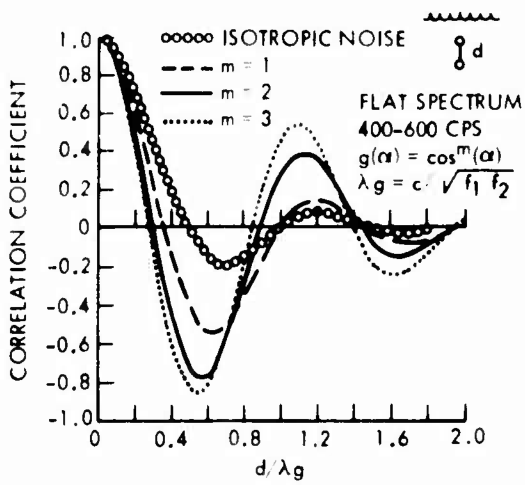

Fig. 14. Spatial Correlation Functions for Vertical Receivers for the Isotropic and Surface-Noise Models in the 400- to 600-Hz Band (From Cron, Reference 23)

Figures 15A and 15B present comparisons of experimental points and theoretical curves for g (α) = cos α for frequency bands of 600 to 800 Hz and 200 to 400 Hz, respectively, both with sea states of 3.[20] Close agreement is seen in the 600- to 800-Hz band, whereas in the 200- to 400-Hz band the obvious failure of the surface-noise model to describe low-frequency and low-wind-speed conditions can be observed. In Fig. 16, experimental points are compared with the spatial-temporal correlation functions of the volume-noise model and the cos α surface-noise model for a band of 800 to 1000 Hz and Sea State 4. The success of the latter theory is evident.

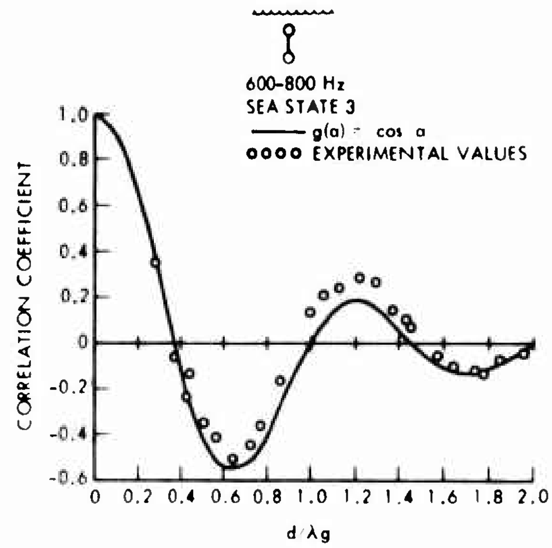

Fig. 15A. Experimental and Theoretical Values of Spatial Correlation for the 600- to 800-Hz Band and Sea State 3 (From Cron, Reference 23)

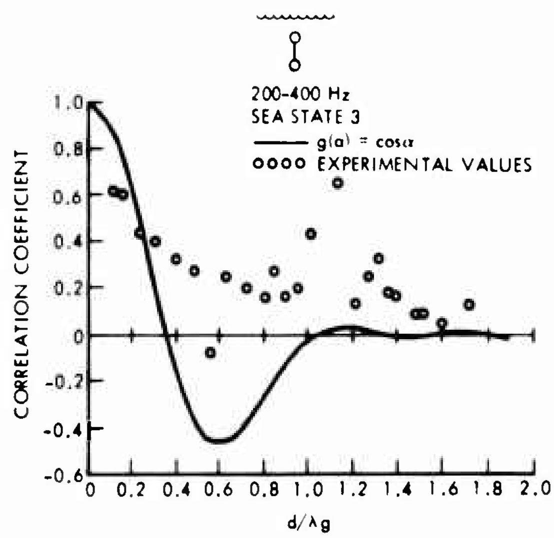

Fig. 15B. Experimental and Theoretical Values of Spatial Correlation for the 200- to 400-Hz Band and Sea State 3 (From Cron, Reference 23)

Assard and Hassell[28] used a deep-submergence vehicle (Diving Saucer SP-300) to test the validity of the surface-noise model for $g(\alpha) = \cos\alpha$. Good agreement was obtained in the 400- to 1200-Hz range at depths of 150 and 300 m with a six-element linear array.

