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APPARENT COHERENT ENERGY LOSS OF ICE-REFLECTED, HIGH-FREQUENCY LFM PULSES

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ABSTRACT

Measurements of the effects of interaction of waterborne, high frequency (HF, 14 to 59 kHz), linear FM (LFM) acoustic signals with the bottom of multiyear pack ice are presented. The underside of arctic sea ice is a random, extended reaction scatterer of incident waterborne sound. At high frequencies, the problem is magnified because ice relief may be many orders of magnitude larger than a wavelength, resulting in significant out-of-plane scattering and multiple scattering. Also, at shorter wavelengths, the complicated water-to-ice transition region, typically about 20 centimeters thick, and other ice inhomogeneities and anisotropy become more important. Interaction of coherent, incident sound with such a complicated elastic medium results in a scattered field of unknown coherence, especially near the reflecting interface.

In April 1986 and April 1987, forward reflection measurements were made at deep-water ice camps in the Beaufort Sea. A linear array of hydrophones was mounted on a rigid strongback and deployed beneath a multi-year ice floe each year. Sixteen phones were distributed along an aperture of 16 m. The data sets reported here were taken with the array deployed horizontally at a depth of 61 m and a source located normal to the array at depths of 55, 61, and 67 m, at ranges about 450, 900, and 1800 m in 1986 and 970 m in 1987.

Significant variations in the apparent reflection loss are observed with only small changes in source depth and between data taken beneath different samples of multi-year ice.

INTRODUCTION

Deep water Arctic spatial coherence experiments were conducted in the springs of 1986 and 1987. The ice camps were set up for the U.S. Navy by the Applied Physics Laboratory, University of Washington in the Beaufort Sea. A linear array of 16 hydrophones was mounted on a rigid support and deployed horizontally below a multi-year ice floe each year. A depth of 61 meters was maintained for all phones. The array was 16 meters long with the hydrophones spaced according to a suboptimal minimum redundancy algorithm. The transmitter was lowered to 55, 61, and 67 meter depths at locations on a perpendicular to the array axis.[1] In 1986 the source was placed at 450, 900, and 1800 meters from the array. In 1987 a range of 970 meters was used. Linear FM (LFM) signals 100 msec long, with a bandwidth of 800 Hz, were transmitted at frequencies between 11 and 59 kHz. The frequencies presented here are 14, 15, 20, 24, 35, 42, and 59 kHz. Signals received by the array were recorded on an extended video cassette recorder(EVCR) as were the source pulses for each frequency. All data were transferred to 9 track computer tape using a MASSCOMP minicomputer and further processing was done on a VAX computer.

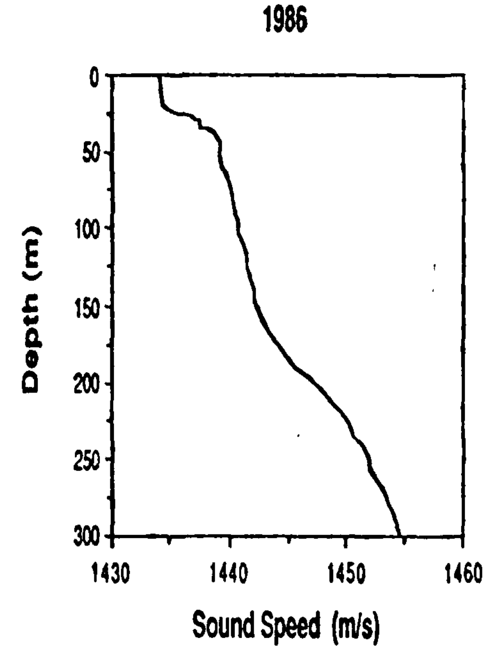

Figure 1. Sound speed profile for 1986 experiment.

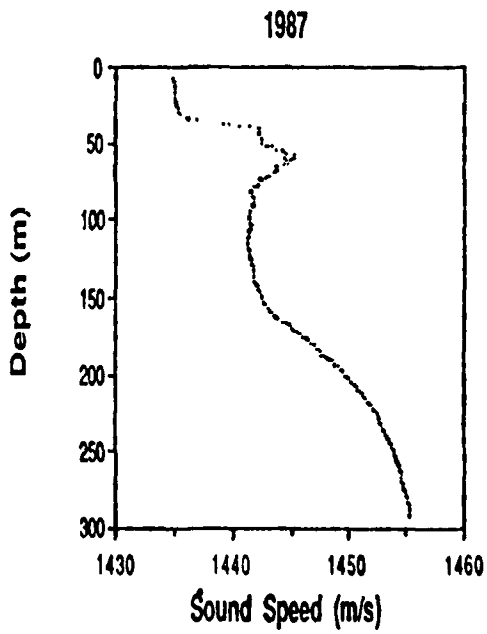

Figure 2. Sound speed profile for 1987 experiment.

