ICE RESEARCH PROJECT
MACDONALD PHYSICS LABORATORY
McGILL UNIVERSITY

Part I

Acoustic Attenuation in Sea Ice

Part II

Reflection of Sound at the Water-Ice Interface

by

M. P. LANGLEBEN and E. R. POUNDER

REPORT S-16

ONR Contract Nonr-4915 (00)
Task No. NR 307-290

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FINAL REPORT | *May 1970*

Prepared for

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

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ABSTRACT

Measurements of the attenuation of acoustic waves in sea ice at frequencies between 10 kHz and 500 kHz were made on the ice cover at Tanquary Fiord, Ellesmere Island (latitude 81°25'N, longitude 76°50'W) during April-May in 1967 and again in 1969. A horizontal transmission path at a depth of 4 ft, mid-way between the top and bottom surfaces of the ice cover, was used at ranges of 4 ft to 25 ft between piezoelectric transducers immersed in oil-filled bore holes. The attenuation coefficient α in db m^{-1} was found to fit the equation $\alpha = c_1 f + c_2 f^4$. The value of the constants of this equation for the 1967 data on biennial ice of salinity about 1 $^o/oo$ were 4.45×10^{-2} db m^{-1} kHz^{-1} and 2.18×10^{-10} db m^{-1} kHz^{-4}. For the 1969 data on first year ice of salinity 4 $^o/oo$, the value of c_1 increased to 6.91×10^{-2} db m^{-1} kHz^{-1}. In both cases, the linear term of the equation was the predominant one, far exceeding the Rayleigh scattering term even at the upper end of the frequency band covered in these investigations.

In an auxiliary experiment in 1969, measurements of the specular reflection of water-borne sound at the water-sea ice interface were made as a function of angle of incidence. The geometric configuration was such that a constant path length was maintained between sound source and detector, and the transducers were aligned carefully at each angle of incidence to match this configuration thus obviating the necessity of having to make corrections for range and for directionality characteristics of the transducers. The amplitude reflection coefficient was found to have a value near 0.1 for near-normal angles of incidence but its value was found to increase rapidly with increasing angle of incidence beyond 30°.

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PART I: ACOUSTIC ATTENUATION IN SEA ICE

INTRODUCTION

The propagation in sea ice of acoustic waves and pulses has been used extensively to investigate the elastic properties of that material (e.g. Anderson, 1958; Pounder and Langleben, 1964). In these studies it has sometimes been noted that the high frequency components tend to suffer greater attenuation than the low frequency components, but no quantitative data on attenuation in sea ice are available. There have been numerous investigations however of acoustic attenuation in other polycrystalline substances such as metals and rocks (e.g. Mason and McSkimin, 1947; Knopoff and MacDonald, 1958) and one on fresh-water ice (Westphal, 1965). The latter has measured the attenuation coefficient of glacier ice over a frequency range of 2.5 kHz to 15 kHz by spectral analysis of the pressure pulses from small explosions of seismic blasting caps. In polycrystalline materials, it has generally been found that the attenuation can be related to scattering at the grain boundaries and to internal friction between the grains.

This report describes a series of detailed in situ attenuation measurements which were made on the natural cover of sea ice in Tanquary Fiord, Ellesmere Island during the spring of 1967 and again in 1969 near the Defence Research Board base camp at latitude 81°25'N, longitude 76°50'W. Observations were made over a frequency band extending from 10 kHz to 500 kHz using CW transmission along a horizontal path. These investigations had been started in 1965 and an account of some results of the early field work and of associated laboratory experiments has been given in Pounder and Langleben (1968) (also published as Report S-14 of the Ice Research Project, McGill University and presented as an Interim Report prepared for the U.S. Naval Ordnance Laboratory in June 1968). The discussion of the work of the 1967 field season in the present report has been extracted from a paper by Langleben (1969) which appeared in the Journal of Glaciology.

EXPERIMENTAL METHODS

The ice cover in Tanquary Fiord is typically about 8 ft thick in the spring. Acoustic measurements were made over a horizontal transmission path starting at an extreme range of 25 ft to a minimum range of 4 ft. Vertical cylindrical holes were drilled in the ice cover to a depth of 5 ft to house the sound source and the detector, and were filled with kerosene to provide good acoustic coupling to the ice. After completion of a set of measurements, a new hole was bored for the detector at a lesser range from the sound source and the procedure was repeated.

The acoustic transducers were piezoelectric barium titanate crystals in ceramic discs of thickness 1/4 inch with a natural frequency of about 450 kHz in thickness expansion. Discs of 1, 4 and 6-inch diameter served in turn as transmitting transducers and a 1/2 inch diameter disc was used as receiving transducer. Each transducer was encased to provide water proofing and adequate electric shielding, and in the process the resonant frequency was reduced by about a factor of two.

For use, each transducer was mounted at the end of a long 3/4 inch diameter pole with its axis perpendicular to the length of the pole. The transducers were then immersed to a depth of 4 ft i.e. mid-way between the top and bottom of the ice cover, to minimize any possible boundary effects on the measurements. Optical alignment of receiving and transmitting transducers was achieved by adjustment of vertical height and orientation fiducial markers on the poles.