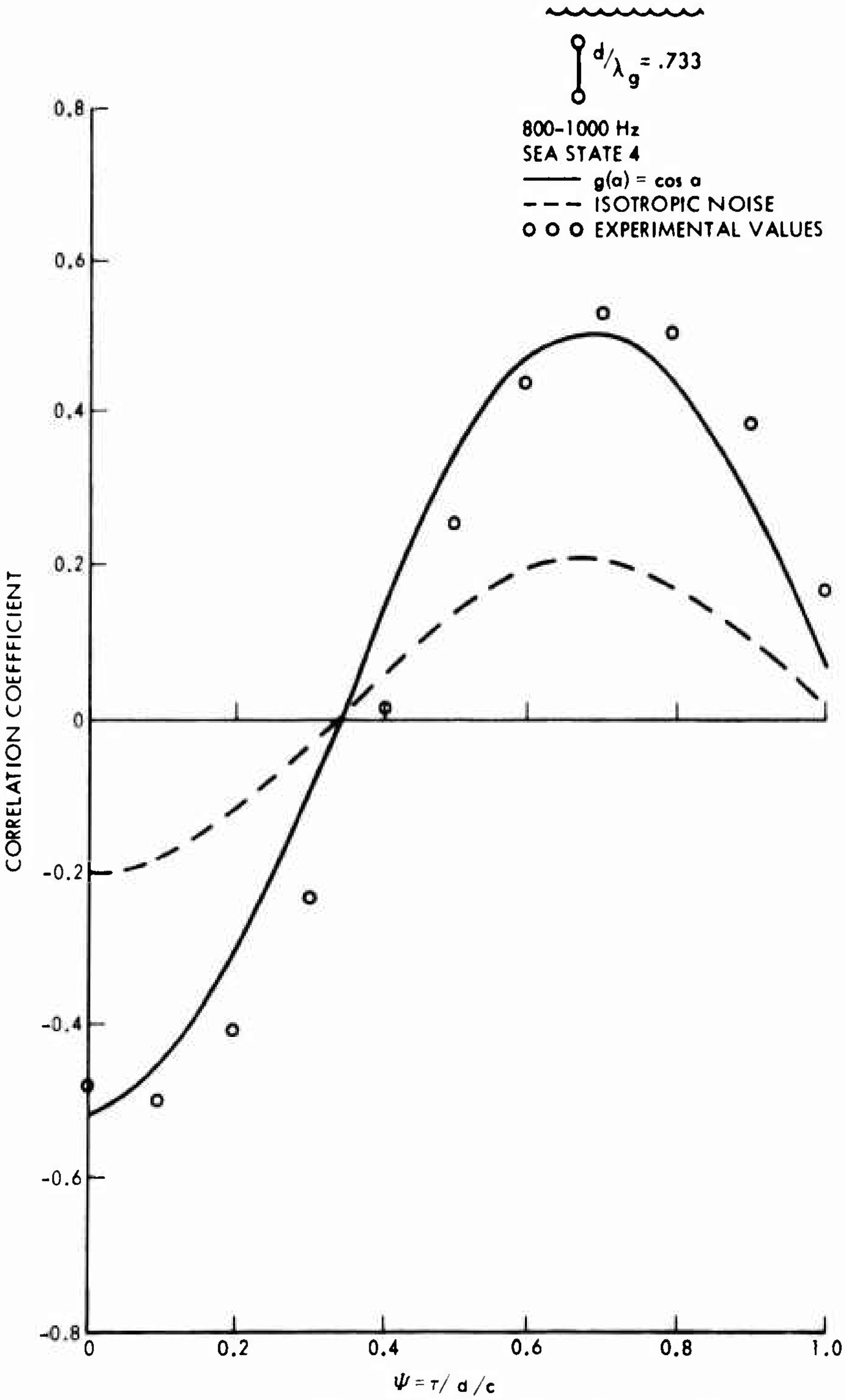

Fig. 16. Experimental and Theoretical Values of Spatial-Temporal Correlation for the 800- to 1000-Hz Band and Sea State 4 (From Cron, Reference 23)

Arase and Arase[22] considered pairs of hydrophones placed both horizontally and vertically. Horizontal pairs were stationed on a bottom 3000 ft deep and frequencies between 22 and 63 Hz were examined. For sea states up to and including 5, a model of surface omnidirection ($g(\alpha) \equiv 1$) sources fit the data. No model could satisfactorily fit the data at 45 Hz and Sea State 8. For vertical pairs, placed from 100 to 400 ft above a 14,500-ft-deep bottom, at 250 Hz and Sea State 5, results obtained with $g(\alpha) = \cos^2 \alpha$ agreed with experimental data; in the 400- to 1131-Hz band at Sea State 5, $\cos \alpha$ is required. With intermediate sea states, a satisfactory fit could not be obtained with the theoretical model.

