ICE RESEARCH PROJECT
MACDONALD PHYSICS LABORATORY
McGILL UNIVERSITY

Acoustic Attenuation in Sea Ice

by

E. R. POUNDER and M. P. LANGLEBEN

REPORT S-14

ONR Contract Nonr-4915 (00)

Task No. NR 307-290

INTERIM REPORT | *June 1968*

Prepared for

U.S. NAVAL ORDNANCE LABORATORY
WHITE OAK
SILVER SPRING, MARYLAND

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ABSTRACT

A study is underway of the acoustic attenuation properties of sea ice. In laboratory tests, (artificial) sea water was frozen in a cubical tank 2 ft to the side. In one series of experiments the resulting slab, 2' x 2' x 1', was clamped in a jig and barium titanate transducers were pressed against it at opposite, central points. The transmitting transducer was driven by a sinusoidal signal whose frequency was swept mechanically over the frequency range 10 to 500 kHz. The suitably amplified signal from the receiving transducer was plotted against frequency on an X-Y recorder. No absolute power measurements were attempted, but the thickness of the slab was reduced by stages and the resulting differences in received power compared. In a second series of laboratory experiments, small transducers were frozen at various positions through the ice sample to permit in situ power measurements.

Field observations were made in 1966 and again in 1967 at Tanquary Fiord, Ellesmere Island. For these, holes were drilled half-way through the ice (to a depth of about 1.3m) and transducers were lowered on wooden mounts. Coupling to the ice was obtained by filling the holes with kerosene.

Results of laboratory and field measurements agree quite well on the pattern of attenuation with frequency, although the numerical values differ somewhat between different samples of ice. The field results were as follows: attenuation was very small below 25 kHz, rose approximately linearly (with log frequency) from there to about 6 db m^{-1} at 150 kHz, jumped abruptly to 54 db m^{-1} at 200 kHz and then increased very slowly to about 56 db m^{-1} at 500 kHz. The large increase between 150 and 200 kHz is attributed to increased scattering as the wavelength of sound decreases to the typical transverse dimension of a sea ice crystal of about 2 to 3 cm.

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INTRODUCTION

The propagation in sea ice of acoustic waves (and other mechanical waves) has received considerable attention as a means of obtaining information on the dynamic elastic moduli of this material. From such investigations it is known that acoustic energy at low frequencies (< 40 kHz) is readily transmitted through sea ice, and that the acoustic coupling across the ice-water interface is excellent (Marsden, 1961). Sound energy generated in the water is readily detected at the upper surface of an ice cover, and vice-versa. However, no quantitative data were available on acoustic attenuation in sea ice, and the present study was undertaken to provide such data in frequency ranges of interest.

This study is continuing, so that the present report is preliminary in the sense that, although we have confidence in the results quoted, there is sufficient variation between the different types of ice studied to make it uncertain as yet how representative the results are.

As a first step, measurements were made in the laboratory on ice frozen from artificial sea water prepared according to the formula of Lyman and Fleming. Later, and in parallel with further laboratory experiments, two short series of field observations were carried out in the springs of 1966 and 1967 on the sea ice cover of Tanquary Fiord, Ellesmere Island ($81^{\circ}25'$N, $76^{\circ}50'$W). Each year the sea ice was about 2.6m thick. The ice cover melted completely in the summer of 1965 but not in the summer of 1966, so that the ice being observed in 1966 was one-year-old (annual) sea ice whereas the cover in 1967 was a conglomerate of two-year-old ice interspersed with annual ice.

METHODS

Ceramic discs of barium titanate were used throughout as transmitting and receiving transducers. They ranged in size from 6-inch (15.2 cm) to 1/2-inch (1.27 cm) in diameter. All power measurements were differential, that is, the attenuation data were calculated from the differences in power received at different distances from the transmitter.