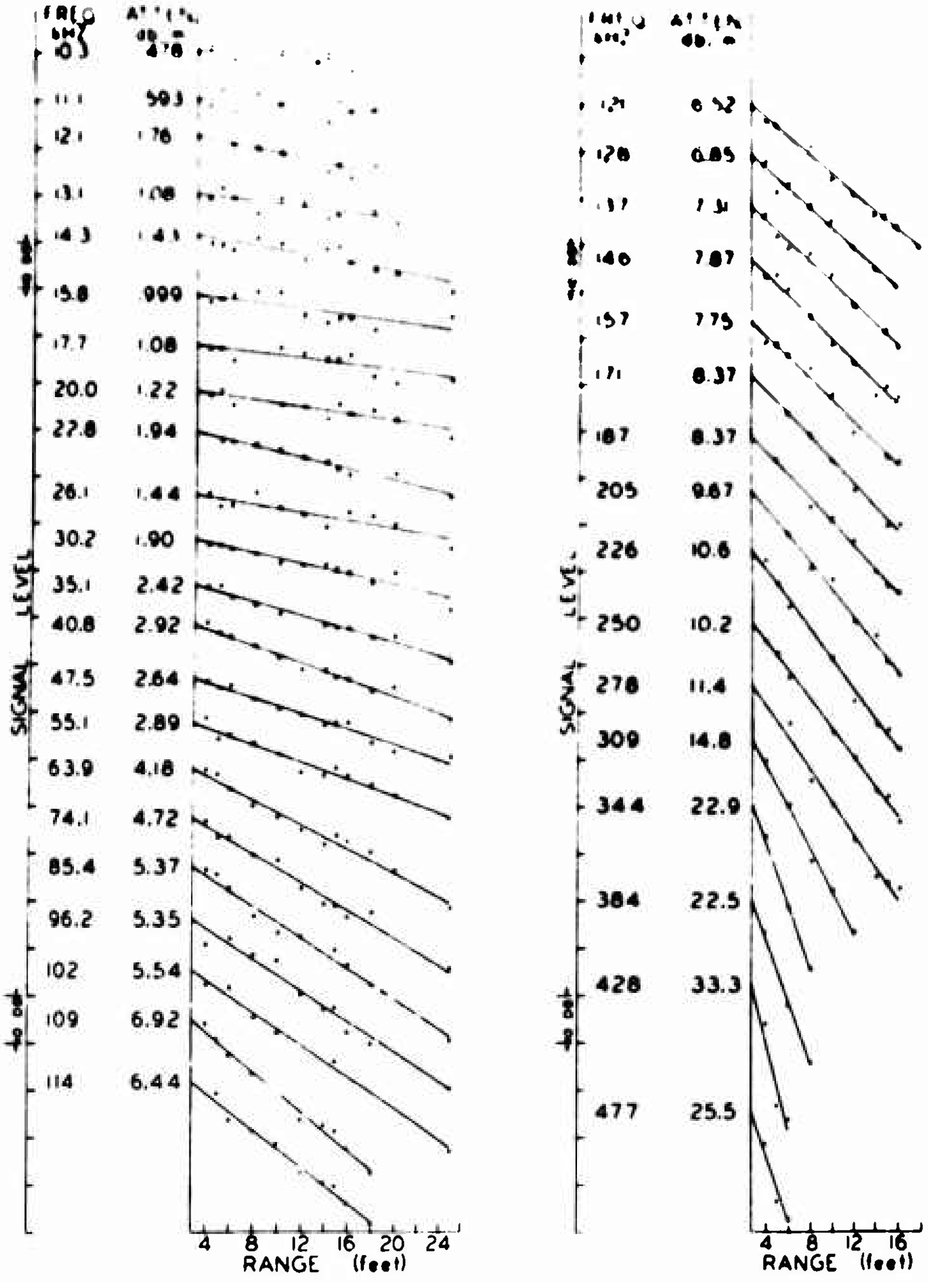
The measuring system may be described as follows. The sound source was driven, in CW excitation, by a Hewlett Packard (HP) 651A oscillator through an HP467A power amplifier. This oscillator was swept in frequency by an HP297A mechanical sweep drive which also generated an electrical output for the X-axis deflection on an HP135C X-Y recorder. The receiving system consisted of an HP400E voltmeter, used as a pre-amplifier, HP466A and 450A amplifiers in cascade and a diode detector leading to the Y-axis input of the recorder. The gain of the system was variable over a wide dynamic range with calibrated attenuators.

In operation, the oscillator was set to sweep the desired frequency band and a graph of received signal as a function of frequency was automatically traced out on graph paper by the X-Y recorder. The procedure was repeated for each reduction in transmitter-receiver range. Care was taken to ensure that the transmitter was driven at constant voltage. In this way, no absolute power measurements were necessary to determine changes in received power or intensity level with changes in length of transmission path.

OBSERVATIONS AND RESULTS

Observations of the ice cover in the vicinity of the operating site indicated that it consisted of two-year-old ice of thickness about 8 ft in the spring of 1967 and of first year ice of the same thickness in 1969. Its salinity at a depth of 4 ft along the transmission path was about 1 ^{o}/oo by weight in 1967 and over 4 ^{o}/oo in 1969. The temperature of the ice at that depth was about -6^{o}C. Horizontal and vertical thin-sections revealed the typical structure of sea ice; crystals long in the growth direction perpendicular to the surface and of horizontal dimensions varying from about 1 cm to greater than 5 cm. The typical crystal size in the horizontal was about 2 cm.

The program of acoustic measurements carried out during each of the two field seasons was similar, as were the subsequent techniques of data analysis. These are now described. Measurements of relative signal intensity level were made at receiver-transmitter ranges of 25, 20, 18, 16, 15, 14, 12, 10, 8, 6, 5 and 4 ft in the order given. At each range, the frequency was swept over the band 10 kHz to 500 kHz. Three such series of measurements were performed using, in turn as transmitter, the 1-inch, 4-inch and 6-inch transducers. Detectable signal was obtained over a considerable band of frequency at all of the twelve ranges used, particularly with the two larger transducers as can be seen in figures 1, 2 and 3. These figures show the 1967 data points of signal strength as a function of range at a number of frequencies. It is seen that fewer data points are available at the low and high ends than in the middle region of the frequency band used. This occurred because at high



6 - INCH TRANSMITTER

Fig. 1: Transmitter of diameter 6 inches. Signal intensity level as a function of range at frequencies between 10 kz and 500 kHz. Values of the attenuation coefficient, listed in the ATTEN. column, are the negative of the slopes of the straight lines.

frequencies where the attenuation was severe, signal merged with background noise at the more distant ranges. At low frequencies, far removed from the resonant frequency of the encased transmitting transducers, the acoustic power output was low and once again the signal could not be distinguished from noise at the more distant ranges used.

The data analysis for each series of measurements was handled in the following manner. Values of recorded signal intensity level were read off the graphs at the grid points of the frequency axis (10 points per inch) and were then put on punch cards. Computer data processing averaged the signal intensity level within frequency increments (38 increments for the frequency band covered) and prepared in tabular form values of signal intensity level under column headings of transmission range and row headings of frequency. It should be pointed out that, as part of the computer program, these signal levels had been range corrected to allow for beam spread of the transmitter. The directionality characteristics of the transducers when immersed in the oil-filled cylindrical holes in the ice cover had been investigated and it was found that they behaved essentially as point sources in these conditions.

In the next step of the analysis, signal intensity level was plotted as a function of range for each of the frequency increments in turn, producing 38 graphs. The straight line of best fit and its slope was computer calculated for each graph using the method of least-squares. These slopes should have established values of the attenuation coefficient and its variation with frequency.