For frequencies of 400 to 1000 Hz and surface wind speeds of 11 to 63 knots, Hassell and Keltonic[29] have demonstrated that experiment and theory agree quite closely on correlation values, with $g(\alpha) = \cos \alpha$. For the 200- to 400-Hz range, horizontally arriving noise predominates for wind speeds under 21 knots. For higher wind speeds, it seems that the surface-noise model applies.

Summary

Research on correlative properties is related to the two predominant sources of ambient noise. Distant shipping noise arrives uniformly from horizontal directions and does not appear to be susceptible to a theoretical treatment. Surface-generated noise can be described by a model assuming a uniform distribution of surface noise sources radiating with a $\cos^n \alpha$ amplitude directionality.

Which source dominates has been found experimentally to depend on frequency and wind speed. The relative areas of dominance are shown graphically in Fig. 17 by Urick.[30] All experimental data agree with this diagram, except for that obtained by Arase and Arase in which a surface model of omnidirectional sources explained their data between 22 and 63 Hz.

Values of n between 1/4 and 3 have been found experimentally to be applicable under a variety of conditions. However, in most cases where surface-generated noise is clearly dominant, $n = 1$ is the best approximation to the data. At frequencies where the two sources both contribute, the appropriate value of n is less clear.

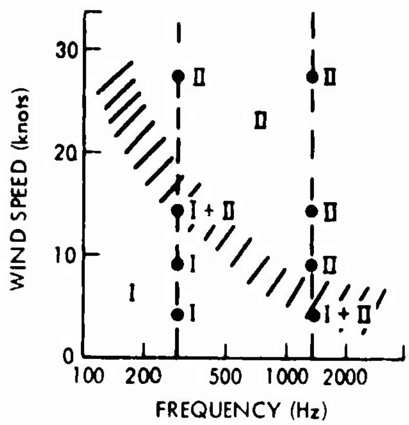

Fig. 17. Graphic Representations of Areas of Dominance of Type I and II Noise (From Urick, Reference 30)

SOURCES OF AMBIENT SEA NOISE

As was discussed in the introduction, surface agitation and distant shipping are nearly always important sources of ambient noise. The contribution of distant shipping is discussed thoroughly by Wenz[4] and is not mentioned here. He also discusses the mechanisms associated with surface-generated noise, but recent experimental results are also presented here and other studies are summarized.

Additional sources that are important are as follows:

a. Biological sources

b. Seismic sources

c. Rain.

Biological sources are thoroughly reviewed in a summary by Tavolga,[5] and Wenz also includes a short discussion. The summary by Tavolga is especially recommended. Seismic sources of ambient noise are covered by Wenz. Rain is discussed here following a summary on surface agitation.

SURFACE AGITATION

Wenz discusses the mechanisms by which the sea surface produces noise.[4] The following discussion will cover the relationship that has been found between environmental parameters and surface-generated noise.

It has always been obvious that ambient noise level is correlated with surface conditions. High wind and rough seas mean higher ambient noise levels. Only recently, however, has it been known that wind speed, rather than wave height or sea state, was best correlated with spectrum levels. The results of a study by Perrone are shown in Fig. 18.[9] He found wind speed to be significantly better correlated with ambient noise levels than is wave height. Other studies substantiate his findings. Sea state is of limited value because it is subjective, and estimates vary from one observer to another. It should be used only if suitable wind speed measurements are not available.

The contribution of surface-generated noise has been generally found to be significant above 100 Hz and between 10 and 15 Hz. However, in Perrone's studies wind-dependent noise has shown up weakly at 28 and 35 Hz also. The correlation coefficients in Fig. 18 reflect the wind dependence.

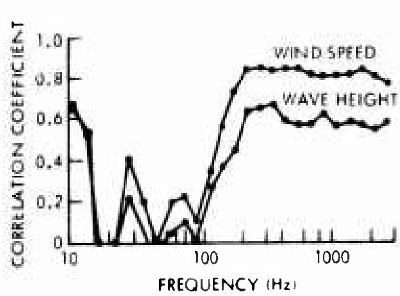

Fig. 18. Cross-Correlation of Ambient Noise Levels with Wind Speed and Wave Height (From Perrone, Reference 9)

The effect of a time lag between changes in ambient noise levels and changes in sea surface conditions has also been investigated by Perrone.[9] The essence of his results are given in Figs. 19 and 20. The relationship between the two most prominent environmental parameters, wind speed and wave height, is shown in Fig. 19. Maximum correlation between wind speed and wave height was found when wind speed leads by 5 to 6 h.

