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INTENSITY-RANGE RELATIONS FOR SHALLOW-WATER SOUND PROPAGATION

by

EDWARD MURPHY and OLE V. OLESEN

1 APRIL 1976

NORTH
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APPROVED FOR DISTRIBUTION

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Intensity-range relations for shallow-water sound propagation

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Convincing experimental evidence is presented to show that various "decay laws" for the decrease of sound intensity with increasing range can give high-quality representation for shallow water data. However, while a sequence of decay laws may fit data well and are simple, the transition ranges for changeover from one law to another can show a complicated dependence on frequency and environmental parameters. Transition ranges are probably no easier to predict or model than is the transmission loss itself.

Subject Classification: [43]30.20, [43]30.25.

INTRODUCTION

Shallow-water sound propagation is relatively complicated, so much so in fact that attempts are often made to go to the other extreme and use relatively simple semiempirical "decay laws" to represent propagation loss (see, for example, Refs. 1–5). "Decay laws" refer to special functions of range R, to represent the falloff or decay of sound intensity with increasing range.

Two forms for decay laws of special significance are the three-halves law ($R^{-3/2}$) and $R^{-1}\,e^{-\alpha R}$. The latter corresponds to cylindrical spreading with an exponential attenuation, and is expected to apply when only one mode is significant. The history and details of these decay laws are reviewed by Weston in Ref. 2.

In early attempts at decay law representations for data (see, for example, Ref. 6), the collection of data was usually limited and insufficient to establish or refute a particular decay law. In fact, a variety of decay law representations for a given set of data were at times of equal quality. Also, sometimes one form of decay law representation seemed a better fit to data when other forms were expected on the basis of theoretical arguments. Weston has discussed this apparent contradiction in Ref. 7.

Any theoretical or semiempirical decay law representation for the decrease in sound intensity with increasing range usually involves a set of range functions from the following collection:

spherical spreading—R^{-2} ,

three-halves law—$R^{-3/2}$,

cylindrical spreading—R^{-1} ,

three-halves law with attenuation—$R^{-3/2}\,e^{-\alpha R}$,

cylindrical spreading with attenuation—$R^{-1}\,e^{-\alpha R}$,

where it is assumed that the contribution from volume absorption has already been accounted for and the exponential factors are a consequence of other losses (e.g., boundary losses). The most significant differences between various decay laws, for example, between the three-halves law $R^{-3/2}=R^{-1}R^{-1/2}$ and the single-mode form $R^{-1}\,e^{-\alpha R}$ are the $R^{-1/2}$ and $e^{-\alpha R}$ factors. Shallow-water sound propagation experiments over a flat bottom are often confined to ranges less than 30 or 40 km. In Fig. 1 the two factors, $R^{-1/2}$ and $e^{-\alpha R}$ are compared for such a range interval. The $R^{-1/2}$ samples, the open circles, are located at those ranges for which the sound field was sampled in one of the propagation trials described below. The $R^{-1/2}$ samples have been fitted, using regression analysis, by an exponential

$$e^{-\alpha R}=e^{-[b/(10\log e)]R} ,$$

where b is the attenuation in decibels/km. This least squares fit gives an attenuation of 0.231 dB/km, with a standard deviation of 1.39 dB. Since shallow-water data considered in the past often covered even a shorter-range interval, had poorer range sampling, and often had fluctuations larger than a few decibels, it is not surprising that difficulties and contradictions arise when considering evidence for a given decay law. It might be anticipated, therefore, that more extensive

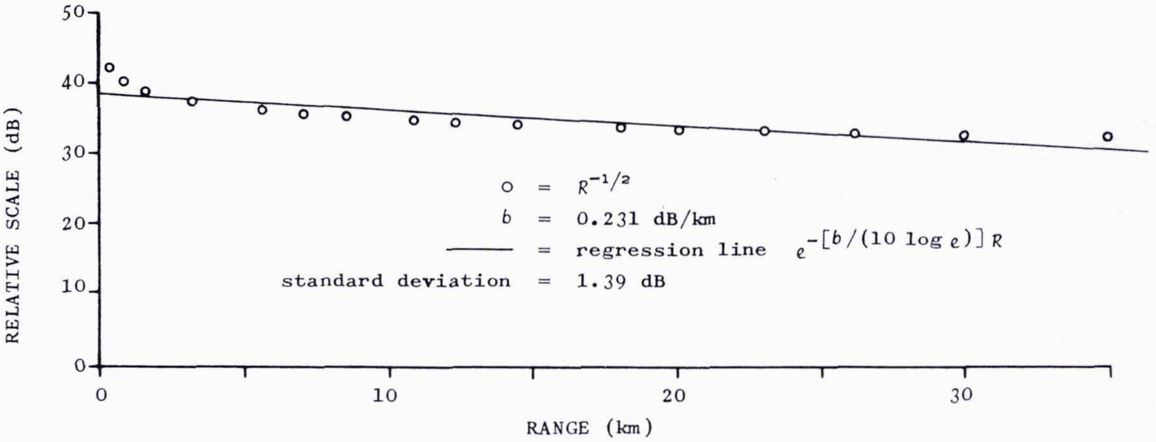

FIG. 1. Regression analysis to determine an equivalent attenuation $b=\alpha 10\log e$ to make $e^{-\alpha R}$ a least-squares fit to an $R^{-1/2}$ law. ($R^{-1/2}$ samples are located at ranges where the sound field was sampled in one of the propagation trials.)

