A review of deep ocean sound attenuation data at very low frequencies

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The behavior of the attenuation coefficient at very low frequencies (below 200 Hz) has been clouded by the unexplained scatter in experimental data. Recent experiments have indicated that some of this scatter reflects a regional dependence. An attempt is made here to review all the relevant data and to achieve some rational grouping in terms of such regional effects.

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INTRODUCTION

In 1965 Thorp[1] published low-frequency attenuation data which showed the measured values of attenuation in the ocean at frequencies below 10 kHz to be greater than those predicted by the Marsh–Schulkin formula.[2] Since that time, various experiments have been conducted and it is evident that the data from all these measurements give reasonably consistent values in the frequency range 200–10 000 Hz even though the data exhibit considerable scatter. Thorp and Browning[3] presented a revised compendium in 1973.

While the anomalous behavior of oceanic attenuation below 10 kHz has been recognized for more than a decade, it is only recently that the cause has been identified as being associated with a boron-related relaxation.[4,5] Further experiments have indicated a marked regional dependence in this effect and have suggested in particular that the excess absorption in the North Pacific Ocean is only about half that given by Thorp's empirical formula,[6] which was based largely on North Atlantic Ocean data. Evidence has recently been presented linking this dependence to *p*H variations in the ocean,[7,8] and the regional implications reviewed.[9]

Below 100 Hz the reported values of attenuation display an even greater scatter than they do in the region 100–1000 Hz and commonly exceed the Thorp predictions (see Fig. 1). The inconsistency in these data has been seen by some as merely reflecting the real experimental difficulties involved in low-frequency measurements and doubts have been expressed as to the reliability of these very low-frequency values.[10] It has been argued that the excess attenuation below 100 Hz arises from a range-dependent environment and the cylindrical spreading assumption traditionally used in evaluating an attenuation coefficient, rather than any real effect in the ocean.

An alternative explanation for the large scatter in attenuation data below 100 Hz arose when an apparent regional dependence in the attenuation coefficients at frequencies below 100 Hz was reported.[11] Since, reports of other measurements[12-16] have been made that provide increasingly convincing evidence for this further regional dependence of attenuation at very low frequencies. Some of these recent contributions[15,16] have pointed, furthermore, to the possibility of a minimum in the attenuation versus frequency curve below 100 Hz. Overall, in spite of the pitfalls inherent in an indiscriminate application of the cylindrical spreading correction in a range-dependent environment, a regional dependence of the attenuation at frequencies below 100 Hz appears to be now as well established as for the boron-related effects.

This paper is concerned with a review of the low-frequency attenuation data relevant to this part of the spectrum and attempts to show that the scatter below 100 Hz from experiment to experiment can largely be accounted for by grouping the data on a regional basis. In this respect it extends the correlations made recently for the southern hemisphere data.[14,17]

I. THE BORIC ACID RELAXATION

The difficulties of long-range propagation experiments are well recognized by all engaged in these programs, and the debate over the reality of the excess attenuations reported at frequencies below 100 Hz has been alluded to above. Skeptics have emphasized that the conventional energy-analysis procedures used in most experimental analyses are strictly valid only under severely limited circumstances. In particular the conventional processing assumes the environment to be range independent, a condition never strictly met in the case of the long oceanic paths involved, and those who doubt the reality of the excess attenuations below 100 Hz make much of this point.

In this review of the most often quoted results relevant to the very low-frequency band, the intention is to accept the analytical procedures used but to reject data for which the experimental conditions do not appear satisfactory for one reason or another. We then attempt to see how much cohesion can be achieved on the basis of the regional dependence of attenuation for which evidence is now strong.

It is obviously an absolute requirement that the data for the low-frequency region should merge smoothly with the data for frequencies higher than 100 Hz. The data for this region have been collated and described in the reviews by Thorp and Browning.[1,3] Both these collations observe that the trend line first proposed by

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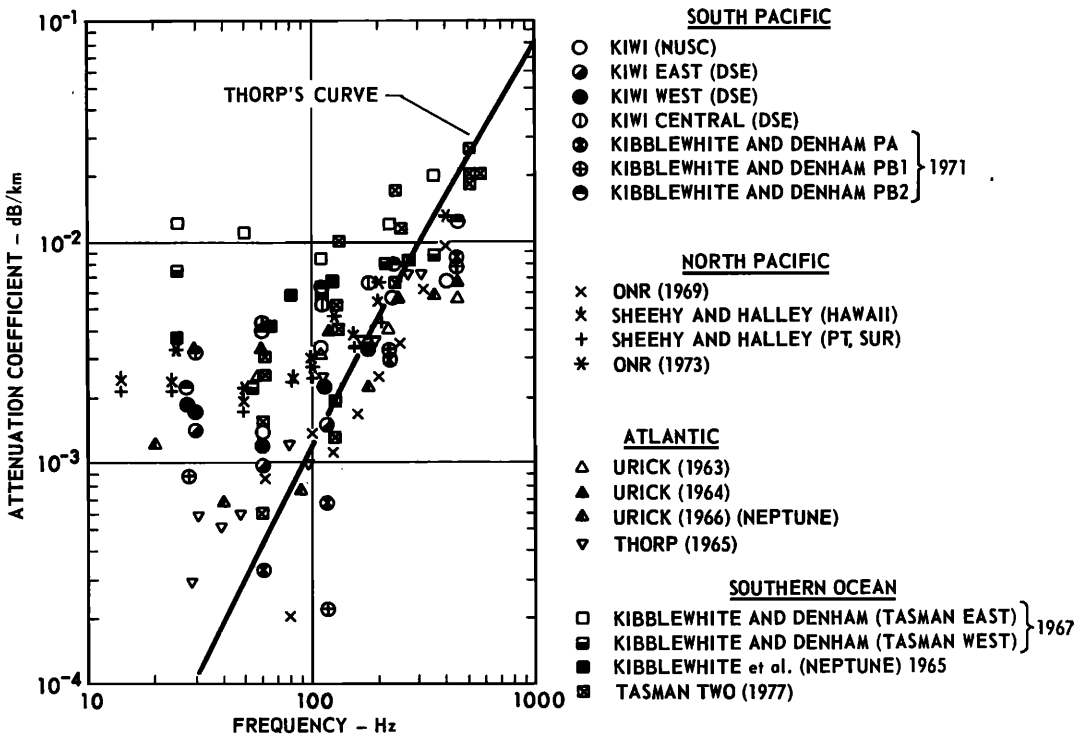

FIG. 1. Low-frequency attenuation data as at 1978.

Thorp,[6] viz.

$$\alpha_A(f) = 0.11f^2(1+f^2)^{-1} + 0.011f^2 \text{ dB/km},$$

$$(f \text{ in kilohertz}), \qquad (1)$$

provides a reasonable approximation for the data between 100 Hz and 100 kHz. The two terms are, respectively, the boric acid relaxation term and the magnesium sulphate relaxation term approximated for $f < 10$ kHz, both averaged over temperature, salinity, and pH.