Ice samples were prepared in the laboratory by freezing the artificial sea water, in a cubical tank 2 ft (61 cm) to the side, in a cold room at an ambient temperature of $-30^{\circ}C$. Pressure relief during freezing was obtained by placing bladders (with overflow tubes) filled with ethylene glycol in the bottom of the tank. This method worked well and very smooth ice covers were obtained. In one series of experiments, after freezing was completed, the ice cover was removed, trimmed to a thickness of 1 ft, and clamped on its side in a specially constructed framework or jig. This jig had two, long, accurately aligned, central bushings which served two roles. Milling cutters mounted on rods through the bushings were used to prepare plane, accurately parallel faces on the ice slab. The input and receiving transducers were also mounted on these rods passing through the bushings, and pressed against the ice with a known pressure. The actual coupling between a transducer and the ice was made with a thin film of oil. Cables from the transducers were led out of the cold room in a duct connected to a room-temperature laboratory where the electronic equipment was located.

The experimental procedure was to vary the frequency of the power delivered to the input transducer and record on an X-Y recorder the amplified output of the receiving transducer as a function of frequency. Next, the milling cutter was used to reduce the sample thickness by 2 or 3 inches, the cuttings being collected and melted to determine the salinity of the ice. Proceeding in this way plots of received power vs frequency were obtained for three or four different ice thicknesses. Note that the transmission path was parallel to the freezing direction, that is, along the long dimension of the ice crystals.

In a second set of laboratory experiments, small transducers (1/2-inch diameter) were mounted in a light plastic frame and frozen into the ice in a horizontal plane about 8 inches below the surface, to permit *in situ* measurements. For most of the frequency range involved, these small transducers acted effectively as point sources and receivers. Two points should be noted. The transmission paths in these observations were horizontal (at right angles to the freezing direction), and calculations involved taking power differences between *different* receiving transducers, which are *not* identical in their frequency responses. Difficulty in matching the response characteristics of the transducers has led to a modification of this second approach, which permits the insertion of the same receiving transducer into holes drilled in the ice at varying distances from the transmitter. Adequate coupling to the ice is ensured by filling the holes with oil. This method has the further advantage that measurements both parallel and perpendicular to the freezing direction can be made on the same sample.

Field observations were made by drilling holes half-way through the ice cover (to a depth of about 1.3 meters) and lowering transducers on wooden or aluminum mounts. Coupling to the ice was obtained by filling the holes with kerosene. One-, four-, and six-inch transducers were used and considerable effort was made to ensure parallelism between transmitter and receiver.

MEASUREMENT TECHNIQUES

Figure 1 shows the arrangement of the apparatus in the first series of laboratory experiments. With minor modifications, the same equipment was used in other laboratory and field measurements. The driving oscillator is a Hewlett Packard (HP) 651A with a range of 10 - 10^7 Hz; the power amplifier is a HP 467A (10 watt output); the HP 297A Drive sweeps the oscillator mechanically over the selected frequency range, and provides a voltage related to frequency to the X-axis amplifier of the HP 135C X-Y recorder. The receiving system consists of a HP 400E voltmeter, used as a pre-amplifier, and a detector which leads to the Y-axis input of the recorder.

In later experiments provision was made for additional amplification between the receiving transducer and the recorder by inserting two amplifiers (HP 466A and HP 45A) in cascade. Calibrated attenuators permitted the gain of the system to be altered in known increments and its dynamic range was increased by using a voltage compressor.

In operation, the oscillator was allowed to sweep a selected frequency band and a graph of response vs frequency was traced out on standard graph paper by the X-Y recorder. The procedure was repeated for several transmitter-receiver distances to avoid the necessity of making absolute power measurements, so that the attenuation could be obtained as the difference in signal intensity level (in db) corresponding to a given change in length of transmission path.

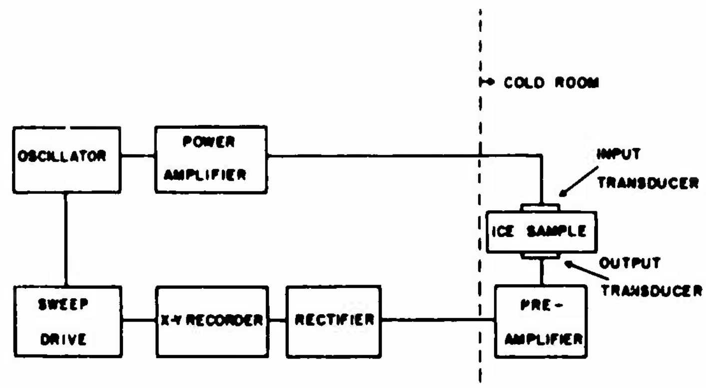

Fig. 1 Block diagram of measuring equipment.