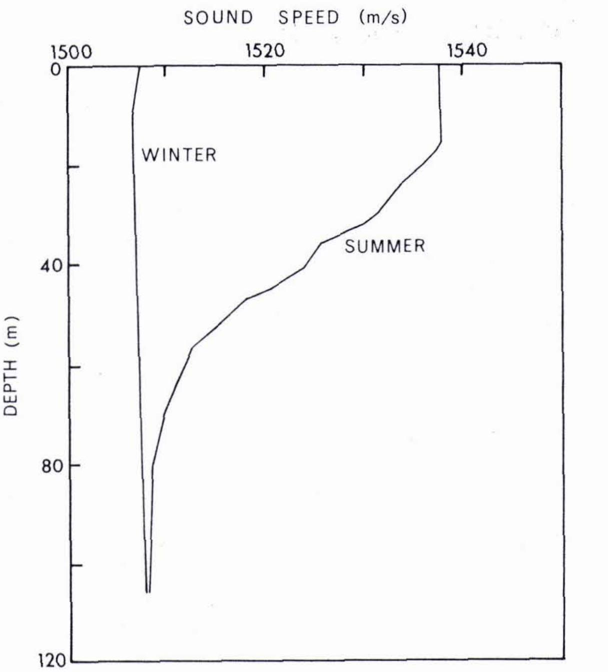

FIG. 2. Sound-speed profiles for the summer and winter trials.

and smoother data would resolve these issues, but we shall see that this is not so.

I. EXPERIMENTS NEAR ELBA

Broad-band shallow-water sound propagation trials have been carried out by the NATO SACLANT ASW Research Centre in trial zones near the island of Elba (Ref. 8). It is pertinent (see Ref. 7) to point out that there is very little biological activity in this area. The measurements, with explosive sources at mid-depth, cover a broad frequency range from 0.1 to 8 kHz. Data are recorded digitally and analyzed for transmission loss in one-third octave bands. A vertical array is used; it is suspended from a spar-buoy with five or six hydrophones distributed in depth in water 110 m deep over a flat bottom of clay and sand sediments that has a high-velocity top layer, 103% of the sound speed in the bottom water. The pertinent sound-speed profiles for the summer and winter trials are shown in Fig. 2. The results reproduce well for repeated trials.

Derivations of decay laws usually involve assumptions that imply some form of averaging over depth, either for source or receiver or for both. When Elba