As was referred to earlier, however, the reports of a pH-related variability in the boron component of the attenuation in the ocean seems to be now also well established.[7,8] This pH-dependence requires a modification of Eq. (1) by introducing a pH-dependent coefficient for the boron related term, so that following Mellen and Browning, the Thorp formula becomes

$$\alpha_A(f) = 0.11Kf^2(1+f^2)^{-1} + 0.011f^2 \text{ dB/km}. \qquad (2)$$

A comparison of the measured at-sea values of absorption and relaxation frequencies shows good agreement with predictions, and that in particular the boron effects throughout the oceans range from 0.5 to 1.1 times that given by Thorp's original formula. Lovett[9] has recently summarized the geographic variations of absorption due to boron effects.

II. REVIEW OF EXPERIMENTAL DATA

As we are primarily interested in the frequency range below 100 Hz, this review is confined to the relevant published data. Most of these are summarized in Fig. 1, although other data will be introduced as appropriate. The locations of the major experiments are given in Fig. 2. In assessing whether various data sets should be discarded it will be convenient to review the experiments in chronological order.

A. Sheehy and Halley, 1957

In this experiment[18] the authors recorded reverberation from throughout the Pacific Ocean at deep bottom-mounted hydrophones off Hawaii and California, subsequent to the detonation of a nuclear bomb in the deep sound channel. They established values of $|\alpha(f) - \alpha(40\text{ Hz})|$ by a procedure which some might challenge. Nevertheless, the data arise from a deep sound channel measurement and are accepted for the present analysis. Before they can be used, however, a value must be allotted to $\alpha(40)$. Thorp[1] adopted the value

$$\alpha(40) = 2.6 \times 10^{-4} \text{ dB/kyd},$$

and we use his modified Sheehy and Halley data based on this value.

The data for the two receivers at Kaneohe and Point Sur differed in one important respect. Because of the experimental geometry, the Kaneohe receiver detected reverberation arising in the main from reflectors on the northwest coast of North America, while the Point Sur hydrophone received signals from reflections from as far away as the Tuamotu Archipelago in the South Pacific Ocean. The transmission paths therefore encompassed mid-latitude water masses in the case of the Kaneohe receiver and equatorial waters in the case of the Point Sur receiver. This point will be relevant to our subsequent analysis.

B. Urick, 1963; Urick, 1964

In 1963 Urick[19] measured attenuation, by energy analysis in octave bands, of the signals received from

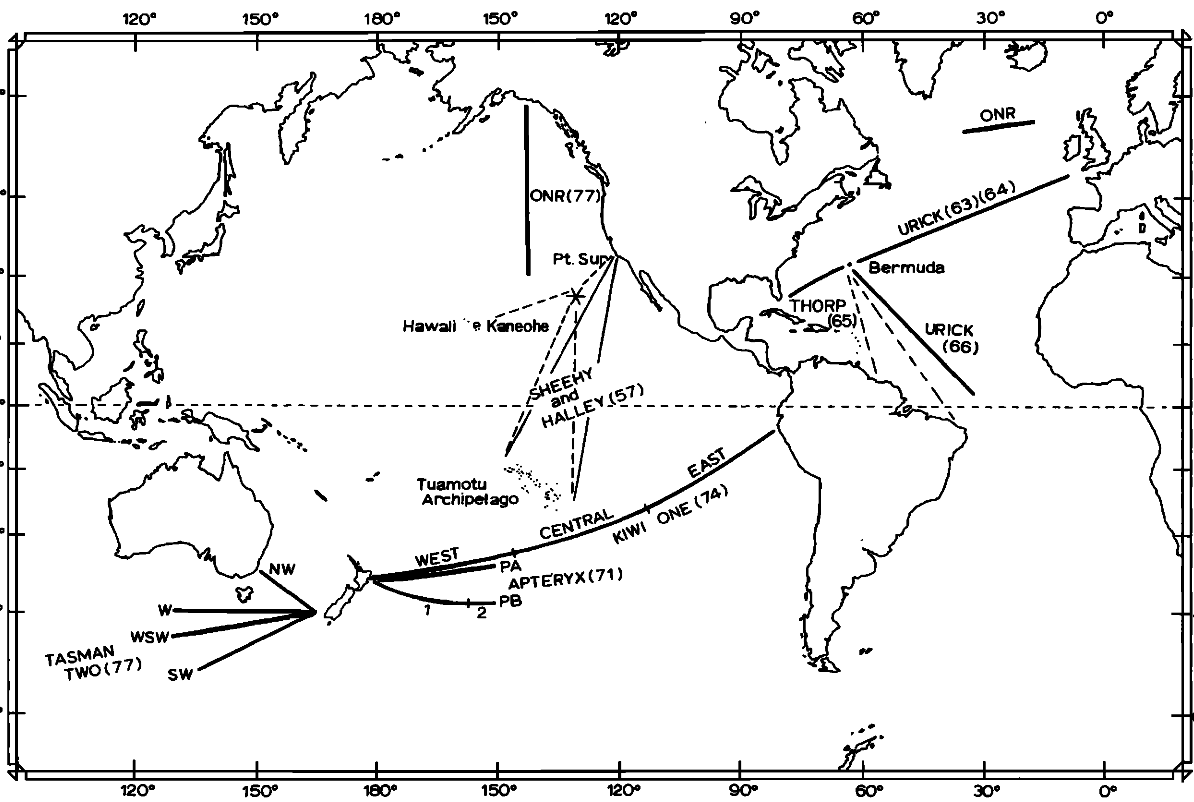

FIG. 2. Geographical locations of the major long-range transmission experiments.

deep explosions (1500 and 3500 ft) at a deep (3900 ft) hydrophone suspended at the SOFAR channel axis near Bermuda. The transmission path was directed roughly northeast towards Britain and crossed the Mid-Atlantic Ridge at a distance of about 1800 miles from the receiver.

Although no bathymetry was reported, the results displayed effects which were obviously attributable to crossing the Ridge. East of the Ridge the data were of little value and were not used to evaluate attenuation coefficients because of the obvious break in the propagation characteristics.

In the 1964 paper Urick[20] reported more data from the same experiment, but in this case involving a receiver on the bottom in 14 000 ft of water, also near Bermuda. He again used conventional processing in octave bands. For this source–receiver geometry the transmission paths must have involved R′SR (refracted-surface reflected) and RR (surface reflected–bottom reflected) propagation. Although greater attenuations are to be expected, Urick reports that the R′SR coefficients were only marginally greater than those measured using the SOFAR channel hydrophone and R′R′ (refracted–refracted) propagation, and reported in the 1963 paper. No explanation is offered for this unexpected result.

For that section of the transmission path west of the Mid-Atlantic Ridge, the attenuation coefficients derived in the course of the 1963 experiment are anomalous with respect to the standard Thorp relationship. These differences with other data available at the time was, in fact, a major reason for the experimental program carried out by Sussman *et al.* to which reference will be made later.