The sound speed profile for 1986 is shown in Figure 1.[2] Figure 2 is the sound speed profile

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array deployed horizontally at a depth of 61 m and a source located normal to the array at depths of 55, 61, and 67 m, at ranges about 450, 900, and 1800 m in 1986 and 970 m in 1987.

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for the 1987 experiment. The sound speed below 40 m, and therefore at the three source depths of interest, was changing only gradually in 1986 but in 1987 increased rapidly above 61 meters then decreased quickly below that depth.

ICE CHARACTERISTICS

Incident waterborne sound is scattered by the underside of the ice in a random extended reaction. The problem is greater at high frequencies since ice relief may be many orders of magnitude larger than a wavelength. Underice profiles obtained by APL/UW using high frequency narrow beam profiling sonar show cross sections of ice ridges and keels as well as medium scale roughness of relatively flat areas.[3] More recent underwater stereo photographs and video recordings obtained by NORDA in recent years reveal details of underice features of various shapes and sizes in the area of the ice camp where the coherence experiments were done. Pictures available have not been correlated with the specific path of the signals transmitted for this experiment but give a general idea of the complexity of the reflecting surface encountered. Scattering from keels and underice roughness can be expected to decrease the amplitude and coherence of reflected arrivals. A theoretical

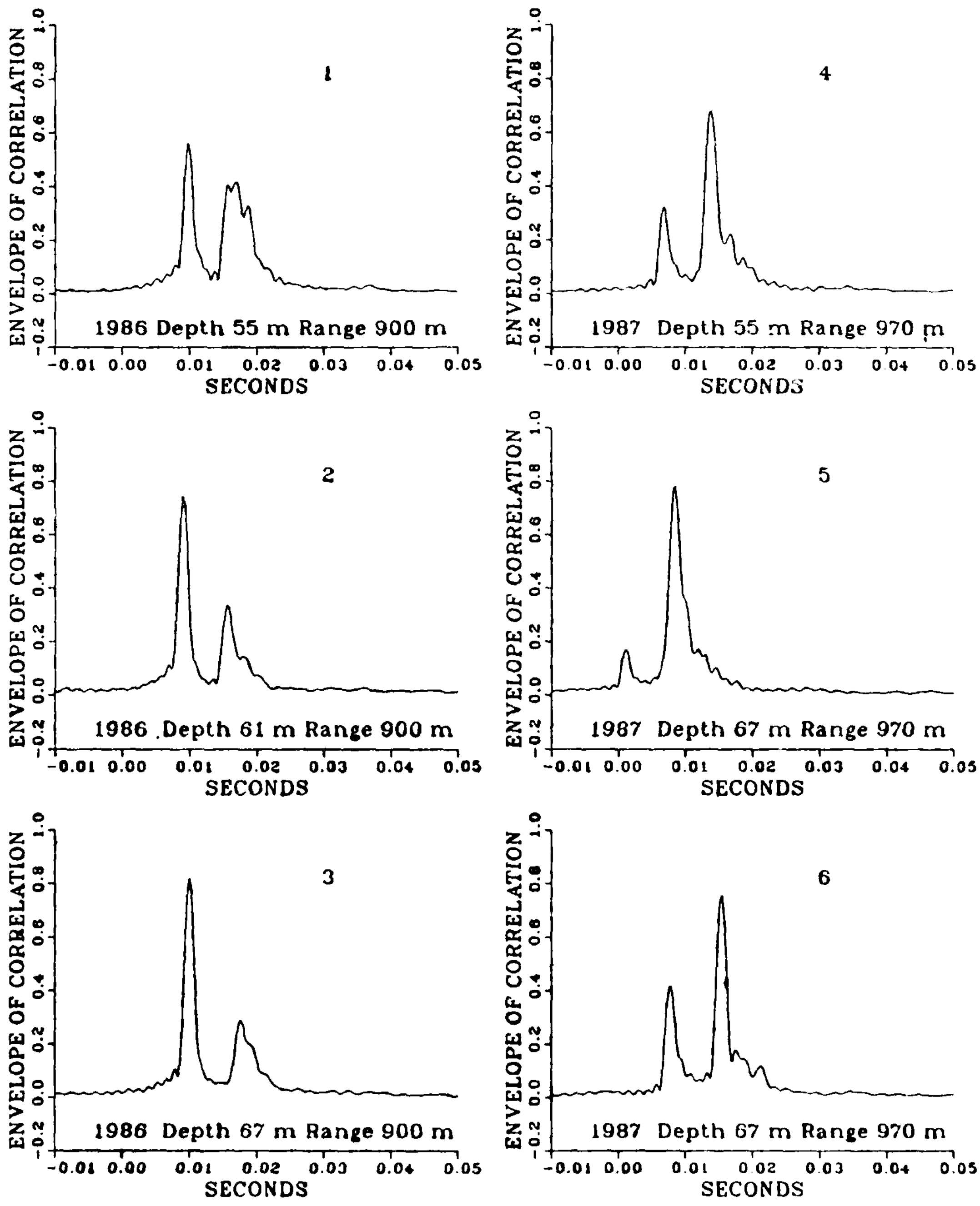

Figure 3. Average envelope of correlation for 24 kHz received signals with similar experimental geometries from 1986 and 1987 data. The direct signal is dominant in the 1986 data on the left while the reflected signal is stronger in the 1987 data on the right.

study of the reflection coefficient versus grazing angle for flat ice points out the importance of ice thickness and the size of the transition zone between solid ice and sea water which is normally about 20 centimeters thick. The reflection coefficient decreases when the horizontal trace velocity of the incoming wave is the same as that of some propagation mode in the ice. At shallow angles relative to the surface, shear properties are more important than compressional properties.