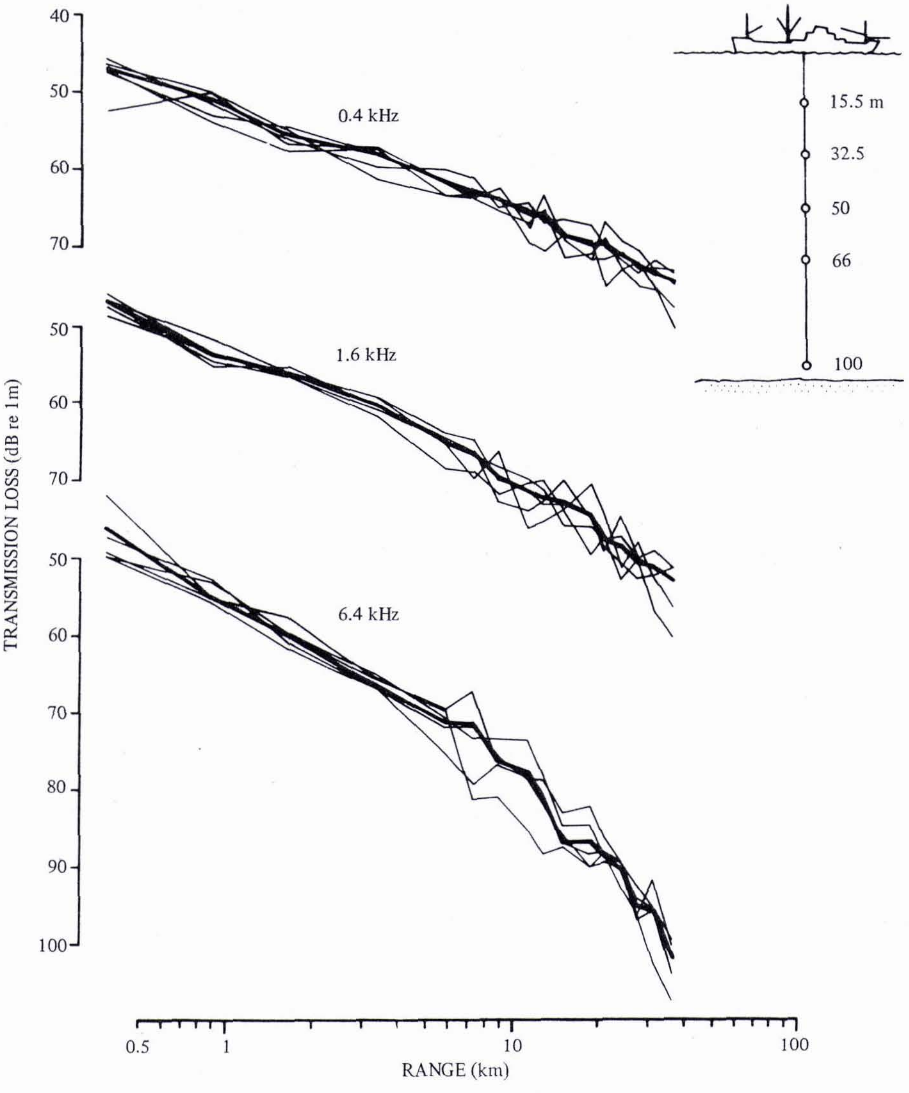

FIG. 3. Comparison of transmission loss for each receiver depth with depth-averaged transmission loss for the 0.4, 1.6, and 6.4 kHz one-third octave frequency bands.

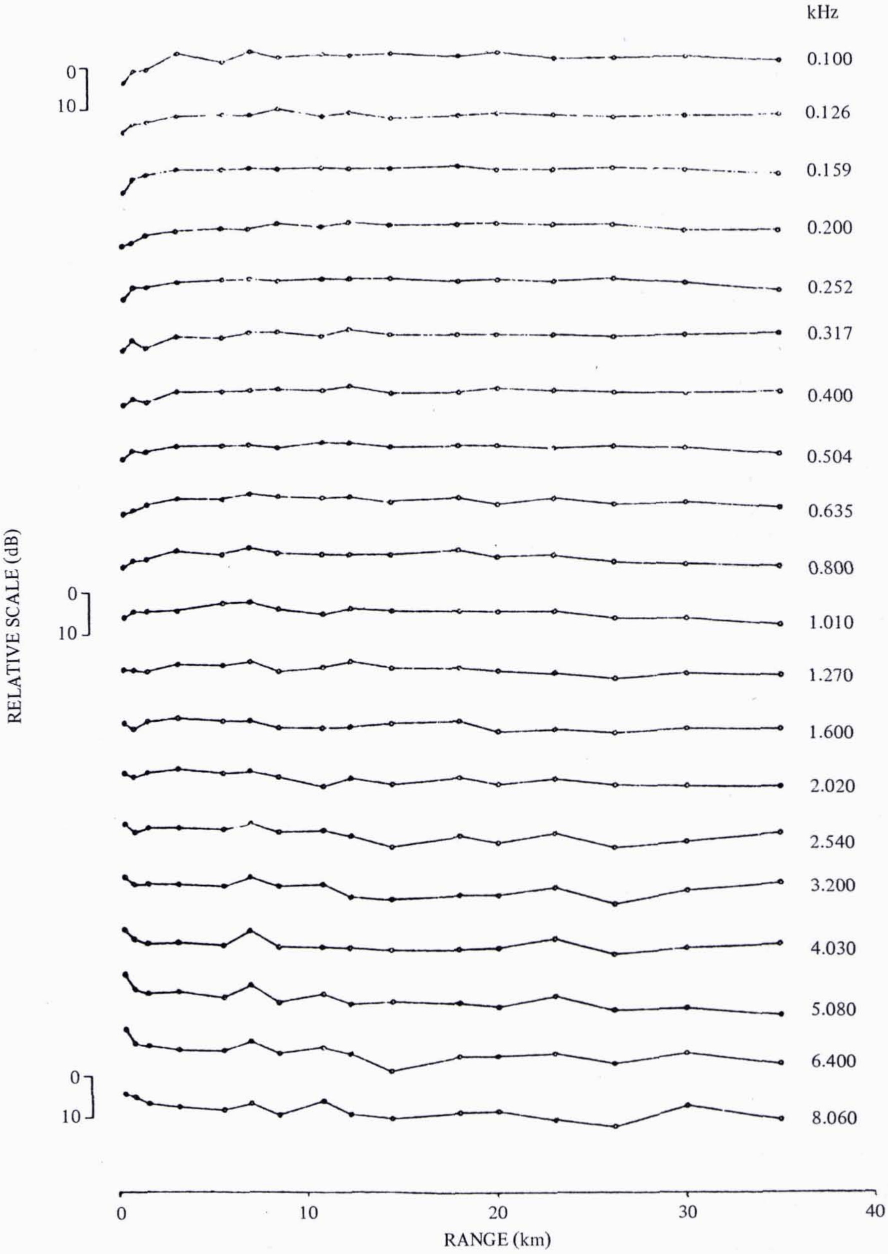

FIG. 4. Three-halves law anomaly, $AN_{3/2}$, linear range scale, for twenty one-third octave frequency bands from a propagation run in isothermal water in winter.