Reference to the sound velocity structure for the transmission path involved, indicates that the hydrophone at 14 000 ft lay at approximately the critical depth (CD) in that region. It was possible, therefore, that the small difference in the attenuation coefficients, as measured by the axial and critical depth hydrophones for these near-axial sources, arose not from sea-surface scattering but from the effect of a scattering process within the body of the water column, such as has been hypothesized in recent years. Accordingly, we used a procedure described elsewhere[15,16] to evaluate the attenuation coefficient for this part of the North Atlantic Ocean. By taking the difference between the attenuation coefficients evaluated for the two hydrophones to obtain α_S (arising from the scattering mechanism assumed dominant at low frequencies, and following the terminology used in Ref. 14) and adding back the Thorp attenuation $\alpha_A(f)$ we could obtain a value for the total attenuation $\alpha(f)$ which was not biased by any difference between the actual spreading loss and the cylindrical spreading assumed by Urick. The velocity structure along the transmission path did show that the environment was not strictly range independent.

Urick does not differentiate between the 1500 and 3500 ft shots in his 1963 paper but the implication is that the attenuation coefficients derived were not significantly different, even though the actual energy levels were 10 dB lower for the shallower shots. With this assumption, values of α based on the difference method were evaluated for both the shallow and deep shots. The values of α obtained for each frequency band were similar for the two cases. On the basis of the evidence for the *p*H dependence of the boron relaxation effects referred to earlier, the full Thorp component $\alpha_A{}^6$ was added to the difference component α_S to establish a total attenuation coefficient $\alpha(f)$ for this region of the Atlantic Ocean.

The attenuation coefficients so obtained prove to be lower than Urick's original 1963 values, less anomalous with respect to the Thorp trend line (T), and display a minimum in the vicinity of 50 Hz. The original and modified Urick data are plotted in Fig. 5. Their relationship to the other data plotted will be discussed later.

C. Kibblewhite *et al.*, 1965 (project Neptune)

In Project Neptune [Project Neptune also involved an experiment in the Atlantic Ocean . Data from this, reported by Urick[21] (1966), are referred to later.] Kibblewhite *et al.*[22] measured the transmission characteristics of the Southern Ocean using sound signals set to detonate at 2000 ft within the SOFAR channel along a track from Capetown to Perth. The signals were received on a bottomed hydrophone at a depth of 360 ft off southern New Zealand, where the continental shelf dips steeply to very deep water. Conventional energy analysis was used.

The results obtained gave attenuation values much larger than the Thorp relationship. For many of the great circle paths involved, however, transmission took place deep into the Southern Ocean (not shown in Fig. 2) and across intervening shallow topography which in some cases blocked transmission altogether. For this reason, and the fact that the transmission path varied so markedly from one shot to the next, the attenuation coefficients evaluated in this particular case, are not considered in the analysis to follow.

D. Thorp, 1965

In the course of reporting an experiment conducted to provide attenuation data in the frequency range 300 to 3000 Hz, Thorp[1] also introduces data for lower frequencies (to 112 Hz) relevant to this review (see Fig. 5 of Thorp, Ref. 1).

The main experiment covering the band 300 to 3000 Hz involved SOFAR transmission along a 500-mile track southwest from Bermuda towards the Bahamas, and covering the latitude range 32°–27° N. The first of the supplementary experiments (Sussman, MacDonald, and Kanabis) extended the measurements downward to 112 Hz. The same SOFAR channel receiving location was used. Although not specifically stated, the transmission path was essentially the same as for the main experiment.

The second set of supplementary data of interest was reported by Thorp and Bernier, 1959 and 1962. The data again refer to SOFAR transmissions. Recordings made at Bermuda of the direct water arrivals at ranges up to 700 miles, plus a sampling of topographically reflected signals traveling paths up to 1500 miles in length, were analyzed in the manner of Sheehy and Halley (see p. 654, Ref. 18). The 1500 mile paths imply the reflections were from geographical features well to the south of Bermuda, and that the transmission was therefore through tropical water, a fact which will be of significance in our later review.

E. Urick, 1966

Urick[21] reports the Atlantic Ocean results from Project Neptune where he describes data from explosions at a depth of 800 ft recorded on a bottom mounted hydrophone at 4000 ft off Bermuda. In this case the transmission path ran south from Bermuda towards Recife in Brazil. Energy analysis was carried out in octave bands and except for the lowest frequency band (17 Hz) the results appear to make up a self-consistent set (see Fig. 7); these will be discussed in more detail later.

F. Kibblewhite and Denham, 1967

In 1967 Kibblewhite and Denham[23] reported the results of a long-range transmission experiment in the South Tasman Sea. The receiver was on the bottom at a depth of 420 ft near the edge of the continental shelf off the southwest of the South Island of New Zealand. The track was directed towards Australia and explosive sources were detonated along the path at a depth of 60 ft in this case.

The general character of the transmission loss curve was observed to change significantly at a point about halfway along the track, at a boundary between two distinct water masses. The signals were processed using conventional energy analysis to establish attenuation coefficients for the two regions. The short-range values proved to be greater than the long-range values but both were much larger than the Thorp curve predictions.

While the data are significant in themselves, they are not included in this review for two reasons. First, the shallow depth of the charges implies that R′SR and RR transmission, rather than R′R′, dominated the received signal, a fact supported by the distinct convergence zones which were observable in the long-range data. Second, the contribution of transmission within a near surface duct to long-range signals when shallow charges are used has been emphasized by Fitzgerald *et al.*[24]

For the same reason all other data involving 60-ft sources have also been discarded. This necessarily causes some unease, particularly in respect of the excellent analysis by Morris,[25] of data recorded in the Office of Naval Research [ONR (77)] experiment carried out in the North Pacific. His results show no excess attenuation at low frequencies and contain, accordingly, a warning regarding the results reported by the Applied Research Laboratories of the University of Texas (ARL:UT) for the same region.[15,16] We will discuss this matter in more detail later.

The South Tasman Sea experiment does emphasize, nevertheless, the order of magnitude of the attenuation coefficients for R′SR propagation and strengthens the contention outlined above that the transmission paths dominating the 14 000-ft hydrophone in the Urick paper[20] were R′R′ rather than R′SR as Urick proposed.

G. Kibblewhite and Denham, 1971

This South Pacific experiment,[11] (referred to here for convenience as Project Apteryx), reported data for transmission paths running east from New Zealand. Explosive sources were detonated at a depth of 800 ft along two tracks, A and B, running at slightly different bearings from a bottomed receiver at 3600 ft some 20 miles offshore. Conventional processing in octave bands was used to derive attenuation coefficients for the two tracks.

The data on track A extended only to 600 miles, at which range bathymetry associated with the Eltanin fracture zone appeared to have blocked the SOFAR channel. Along path B a pronounced break in the transmission loss curve occurred at 950 miles. While topographic influence was again likely, the possibility of the effect arising from the path crossing a water-mass boundary was considered. Attenuation coefficients could be evaluated for each region of track B. The long-range data gave high values, while the first part of the track yielded values which, except for the lowest frequency analyzed, were comparable to those for track A, but less than Thorp's prediction curve. The long-range data from profile PB (Fig. 2) are not incorporated in this analysis because it is not possible to resolve whether the effects observed had a hydrological or a topographical origin.