[4] Yang and Votaw measured the reflectivity coefficient at several angles of incidence for frequencies from 100Hz to 1kHz. The results are complex, with several deep dips of 20 dB or more at several angle/frequency combinations.[5] In a study by McCammon and McDaniel the ice depth and shear attenuation are shown to be critical in determining the pattern of reflection coefficient peaks and nulls for frequencies from .5 to 3kHz.[6] Many ice reflection studies have been published for lower frequencies or shorter ranges.[7] This paper will show experimental results for 14 to 59 kHz LFM pulses at ranges from 450 to 1800 meters.

METHOD OF ANALYSIS

The Generic Sonar Model[8], set to assume perfect reflections from a flat ice surface, was used to obtain ray traces and arrival amplitudes which formed a baseline for comparison with the experimental data. A directional source was used in the 1986 experiment. Therefore corrections for the effect of the beam pattern for each frequency were applied to this baseline. The angle from which the predicted ray for the reflected signal left the source was about 15° for 450 m range data, 7° for 900 m range, and 2.6° for 1800 m range. Although conditions were reportedly calm, deviations in source tilt of up to 2° from the horizontal could occur. Therefore, at the 450 m range, calculations of beam pattern corrections for frequencies above 30 kHz could be changed by 3 dB or more by this slight change in orientation of the source. The same is true at 59 kHz and 900 m range. Consequently these cases were not included in the final results. At the 1800 m range 59 kHz LFM signals, which had predicted amplitudes of -100 dB or less, were too week to be received at the array.

The 1987 source was omnidirectional, so data from 59 kHz and the 970 m range are shown. The Generic sonar model at 24 kHz and 61 meter source depth gave a level close to -120 dB for the reflected ray at 900 meters range and did not show any reflected ray at all for 1000 meters. Therefore, an exact value at 970 meters could not be determined and the comparison between the model and the experiment was not calculated.

An average coherence was obtained by convolving the signal on each channel with a source pulse, obtaining the envelope of the correlation time series, and averaging results for the 16 channels. Figure 3 shows the results for 1986 and 1987 data with similar frequencies, ranges, and source depths.

