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Vertical Noise Directionality in the Deep Ocean: A Review

A Paper Presented at the
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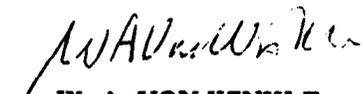
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PREFACE

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VERTICAL NOISE DIRECTIONALITY IN THE DEEP OCEAN: A REVIEW

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INTRODUCTION

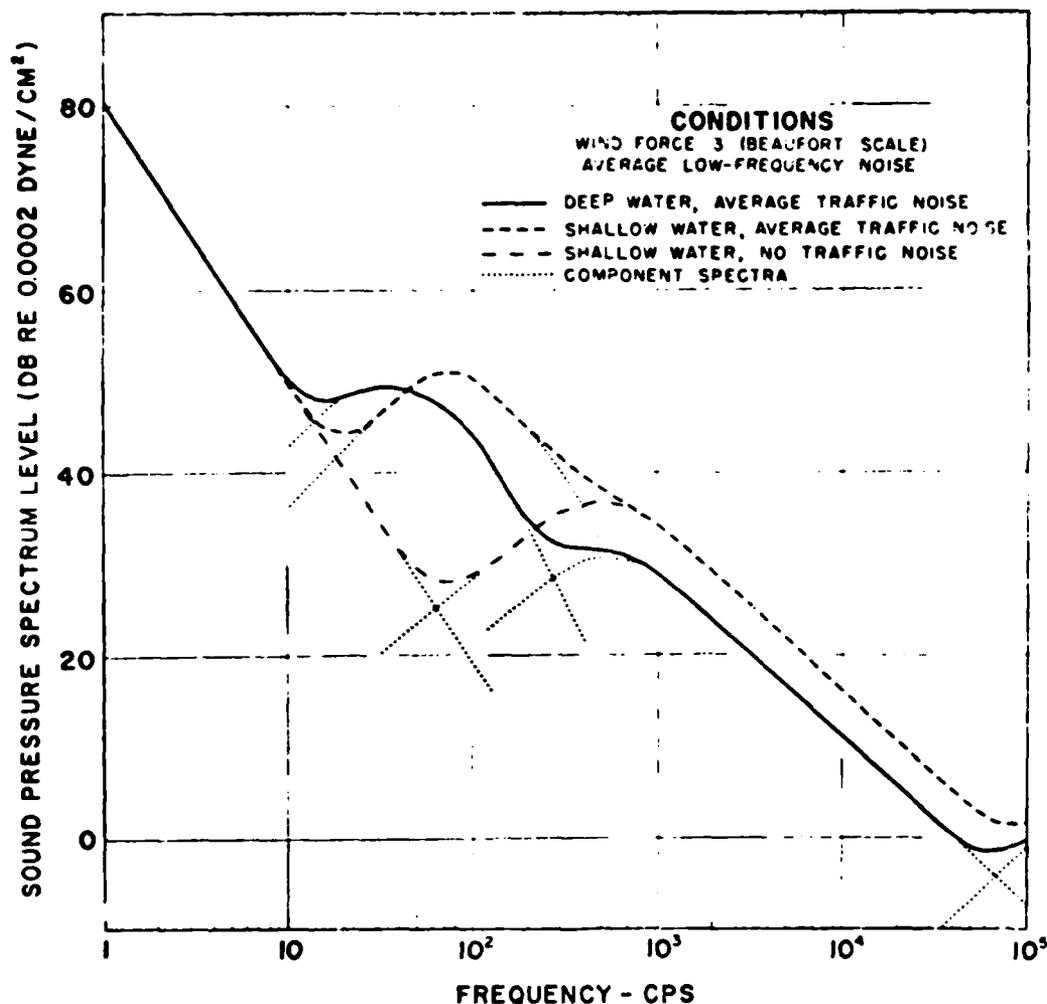
The study of ambient noise is best served by long-term data collection. Unfortunately in an age of quick-looks, hot-wash results, and leveraged investment strategies, we tend to be long on words but short on data.

It is worthwhile, however, to collect the pieces of data that have accumulated and present review papers as is being done here today. We can try to see what trends have developed and perhaps what significant gaps exist. Our paper presents a review, albeit somewhat subjective as most reviews are, of vertical directionality of ambient noise in the deep ocean.

--Slide 2, please--



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SLIDE 2*

From the classic paper of Wenz¹ we know that, in general, omnidirectional ambient noise increases at lower frequencies just as the corresponding transmission loss decreases. In the practical world of signal-to-noise we are, therefore, interested in directionality -- albeit at an increased cost of system development -- to keep the advantage of a strong signal while reducing the disadvantage of increased noise.

--Slide 3, please.--

*From reference 1.

DIRECTIONALITY

$$D(V) = \frac{\sum_V S(N) \times TL}{\overline{S(N) \times TL}}$$

IN REALITY MOST NOISE SOURCES IN DEEP WATER ARE AT THE SURFACE.