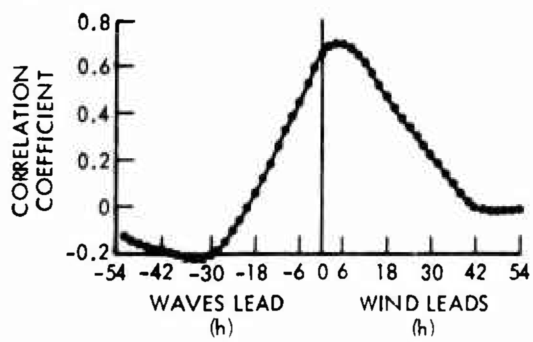

Fig. 19. Cross-Correlation of Wind Speed with Wave Height for Time Delays Up to 54 h (From Perrone, Reference 9)

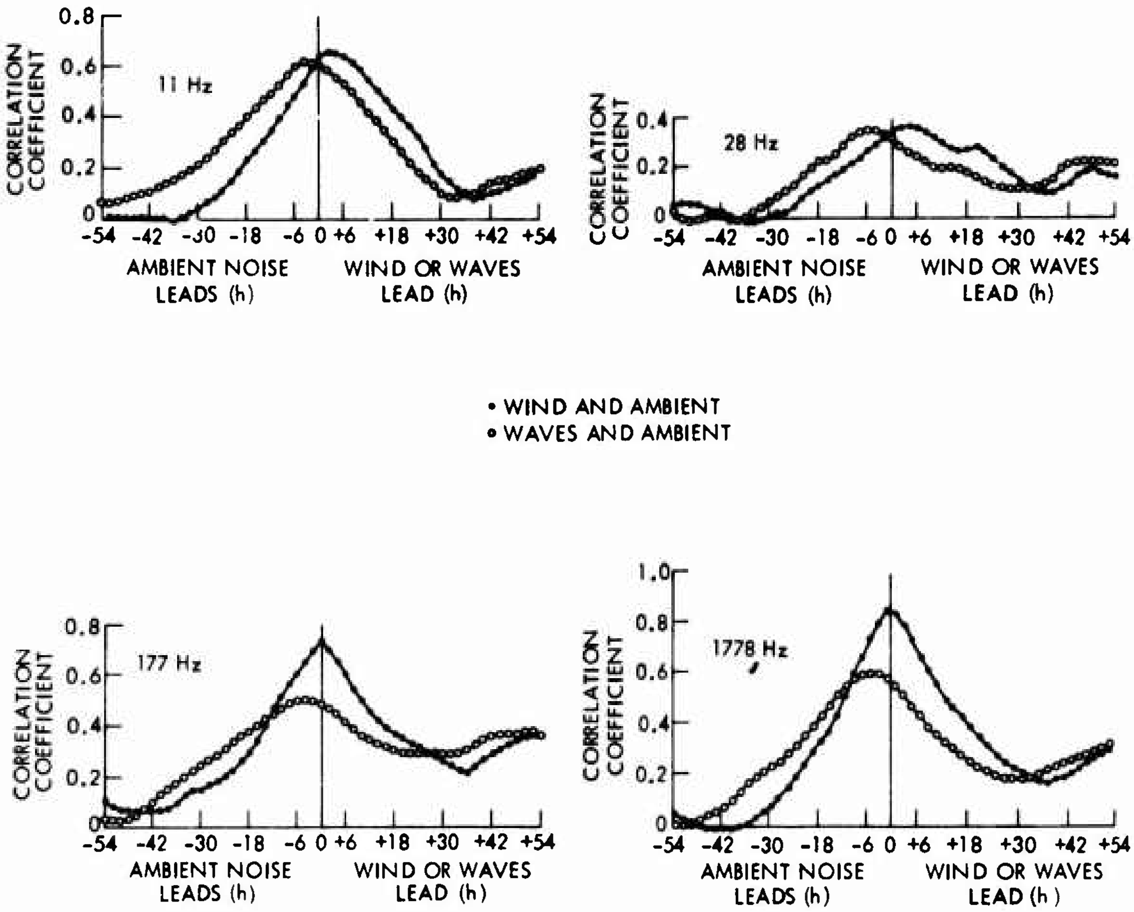

Fig. 20. Cross-Correlation of Ambient Noise with Wind Speed and Wave Height for Time Delays Up to 54 h (From Perrone, Reference 9)

Figure 20 shows that ambient noise levels correlate best with wind speed at zero time lag for the frequencies of 177 and 1778 Hz, which are taken to be typical of the frequency range from 112 to 2812 Hz. At 11 and 28 Hz, the maximum coefficient occurs when the wind leads the noise by about 6 h. This and other factors led Perrone to suggest that ambient noise due to surface agitation at the lower frequencies is attributable to a different mechanism than that above 100 Hz.