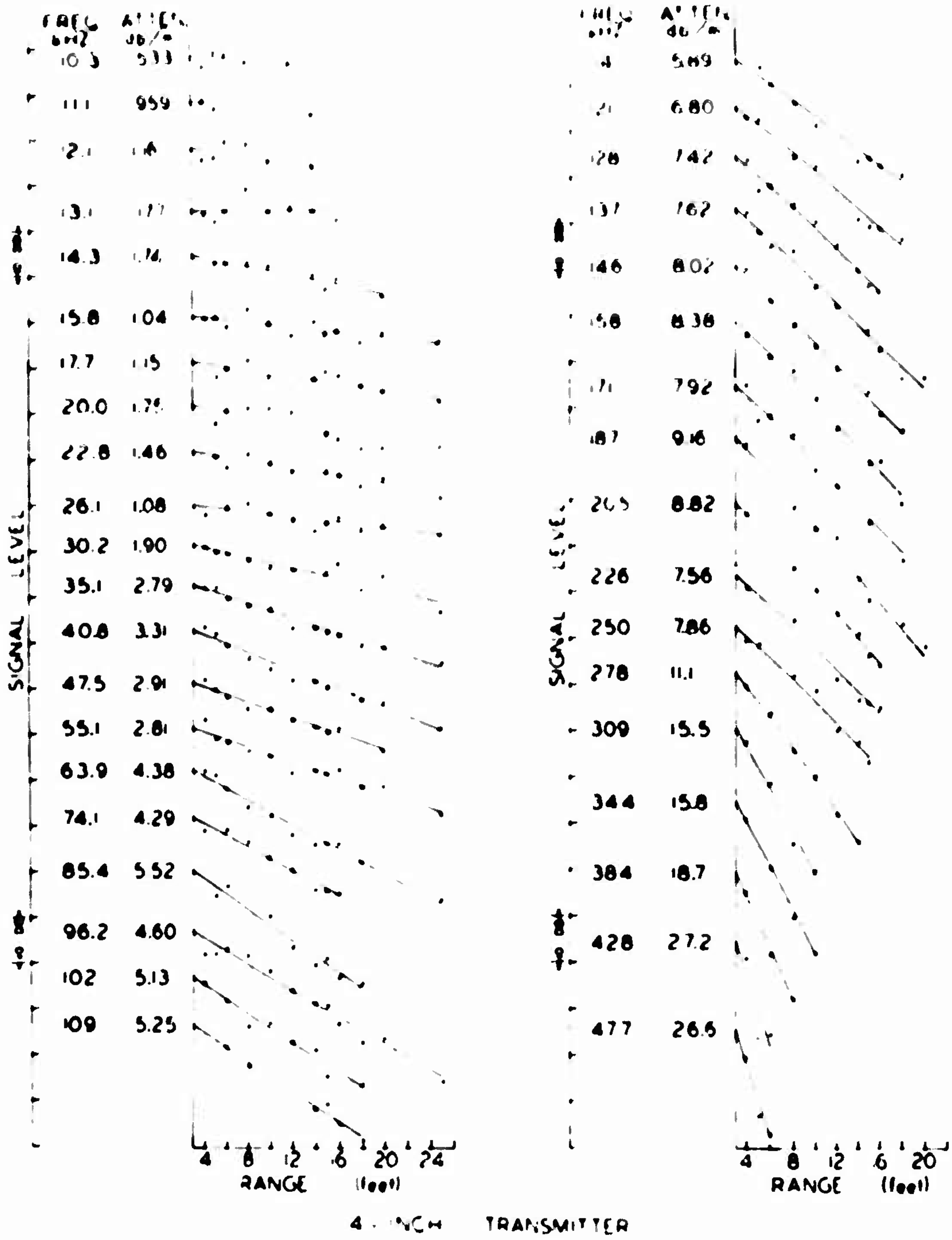


Fig. 2: Transmitter of diameter 4 inches. Signal intensity level as a function of range at frequencies between 10 kHz and 500 kHz. Values of the attenuation coefficient, listed in the ATTEN. column, are the negative of the slopes of the straight lines.

However, some of the data points on the graphs were obviously spurious, a not uncommon occurrence in acoustical measurements. Points which deviated most from the line of best fit were removed one by one, recalculating a new line of best fit each time, until the scatter was limited to within 3 db.

The final results of this procedure are shown in Figure 1, 2 and 3 for the three series of measurements in 1967 with transmitting transducers of respectively 6, 4 and 1-inch diameter. In each diagram, the ordinate is received signal as intensity level in db and the abscissa is the length of the transmission path or range in ft. The series of graphs display the measured points and the lines of best fit at the various frequencies. The two columns beside the graphs list the relevant frequencies in order of increasing magnitude and the corresponding attenuation coefficients in db m^{-1} (1 db m^{-1} = 0.115 nepers m^{-1}) which are equal to the negative of the slope of the lines of best fit. An identical procedure was used to analyse the 1969 field data.

Attenuation in two-year-old ice (1967). The results obtained from the sound transmission measurements are displayed in Figures 1, 2 and 3. The trend indicated in these figures is that the attenuation coefficient increases with increasing frequency, i.e. that the slope becomes progressively more negative. Since attenuation is a property of the medium and not of the measuring system, the data of Figures 1 to 3 were combined, weighing the slopes at each frequency according to the number of points used to establish the slopes. The results are plotted as points in Figure 4 for attenuation coefficient

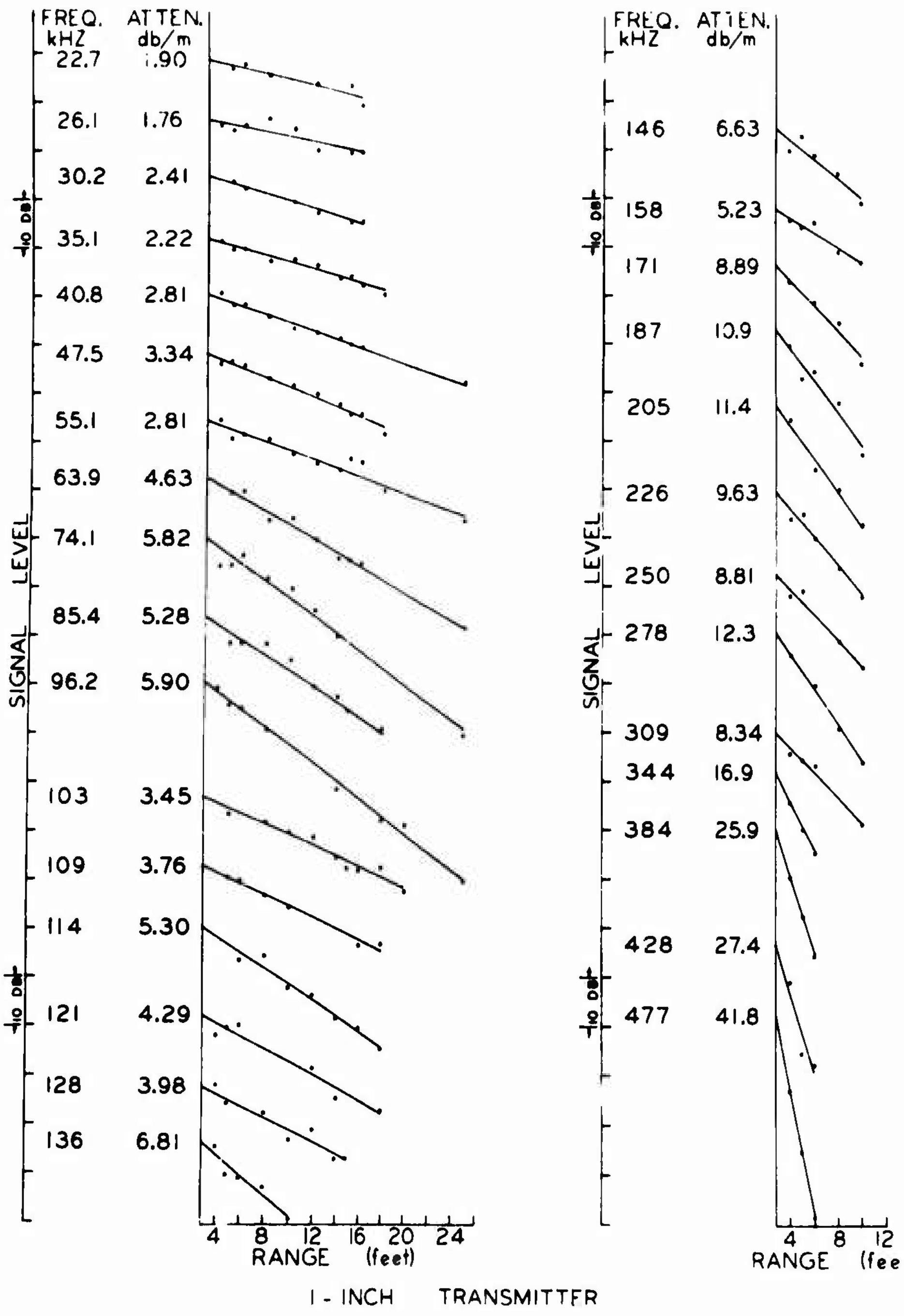


Fig. 3: Transmitter of diameter 1 inch. Signal intensity level as a function of range at frequencies between 10 kHz and 500 kHz. Values of the attenuation coefficient, listed in the ATTEN. column, are the negative of the slopes of the straight lines.