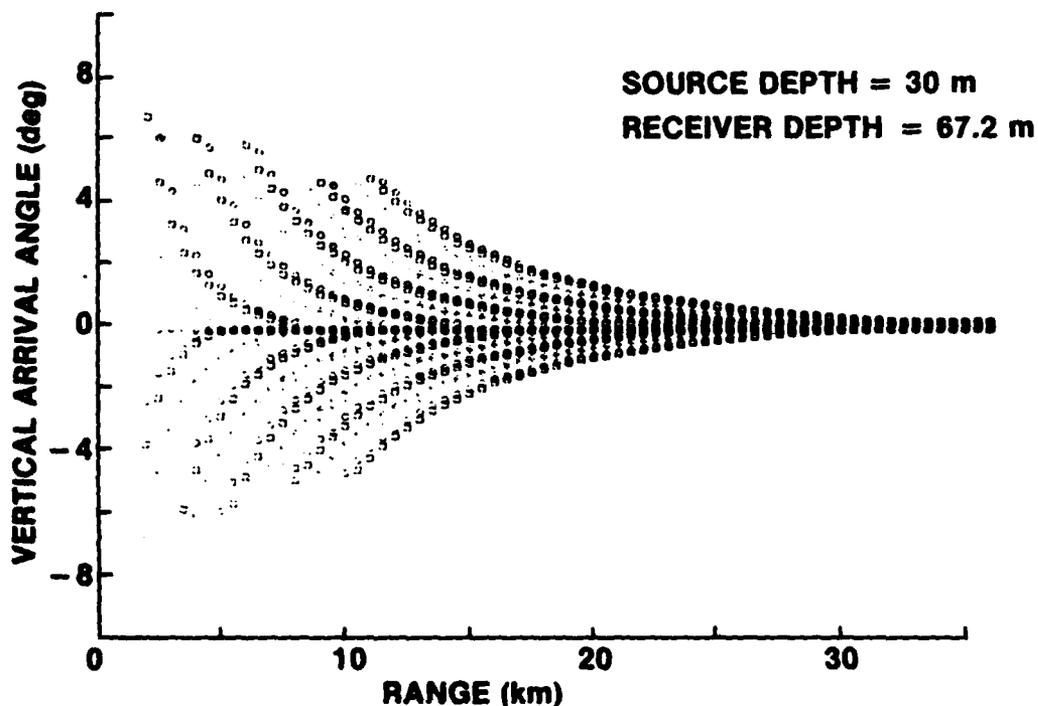
SLIDE 3

A definition of directionality is straightforward. We wish to determine the relative noise in a given direction. For vertical directionality we, of course, limit ourselves just to the vertical plane.

In the real, deep ocean we find that noise sources are generally limited to on or near the surface simplifying the distribution problem, as has been presented in the previous papers.

--Slide 4, please.--

RAYPATH ARRIVAL ANGLES vs RANGE



SLIDE 4

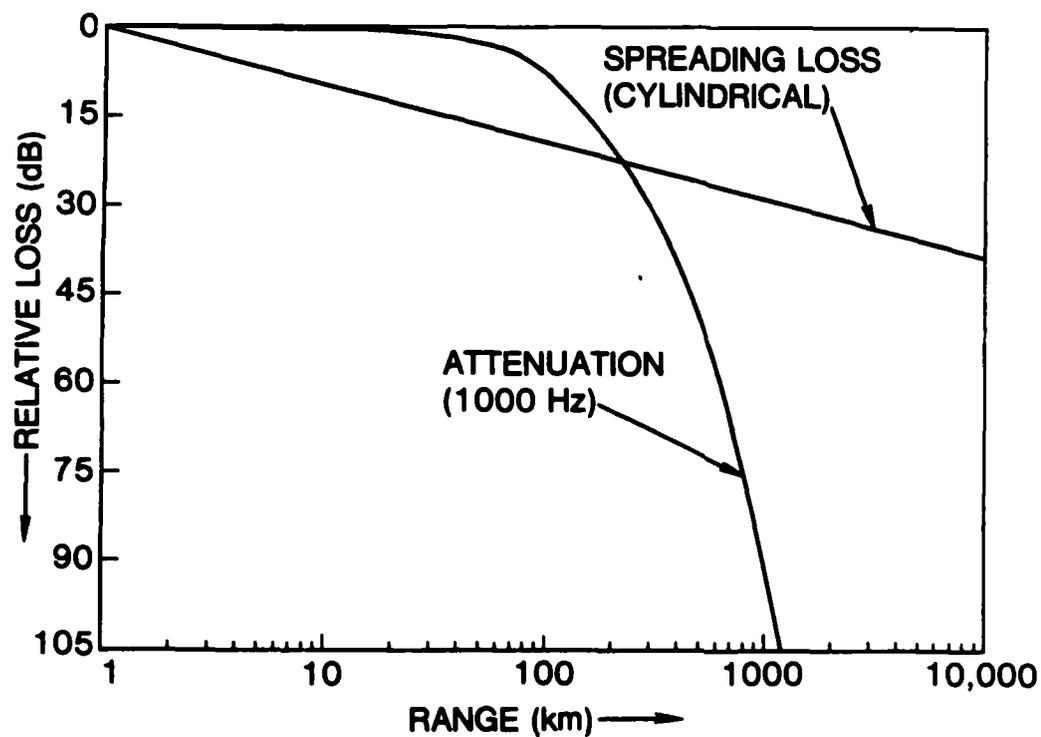
ENVIRONMENTAL FACTORS

There are two environmental factors that impact on the noise directionality. The first is the sound speed profile. For a typical deep water profile you do not have high angle rays reaching the surface at longer ranges.² We are not considering bottom bounce paths.

So at relatively short ranges we can have many high angle paths, but at long range the paths will be nearly horizontal. Note, however, that the long range asymptotic arrival angles are not zero but typically something like $\pm 10^\circ$.

--Slide 5, please.--

ATTENUATION vs. SPREADING LOSS

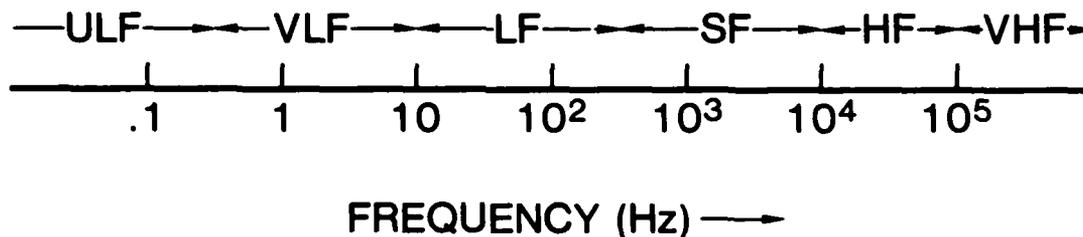


SLIDE 5

The second factor that determines what the maximum range will be is attenuation. We know that attenuation generally increases with the square of the frequency.³ Of importance to us is the relationship between attenuation loss and spreading loss as a function of range. This results in what Bob Mellen refers to as a "curtain effect;" when attenuation starts to dominate, the propagation loss at further ranges becomes prohibitive.