The first peak in each plot represents the direct arrival and the second shows the relative amplitude and arrival time of the signal reflected by the ice. In 1986 the direct arrival is stronger, but in 1987 the reflected signal is more prominent. This agrees with the sonar model predictions for these geometries and sound speed profiles. Figure 4 shows the dB levels, relative to the level at the source, as predicted by the Generic Sonar Model for 24, 35, and 42 kHz direct and reflected paths at all three source depths. A closer comparison of the amplitude of the reflected signal relative to that of the direct signal, however, shows differences as large as 30 dB between the predicted and experimental levels. In order to compare the two, it was necessary to convert the

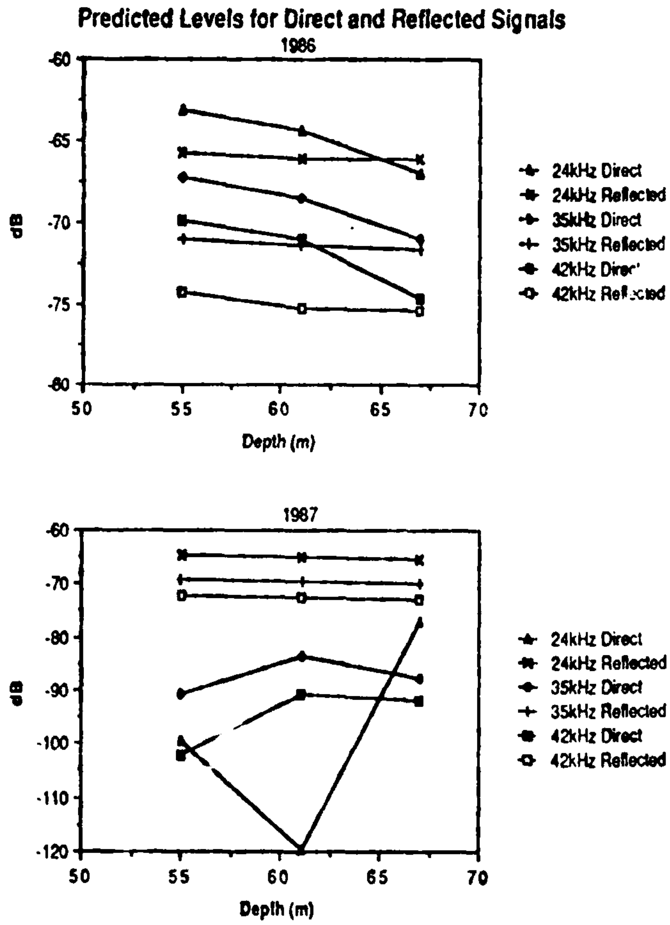

Figure 4. Amplitudes in dB, relative to the source level, of reflected and direct rays predicted by the Generic Sonar Model for 1986 data at 900 meters range and 1987 data at 970 meters range.

coefficients in the experimental data to dB levels using the formula 20 log (D/R) where D is the correlation value for the direct signal and R is the value for the reflected signal. This corresponds to subtracting the predicted dB level of the reflected signal from that of the direct signal. The difference between the predicted and experimental values for each geometry and frequency was called apparent ice reflection loss. The positive numbers indicate the amount of loss while a negative number occurs if the reflected arrival is larger than predicted. The term apparent reflection loss is used since other causes, such as scattering, in addition to energy absorbed at the reflection may contribute to the loss observed. The ice reflection angles are calculated using Snell's law. The angle is a grazing angle measured between the ray path of the signal and a horizontal line at the point where the signal intersects the ice.

RESULTS

Table 1 lists the apparent ice reflection loss in dB for each geometry and frequency for which dependable data were available. In 1987 15 kHz pulses were used where in 1986 there were 14 kHz pulses. Data for 20, 24, 35, and 42 kHz are shown for both years. For 1987 59-kHz data were also available.

Table 1

Apparent Ice Reflection Loss (dB)

Range (m)	Depth (m)	14kHz	20kHz	24kHz	35kHz	42kHz
1986						
450	55	7.2	8.9	7.8		
	61	9.5	5.2	2.0		
	67		5.5	9.9		
900	55	6.5	8.0	-.3	-1.8	-1.1
	61	7.5	7.2	4.5	6.9	7.4
	67	9.9	7.5	9.9	7.6	7.0
1800	55	10.3	16.1	19.9	5.6	9.6
	61	13.5	12.9	14.2	16.1	16.3
	67	5.6	-8.2	-.7	-2.5	2.1

Range (m)	Depth (m)	15kHz	20kHz	24kHz	35kHz	42kHz	59kHz
1987							
970	55	11.8	24.6	28.8	20.8	30.2	24.5
	61	-10.0	10.7		2.6	8.4	6.8
	67	15.2	9.2	6.5	24.0	21.6	16.1

Figure 5 shows the apparent ice reflection loss of the 1987 data as a function of ice reflection angle and range at reflection for six frequencies. Ice conditions at 440 meters from the source and 8.2° ice reflection angle gave 8 to 18 dB more loss for frequencies greater than 15 kHz. At 484 meters from the source there was a 12-dB difference between the 15-kHz signal which was amplified and the higher frequency signals which showed a 2 to 11 dB loss.