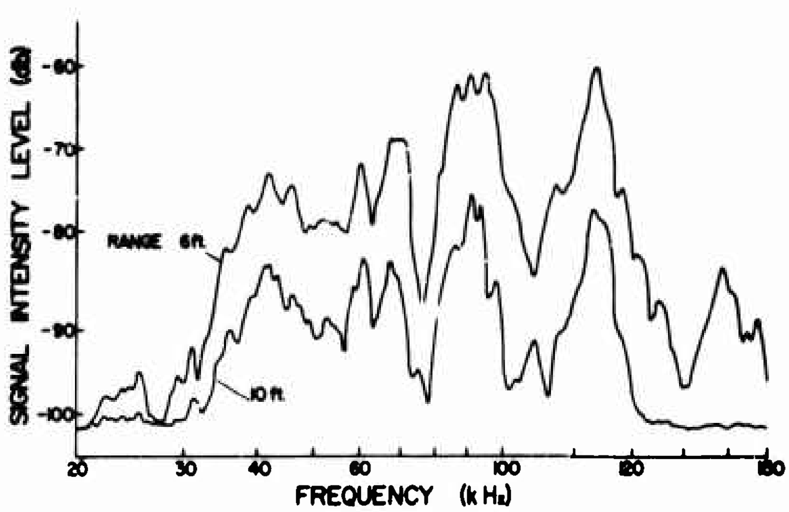

Fig. 2 Typical recording of received signals.

OBSERVATIONS AND RESULTS

The analysis of the data obtained both in the field and in the laboratory has presented problems because of the extremely irregular or "noisy" signals received. Figure 2 shows a typical X-Y plot of one field run. The two traces show the power received at 6 ft and 10 ft from the transmitter. The acoustic power transmitted through sea ice is a very rapidly changing function of frequency - it is quite common for the transmission level to fluctuate up and down by 20 or 30 db four or five times as the driving frequency is altered by 5 kHz. These fluctuations are quite reproducible when measurements on the sample are repeated, so that we are dealing with a real phenomenon and not just an artifact of the measuring system. The transducers do cause some of the fluctuation because they are made up of many tiny crystals of barium titanate bonded together. Ideally, the transducer should vibrate as a rigid, plane piston but in fact this is only a rough approximation. However, experiments with the same transducers operated in water show much less variation of transmission with frequency than occurs when the power passes through sea ice.

Presumably, most of the variations in the received power level result from the inhomogeneous nature of sea ice. Crystals vary considerably in size, and in the orientation of crystal boundaries. As the exciting frequency is changed, different crystals come into resonance and the reflection coefficients of different boundaries change also. The receiving transducer integrates the power transmitted directly to it together with the power scattered to it by reflections. These various components will arrive with many different phase angles. The problem is to apply some type of averaging to extract meaningful attenuation data from the very "noisy" records.

The first method tried was to ignore all peaks and valleys, and to compare curves for different ranges in sea ice at frequencies where the curves have similar shapes. Figure 3 was derived in this way from the field data obtained in Tanquary Fiord in 1966. The observations were made over a horizontal transmission path at a depth of about 1.2m in ice of thickness 2.5m. The salinity and temperature of the ice at transmission depth were 4 $^o/oo$ and -13^oC. The points plotted in Figure 3 show a considerable scatter but some interesting features appear. The abrupt increase in attenuation occurs at a frequency of about 175 kHz. For a sound velocity of 3.5 km/sec, this corresponds to a wavelength of 2 cm which agrees quite closely with the mean minimum dimension of sea ice crystals. Attenuation would, of course, be expected to increase sharply for wavelengths equal to or smaller than the size of the obstructions. The line of best-fit from 20 to 150 kHz is plotted on Figure 3. Its equation is

$$\alpha = -12.7 + 8.90 \log f \qquad (1)$$

where α is the attenuation in db m^{-1} at a frequency f in kHz. The line of fit drawn above 200 kHz is of dubious value.