---Slide 6, please.---

VERTICAL DIRECTIONALITY DOMAINS



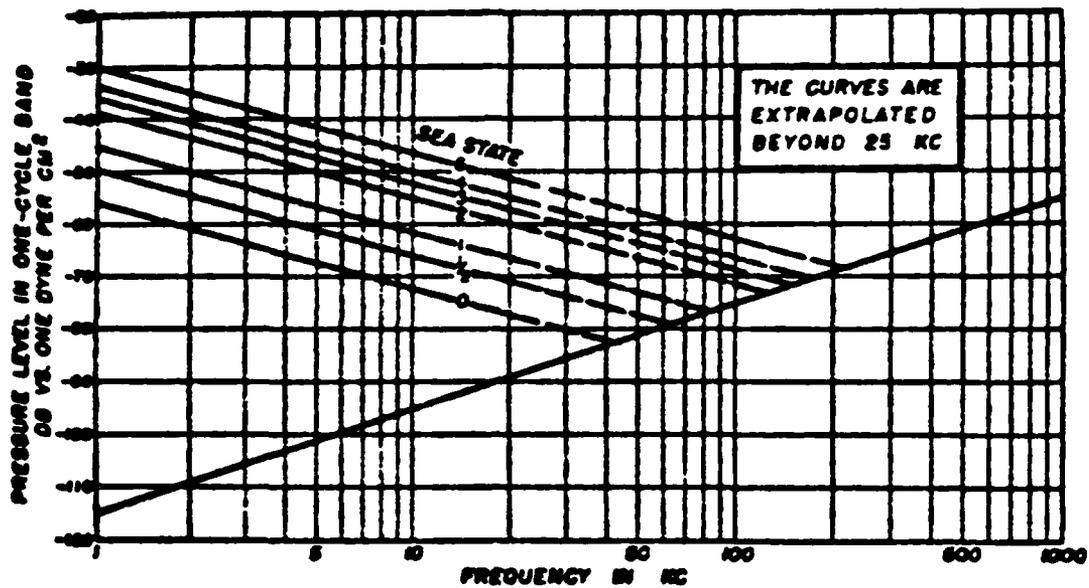
VHF > 100 kHz
 HF 10-100 kHz
 SF 200 Hz — 10 kHz
 LF 10 Hz — 200 Hz
 VLF .5 Hz — 10 Hz
 ULF < .5 Hz

SLIDE 6

FREQUENCY DOMAIN ANALYSIS

We have chosen to break up our review of vertical directionality into six frequency domains. We will show that although the sources are at the surface, the changing environmental factors will result in different vertical directionality through the domains. For completeness we have covered a wide frequency range with the realization that at the extremes, directionality may become meaningless or undefined.

—Slide 7, please.—



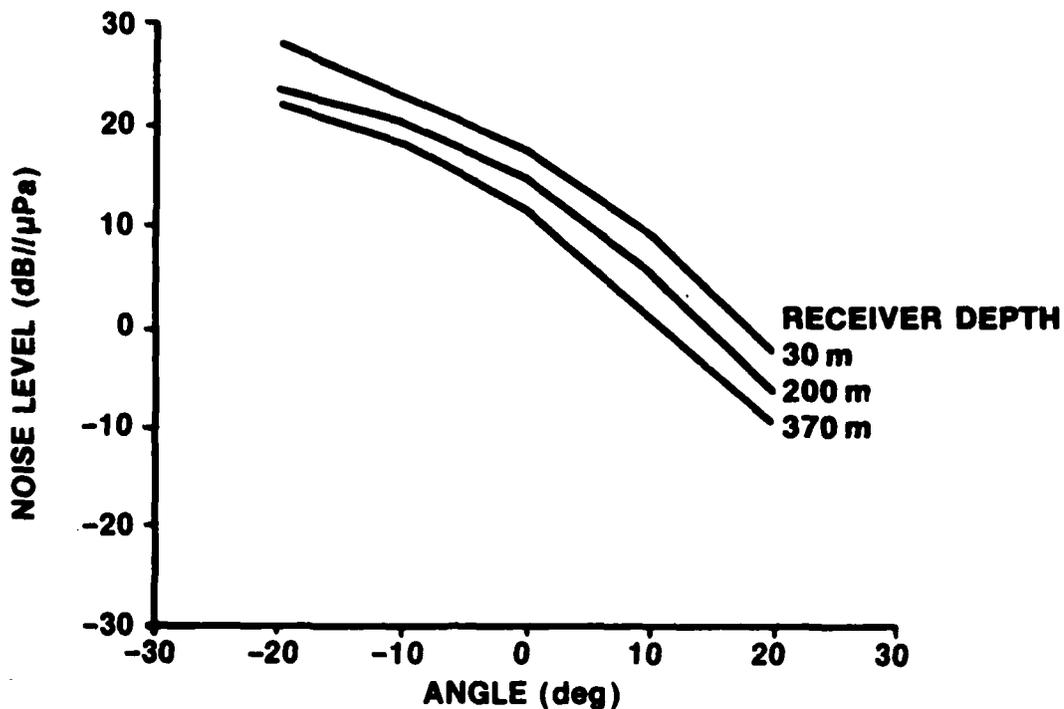
SLIDE 7*

VERY HIGH FREQUENCY (VHF) DOMAIN

For the highest frequency domain (above 100 kHz), the principal noise source, as Mellen showed in his definitive paper,⁴ is the thermal agitation of the seawater constituent molecules at the hydrophone. This noise is proportional to the absolute temperature, making practical ocean temperature changes small. This coupled to the high attenuation results in meaningless directionality except for an extreme case.

--Slide 8, please.--

*From reference 4.