(db m^{-1}) against frequency (kHz). It is seen that attenuation is an ever rapidly increasing function of frequency. The attenuation coefficient increases from a value of less than 1 db m^{-1} at 10 kHz, to about 5 db m^{-1} at 100 kHz and to more than 35 db m^{-1} at 500 kHz. As comparison, Westphal (1965) obtained a value for the attenuation coefficient of 0.215 nepers m^{-1} ($\sim$ 1.9 db m^{-1}) at 15 kHz in glacier ice.

A considerable body of evidence exists (e.g. Mason, 1964, p. 163) to indicate that in polycrystalline materials the attenuation may vary as the sum of two frequency dependent terms. One involves a linear dependency on frequency and is caused by frictional loss mechanisms between grains. The other is a fourth power frequency term and arises from scattering at the grain boundaries caused by discontinuities in the elastic constants in going from one crystal to the adjacent one. The data of Figure 4 were accordingly fitted, using the least-squares method, by an equation of the form

$$\alpha = c_1 f + c_2 f^4$$

where α is the attenuation coefficient in db m^{-1}

f is the frequency in kHz

$c_1 = 4.45 \times 10^{-2}$

and $c_2 = 2.18 \times 10^{-10}$.

It is seen that the curve fits the data points reasonably well. The points seem to follow a series of oscillations above the curve which may be caused by thermal relaxation processes. However no attempt was made to investigate these features.

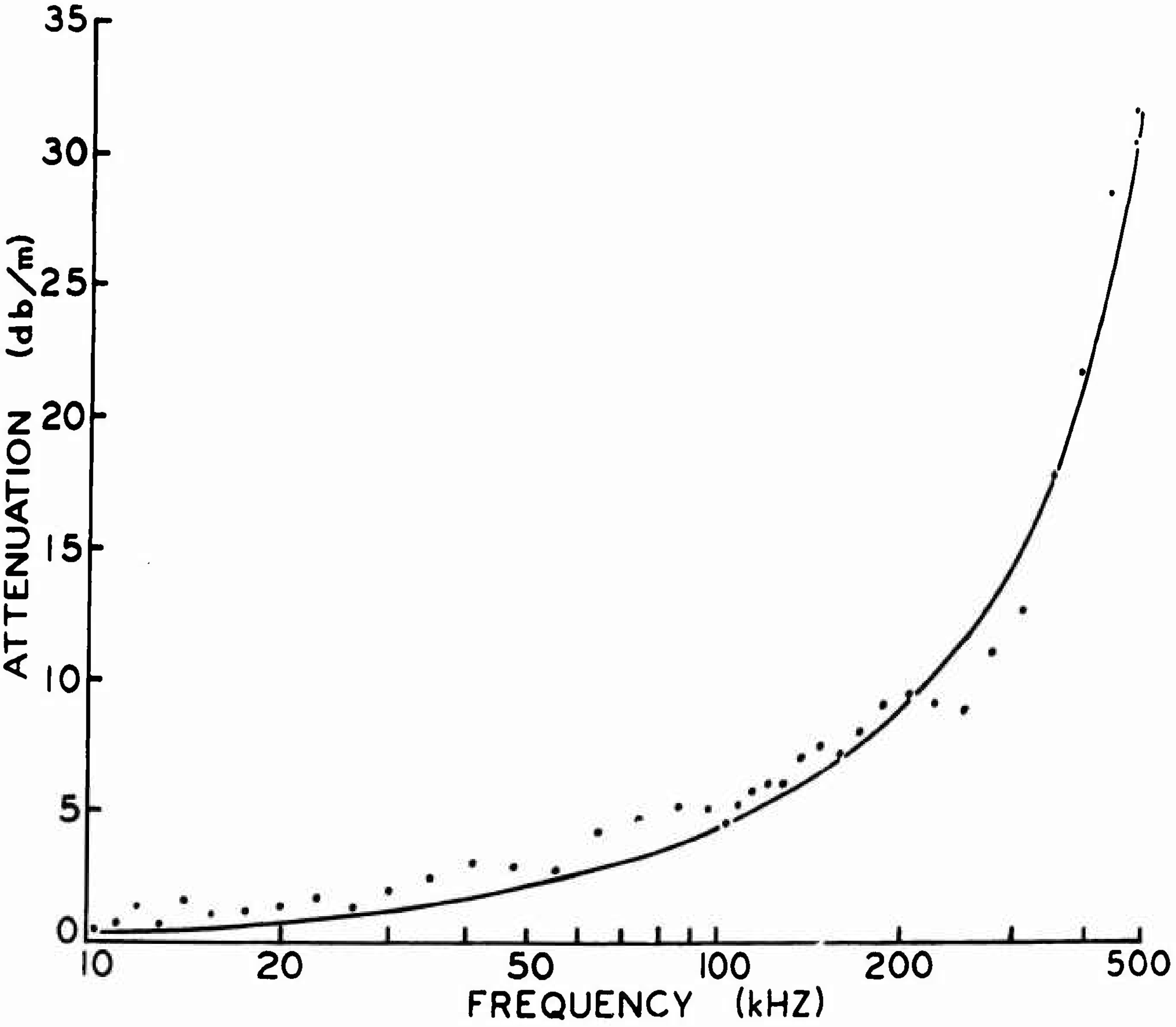


Fig. 4: Attenuation coefficient as a function of frequency for 1967 data on sea ice of salinity 1 $^{o}/oo$.

Attenuation in first year ice (1969). Two sets of CW transmission measurements, similar to those of the 1967 study, were performed in 1969. Since the method of analysis of the data has already been described, only the final results will be discussed here.

These results are plotted in Figure 5 as attenuation coefficient against frequency. The data of Figure 5 have been fitted with an equation of the same type as used to fit the 1967 data. It will be recalled that for the 1967 observations it was found that $c_1 = 4.45 \times 10^{-2}$ and $c_2 = 2.18 \times 10^{-10}$. Since the dimensions of the ice crystals do not differ markedly in first and second year ice, it is reasonable that the Rayleigh scattering term in the above expression should remain unchanged. A least-squares analysis, in which the coefficient c_2 was given its 1967 value, was used to determine the coefficient c_1. The value found by this method was $c_1 = 6.91 \times 10^{-2}$, an increase of about 50% over the 1967 value associated with the higher salinity of first year ice.

In addition, a set of pulsed transmission measurements was carried out at a number of frequencies within the band used for the CW measurements. Some further values of attenuation have been calculated from these observations. These are listed in the table below and compare favorably with those determined from CW measurements.