Because of the subjective element in the above approach, subsequent analysis was done by numerical averaging. The original X-Y plots, such as Figure 2, had non-linear scales in both signal intensity and frequency, but the graph paper had a uniform rectangular grid. The processing of the data from one laboratory experiment (using 1/2-inch transducers) will be described in detail. In this experiment, receiving transducers were frozen in the ice at 10, 20, and 30 cm from the transmitter. After freezing, the ice was kept for some time at -22^oC and two complete sets of observations were made on the same sample, with an interval of 10 days between

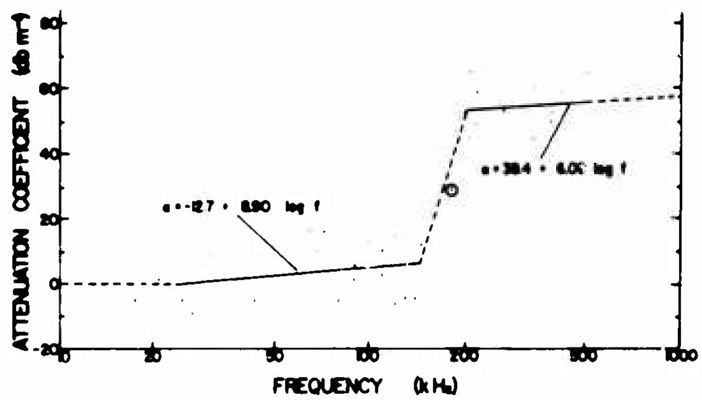

Fig. 3 Attenuation - frequency plot for one-year sea ice (1966).

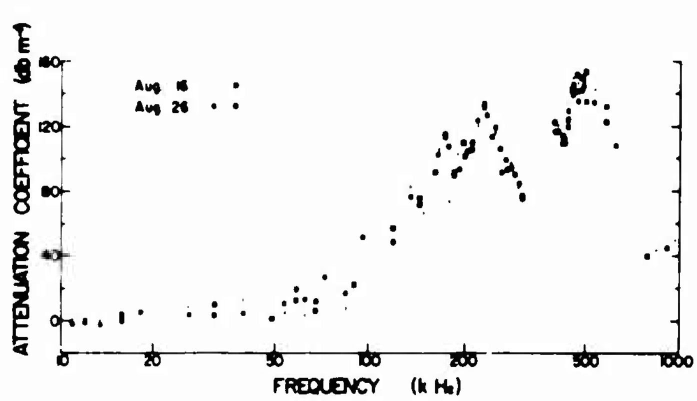

Fig. 4 Attenuation - frequency plot for artificial sea ice.

them, to determine the reproducibility of the data, as well as any "aging" effect. The salinity of the sample was 4.6 °/oo.

A total of 720 points were read off each curve at equal intervals of the abscissa on the rectangular grid and the data were punched on cards for computer processing. Sub-programs converted the grid points to db and frequency values, and applied an inverse-square distance correction to allow for beam spread. The computer then averaged eighteen successive values of power and frequency, i.e. points 1 to 18, 19 to 36, etc., finally producing 40 averaged values for each curve.

Differences were then taken of the power at 10 cm from the source less that at 30 cm (i.e. corresponding to a 20 cm transmission or attenuation path); and of the power at 20 cm less that at 30 cm (i.e. for a 10 cm attenuation path). The attenuation per 10 cm was then calculated as the sum of these two differences divided by 3. (This puts double weight on the difference for the 20 cm path.)

The results for the two runs are shown in Figure 4. The attenuation values are plotted as dots and circles as a function of frequency. It should be pointed out that some of the forty values of attenuation obtained from each run have been rejected as unreliable. The criterion used was that if the power difference for the 10 cm path failed to fall within ± 1/2 db or 30% of the attenuation value as calculated above, then the attenuation value was rejected. The results, for example, were found unreliable at frequencies between 310 and 390 kHz, in the vicinity of the upper shoulders of the resonance curves of the transducers, which did not coincide. The squares in the figure again represent averages of eighteen obtained from the same original data by discarding the first and last 9 points of the 720 taken and then averaging points 10 to 27, 28 to 45, etc. The consistency of the results between dots and squares indicates that averaging in groups of eighteen achieves sufficient smoothing.