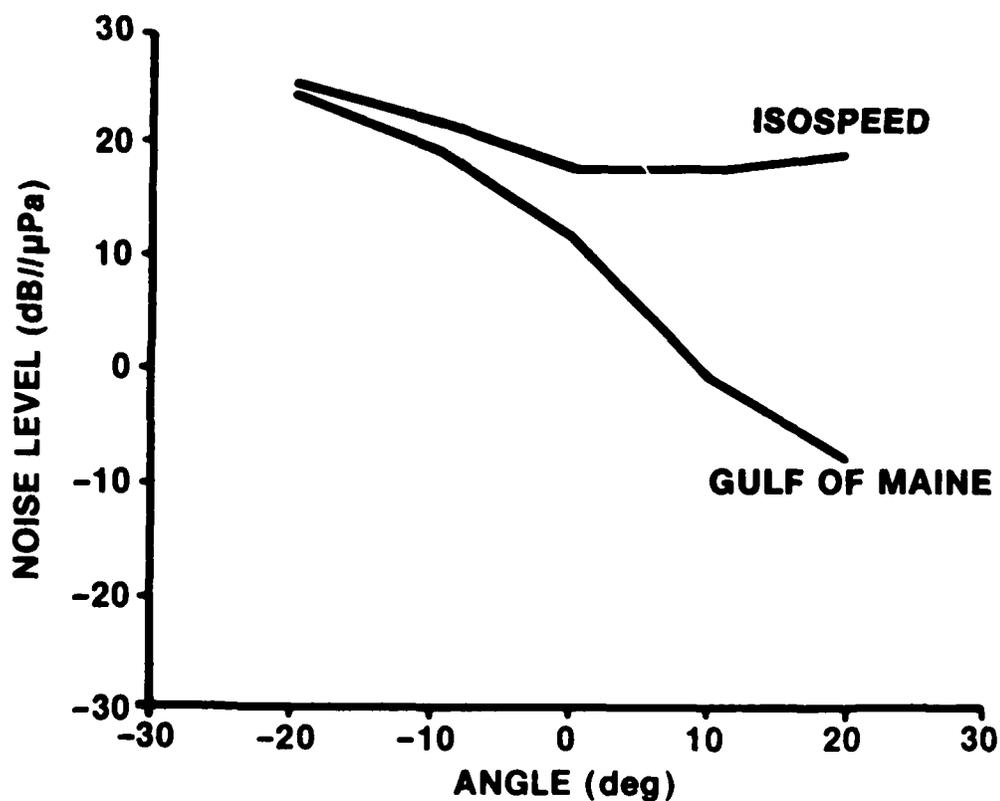
SLIDE 8*

HIGH FREQUENCY (HF) DOMAIN

In the next frequency domain (10 to 100 kHz) the surface sources become dominant. However, attenuation is a critical factor. Richard Robinson⁵ has shown that for typical profiles the initially downward paths from a receiver will be significantly more attenuated due to their greater path length than upward paths, thus causing a vertical directionality favoring the higher positive angles.

--Slide 9, please.--

⁵From reference 5.

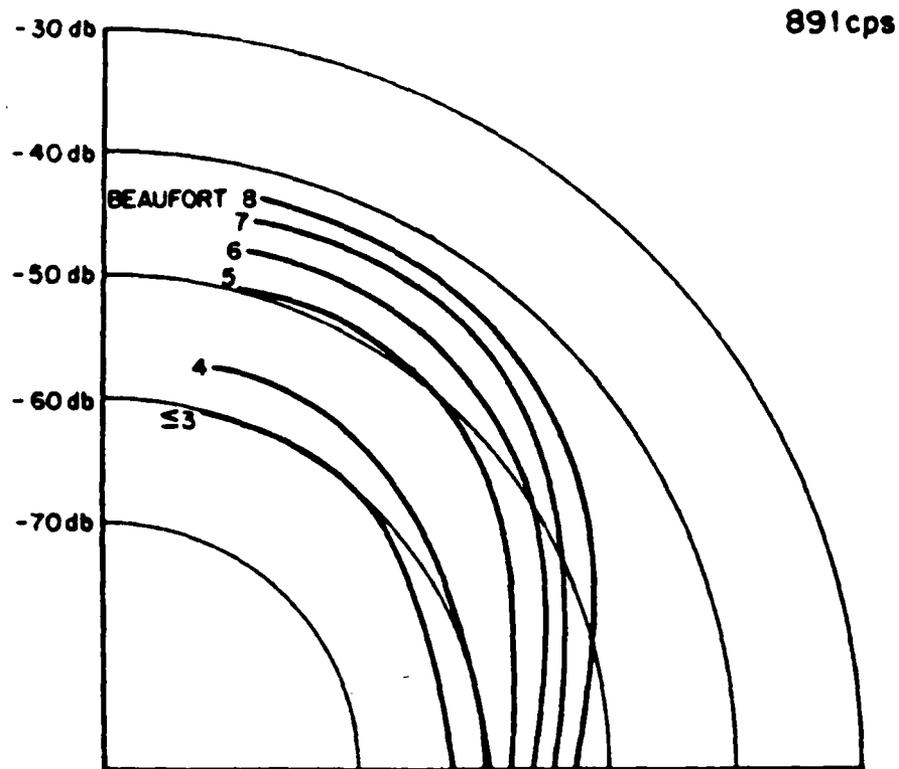


SLIDE 9*

Robinson⁵ also addressed the other factor we mentioned (sound speed profile). And as you can see, although the trend remains the same there can be a significant difference between profiles. This also demonstrates (even to a couple of experimentalists) that we presently have greatly improved modeling capability to predict what the directionality might be for various configurations.

--Slide 10, please.--

*From reference 5.



SPECTRUM LEVEL IN db // $(\mu b)^2$ / STERADIAN / CYCLE per SECOND

SLIDE 10*

SONAR FREQUENCY (SF) DOMAIN

In the next important domain (200 Hz to 10 kHz) distinctions between upward and downward paths become small. Pioneering work by Von Winkle^{6,7} and others^{8,9} at Bermuda during the 1960's showed that the surface sources were still local (say within a convergence zone) resulting in relatively higher levels at higher angles and a relative null at 0°. Since the array was near the bottom, no negative angles were measured.

--Slide 11, please.--

*From reference 6.