H. Browning *et al.*, 1974 (project Kiwi One)

In the definitive experiment, Project Kiwi One,[12] deep water hydrophones were operated at each end of a 10 000-km transmission path crossing the South Pacific Ocean between latitudes 40° and 10° S—Fig. 2. Explosive charges were dropped at roughly 30-km intervals along the whole path and detonated at the nominal depth of the SOFAR channel axis (1000 m). Signals were received on both receivers, and these were later analyzed to obtain attenuation coefficients over the frequency range 32–500 Hz.

Besides indicating that the boron related relaxation effect[7,8] was only one-half that observed in the Atlantic Ocean, the results gave the first unequivocal evidence of a regional dependence in the absorption at frequencies below 100 Hz. Three distinct regions could be identified with the same effects apparent in the data from both ends of the transmission path. The highest attenuations were recorded in the central region of the path. Abrupt changes in attenuation on each side of this zone appeared to be the result of hydrological rather than topographic influences.

I. Recent North Pacific Ocean data, 1977 (ONR)

Two major experiments have been carried out in the Northeast Pacific Ocean in the past few years under the auspices of the U. S. Office of Naval Research (ONR). In both cases the transmission path ran north–south through a latitude range of roughly 30°–60°N—see Fig. 2. Hydrophones were deployed at various depths at a number of receiving positions and a large number of explosive signals were detonated along the transmission paths, most at either 18- or 91-m depth.

These experiments were not designed for the specific purpose of evaluating attenuation coefficients and an analysis of the complications introduced by the changes in hydrology along these meridionally directed paths[26] emphasizes the dangers in an indiscriminate use of these data for this purpose. Several analyses have nevertheless been made, particularly by the Applied Research Laboratories of the University of Texas (ARL:UT), and values of attenuation coefficients are available for some of these North Pacific data.[7,15,16,25] For this review, however, only the attenuation coefficients from the ARL:UT papers are considered. The exclusion of Morris' data[25] in particular requires further comment.

Morris' results show no excess attenuation from scattering at low frequencies and he is understandably skeptical regarding the ARL:UT results reported for the same region.[15,16] We agree that the discrepancies must be satisfactorily resolved in the future and at this time can only make the following comments:

(i) In the analysis carried out at ARL:UT we examined the signals from both 18-m (60 ft) and 91-m (300 ft) sound sources. Differences between the nature of the attenuation curves for the two sources led us to conclude that the surface duct was influencing the shallow source data.

(ii) An independent unpublished measurement by the Canadian Defence Research Establishment, (cited in Refs. 13 and 16), carried out during the same ONR experiment and based on a receiver at the northern end of the propagation path, produced an attenuation-frequency curve for the region of interest almost identical with that reported by ARL:UT[16] for the same latitude range; both being characterized by a "scattering" related attenuation excess at very low frequencies.

(iii) An evaluation based on ambient noise and using completely different analysis procedures showed the same attenuation excess.[15]

(iv) Of the data which show the same behavior as that reported by Morris and given in Fig. 2 of Ref. 13, we note that: (a) the Sheehy and Halley data refer to either equatorial paths or near zonal paths at latitudes which other measurements have shown to have very low values of attenuation and insignificant scattering loss (see Ref. 16, p. 1174); (b) the Thorp data are unpublished so it is not known whether the source was shallow or deep in this case; (c) the Lovett data are at frequencies too high to resolve the issue.

On the above grounds we have justified the exclusion of very shallow source data. Nevertheless, we acknowledge that Morris introduces an appropriate caution into any review of this nature.

The Lovett data,[27] which also appear in other references, apply primarily to the frequency region above 1 kHz, but one appropriate value is incorporated in Fig. 3.

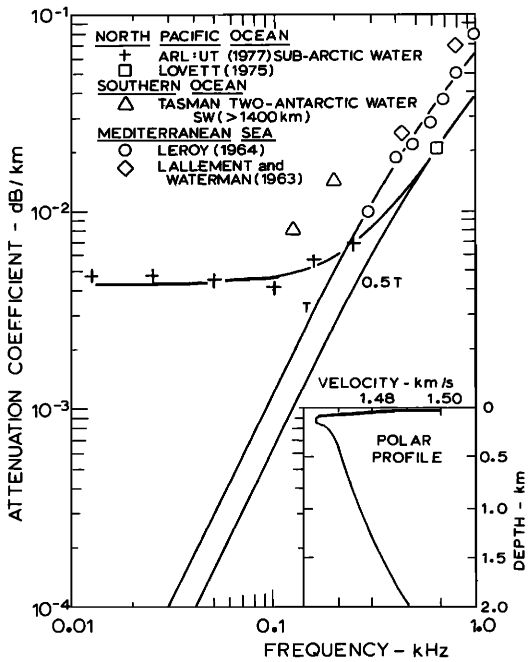

FIG. 3. Attenuation data for a "polar" sound-velocity profile.

J. Bannister *et al.*, 1977 (Project Tasman Two)

In February 1975, a follow-up experiment in the New Zealand based low-frequency propagation program, Project Tasman Two, was conducted in the South Tasman Sea.[14] Sound sources were airdropped out to a range of 3000 km from a hydrophone laid on the sea floor in a water depth of 350 m, off the southwest of the South Island. Transmission paths were selected to sample the four distinct water masses in the area—Fig. 2.

Received signals were analyzed to determine the energy in $\frac{1}{3}$ octave bands at frequencies between 16 and 1000 Hz but the data in the two lowest frequency bands proved unreliable because of the poor signal-to-noise ratio. Attenuation coefficients were evaluated by applying the standard procedures. These values are referred to later.

The results identified three different water masses, each with its distinctive propagation characteristics at low frequencies. Thus, as in the case of other South Pacific Ocean experiments, the excess attenuation at very low frequencies appeared to be regionally dependent and the boron-related absorption to be less than that found in other oceans.

K. Attenuation studies in the Mediterranean Sea

Many of the papers dealing with the question of ocean attenuation at low frequencies cite data from the Mediterranean Sea. In particular the results of Lallement and Waterman,[28] and Leroy[28] often appear in attenuation compilations (see for example Ref. 1).

While these data refer to frequencies above 200 Hz, and are thus primarily relevant to the boron-related effects around 1 kHz, they have nevertheless been incorporated in the results presented below for a reason which will be discussed in due course.