data is averaged for the five or six receivers, the resulting depth-averaged transmission loss (ATL) is often a very smooth function of range over the 35-km track of these trials. This is illustrated in Fig. 3 where transmission loss data are plotted for individual receivers, the thin lines, and for depth-averaged transmission loss, the thick line, for some sample frequencies. (To simplify the graph, curves for each receiver are not identified.) The vertices in the curves are the result of straight-line connection of the data points. While fluctations in the transmission loss versus range curves for individual receivers are large, the curve for ATL is relatively smooth. This might lead one to try to divide the problem into a study of "averaged decay laws," and a statistical study of the fluctuations.

The extensive collection of Elba data from summer and winter trials in 1969–1971 offers the opportunity to assess the quality of evidence in data for representation by various decay laws.

II. EVIDENCE FOR THE THREE-HALVES LAW

The experimental results for ATL for 20 one-third octave bands from a propagation run north of Elba in winter (isothermal water) are given in Fig. 4 in a form we refer to as a "three-halves law anomaly" $AN_{3/2}$, where

$$AN_{3/2} = \mathrm{ATL} - 15 \log R - vR.$$

The 15 log R term removes from ATL the loss due to a three-halves spreading law; the vR term removes from ATL the loss due to the volume absorption. It is assumed that values for the volume absorption coefficient v can be taken from results from deep water measurements (for example, we use Ref. 9). The resulting

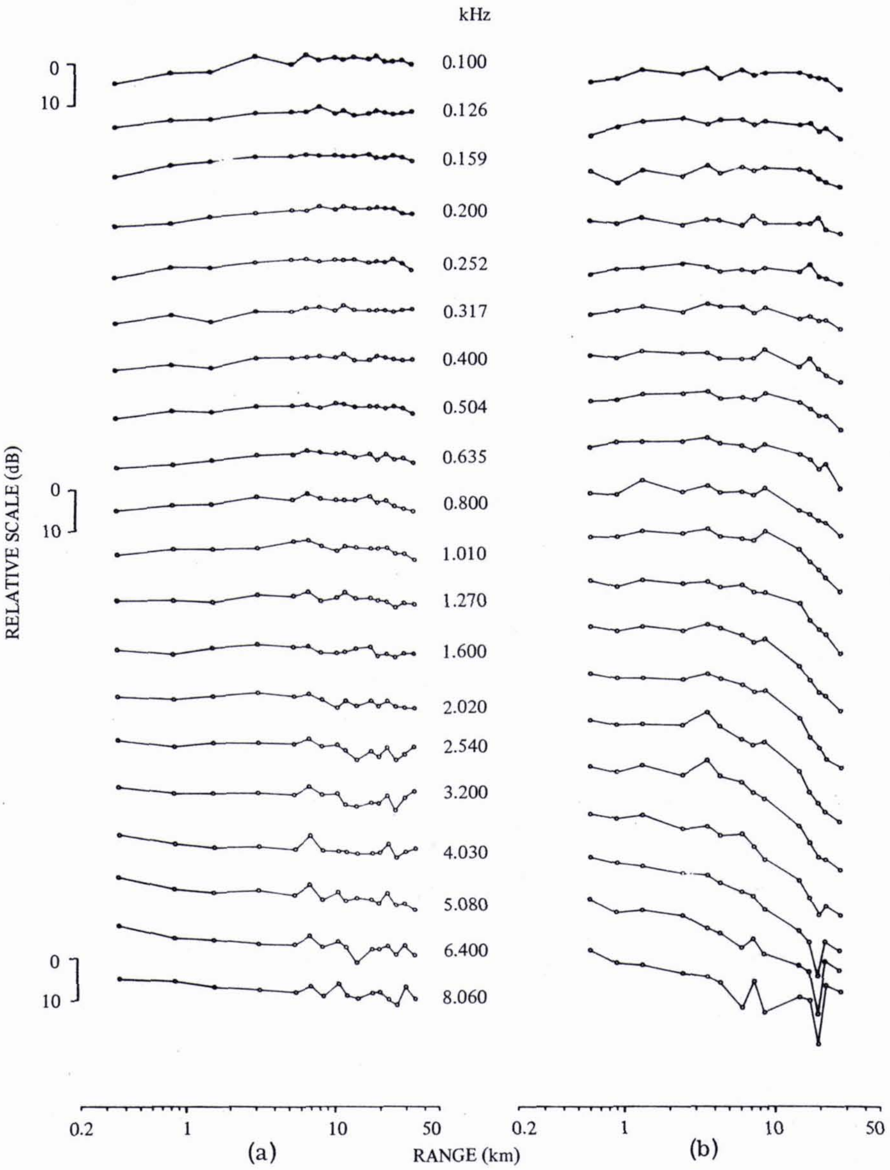

FIG. 5. Three-halves law anomaly, $AN_{3/2}$, logarithmic range scale, for twenty one-third octave bands from two propagation runs: (a) Measurements in isothermal water in winter (same data as in Fig. 4); and (b) Measurements under downwards refraction conditions in summer (same data as in Fig. 7).