Frequency (kHz)	Attenuation (db m^{-1})	r.m.s. error
41.7	4.56	1.27
47.2	6.98	0.92
53.3	6.82	1.22
64.1	5.05	2.42
88.5	9.66	1.30
89.3	8.10	1.38
199	16.0	2.49
224	20.9	2.52

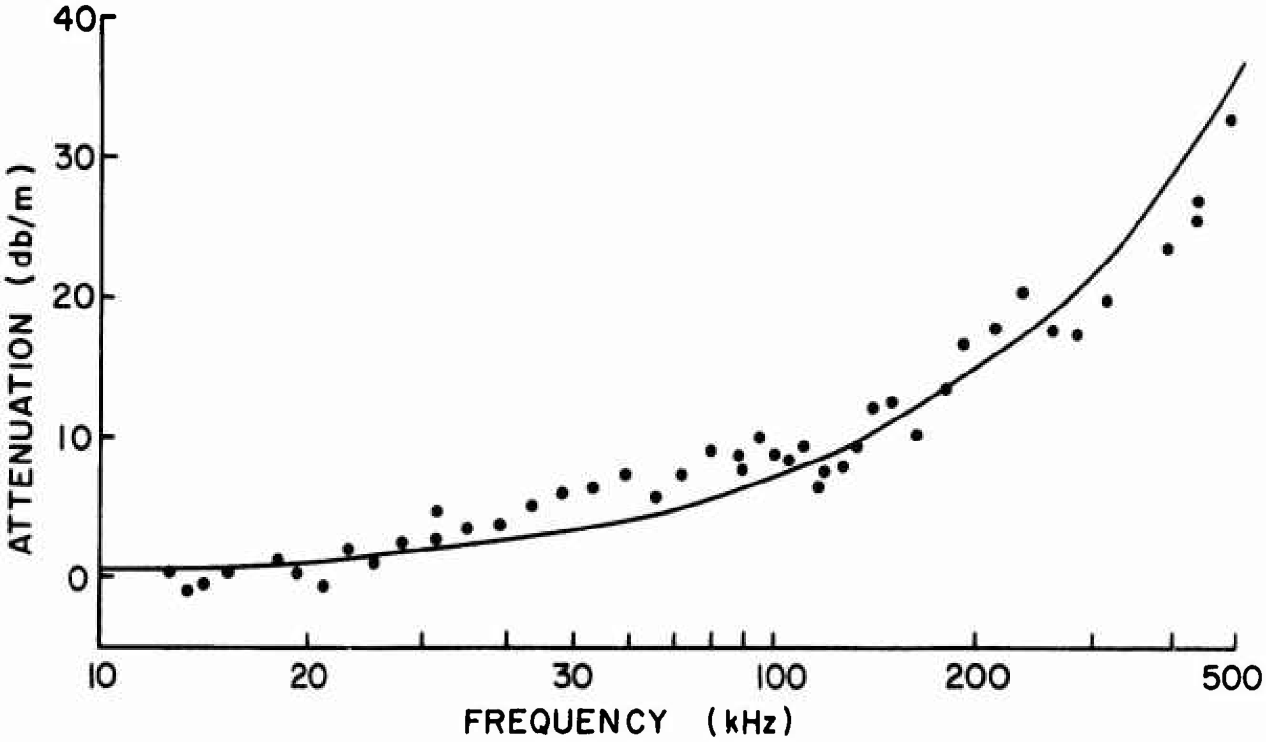


Fig. 5: Attenuation coefficient as a function of frequency for 1969 data on sea ice of salinity 4 ^{o}/oo.

CONCLUSIONS

These investigations have shown that acoustic attenuation in sea ice increases rapidly with increasing frequency and to some extent with increasing salinity. The variation of the attenuation coefficient with frequency can be represented by an equation as the sum of two terms, a linear term proportional to the first power of the frequency and a Rayleigh scattering term proportional to the fourth power of the frequency. Calculations with this equation indicate that the linear term is the predominant one in the frequency band studies. In the 1967 study, it accounted for more than 99.9% of the attenuation at frequencies below 60 kHz, for 99% at about 120 kHz, for 90% at somewhat less than 300 kHz and for 60% at about 500 kHz. This result is not entirely unexpected when one considers that sea ice has a complicated substructure of platelets with heavy concentration of liquid brine in cells between the platelets and also numerous air bubbles. The brine cells, air bubbles, platelets and even grains may act as sites of strain concentration resulting from passage of the acoustic pressure wave. Savage (1965) points out that localized temperature fluctuations would be induced at such sites and that the diffusion of these fluctuations by conduction produces the loss mechanism which he calls thermoelastic internal friction.

As for the scattering term, since the velocity of compressional waves in sea ice of the properties encountered is about 3.7×10^5 cm sec^{-1} (Langleben, 1962), the wavelength of the acoustic waves approaches the typical horizontal dimension of the ice crystals, about 2 cm, at a frequency of approximately 130 kHz. It would thus appear that, in a lossy medium such as sea ice, Rayleigh-type scattering is insignificant compared with other loss mechanisms until frequencies having wavelengths which are less than the average crystal size are attained.

For the 1967 data, it has been pointed out that the contribution to the attenuation from the linear frequency term was very much greater than from the fourth power term. In the more saline ice measured in 1969, this effect was more pronounced, to the extent that an equally good fit to the data could be obtained by neglecting the Rayleigh scattering term and expressing the attenuation as a linear function of frequency.

i.e. $\alpha = c_3 f$ where $c_3 = 7.64 \times 10^{-2}$.

REFERENCES

Anderson, D.L. 1958. Preliminary results and review of sea ice elasticity and related studies. Transactions, Engineering Institute of Canada, Vol. 2, No. 3, p. 116-122

Knopoff, L. and MacDonald, G.J.F. 1958. Attenuation of small amplitude stress waves in solids. Review of Modern Physics, Vol. 30, No. 4, p. 1178-1192.

Langleben, M.P. 1962. Young's modulus for sea ice. Canadian Journal of Physics, Vol. 40, No. 1, p. 1-8.

Mason, W.P. and McSkimin, H.J. 1947. Attenuation and scattering of high frequency sound waves in metals and glasses. Journal of the Acoustical Society of America, Vol. 19, No. 3, p. 464-473.

Mason, W.P. 1964. Physical Acoustics. Principles and Methods. Vol. 1, Part A. Academic Press. New York.

Pounder, E.R. and Langleben, M.P. 1964. Arctic sea ice of various ages. II. Elastic Properties. Journal of Glaciology, Vol. 5, No. 37, p. 99-105.

Pounder, E.R. and Langleben, M.P. 1968. Acoustic attenuation in sea ice. Report S-14, submitted by the Ice Research Research Project to U.S. Naval Ordnance Laboratory.

Savage, J.C. 1965. Attenuation of elastic waves in granular mediums. Journal of Geophysical Research, Vol. 70, No. 16, p. 3935-3942.

Westphal, J.A. 1965. In situ acoustic attenuation in glacial ice. Journal of Geophysical Research, Vol. 70, No. 8, p. 1849-1853.