The results obtained from these sets of measurements are roughly similar to those shown in Figure 3. They do however differ in two respects. In the laboratory-based results, the attenuation a) begins to increase rapidly at a lower frequency, about 90 kHz as compared to 150 kHz for the earlier work and b) increases to a value of about 120 db m^{-1}, as compared to 60 db m^{-1}, at frequencies of several hundred kHz.

For the 1967 season, an incomplete analysis of the field data, extended to a frequency of about 150 kHz, shows results similar to the previous ones, as may be seen in the Figure 5. This attenuation-frequency plot is one of three obtained with different sized transmitting transducers. The received power was measured at ranges of 4, 6, 8, 10 and 12 ft from the 1-in diameter transmitter. For the 4 and 6-in diameter transmitters, the ranges selected were from 8 to 16 ft in 2-ft intervals. The power curves, as before, were averaged over small increments of frequency and about 25 averaged values were obtained from each curve.

The five power values available for analysis at each frequency, corresponding to the five lengths of transmission path used, were then plotted against the range. A least-squares straight line was fitted to the data and its slope was calculated to determine the attenuation at that particular frequency. The standard deviation in the slope was also evaluated and has been indicated, for example, by the error bars in Figure 5. Upon completion of these calculations at each of the averaged frequencies, an attenuation against log frequency plot was made as in Figure 5. The data appeared to fall, more-or-less, along a straight line and a least-squares analysis, weighing each point according to the size of its error bar, was performed to obtain the equation of the straight line.

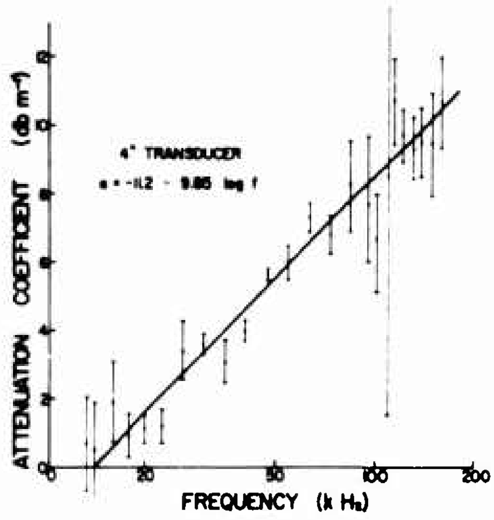

Fig. 5 A sample attenuation - frequency plot for two-year sea ice (1967).

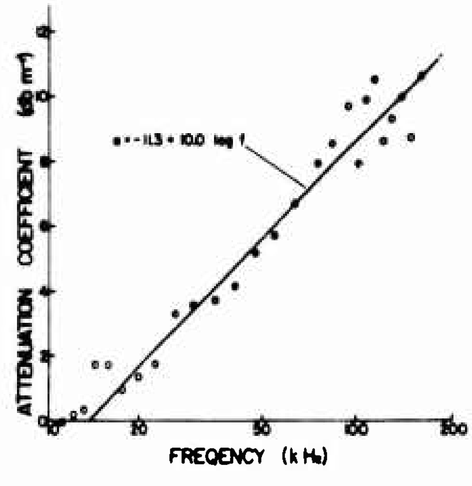

Fig. 6 Composite attenuation curve for two-year sea ice (1967).

The results for the 1, 4 and 6-in transducers are respectively,

$$\alpha = -11.7 + 10.1 \log f$$

$$\alpha = -11.2 + 9.85 \log f$$

$$\alpha = -11.9 + 10.6 \log f$$

with α in db m^{-1} and f in kHz.