simplification in the decay law representations presented in Fig. 4 may give some indirect justification for this assumption for the Elba trial zone.

If the data actually obeyed the three-halves law, and if deep water values for v are appropriate, then $AN_{3/2}$ should be independent of range, all range dependence having been accounted for.

The results in Fig. 4 show that over a wide range interval and for a broad range of frequencies $AN_{3/2}$ is indeed constant to better than 1 or 2 dB. In fact, for regression analysis over the range interval from a few kilometers to the maximum range of the experiments, the standard deviation is less than 1 dB. So here is some convincing experimental evidence for the three-halves law.

At lower frequencies and shorter ranges the propagation is better than the three-halves law (15 log R overcompensates). This behavior may represent the R^{-1}, or cylindrical spreading region, predicted by Weston[2] that could appear after the very-short-range region where spherical spreading (R^{-2}) applies, and before the onset of the three-halves law behavior. This short-range behavior is emphasized in more detail in Fig. 5(a), where $AN_{3/2}$ for the same trial of Fig. 4 is plotted with a logarithmic range scale. For the first shot in this trial the surface-reflected arrival was unusually large, in fact twice the amplitude of the direct arrival. This is not a rare phenomenon (see, for example, Refs. 10 and 11). This resulted in increases of 2 or 3 dB in the levels for depth-averaged data for this shot at the higher frequencies (above a few kilohertz). Nevertheless, there may be slight evidence in Fig. 5(a) for a falloff in $AN_{3/2}$ with increasing range, at short ranges, perhaps a spherical spreading region.

These results can be summarized with a decay law "map" as sketched in Fig. 6. In the frequency-range plane, contours are drawn to indicate where, at a given frequency, the transition from one decay law to another occurs. Though the evidence is vague a spherical spreading region is included.

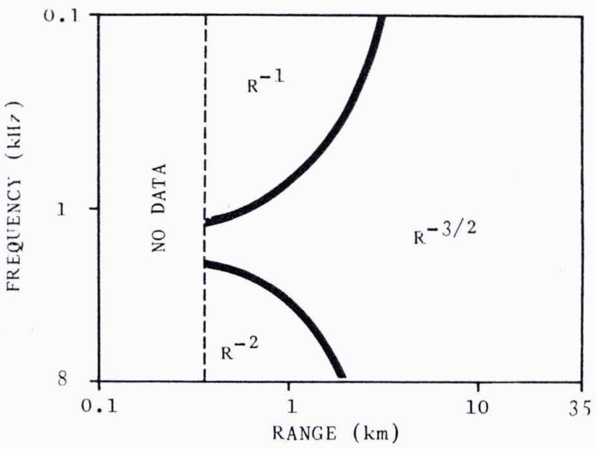

FIG. 6. Decay law map showing the transition from one decay law to another for the winter data in Figs. 4 and 5 (a).