PART II: REFLECTION OF SOUND AT THE WATER-SEA ICE INTERFACE

INTRODUCTION

Ice growth continues throughout almost the entire year at the bottom of the cover of sea ice in the Arctic by the normal process of crystallization from the melt, except for a period of a month or two during the short summer season. During this growth process, the ice-water interface is ill-defined. A transition or skeleton-like layer, of thickness dependent on growth rate and typically about one or two centimetres, exists at the interface and consists of a loosely knit structure of vertically oriented ice platelets or dendrites projecting into the sea.

The presence of this skeleton layer and the consequent gradual transition from consolidated sea ice through this layer to the sea acts as an excellent acoustic coupling between these two media. Thus Marsden (1961) was able to demonstrate that echo soundings of the ocean bottom could be performed with relative ease from the upper surface of the ice cover. Since acoustic energy is readily transmitted across the ice-water interface, the implication is that the fraction of the incident energy reflected at this interface is small. For this reason and because of severe attenuation in sea ice at ultrasonic frequencies (Langleben, 1969) it has not been possible to develop acoustic ice thickness measuring devices suitable for sea ice. However, acoustic attenuation at limited range is not severe in sea water and successful measurements of under-ice profiles have been made (Lyon, 1961) with vertically pointing sonar on submarine traverses of the Arctic Ocean, indicating that a finite quantity of acoustic energy is being returned by the interface. No quantitative data were available on acoustic reflection at the water-sea ice interface and the present study was undertaken to provide such information in the frequency range of about 20 kHz to 450 kHz. It included an investigation of the variation of the reflectivity with angle of incidence. The measurements were performed in Tanquary Fiord, Ellesmere Island, N.W.T. in April and May 1969.

EXPERIMENTAL METHODS

In this experiment, a sound source beneath the underside of the ice cover was arranged to emit pulse trains at a selected angle of incidence to the water-ice interface. A detector was located at the same depth beneath the ice cover, and some distance away, and oriented to receive the specularly reflected pulse trains. This procedure was repeated for various angles of incidence by adjusting the orientation of the transducers. The separation between sound source and receiver, and the depth of immersion of the transducers were changed for each angle of incidence so as to maintain a constant total path length for the pulses reflected at the water-ice interface. The geometrical configuration is shown in Figure 6. It is seen that the locus along which the transmitting and receiving transducers are required to move to maintain a constant path length is a semi-circle of diameter equal to path length. If D is the path length and Θ the angle of incidence of the sound pulses at the interface, then the horizontal separation between receiver and detector is $d = D \sin \Theta$, and their depth

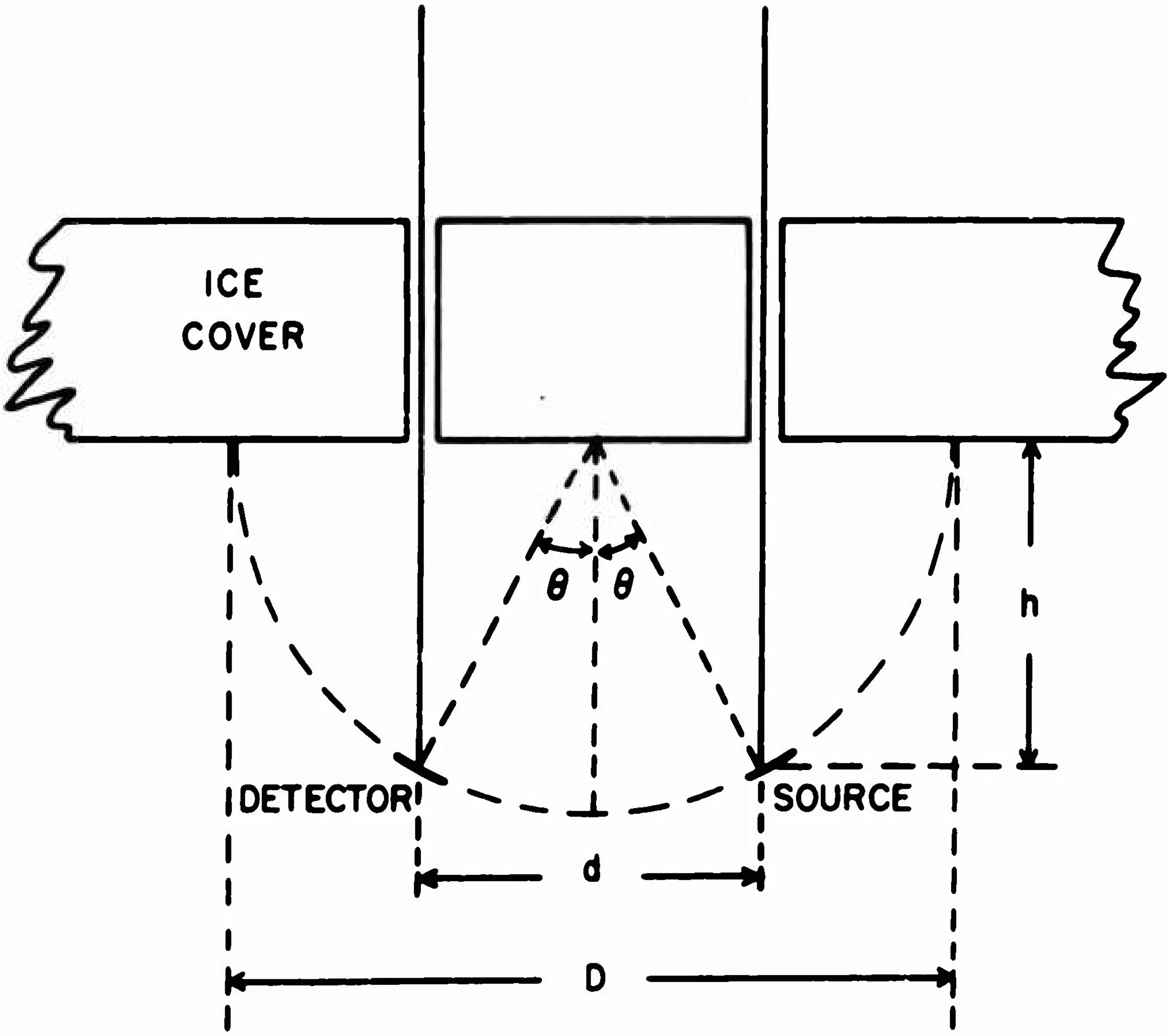


Fig. 6: Geometrical configuration for a constant transmission path length D between source and detector. With varying angle of incidence Θ, the source and detector move along the semicircle such that their horizontal separation is $d = D \sin \Theta$, and their depth of immersion $h = \frac{D}{2} \cos \Theta$.

of immersion is $h = \frac{D}{2} \cos \theta$. In this manner it was possible to avoid the necessity of having to correct for beam spread or directional characteristics of the transducers, and for attenuation in the water; for one could compare the intensity of signal received at the various angles of incidence with that received over a direct water path of the same length.

Ceramic discs of barium titanate, encased for waterproofing and electrostatic shielding, were used as acoustic transducers. Several of these, of up to 6-inch diameter and of thickness of 1/8 inch and 1/4 inch, were fabricated and were substituted for each other to obtain sufficient acoustic output over the frequency band of 20 kHz to 450 kHz. In use, the sound source and detector were each mounted in a special jig with settings prealigned along the required angles of incidence (or of reflection) and each jig was fastened to a long piece of aluminum tubing. Holes of diameter 8 inches were then bored through the ice cover with a motorized drilling auger and the transducers were inserted into the sea through these holes. Optical sights, bolted to the aluminum tubing at eye level, were available for purposes of adjustment of the depths of the transducers to the same immersion and of the orientation of each transducer with respect to the other.