III. REGROUPING OF ATTENUATION DATA

The gross scatter in the collected data (Fig. 1) and the complication of the *p*H dependence of the boron-related contribution to the attenuation[7,8] have tended to obscure the true nature of the regional dependence of the scattering component. While the excellent results of Projects Kiwi One and Tasman Two were welcomed by those who had long believed in the reality of the excess attenuation at very low frequencies as a vindication of these views, the scatter within the total data, and a number of obvious anomalies, have continued to provide some justification for the skepticism of those who prefer to explain the excess attenuations simply in terms of an ill-defined spreading loss in a range-dependent environment.[10]

In an attempt to further clarify this issue we now consider only the results of the experiments selected in the above review. We replot the available data, grouped broadly in accordance with a water-type classification based on the shape of the sound-velocity profile characteristic of the region in which the measurements were made. Obviously, however, the sound-velocity profile is only a convenient index of the water properties involved. The currently available data justify only a gross grouping, but on this basis the water types involved can be considered as polar, subpolar, mid-latitude, and tropical in nature.

As we have seen, Schulkin and Marsh[8] have recently shown that the low-frequency excess attenuation due to the presence of boron depends upon the *p*H, temperature, and salinity. They have given a practical formula to calculate the attenuation, which accounts not only for the variation in *p*H, but also the influence of temperature and salinity on the boric acid relaxation frequency. In any comparison of experimental data with predictions, we should strictly use their formulation but this is an unjustified refinement at this stage. As most of the data were obtained in either the Pacific or Atlantic Oceans it is sufficient for our purposes to consider the data against the trend lines for the two extreme cases (labeled T and 0.5 T) on the figures presented below.

A. The Polar profile

Those data obtained in water characterized by a "polar" sound-velocity profile are grouped in Fig. 3. The particular profile was recorded at 55°N during experiment ONR 77, but the shape is just as relevant for the Southern Ocean serials.

When the attenuation coefficients reported in Ref. 16 were compiled, the regional variation of the boron-related absorption was not firmly established and the Thorp term used was based on the 0.1-f^2 relationship; i.e., in Eq. (2) K was taken as 1.0 (Ref. 16, p. 1175). The data from Ref. 16 presented here have been recalculated using the value of $K=0.5$ which is more appropriate to the North Pacific Ocean. These modified data, labeled ARL:UT in Fig. 3, now merge smoothly with the Lovett data at higher frequencies and suggest a value of α_S of around 4.2×10^{-3} dB/km.

The Southern Ocean data are from serial SW of Tasman Two.[14] While these data are limited to 125 and 200 Hz, the attenuation coefficients do appear to be higher than for the North Pacific experiment. Although variations of this magnitude are not necessarily significant, it may be noted that in another interpretation of the Tasman Two data,[17] the change in propagation characteristics at 1400 km along radial SW were interpreted as indicating that the path crossed the Antarctic Convergence at this point, rather than the Australiasian Subantarctic Front as proposed by the authors. It may be reasonable to attribute the "higher" attenuations to this fact.

Because of the properties of the near surface waters, the sound-velocity profile in the Mediterranean Sea is also characterized by a very shallow SOFAR channel axis. At the appropriate time of the year indeed the sound-velocity profile resembles closely the polar profile identified in Fig. 3. At present, the available Mediterranean attenuation data[28] do not extend below 100 Hz—see Fig. 3. In accordance with predictions[9] these data lie closer to the trend line based on the full, rather than the fractional, value of the Thorp empirical formula. From the stand point of the present analysis it will be instructive to see whether any attenuation coefficients established in the future do show a high scattering component at frequencies below 200 Hz.

B. The subpolar profile

The only published data from waters for which a subpolar sound-velocity profile is characteristic is from the Tasman Two experiment.[14] These data are presented in Fig. 4. The attenuation values for radials SW and WSW both relate to Australiasian Subantarctic water. The North Atlantic data presented in Fig. 4 are from an unpublished analysis of propagation data obtained in an ONR experiment conducted in the Icelandic Basin. While the general sound velocity profile was

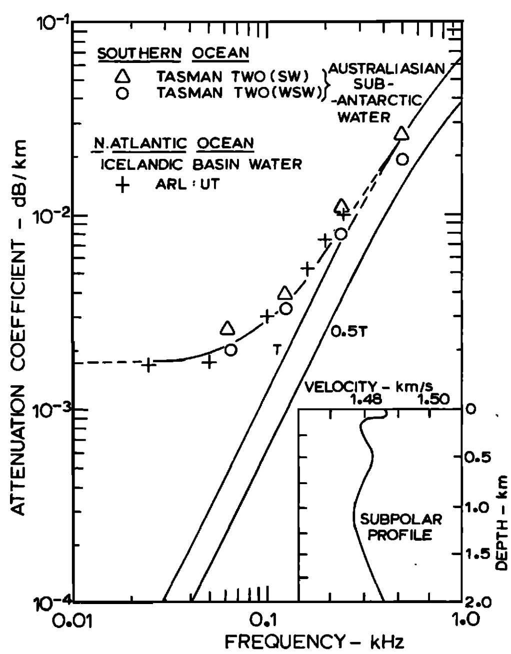

FIG. 4. Attenuation data for a "subpolar" sound-velocity profile.

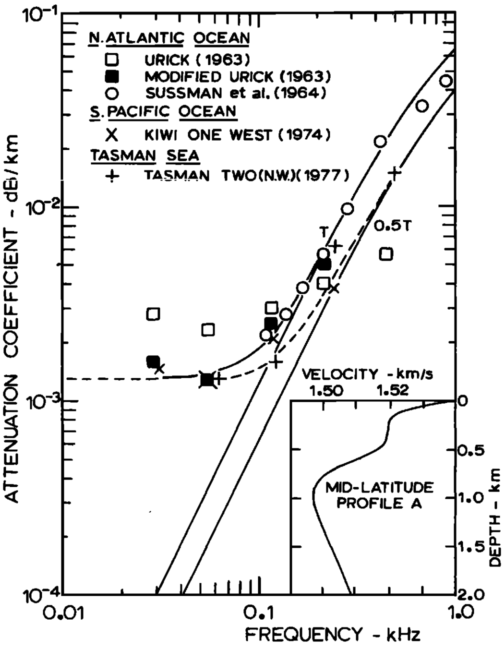

FIG. 5. Attenuation data for a mid-latitude sound-velocity profile "type A."

subpolar in type, the complexity of the hydrology must place some doubts on the attenuation coefficients so obtained. However, because of the similarity of the data sets they are included here.

Both sets of data suggest a value of the scattering coefficient α_S of about 1.8×10^{-3} dB/km. At the higher frequencies both data sets follow the trend line T, for which $K=1$, reasonably closely, in accordance with the values of K appropriate to these oceans [see Eq. (3)]. For the Atlantic Ocean, K is approximately unity,[7,9] while the value relevant to radials SW and WSW of Tasman Two is quoted as approximately 0.83.[14,9]

C. Mid-latitude profile A

Mid-latitude waters encompass a range of sound-velocity profile types. Waters with the sound velocity structure shown in Fig. 5 are found at various latitudes in the oceans of the world. For instance in the North Atlantic this structure exits between roughly 25° and 35°N on the west of the Mid-Atlantic Ridge (see, for example, Ref. 24). In the North and South Pacific Oceans it can be found between 35° and 45° depending upon longitude.[12,14,15,26]

The experimental data representative of waters with this velocity profile are also plotted in Fig. 5. It can be seen that, assuming we can accept the modified data for the Urick (1963) experiment,[19] there is again a consistency in the attenuation coefficients. The anomalous point at 450 Hz in the original Urick (1963) data could not be modified, as no attenuation value was available at this frequency for the 14 000-ft (critical depth) hydrophone. The value of α_S for this profile is about 1.3×10^{-3} dB/km.