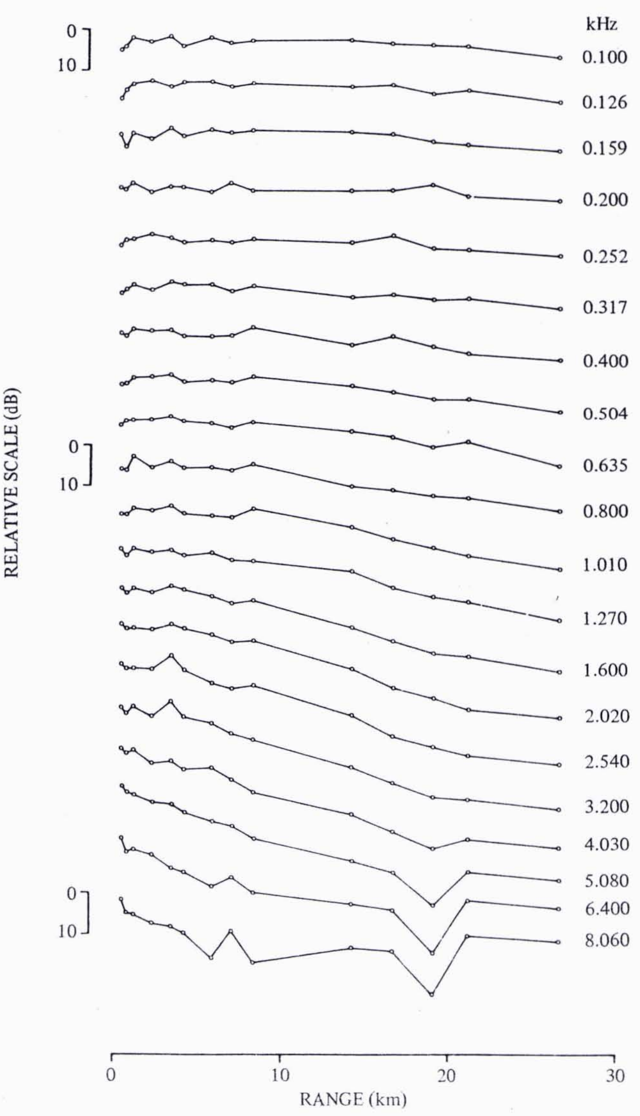

FIG. 7. Three-halves law anomaly, $AN_{3/2}$, linear range scale, for twenty one-third octave bands, from a propagation run under downward refraction conditions in summer.

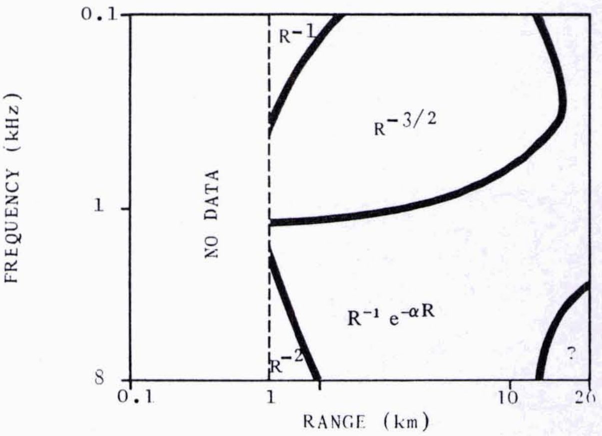

FIG. 8. Decay law map showing the transition from one decay law to another for the summer data in Figs. 7 and 5 (b).

Measurements were also made in summer under downward refraction conditions. Results for a summer run north of Elba are given in Fig. 7 with a linear range scale, and in Fig. 5(b) with logarithmic range scale. At low frequencies the results are similar to those for winter; at long wavelength the sound speed structure in the water has less influence. The short-range summer data show a systematic change in behavior with increasing frequency that is similar to that for the winter data. With regard to the three-halves law, we could perhaps convince ourselves that at intermediate ranges and frequencies below a few kilohertz, $AN_{3/2}$ is reasonably constant. The rapid falloff at longer ranges and higher frequencies could be the $R^{-1}e^{-\alpha R}$ region. A decay law map for these data would then look something like the sketch in Fig. 8. Here, unlike the situation for the winter data, we are more or less forcing the representation into the anticipated sequence of decay laws.

III. SINGLE-MODE REPRESENTATION

Now we consider an alternative decay-law representation for the winter and summer data, namely an attempt to use $R^{-1}e^{-\alpha R}$ over a wide range interval. This form of decay law is usually expected to apply for range intervals where only one mode is significant. We would not anticipate that it would give a very extensive fit to the data, especially the winter data. For the conditions of these trials, only at long range, and perhaps only in summer, would the single-mode region be attained.

We now use a "cylindrical anomaly," AN_1, given as follows:

$$AN_1 = ATL - 10 \log R - vR \ ,$$

where only a 10 log R rather than 15 log R has been removed from ATL. If the data actually obeyed an $R^{-1}e^{-\alpha R}$ law, after volume absorption is accounted for, then AN_1 should be linear when plotted with a linear range scale, and the slope of the line gives the attenuation b, where

$$b = \alpha 10 \log e \ ,$$

in dB/km. AN_1 is plotted in this way in Fig. 9 for the winter data and in Fig. 10 for the summer data.