There is still some question as to whether distant storms contribute to local ambient noise levels. It is doubtful that they do; nevertheless, studies to date are inconclusive. Frisch found that "Many of the forms of weather data now available no not lend themselves well to this type of study."[31] The only thing he could say on this topic as the result of his study was that "The results do not support the hypothesis of very-long-range noise/storm dependence."

Surface-generated noise has been shown to have a distinctive relationship to the logarithm of wind speed by Piggott.[32] He found that

$$L(f) = A(f) + 20\, n(f) \log v \quad ,$$

where

$A(f)$ = spectrum level in dB at 1 knot wind speed
$20\, n(f)$ = the slope in dB per decade
v = wind speed;

i.e., ambient noise levels are linearly related to the logarithm of wind speed. Figure 21 demonstrates his findings at several frequencies.

Several sets of data taken near Bermuda by NUSC scientists have also been analyzed and found to show a similar relationship at frequencies where wind dependence was observed.[10] Figure 22 shows data taken by Perrone as an example. This distinct relationship is striking and was discovered by Piggott 6 years ago. However, ambient noise researchers have not yet taken it into account in analysis and modeling. It would seem to be a powerful tool if applied.

RAIN

Rain can be a significant source of noise in the ocean, as shown in Fig. 23. Increases in ambient noise levels from 10 to 35 dB were measured by Bom,[33] and similar results have been reported by other authors.

Bom's measurements are the most extensive that have been published. He made them in a small circular lake (diameter about 250 m) with a maximum depth of 10 m. He estimates that bottom reflections contribute about 1.4 dB to the measured noise levels. Because of the small size of the lake, ambient noise levels appeared to be independent of wind speed up to 15 knots, which includes all the data he reported on. The curves in Fig. 24 represent best fits to the data for each of the five frequency bands studied. In Bom's article, 95-percent-confidence limits are also given.

The other major work on this topic is a theoretical study by Franz.[34] He predicts the spectrum levels shown in Fig. 25 for the various rain rates shown.

A comparison of his predictions and Bom's measurements was given in Bom's article and is reproduced as Fig. 26. Bom's measurements are significantly higher than Franz's calculations, but no explanation for the discrepancy is available.