As expected, at high frequencies the Atlantic data merge with the trend line for which $K=1$, while the

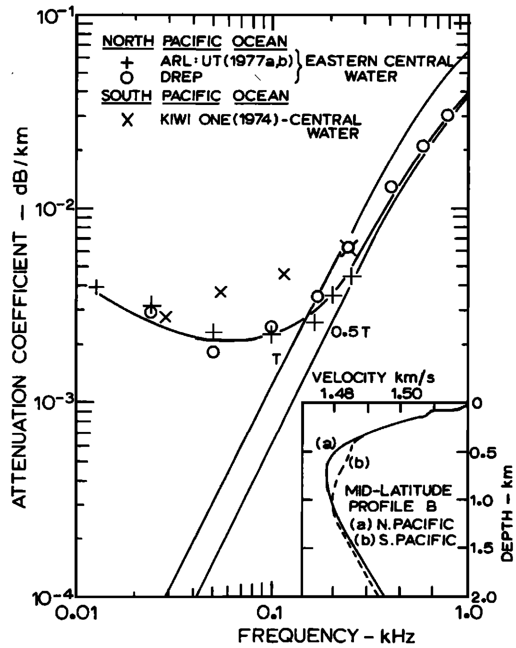

FIG. 6. Attenuation data for a mid-latitude sound-velocity profile "type B."

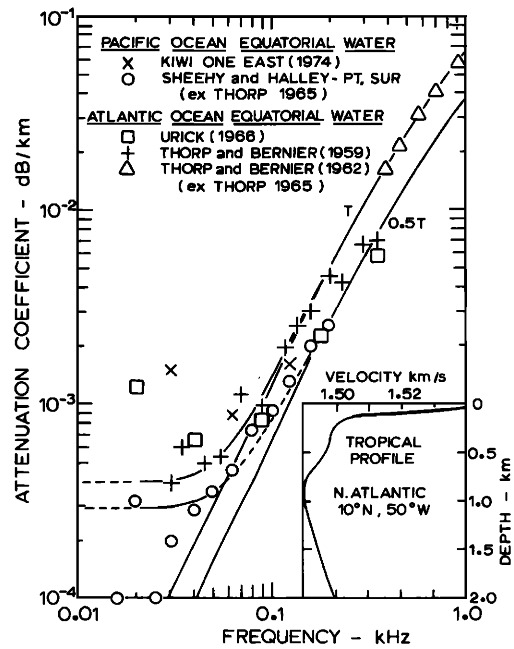

FIG. 7. Attenuation data for a "tropical" sound-velocity profile.

Pacific Ocean and Tasman Sea data lie closer to that for $K=0.5$.

D. Mid-latitude profile B

Data for another temperate water profile are grouped in Fig. 6. The North Pacific Ocean data labeled "ARL:UT (1977a, b)" are from Refs. 15 and 16, respectively, but again adjusted for the value of $K=0.5$ in Eq. (2). Those labeled DREP are taken from Ref. 13, and represent an independent analysis of the ONR (77) experiment referred to earlier. The Kiwi One data are from the central region of this South Pacific transmission path.[12]

The North Pacific values agree closely, as they should, since the same water mass is involved. The Kiwi One values for 50 and 100 Hz are somewhat higher than the others, but overall the consistency of the whole data set is notable. A value of about 2.0×10^{-3} dB/km for α_S is suggested.

As all the data are from the Pacific Ocean, the higher-frequency values should merge with the Thorp trend line for which $K=0.5$, as is observed.

E. The tropical profile

The data which can be grouped under a tropical sound-velocity profile are plotted in Fig. 7. The justifications for incorporating the Sheehy and Halley values for the Point Sur hydrophone, and those of Thorp and Bernier, were presented earlier. Once again, it is suggested, this particular grouping brings consistency to the results. In this case the attenuation coefficients at the lowest frequencies are very small indeed, and there is a suggestion that α_S may be smaller in the Pacific than in the Atlantic. However, the uncertainty of the data, particularly that of Sheehy and Halley, makes this difference of limited significance. While it is difficult to assign a value to α_S, it is certainly less than 10^{-3} dB/km and it appears a value between 0.4×10^{-3} and 0.2×10^{-3} dB/km might be appropriate, the Atlantic values seeming to be higher than those for the Pacific Ocean.

As expected, the Pacific and Atlantic Ocean data merge with the Thorp trend line appropriate to each ocean.

F. Other data

Sets of data, which at first sight do not appear to fit any of the groupings discussed in Figs. 3–7, are pre-

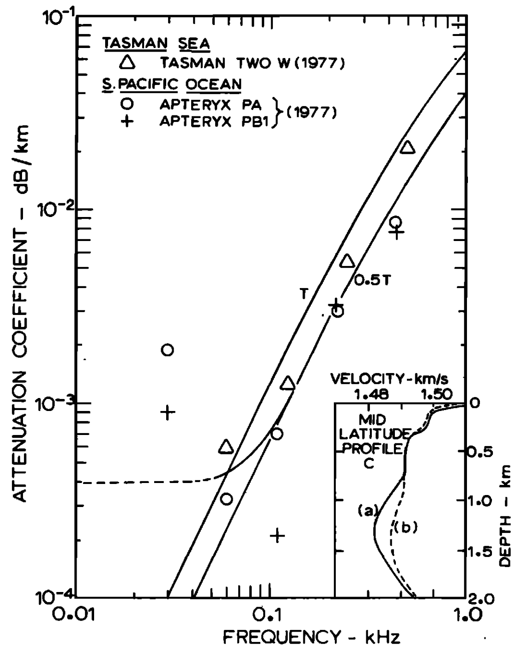

FIG. 8. Attenuation data for a mid-latitude sound-velocity profile "type C."

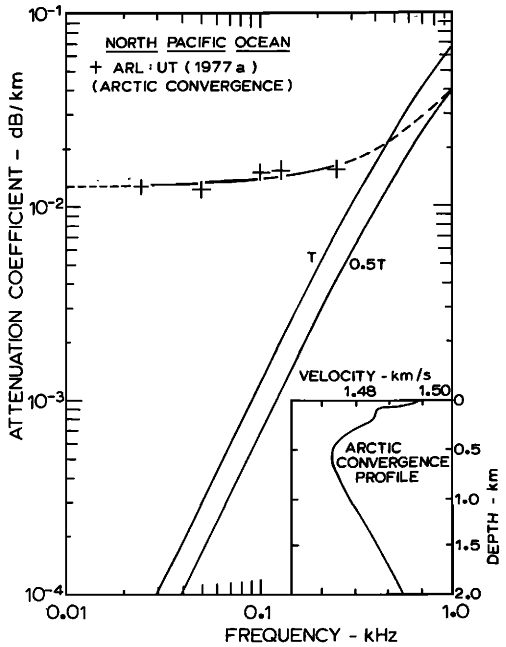

FIG. 9. Attenuation data for the Arctic Convergence in the eastern North Pacific Ocean.

sented in Figs. 8 and 9.