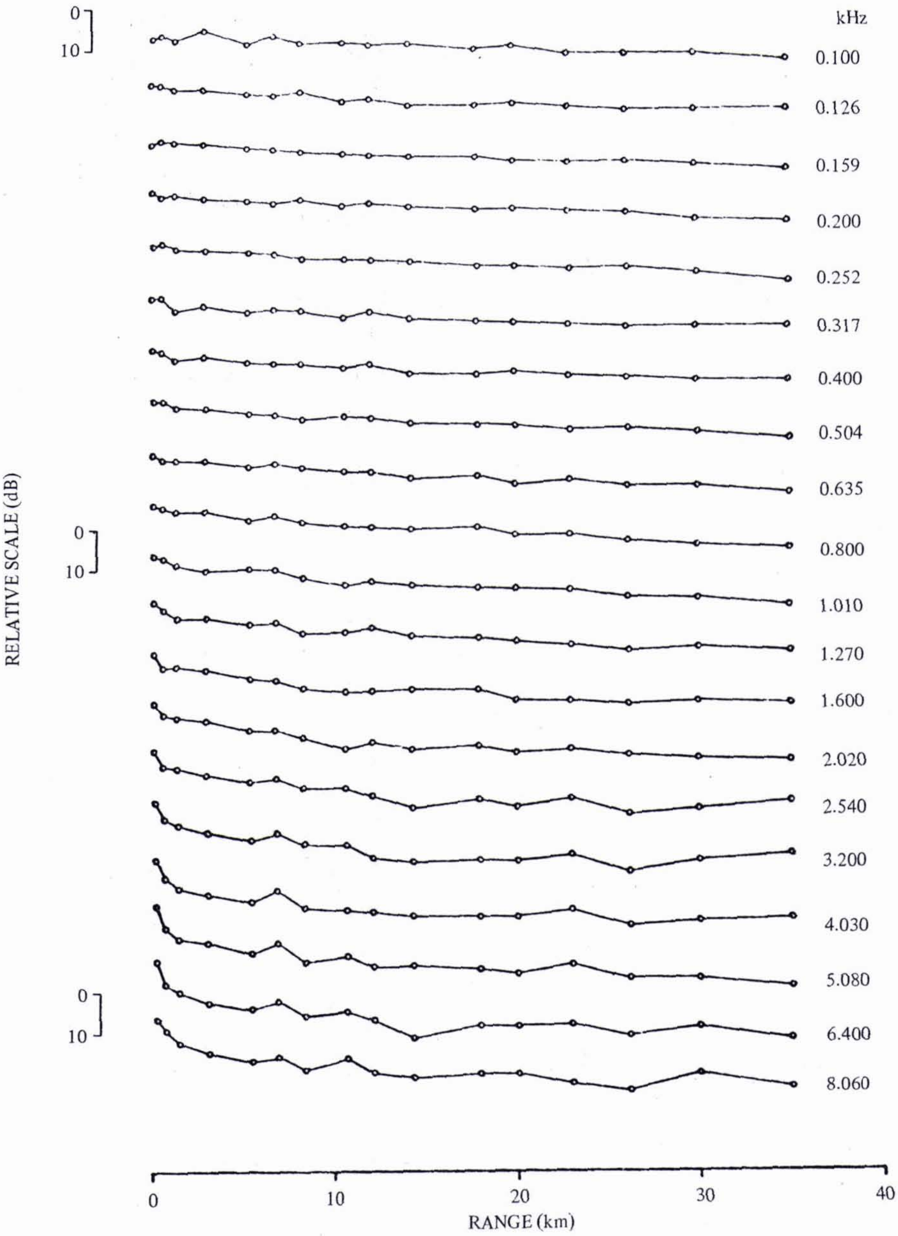

FIG. 9. Cylindrical anomaly, AN_1, linear range scale, for 20 one-third octave bands, from a propagation run in isothermal water in winter. [Same data as in Figs. 4 and 5(a).]

Lo and behold! There is a more universal fit to the data with this representation. For frequencies below a few kilohertz AN_1 is linear to better than 1 or 2 dB over nearly the entire range of the run. A decay law map for this representation is sketched in Fig. 11 for winter data and in Fig. 12 for summer data.

IV. DISCUSSION

Note one peculiar feature in Fig. 9: The slopes of most of the lines are nearly identical, implying an attenuation coefficient insensitive to frequency. The value lies between 0.2 and 0.3 dB/km. This may explain the ambiguity in the winter data, in that the $e^{-\alpha R}$ factor may be artificially fitted to what in reality is a frequency-independent $R^{-1/2}$ behavior. The results in Fig. 1 show that for a range interval from 1 to 35 km, the least-squares fit of $e^{-\alpha R}$ to the $R^{-1/2}$ samples gives an "attenuation" of 0.231 dB/km. On the other hand, for the summer data, attenuation extracted from the AN_1 in Fig. 10 show a strong frequency dependence. However, at frequencies below a few hundred hertz, the values are all near 0.3 dB/km, so an $R^{-1/2}$ fit could approximate quite well, at low frequencies, what in reality may be a single-mode $e^{-\alpha R}$ factor.

So the ambiguity, in that anticipated and unanticipated decay law schemes represent the data with equal quality, may be fortuitous. The kind of range intervals covered in the usual experiments, and the kind of attenuations extracted from data at some frequenceis are such that, in fact, either factor $R^{-1/2}$ or $e^{-\alpha R}$ may fit the same data well.