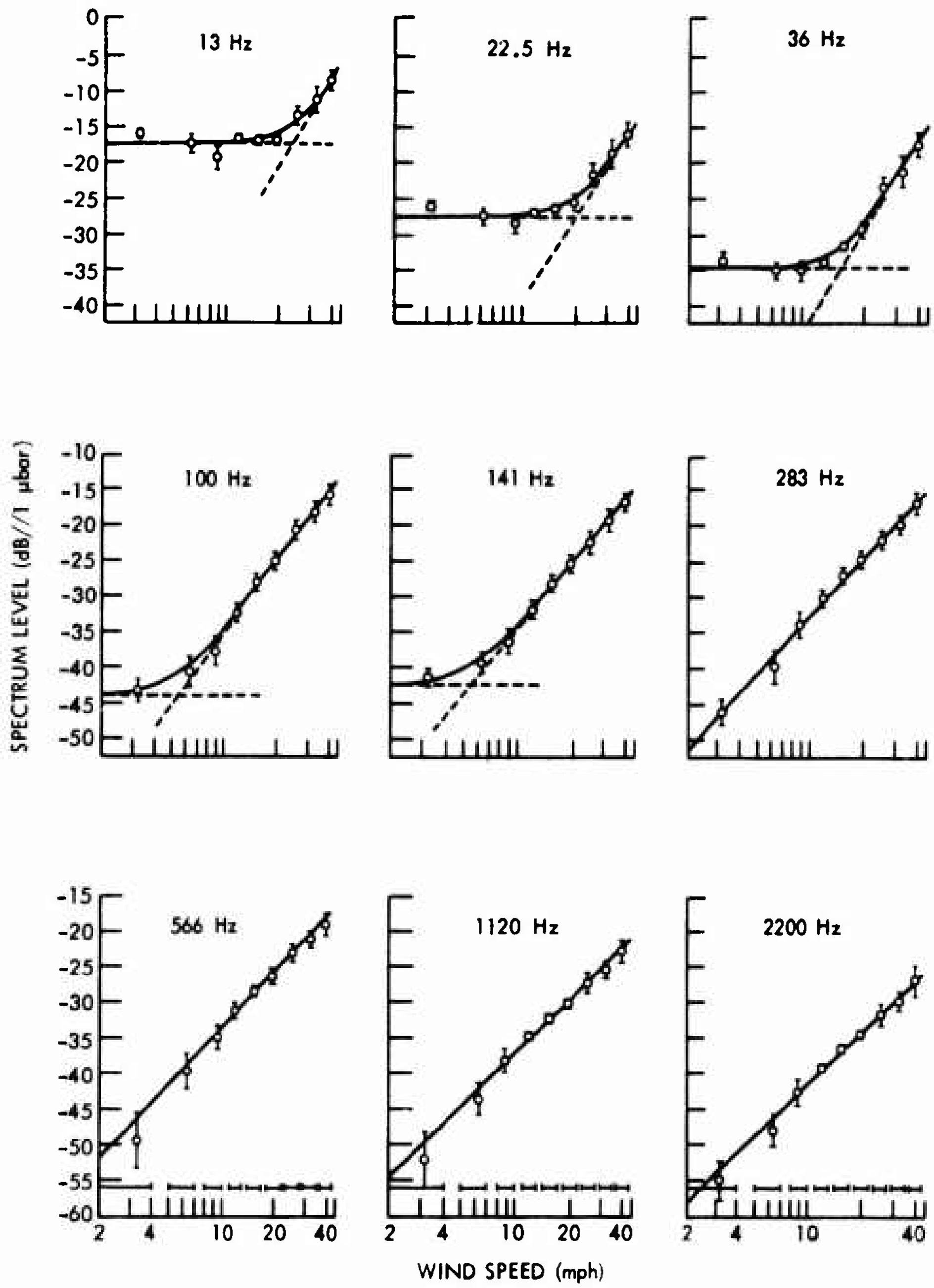

Fig. 21. Spectrum Levels versus Wind Speed for Shallow Water
(After Piggott, Reference 32)