Figure 6 shows the amount of loss as a function of frequency. Loss does not increase steadily as a function of frequency for the 8.2° reflection angle and 55 m source depth and although a similar pattern with about 20 dB less loss is seen at 61 meters source depth with 8.64° reflection angle, the pattern seems to be reversed for the 67 meter source depth at 8.87° reflection angle. For the latter geometry, 24 kHz shows the least loss, followed by 20 kHz, then 15 kHz. The three higher frequencies do experience a greater loss than the three lower frequencies, but 35 kHz has the most loss, 42 kHz a little less, and 59 kHz even less.

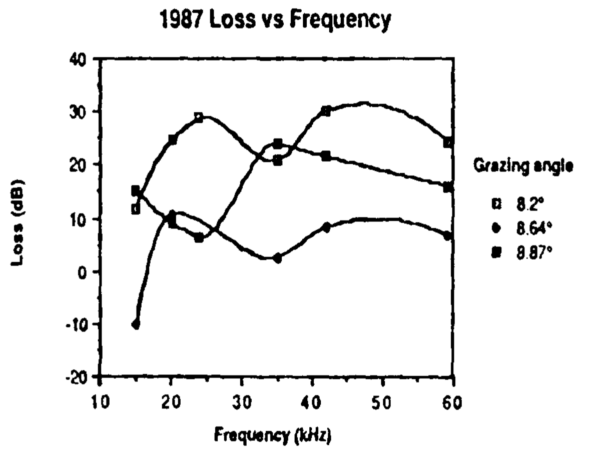

Figure 6. Apparent ice reflection loss as a function of frequency for slightly different ice reflection angles at the same horizontal range but slightly different source depths. The range at reflection for 8.2° was 440 m, for 8.64° was 484 m, and for 8.87° was 510 m.

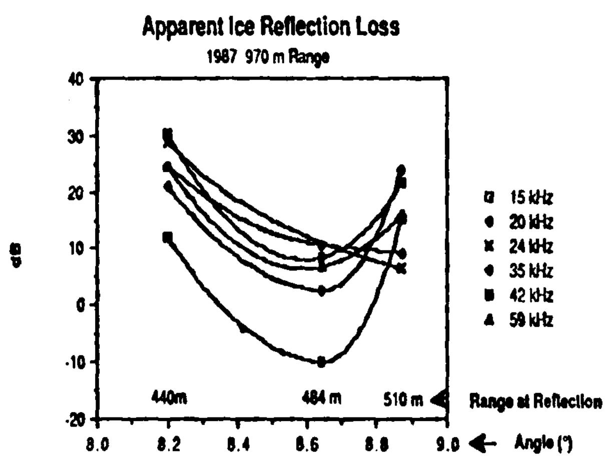

Figure 5. Apparent ice reflection loss vs reflection angle and range for the 1987 data. The numbers inside the lower axis indicate the horizontal range from the source at which the reflection occurred.

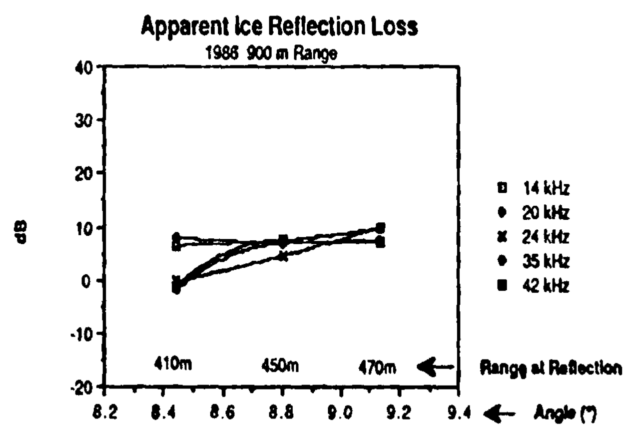

Figure 7. Apparent ice reflection loss for 900 m 1986 data.