The Fig. 8 data refer to the radial W from the Tasman Two experiment and those Apteryx data which were accepted in the earlier review. Both sets are plotted together on the basis of their sound velocity profiles, identified here as "mid-latitude profile C." Apart from three anomalous points, the remaining values appear to represent a self-consistent subset, involving a low value of α_s, of the same order (0.4×10^{-3} dB/km) as applied in the case of mid-latitude profile B. At the higher frequencies the data lie close to the line $K = 0.5$. (According to the authors K is expected to be about 0.6 for the radial W.)

In Fig. 9 we plot attenuation values evaluated for the subarctic convergence zone in the Northeast Pacific Ocean.[16] This is a limited region of pronounced hydrological complexity and the high values of attenuation are not considered surprising. The data produce the highest value of α_s encountered in this review, 15.0×10^{-3} dB/km. We will refer to this later.

IV. DISCUSSION

The most recent long-range acoustic experiments, and in particular the two Southern Hemisphere experiments Kiwi One and Tasman Two, have given strong support to the suggestion that in SOFAR channel propagation there are two regionally dependent mechanisms adding to the losses arising from simple geometrical spreading. Evidence is now strong that below 1 kHz the SOFAR attenuation should vary with frequency according to an expression of the form

$$\alpha(f) = \alpha_s + 0.11Kf^2(1+f^2)^{-1} + 0.011f^2 \text{ dB/km}, \qquad (3)$$

where α_s represents the additional scattering term and K is the coefficient which accounts for the regional variation of the boron-related effects.

Many oceanic phenomena can be considered as potential sources of the scattering process and several models have been proposed to account for effects observed below 100 Hz.[19,29-32] These analyses have shown that the effects of boundary induced absorption in the deep ocean will be significant only at frequencies below 10 Hz and that by implication the excess attenuation between 10 and 100 Hz, if real, is related to an oceanic agency within the water mass. For example, assuming random perturbations in the sound field arising from internal waves, Mellen *et al.*[31] have derived an estimate of the scattering loss contribution which is consistent with some of the experimental values reported. Others have drawn attention to the influence that fine structure in the water-current, velocity-depth, and temperature-depth profiles can have on the amplitude and phase of underwater sound.[33,34]

As Guthrie[32,16] emphasizes in his model, however, the scattering loss will involve some product of the mode amplitude and the magnitude of the scattering agency integrated over the water column. It is the sound-velocity profile which controls the mode amplitude and hence determines the degree to which any depth-dependent scattering agent, of whatever origin, influences the transmission of underwater sound at very low frequencies.

We are not concerned here, however, with identifying the precise mechanism involved, but rather in achieving some sort of order in the confusion of low-frequency attenuation results reported in the literature. Without concerning ourselves with the nature of the scattering agency we have assumed the likely relevance of the sound-velocity profile and restricted ourselves at this stage to seeking some sort of the regional classification in terms of this, rather than a more complicated oceanographic parameter. While the large standard errors involved in individual values can obviously influence the groupings, the analysis described does show that the scattered data of Fig. 1 can be resolved into self-consistent subsets (Figs. 3–9) on the basis of the sound-velocity profile alone. Several features of these groupings are of interest.

Ignoring the anomalous case of the SubArctic Convergence (Fig. 9), the highest value of α_s is seen to be associated with the polar and the lowest with the tropical sound-velocity profile. The values for each subset are presented in Table I.

Although α_s is ill defined in the tropical subset, it is clearly an order of magnitude lower than its polar counterpart, and appears to be smaller in the Pacific than in the Atlantic Ocean. While the probable errors involved and the particular analysis employed by Sheehy

TABLE I. Scattering attenuation coefficient—dB/km.

	Water classification					
Attenuation coefficient	Polar	Subpolar	Mid-latitude A	B	C	Tropical
α_s—dB/km $\times 10^{-3}$	4.2	1.8	1.3	2.0	0.4	0.2–0.4

and Halley make this difference of doubtful significance, we have noted that other unpublished tropical data from the North Pacific (Ref. 16, p. 1174) also imply extremely low values of attenuation at low frequencies.

On the evidence available, it is not clear whether α_s is frequency dependent as suggested by one analysis,[15] but if it is, it is only marginally so. The question of a minimum in the attenuation versus frequency curve around 50 Hz[15] is also unresolved on the evidence available, although the data for the subgroups involving the lower values of α_s indicate such a minimum is a possibility.

The various subgroups give some insight into those oceanic properties which may be of importance to acoustic absorption at low frequencies. In the case of Fig. 9, for instance, the very high attenuations must be associated with some property of the subarctic transition zone waters to which the data refer. This is a region of convergence and is one characterized by great hydrological complexity and above average inhomogeneity and turbulence. High turbulence associated with strong current flow was also suggested as the reason for the high attenuation in the central region of the Kiwi One transmission path[12] (Fig. 6). It is possible this accounts for its anomalous position in its subgroup. Furthermore we recall the suggestion[17] that the anomalously high value of α_s for the region beyond 1400 km along radial SW in Tasman Two (see Fig. 3) may arise from effects associated with the Antarctic Convergence. If this interpretation was correct, the correlation between attenuation and turbulence associated with vertical velocity shear would appear to be high.

In contrast we note the very low value of α_s implied in Fig. 8. The ocean regions involved in Serial W of Project Tasman Two, and the two Apteryx serials PA and PB1, are all immediately north of the subtropical Convergence. In this connection it is of interest to recall the temperature measurements made in this region. Minimal fine structure was recorded in the temperature profile to a 300-m depth. In the Tasman this region is thus apparently characterized in the upper few hundred meters by two very well-mixed layers separated by a thin region of high stability. The low attenuation in these waters may be related to these properties.

Ignoring the regions of high turbulence, the results presented in Figs. 3–8 show that the excess attenuation is greatest for the polar and least for the tropical profile. While the changes between these extremes are not simply monotonic, there is a strong suggestion that the scattering agency is depth dependent and dominant in the upper few hundred meters of the ocean. Internal wave activity is a likely scattering agency in such regions, but further analysis will be required to positively identify the cause of the excess attenuation at frequencies below 100 Hz.

V. CONCLUSION

We believe that grouping the low-frequency attenuation data on the basis of the sound-velocity profile has established some order in the scatter at frequencies below 100 Hz. Using profiles characteristic of polar, subpolar, tropical, and mid-latitude waters has produced self-consistent subsets of the attenuation coefficient for these regions. These subsets still, however, emphasize an excess attenuation at frequencies below 100 Hz when compared with the Thorp empirical formula. While the actual oceanic agency responsible for the excess attenuation is still not established, its depth and regional dependence seem to be indicated. Furthermore, whether or not they are always the dominant factors, internal waves, turbulence, and strong velocity shearing are all likely to be important to acoustic propagation at very low frequencies.