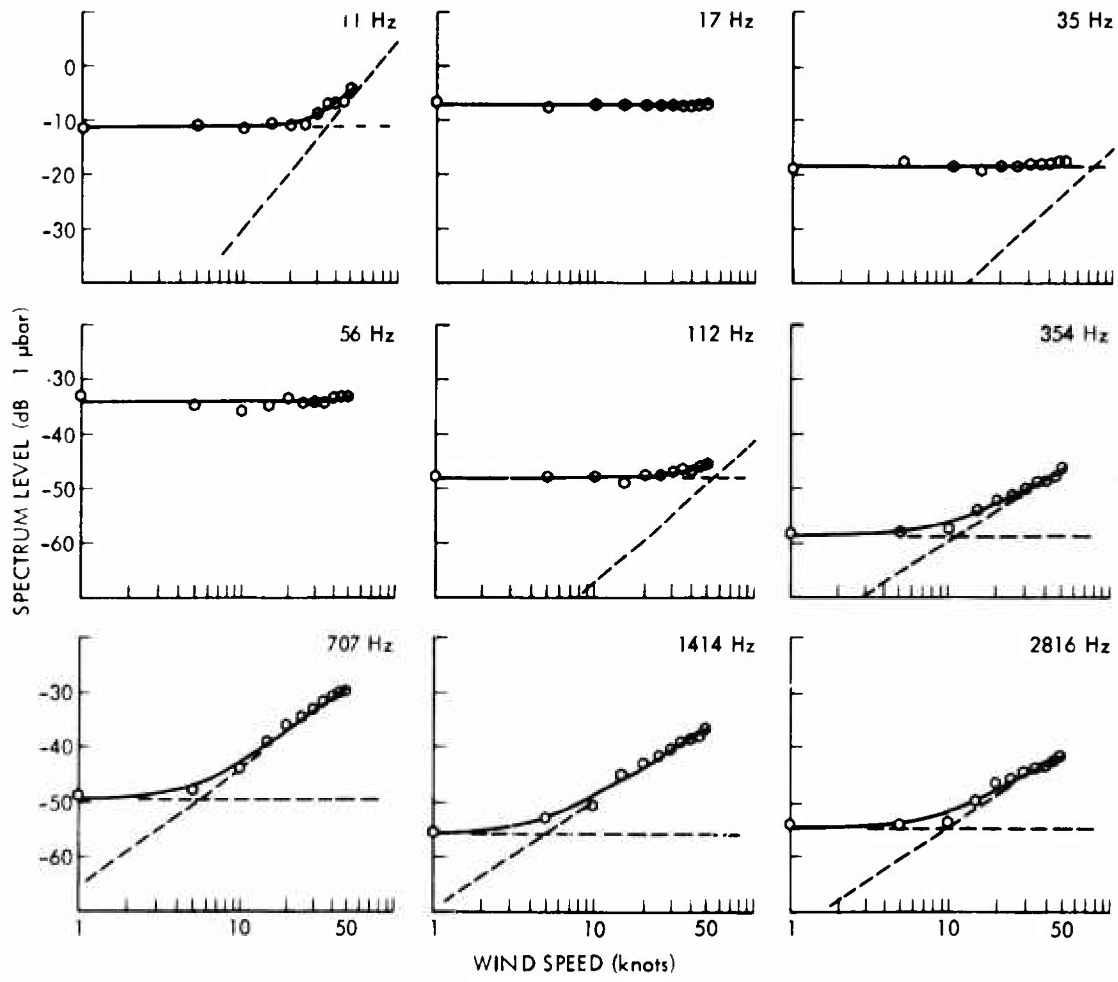

Fig. 22. Ambient Noise Spectrum Levels versus Wind Speed for Deep Water

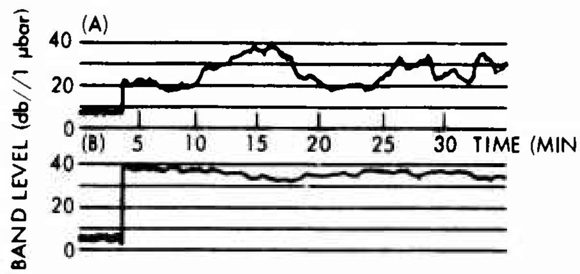

Fig. 23. Examples of Underwater Noise During Rainfall for "Slight Continuous Rain" (A) and "Moderate Continuous Rain" (B) in a 300- to 9600-Hz Band (After Bom, Reference 33)

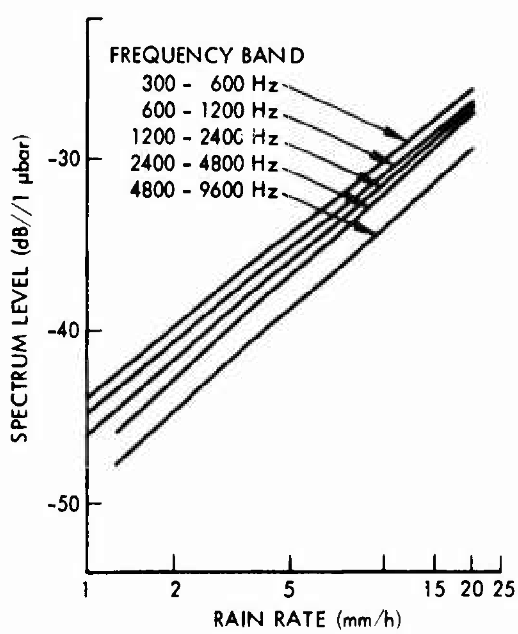

Fig. 24. Bom's Results for Spectrum Levels Due to Rainfall as a Function of Frequency and Rain Rate

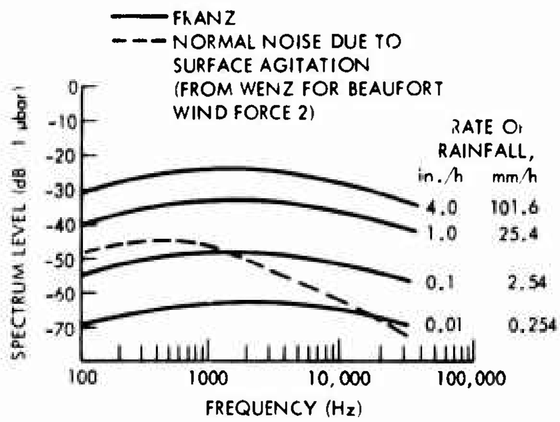

Fig. 25. Franz's Theoretical Results for Spectrum Levels Due to Rainfall as a Function of Frequency and Rain Rate