These results, with differently sized transducers, are reasonably similar and the data have therefore been combined in Figure 6. The points are seen to fall close to the straight line whose equation is given by

$$\alpha = -11.3 + 10.0 \log f \text{ for } 15 \text{ kHz} < f < 150 \text{ kHz}. \qquad (2)$$

The work in the 1967 season was performed on two-year-old ice whose salinity over the horizontal transmission path, at depth 4 ft, was about 1.6 $^o/oo$. Field work during the previous season, with results given by equation (1), was on one-year-old ice with salinity about 5 $^o/oo$. The results are not very different and would seem to indicate that salinity has little effect on attenuation, at least for frequencies up to about 150 kHz.

The most recent measurements have been made on a laboratory sample of salinity 6 $^o/oo$ and temperature -30^oC. Both horizontal and vertical transmission paths were used (i.e. perpendicular to and parallel to the freezing direction respectively). At frequencies between 300 and 500 kHz, the attenuation perpendicular to the direction of freezing was about 45 db m^{-1}, a result similar to that found from field observations at comparable frequencies (Figure 3). However the attenuation in the direction of freezing was only two-thirds as large. At lower frequencies, where lesser attenuation is anticipated, the results are unreliable. The comparison of signal intensities for path lengths differing by only

3 inches is not satisfactory since the random errors of measurement are of the same size as the small differences in intensity level that are expected.

Radiation pattern. In obtaining the results discussed above, no account was taken of the radiation field of the transmitting crystal other than an inverse-square law correction for distance. This is justified by the small size of the transmitting crystal or the large length of the transmission path relative to the crystal size. For large crystals (such as the 6-inch transducers) and transmission paths of the order of a few tens of centimetres, corrections are needed for the varying power level over the surface of the receiving crystal. In extreme cases at high frequencies, the width of the receiver may be greater than the width of the main lobe radiated.

This problem has been investigated by Mr. C.-Y. Hwang (1967). A 6-inch transducer was pressed against one side of a slab of ice 21.5 cm thick. The radiation field was mapped with a 1-inch transducer as receiver, by placing it in successive positions along a line on the ice slab perpendicular to the axis of the transmitter. The simplest model for the transmitter is that of a rigid piston in an infinite baffle. This is solved in Morse (1948, p. 329) for a half-space filled with fluid. He shows that most of the energy is radiated into a main lobe of half-angle

$$\theta = \sin^{-1} (\lambda/2a) \qquad (3)$$

where $2a$ is the diameter of the piston and λ is the wavelength of the sound. The present situation is considerably more complex because the piston radiates into a solid, which can support transverse as well as longitudinal waves, and which moreover is far from isotropic. Hwang found that the main lobe became sharper and the side lobes decreased from 49 to 90 kHz, and again from 150 to 220 kHz, but that in the intermediate range the main lobe actually increased slightly in half-angle with frequency. The empirical equation

$$P(\theta, \phi) = P_o(\theta) \cos \left(\frac{g \pi \phi}{2\theta}\right) \qquad (4)$$

was found to fit the radiation pattern fairly well in the regions of convergence with frequency. In this equation $P(\theta, \phi)$ is the power radiated per unit solid angle in a direction ϕ with the axis, $P_o(\theta)$ is the power radiated per unit solid angle on the axis, θ is defined in (3), and g is an empirical parameter equal to 1.0 in the lower frequency range and 0.6 in the upper one.

CONCLUSIONS

In the frequency range below 100 kHz, the similarity between Figures 3, 4, and 6 suggests that the attenuation in sea ice is essentially independent of the salinity and structure of the ice. These tests included artificial sea ice and natural covers which were of both one-year and two-year old sea ice. Salinities ranged from 1 $^{0}/oo$ to 9 $^{0}/oo$. The effect of structure is very marked when the wavelength of sound becomes comparable to crystal dimensions. The very sharp increase in attenuation in Figure 3 for one-year, natural sea ice and the more gradual increase in Figure 4 probably indicate a greater uniformity in crystal size in the natural cover. The high-frequency (> 150 kHz) data from 1967 observations (Figure 5) are unfortunately very erratic. There is no clear evidence for any marked increase in attenuation.

ACKNOWLEDGEMENTS

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