V. SUMMARY

In spite of the fact that the data presented here, when plotted in the form of various anomalies, may show small deviation from constancy, or linearity, over wide

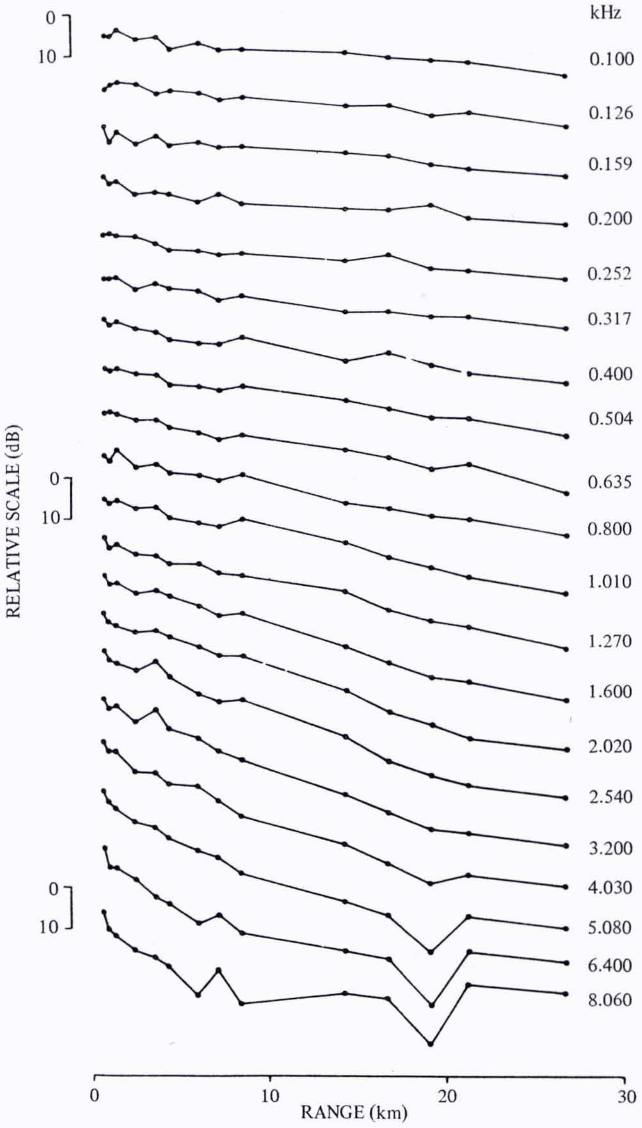

FIG. 10. Cylindrical anomaly, AN_1, linear range scale, for 20 one-third octave bands, from a propagation run under downward refraction conditions in summer. [Same data as in Figs. 7 and 5(b).]

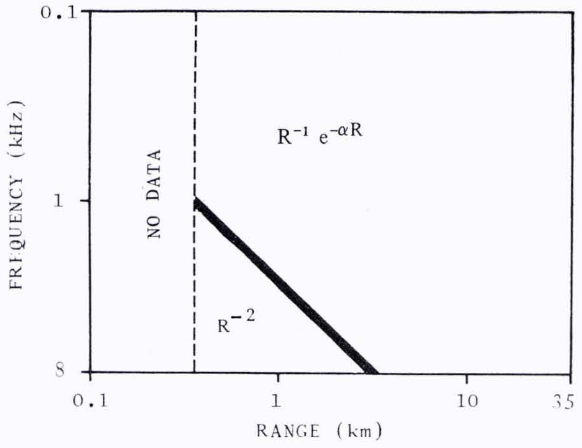

FIG. 11. Decay las map showing the transition from one decay law to another for the winter data in Fig. 9.

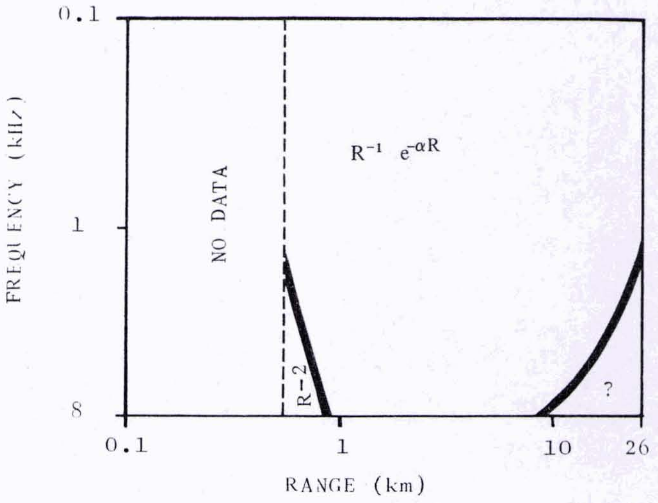

FIG. 12. Decay law map showing the transition from one decay law to another for the summer data in Fig. 10.

range intervals, alternative decay law representations are contenders of equal quality. The ambiguities, contradictions, etc., remain.

While the decay laws themselves may be simple representations for the data, it is most important to realize that the transition ranges for changeover from one law to another, the decay law maps, may be very complicated functions of frequency, refraction conditions, and location. Therefore, it may require as much effort and environmental knowledge to predict them as would a complete ray or mode calculation; decay law representations may continue to be of academic interest.

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