The sound source was driven in a pulsed mode in the following manner. A CW sinusoidally-varying signal at any frequency selected within the desired band of 20 kHz to 450 kHz was generated within a Hewlett-Packard (H.P.) 651A oscillator, amplified by the H.P. 450A amplifier and fed through a gate of variable width using a General Radio 1396 tone-burst generator. (The gate was kept open to produce a pulse length of sufficient duration for the steady state amplitude of vibration of the transducers to be established.) The gated signal was amplified further with a H.P. 467A amplifier and then the pulses were fed to the sound transmitter. The signal at the detector was amplified in a H.P. 400E voltmeter-preamplifier and then in the vertical deflection amplifiers of a Tektronix 422 cathode-ray oscilloscope. The horizontal sweep of the oscilloscope was initiated by synchronization with the GR 1396 tone-burst generator. The display on the face of the 'scope was photographed with a Polaroid Land camera and readings of all attenuator settings were noted.

OBSERVATIONS AND RESULTS

In the spring of 1969 the sea ice in Tanquary Fiord was a smooth cover of first-year ice of thickness 93 inches and salinity about 4 $^{o}/oo$. Although air temperatures were moderating, the temperature gradient throughout most of the ice cover was still indicative of continuing growth at the ice-water interface. It is not unusual to find the ice sheet still growing at its bottom even after the upper surface has started its summer melt.

A constant sound transmission path length of 28.28 ft was used in the measurements. The first observations were made along a direct path of this length between transducers inserted well below the base of the ice cover through drill holes. The separation between drill holes was then reduced in steps, conforming to the geometry of Figure 6 for angles of incidence (and of reflection) of 75°, 60°, 45°, 30° and 15°, and the sound reflection measurements were performed. At any given frequency, the power input to the sound source was maintained constant so that the measurements of signal detected over the direct path then served as reference signal levels for comparison to the signals subsequently detected over the reflected paths. The results are presented in Table I as amplitude reflection coefficients, i.e. ratios of the amplitude of the reflected signal to the amplitude of a signal along a direct path of the same length, for the various frequencies and angles of incidence.

TABLE I: Amplitude reflection coefficients at the water-ice interface

	Angle of incidence (deg)				
Frequency (kHz)	15	30	45	60	75
17.9	0.24	0.20	0.48	0.36	0.88
23.1	0.091	0.034	0.18	0.41	0.51
24.8	0.13	0.070	0.29	0.63	0.38
47.0	0.056	0.17	0.89	0.89	1.22
56.5	0.083	0.25	0.42	0.75	0.75
89.9	0.039	0.053	0.41	0.63	0.96
118	0.13	0.16	0.72	0.88	1.06
126	0.055	0.036	0.32	0.69	0.81
184	0.056	0.11	0.56	0.75	0.97
227	0.021	0.005	0.43	0.44	0.91
332	0.17	0.22	0.019	0.50	0.45
387	0.083	0.091	0.36	0.16	1.00
435	0.066	0.088	0.016	0.11	0.94

There does not appear to be any smooth variation of amplitude reflection coefficient with either frequency or angle of incidence. However two general trends are apparent from a closer examination of the data in Table I. These are that the amplitude reflection coefficients (a) generally tend to increase with increasing angle of incidence and (b) show no such tendency with change of frequency. The data have therefore been averaged over frequency and the mean values of the reflection coeffients and the standard deviation in each have been plotted in Figure 7 as a function of angle of incidence. In spite of the large scatter in the coefficients in Table I, it is seen that the mean values are reasonably smooth function of angle of incidence. The amplitude reflection coefficient increases very slowly for angles of incidence up to 30° and has a value of about 0.1. Beyond 30°, the reflection coefficient increases rapidly with increasing angle of incidence.

DISCUSSION

The results of the previous section, in combination with the theory of specular reflection of sound waves at oblique incidence, may be used to infer some properties of the water to ice interface at the bottom of a growing ice cover. According to Lord Rayleigh (Vol. II No. 270) for the case of a sound wave in medium 1 (sea water) incident on medium 2 (the skeleton layer), the ratio of reflected to incident displacement amplitudes is

$$R = \frac{\dfrac{\rho_2}{\rho_1} - \dfrac{\cot \theta_2}{\cot \theta_1}}{\dfrac{\rho_2}{\rho_1} + \dfrac{\cot \theta_2}{\cot \theta_1}}$$

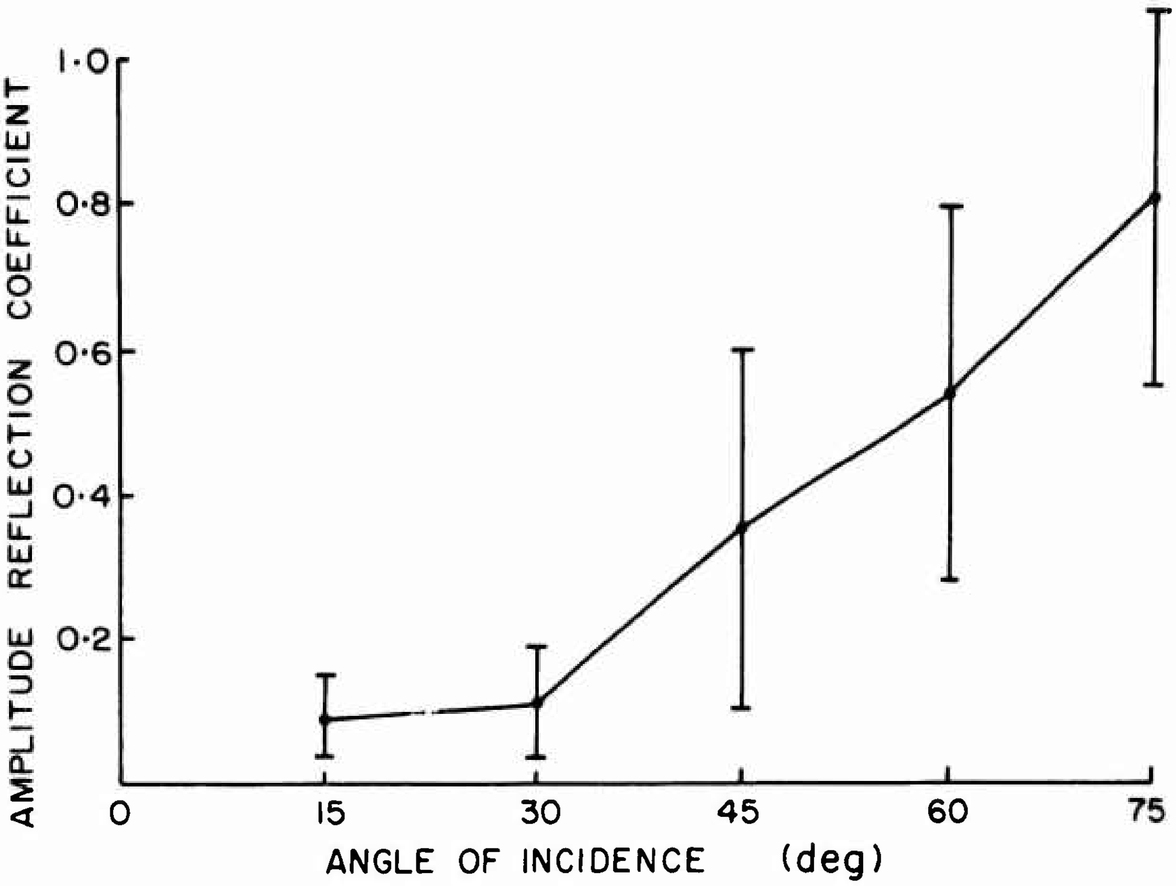


Fig. 7: Amplitude reflection coefficient of water-borne sound waves reflected by the skeleton layer at the underside of a growing cover of sea ice as a function of angle of incidence.

where Θ_1 and Θ_2 are the angles of incidence and of refraction and ρ_1 and ρ_2 the densities of the media.