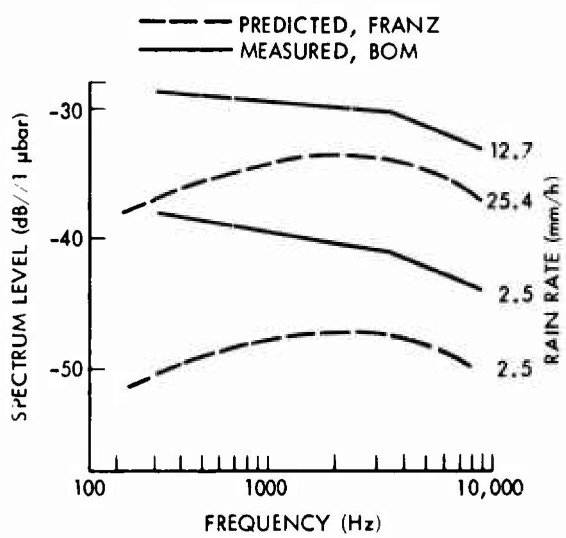

Fig. 26. Comparison of Results by Franz and Bom (From Bom, Reference 33)

Two other sets of measurements that show higher levels than those predicted by Franz are also available. Heindsmann et al. measured ambient noise levels during the passage of two "heavy rainstorms over an off-shore bottomed hydrophone system."[35] It was located in 120 ft of water near the eastern end of Long Island Sound. Figure 27 shows spectrum levels for one of the storms. Figure 28 shows noise levels during rain reported by Arase.[36] No details of the measurement conditions are given.

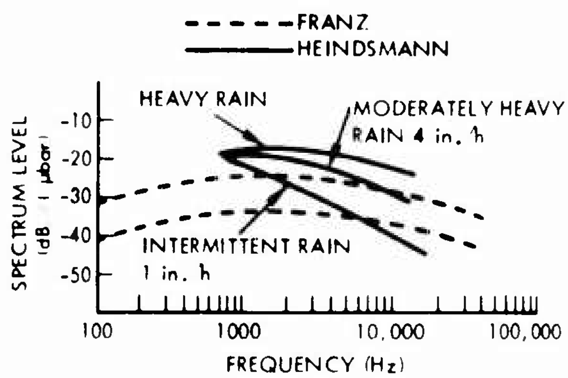

Fig. 27. Measurements of Spectrum Levels During Rainfall by Heindsmann

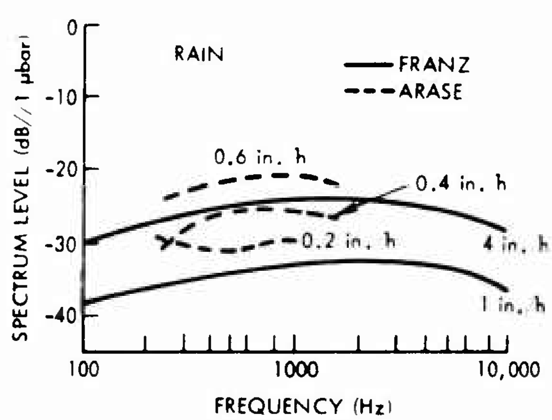

Fig. 28. Measurements of Spectrum Levels During Rainfall by Arase (After Arase, Reference 19)

CONCLUSION

This report supplements and updates earlier summaries of ambient sea noise. Other works have been cited freely, and only information pertinent to this review has been duplicated here. Thus, this document along with others cited provides an up-to-date summary of knowledge about ambient sea noise in the 10-Hz to 10-kHz band.

Characteristics of ambient sea noise that are most often important and sources of ambient sea noise of primary interest have been identified as follows:

a. Spectrum levels

b. Directionality

c. Correlative properties

d. Amplitude statistics

e. Surface agitation

f. Distant shipping

g. Precipitation

h. Biological

i. Thermal

j. Seismic.

References were given for all of these characteristics and sources, but only spectrum levels, directionality, correlative properties, surface agitation, and rain were discussed in any detail in this report.

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13. ABSTRACT

Knowledge about ambient sea noise between 10 Hz and 10 kHz is summarized. Information is included on several characteristics of ambient noise (variation of spectrum levels, directionality, and correlative properties) and two sources (surface agitation and rain). Other summaries are recommended that cover the prediction of spectrum levels associated with additional sources (distant shipping, biological, thermal, and seismic).

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