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[1]W. H. Thorp, "Deep-Ocean Sound Attenuation in the Sub- and Low-kilocycle per second Region," J. Acoust. Soc. Am. **38**, 648–654 (1965) (also includes supplementary sources referred to in the article; Sussman *et al.*; Thorp and Bernier).
[2]M. Schulkin and H. W. Marsh, "Absorption of Sound in Sea Water," J. Br. Inst. Radio. Eng. **25**, 493–500 (1963).
[3]W. H. Thorp and D. G. Browning, "Attenuation of Low Frequency Sound in the Ocean," J. Sound Vib. **26**, 576–578 (1973).
[4]E. Yeager, F. H. Fisher, J. Miceli, and R. Bressel, "Origin of the Low Frequency Sound Absorption in Sea Water," J. Acoust. Soc. Am. **53**, 1705–1707 (1973).
[5]F. H. Fisher and V. P. Simmons, "Discovery of Boric Acid as a Cause of Low Frequency Sound Absorption in the Ocean," IEEE Ocean **75**, 21–24 (1975).
[6]W. H. Thorp, "Analytic Description of the Low-Frequency Attenuation Coefficient," J. Acoust. Soc. Am. **42**, 270 (1967).
[7]R. H. Mellen and D. G. Browning, "Variability of Low-Frequency Sound Absorption in the Ocean: pH Dependence," J. Acoust. Soc. Am. **61**, 704–706 (1977).
[8]M. Schulkin and H. W. Marsh, "Low Frequency Sound Absorption in the Ocean", J. Acoust. Soc. Am. **63**, 43–48 (1978).
[9]J. R. Lovett, "Geographic Variation of Low-Frequency Sound Absorption in the Atlantic, Indian and Pacific Oceans," J. Acoust. Soc. Am. **65**, 253 (1979).
[10]J. S. Hanna and P. V. Rost, "The Influence of Range-Dependent Environments on Low Frequency Volume Attenuation Measurements," J. Acoust. Soc. Am. **61**, 369–374 (1977).
[11]A. C. Kibblewhite and R. N. Denham, "Low Frequency Sound Absorption in the South Pacific Ocean," J. Acoust. Soc. Am. **49**, 810–815 (1971).
[12]D. G. Browning, W. R. Schumacher, R. W. Bannister, and R. N. Denham, "Project KIWI ONE: Low Frequency Sound Attenuation Measurements in the South Pacific Ocean," Naval Underwater Systems Center Technical Report No. 4949 (June 1974).
[13]R. H. Mellen and D. G. Browning, "Low Frequency Attenuation in the Pacific Ocean," J. Acoust. Soc. Am. **59**, 700–702 (1976).
[14]R. W. Bannister, R. N. Denham, K. M. Guthrie, and D. G. Browning, "Project TASMAN TWO: Low Frequency Propagation Measurements in the South Tasman Sea," J. Acoust. Soc. Am. **62**, 847–859 (1977).
[15]A. C. Kibblewhite, J. A. Shooter, and S. L. Watkins, "Examination of Attenuation at Very Low Frequencies Using

the Deep Water Ambient Noise Field," J. Acoust. Soc. Am. **60**, 1040–1047 (1976).
[16]A. C. Kibblewhite, N. C. Bedford, and S. K. Mitchell, "Regional Dependence of Low-Frequency Attenuation in the North Pacific Ocean," J. Acoust. Soc. Am. **61**, 1169–1177 (1977).
[17]A. C. Kibblewhite, T. G. Shirtcliffe, and B. R. Stanton, "The Effects of Temperature Microstructure on Low Frequency Propagation in the South Tasman Sea," J. Acoust. Soc. Am. **62**, 308–319 (1977).
[18]M. J. Sheehy and R. Halley, "Measurement of the Attenuation of Low-Frequency Underwater Sound," J. Acoust. Soc. Am. **29**, 464–469 (1957).
[19]R. J. Urick, "Low-Frequency Sound Attentuation in the Deep Ocean," J. Acoust. Soc. Am. **35**, 1413–1422 (1963).
[20]R. J. Urick, "Attenuation over RSR Paths in the Deep Sea," J. Acoust. Soc. Am. **36**, 786–787 (1964).
[21]R. J. Urick, "Long-Range Deep-Sea Attenuation Measurements," J. Acoust. Soc. Am. **39**, 904–906 (1966).
[22]A. C. Kibblewhite, R. N. Denham, and P. H. Barker, "Long-Range Sound-Propagation Study in the Southern Ocean—Project Neptune," J. Acoust. Soc. Am. **38**, 629–646 (1965).
[23]A. C. Kibblewhite and R. N. Denham, "Long-Range Sound Propagation in the South Tasman Sea," J. Acoust. Soc. Am. **41**, 401–411 (1967).
[24]R. M. Fitzgerald, A. C. Guthrie, D. A. Nutile, and J. D. Shaffer, "Influence of the Subsurface Sound Channel on Long-Range Propagation Paths and Travel Times," J. Acoust. Soc. Am. **55**, 47–53 (1974).
[25]G. B. Morris, "Low Frequency Sound Attenuation in the Northeast Pacific Ocean," J. Acoust. Soc. Am. Suppl. 1 **59**, S544(A) (1976).
[26]H. Weinberg and R. Burridge, "Horizontal Ray Theory for Ocean Acoustics," J. Acoust. Soc. Am. **55**, 63–79 (1974).
[27]J. R. Lovett, "Northeastern Pacific Sound Attenuation Using Low Frequency CW Sources," J. Acoust. Soc. Am. **58**, 620–625 (1976).
[28]*Underwater Acoustics*, edited by V. M. Albers (Plenum, New York, 1967), Vol. 2, p. 229.
[29]C. B. Brown and S. J. Raff, "Theoretical Treatment of Low Frequency Sound Attenuation in the Deep Ocean," J. Acoust. Soc. Am. **35**, 2007–2009 (1963).
[30]R. H. Mellen, D. G. Browning, and J. M. Ross, "Attenuation in Randomly Inhomogeneous Sound Channels," J. Acoust. Soc. Am. **56**, 80–82 (1974).
[31]R. H. Mellen, D. G. Browning, and L. Goodman, "Diffusion Loss in a Stratified Sound Channel," J. Acoust. Soc. Am. **60**, 1053–1055 (1976).
[32]K. M. Guthrie, "The Propagation of SOFAR Signals," Ph. D. dissertation, Department of Physics, The University of Auckland, New Zealand (1974).
[33]T. B. Sanford, "Observations of Strong Shears in the Deep Ocean and Some Implications on Sound Rays," J. Acoust. Soc. Am. **56**, 1118–1121 (1974).
[34]T. E. Ewart, "Acoustic Fluctuations in the Open Ocean—A Measurement Using a Fixed Refracted Path," J. Acoust. Soc. Am. **60**, 46–59 (1976).