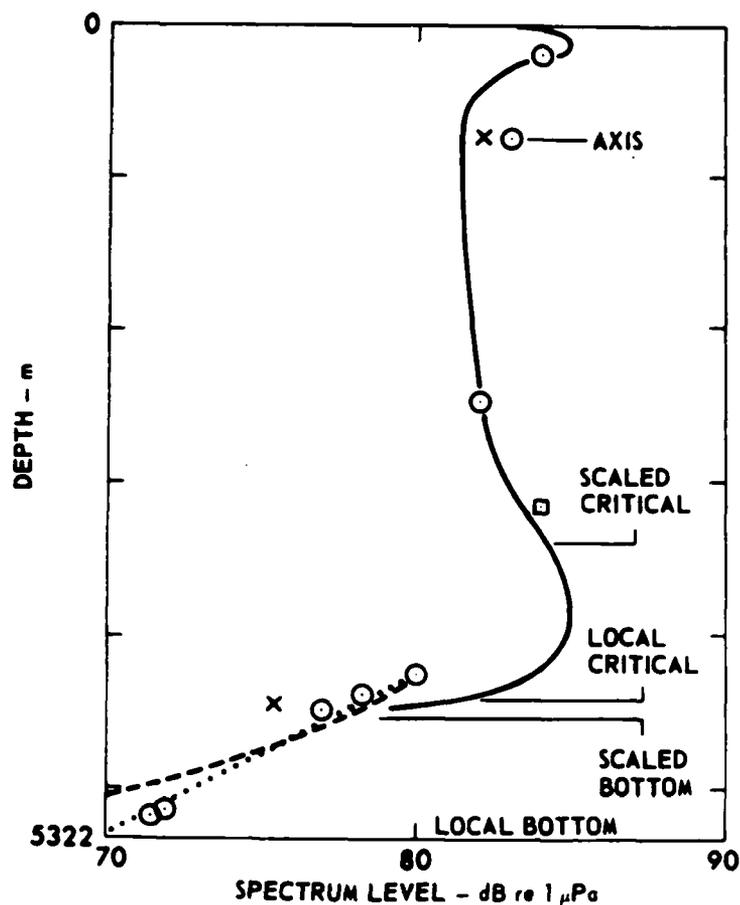


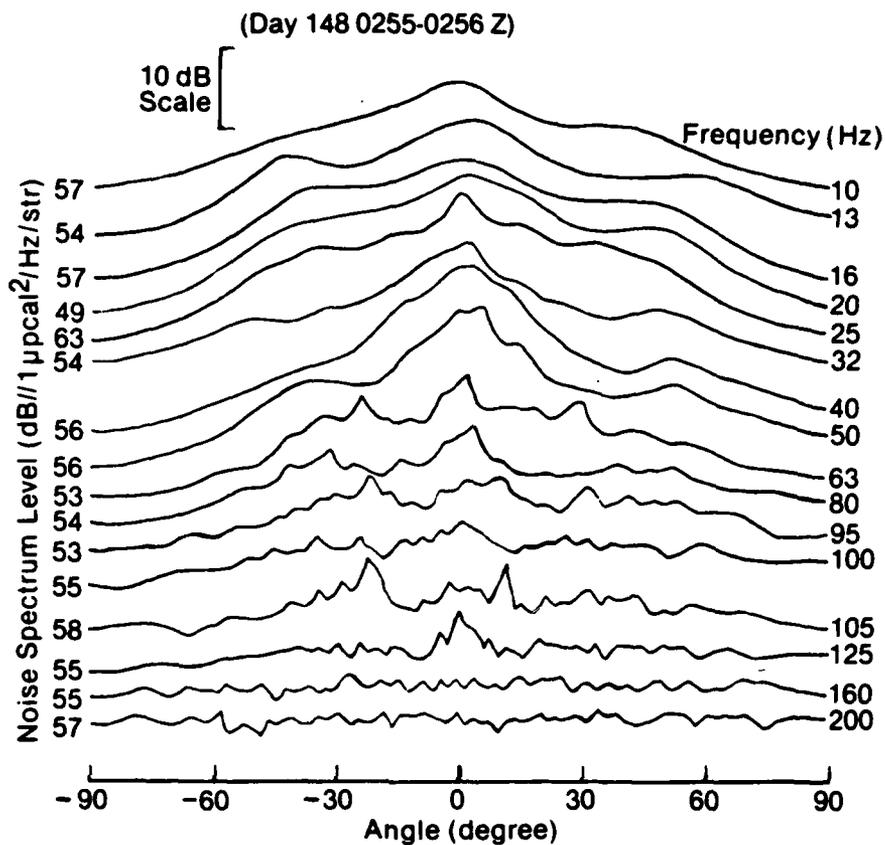
FIG. 2. Sample comparisons with ambient noise measurements at 50 Hz. Data: \odot from Ref. 7, x from Ref. 5, \square conjugate depth point from Ref. 7. Models: — dipole, \cdots exponential, --- cosine-derived.

SLIDE 11*

Weston¹⁰ has made predictions for the noise distribution with depth at these frequencies, but experimentally much remains to be done (or be revealed) concerning possible vertical directionality for shallow or very deep receivers. Shallow depths are of particular practical interest but present experimental difficulties, especially in trying to decouple a receiving array from surface motion.

--Slide 12, please.--

*From reference 10.

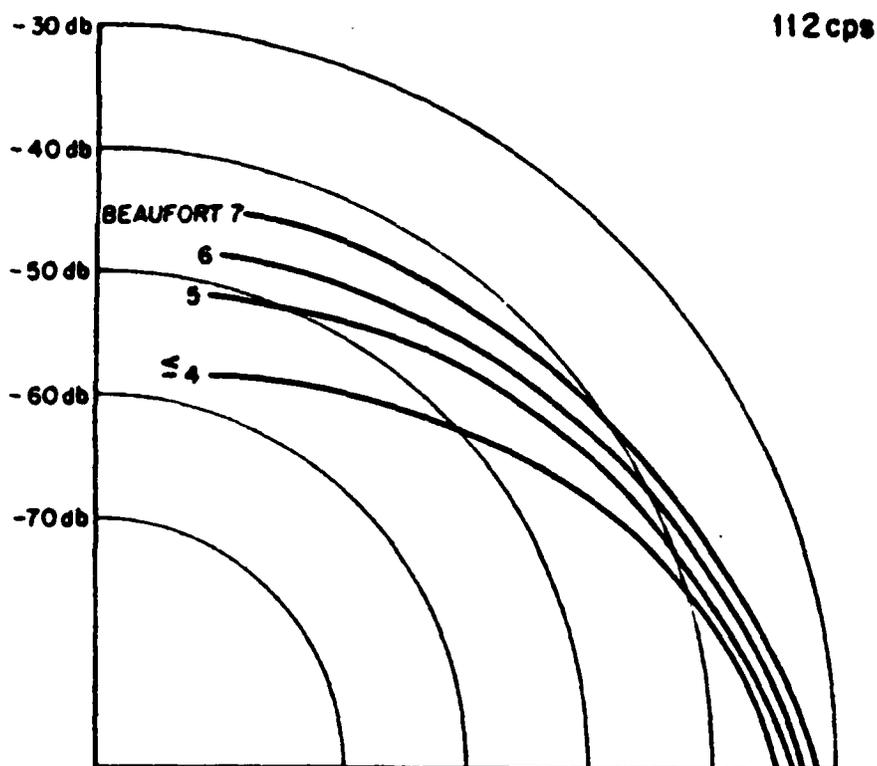


SLIDE 12*

Recently reported results from typically the center of the water column by Morris¹¹ (North Pacific), Perrone¹² (North Atlantic), and Bannister¹³ (South Pacific) show little if any directionality. (Bannister is shown here for the frequencies at the bottom of the slide.) Some have reported a slight negative slope, some a slight positive one, the differences may be explained by changes in sound speed profile shape.