Figures 7, 8 and 9 show apparent ice reflection loss versus ice reflection angle and range from the source at which the reflection occurs for the 1986 data. Comparing Figures 5 and 7 shows little similarity between the results for the two years at about the same ranges and angles. The amount of scattering by the ice features near the surface from which the pulses are reflected may be the key factor determining the loss derived in the 1987 data.

In Figure 8 the source to receiver range is 1800 m. Each angle has a different order of frequencies from least to greatest loss. At the 840 m reflection range, data is spread out from 5 to 20 dB loss. At 900 m source-to-reflection range, all five frequencies are grouped within 5 dB of each other around 15 dE loss. For 980 m source-to-reflection range, the frequencies spread out between 6 and -9 dB with 35, 24 and 20 kHz showing a reflection gain instead of a loss.

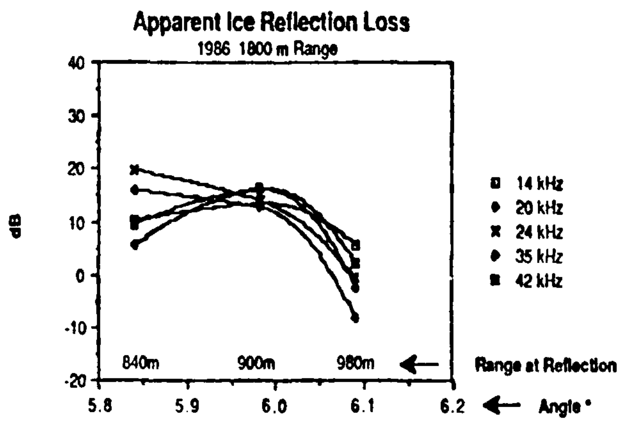

Figure 8. Apparent ice reflection loss for 1800 m range 1986 data.

Figure 9 shows the short range data. Only the lower three frequencies are shown. Ice reflection losses are between 2 and 10 dB.

CONCLUSIONS

The apparent strength of forward reflection sometimes changes significantly with even a

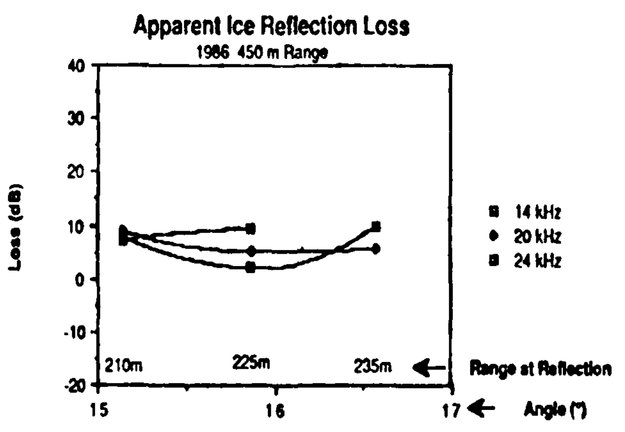

Figure 9. Apparent ice reflection loss for 450 m range 1986 data.

small change in frequency or source depth. Large changes with frequency could be due to the interference of multiple reflections, but the averaging of received amplitudes over the 16 meter array aperture should minimize such variations. A more likely explanation of the observed frequency dependence is the extended reaction nature of the interaction of the water-borne sound with complicated and unknown underice features. Video explorations of the undersides of the 1986 and 1987 floes revealed numerous, irregularly shaped, well weathered features which could extend to depths of 20 meters or more. These multi-year keels showed little resemblance to first year keels, having neither sharp edges nor flat facets. Just as incident fields can couple into dispersive modes of flat ice plates[4], so they can couple into shear and compressional modes of more complicated features and produce nulls and peaks in the frequency dependent reflection coefficient.

A source depth change at a given range changes the location of ice interaction and the grazing angle of the eigenray which would hit an idealized flat interface. Of course, the interface is not at all flat, so the slight differences in grazing angle due to small displacements of the source are not meaningful. Therefore, resulting large changes in reflected energy must be caused by differing ice conditions at the respective interaction locations. In fact, the ice sometimes focuses its reflection on the array, displaying an apparent reflection gain.

Data reported here is undergoing further analysis to determine the spatial coherence of reflected arrivals.

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