But by the law of refraction

$$\frac{\sin \Theta_1}{\sin \Theta_2} = \frac{c_1}{c_2}$$

where c_1 and c_2 are the velocities of sound in the two media.

$$\text{i.e. } \cos \Theta_2 = \left[1 - \left(\frac{c_2}{c_1} \sin \Theta_1\right)^2\right]^{1/2}$$

$$\text{and } R = \frac{\rho_2/\rho_1 \cos \Theta_1 - \left[\left(\frac{c_1}{c_2}\right)^2 - \sin^2\Theta_1\right]^{1/2}}{\rho_2/\rho_1 \cos \Theta_1 + \left[\left(\frac{c_1}{c_2}\right)^2 - \sin^2\Theta_1\right]^{1/2}}$$

for angles of incidence less than the critical angle.

Let $a = \rho_2/\rho_1$ and $b = c_1/c_2$ where we expect to evaluate a and b from the experimental data on R and Θ_1. Then the last equation can, after some algebraic manipulation, be rewritten as

$$\frac{1}{\sin^2\Theta_1} = \left(\frac{a}{b}\right)^2 \left[\frac{\cos \Theta_1 \ (1 - R)}{\sin \Theta_1 \ (1 + R)}\right]^2 + \frac{1}{b^2}$$

which is an equation of the straight line

$$y = \left(\frac{a}{b}\right)^2 x + \frac{1}{b^2}$$

$$\text{where } x = \left[\frac{\cos \Theta_1 \ (1 - R)}{\sin \Theta_1 \ (1 + R)}\right]^2 \text{ and } \quad y = \frac{1}{\sin^2\Theta_1} \ .$$

A least-squares fit of this linear equation was performed on the data plotted in figure 7 and the following results were obtained:

$$b = c_1/c_2 = 0.828$$

and

$$a = \rho_2/\rho_1 = 0.977$$

and from the law of refraction, the critical angle of incidence was found to be $\Theta_{1c} = 56^\circ$. (The datum point at the angle of incidence of 75° was omitted from the analysis as being far beyond the critical angle. The value at 60° was retained as being within experimental error.)

Now ρ_1 = density of sea water = 1.02 g cm^{-3} and these results would indicate that the density of medium 2 at the interface, $\rho_2 = 0.996$ g cm^{-3} which is much higher than the density of sea ice $\rho_i = 0.917$ g cm^{-3}.

Also, c_1 = speed of sound in water = 1.5×10^5 cm sec^{-1} and the velocity in medium 2 at the interface, $c_2 = \frac{1.5}{0.828} \times 10^5 = 1.81 \times 10^5$ cm sec^{-1} is very much less than the velocity of sound in sea ice $c_i \simeq 3.5 \times 10^5$ cm sec^{-1}.

These results are plausible since the reflecting interface in this series of measurements did not represent an abrupt change from the medium water to the medium solid ice. The observations were made on first-year ice which was still growing on its underside and had a skeleton layer attached to it. The value of the density of this skeleton layer, which in situ includes ice and water, would tend to lie between that of ice and of water which is consistent with our result. Similarly, the velocity of sound in this layer would have a value intermediate between that in water and in ice.

It is possible to estimate the fractional volume of ice in the skeleton layer using its calculated density. For any volume V in the skeleton layer, the conservation of mass dictates that

$$\rho_2 V = \rho_i V_i + \rho_w (V - V_i)$$

where V_i is the volume of ice in volume V,

ρ_2 is the density of the skeleton layer in situ,

and ρ_w and ρ_i the densities of water and ice respectively.

Hence the fractional volume of ice in the skeleton layer is

$$\frac{V_i}{V} = \frac{\rho_w - \rho_2}{\rho_w - \rho_i} = \frac{1.02 - 0.996}{1.02 - 0.917} = 0.24,$$

which may not be an unreasonable value near the bottom of a growing ice cover.

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REFERENCES

Langleben, M.P. 1969. Attenuation of sound in sea ice, 10-500 kHz. *Journal of Glaciology*, 8, 399-406.

Lyon, W. 1961. Ocean and sea-ice research in the Arctic Ocean via submarine. *Trans. N.Y. Acad. Sci.* (series II), 23, 662-674.

Marsden, M. 1961. Sub-marine topographical studies in the Queen Elizabeth Islands, 1960. *Polar Record*, 10, 388-390.

Rayleigh, J.W. STRUTT, LORD. 1894. *The Theory of Sound*. 2nd ed. Vol. II, Sect. 270, 78-85. Dover Publications, New York (1945 reprinting).

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13 ABSTRACT

Measurements of the attenuation of acoustic waves in sea ice at frequencies between 10 kHz and 500 kHz were made on the ice cover at Tanquary Fiord, Ellesmere Island (latitude 81°25'N, longitude 76°50'W) during April-May in 1967 and again in 1969. A horizontal transmission path at a depth of 4 ft, mid-way between the top and bottom surfaces of the ice cover, was used at ranges of 4 ft to 25 ft between piezoelectric transducers immersed in oil-filled bore holes. The attenuation coefficient α in db m^{-1} was found to fit the equation $\alpha = c_1 f + c_2 f^4$. The value of the constants of this equation for the 1967 data on biennial ice of salinity about 1 °/oo were 4.45×10^{-2} db m^{-1} kHz^{-1} and 2.18×10^{-10} db m^{-1} kHz^{-4}. For the 1969 data on first year ice of salinity 4 °/oo, the value of c_1 increased to 6.91×10^{-2} db m^{-1} kHz^{-1}. In both cases, the linear term of the equation was the predominant one, far exceeding the Rayleigh scattering term even at the upper end of the frequency band covered in these investigations.

In an auxiliary experiment in 1969, measurements of the specular reflectio of water-borne sound at the water-sea ice interface were made as a function of angle of incidence. The geometric configuration was such that a constant path length was maintained between sound source and detector, and the transducers were aligned carefully at each angle of incidence to match this configuration thus obviating the necessity of having to make corrections for range and for directionality characteristics of the transducers. The amplitude reflection coefficient was found to have a value near 0.1 for near-normal angles of incidence but its value was found to increase rapidly with increasing angle of incidence beyond 30°.

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