--Slide 13, please.--

*From reference 13.



SPECTRUM LEVEL IN db // $(\mu b)^2$ / STERADIAN / CYCLE per SECOND

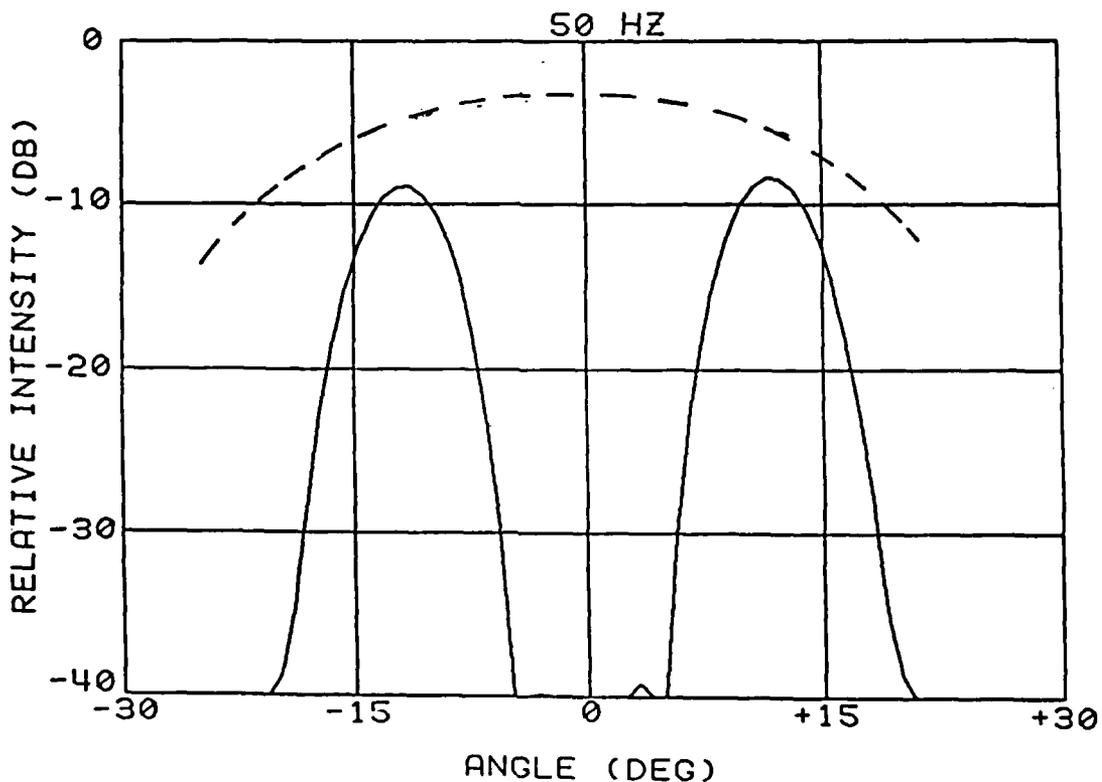
SLIDE 13*

LOW FREQUENCY (LF) DOMAIN

The next domain (10 to 200 hz), which has been a region of recent interest, shows an interesting change illustrated again by Von Winkle's work.^{6,7} We have rapidly gone from the domination of local noise sources to a significant contribution of long range (low angle sources). The attenuation curtain has lifted and long range sources, due to the profile, are low angle sources, a combination of the two environmental effects we mentioned earlier.

--Slide 14, please.--

*From reference 6.



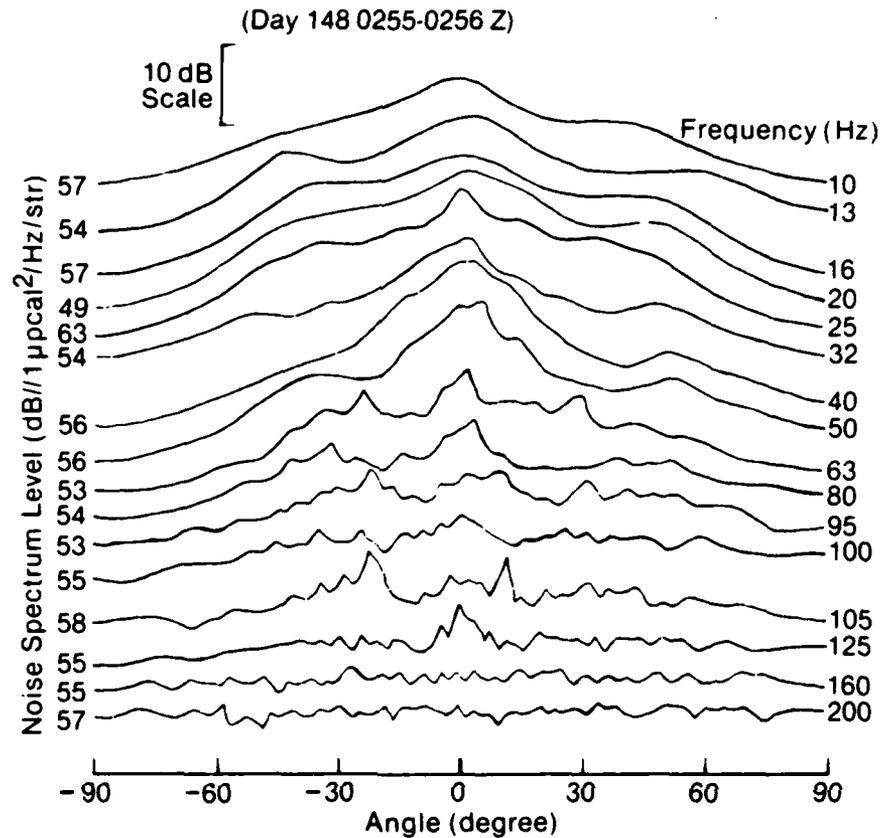
SLIDE 14*

MODEL PREDICTIONS

This was to result in an interesting dilemma. Modeling predictions^{14,15} would indicate that the result of long range paths would maxima at typically $\pm 12^\circ$ corresponding to the long range array angles asymptote shown earlier, and a null at 0° (horizontal). However, typical data (dashed line) are significantly different.

--Slide 15, please.--

*From reference 14.

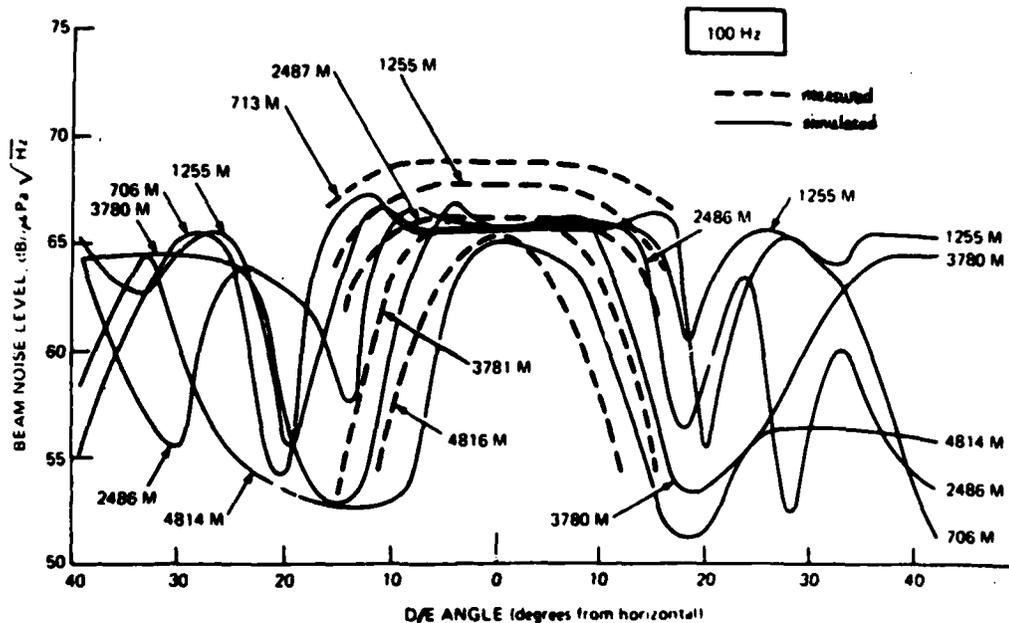


SLIDE 15*

In reality actual measurements starting with the classic North Pacific work of Anderson¹⁶ through to the South Pacific results of Bannister et al¹³ (shown here) and Burgess and Kewley¹⁷ indicate a broad peak centered at the development of this broad maxima as we go from higher to lower frequencies (bottom to top), transitioning between domains.

---Slide 16, please---

*From reference 13.



SLIDE 16*

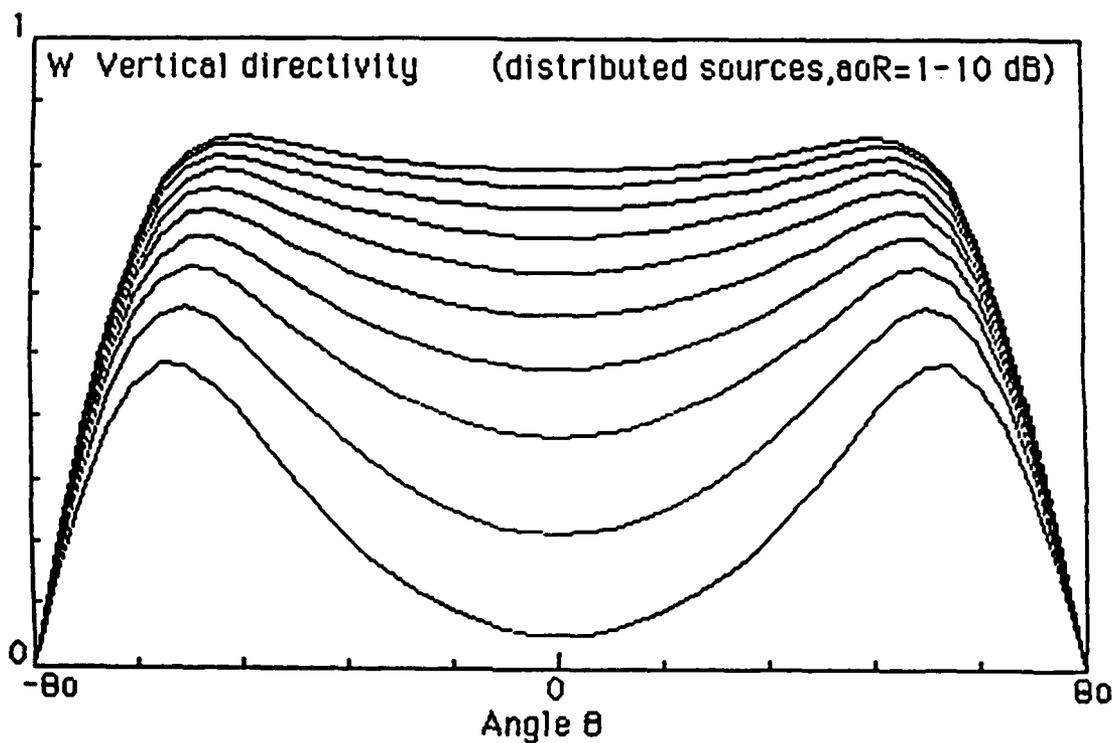
Ron Wagstaff¹⁸ proposed a simple yet brilliant solution. Shipping noise could bounce down bathymetric slopes to the sound channel axis providing what he called the "missing component." He and Bill Carey¹⁹ have expanded on this in a recent paper at a SACLANT meeting and it is an excellent summary.

What is good for the heavily trafficked Northern hemisphere may not apply to the Southern hemisphere. Bannister²⁰ has recently suggested that wind generated noise in the roaring forties (the sound channel axis reaches the surface there) may play the same role in the Southern oceans.

It may well be that both wind and shipping contribute in a varying mixture depending on location and we suspect that Bill Carey²¹ has covered this in the preceding paper.

--Slide 17, please.--

*From reference 18.

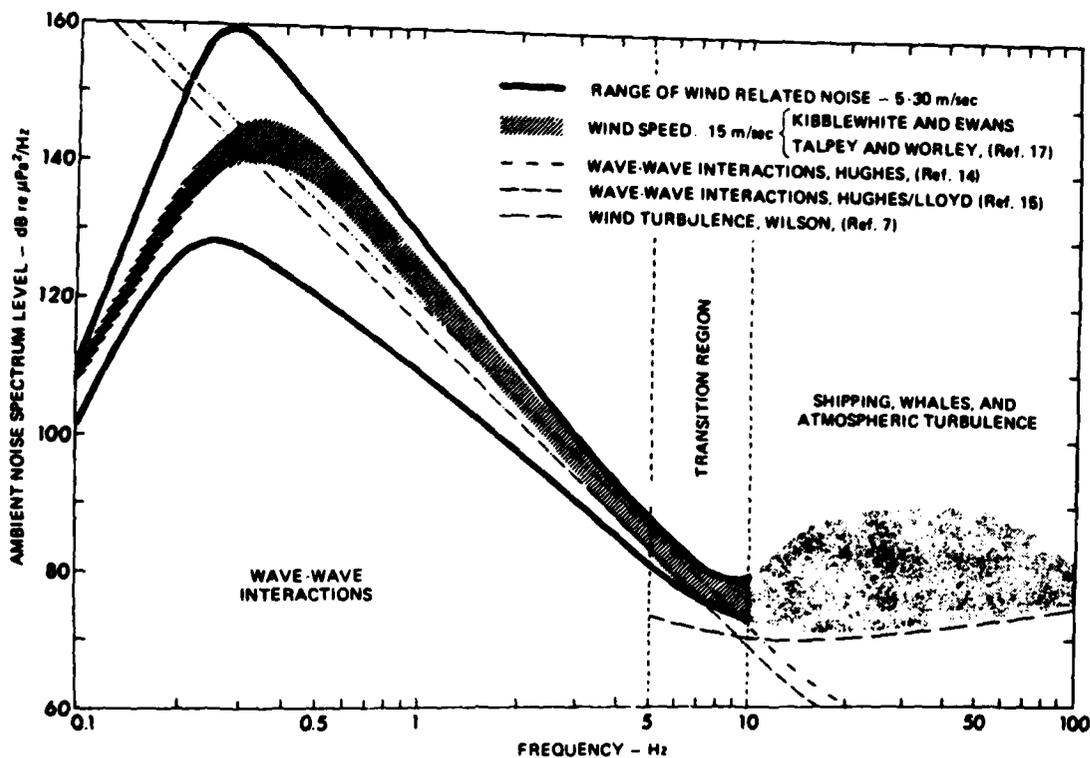


SLIDE 17*

Another suggested possibility is that energy is scattered down to the sound channel axis by oceanographic inhomogeneities. Recent attempts by Munk²² (internal waves) and Mellen¹⁴ (diffusion theory) have not provided any conclusive evidence but this may be a significant piece of the total picture. Again, we would make the plea that long term measurements in select locations throughout the world are needed to verify any theory.

--Slide 18, please.--

*From reference 14.



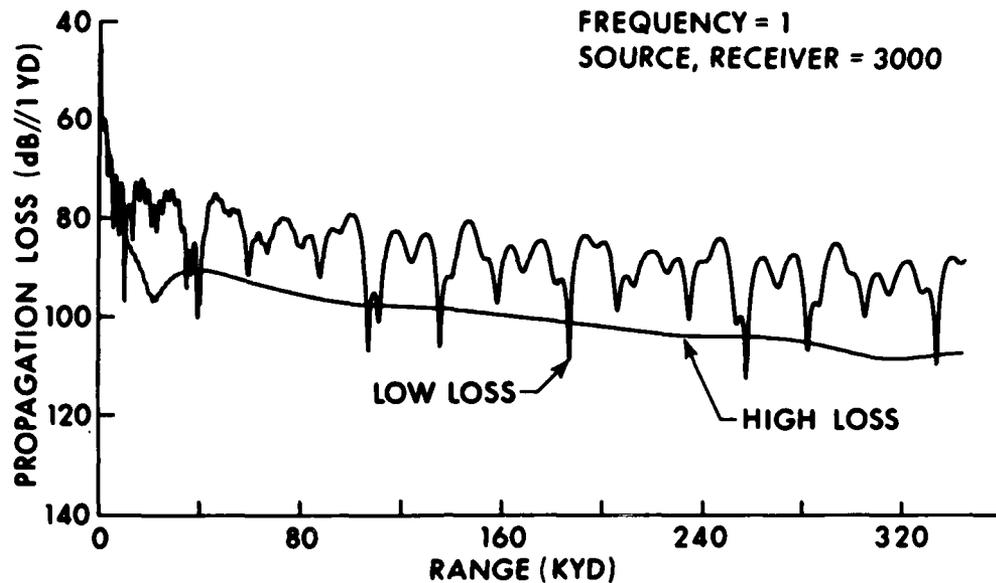
SLIDE 18*

VERY LOW FREQUENCY (VLF) DOMAIN

In the next domain (0.5 to 10 Hz) the wavelengths are becoming long enough to make directionality less meaningful. Kibblewhite²³ has recently shown however that the surface sources are stronger than ever to 0.5 Hz, which may be the effective cut-off frequency in the sound channel. There is plenty of noise here and it is still propagating well although the horizontal directivity would probably be more significant (and interesting) than the vertical directivity.

--Slide 19, please.--

*From reference 23.



SLIDE 19*

ULTRA LOW FREQUENCY (ULF) DOMAIN

Finally below 0.5 Hz we may be in a meaningless region as we were at the very high frequencies. It is not obvious how propagation modes would be excited but some earlier work by DiNapoli²⁴ suggests that the fundamental water mode is still excited though less efficiently. Whether bottom modes would come into play and if they would impact vertical directionality, we just don't know.

--Slide 20, please.--

*From reference 24.

CONCLUSIONS

- FOR MOST FREQUENCIES SOURCES ARE AT/NEAR SURFACE
- EMPHASIS EVOLVES FROM HIGH ANGLES (VERTICAL) TO LOW ANGLES (HORIZONTAL)
- MANY ASPECTS (SHALLOW RECEIVER AT SF FOR EXAMPLE) REMAIN UNVERIFIED

SLIDE 20

Any short summary such as this is a broad generalization at best and we are the first to realize its limitations and our time-limited failure to recognize all the excellent work that has been reported.

In summary we make the following points:

- The problem of vertical directionality is somewhat simplified by the preponderance of surface or near surface sources in deep water.
- At low frequencies we evolve rapidly from the dominance of nearby sources to far away sources.
- Finally, unglamorous as it may be, noise still needs to be measured for long periods at many locations before we will have a full understanding of its causes.

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