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C-BAND MEASUREMENTS OF RADAR BACKSCATTER FROM ICE PROJECT SUMMARY REPORT

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ABSTRACT

The ability to measure the radar scattering coefficient of ice with a helicopter or surface spectrometer has been extended into the 4-8 GHz spectral region. Measurements of the scattering coefficient have been conducted at Mould Bay, N.W.T., over a frequency range from 4 to 18 GHz for both summer and fall conditions. Other measurements were made of scatter from fresh-water ice in the St. Lawrence River and from numerous seasonal sea-ice types along the coast of Newfoundland.

The C-band (near 5 GHz) scattering cross-section for different types of ice has been found to show poorer contrast than the scattering coefficient at higher frequencies, but better contrast than the negligible value found at L band (1.5 GHz). At frequencies above 4 GHz the contrast in scattering coefficient between the different ice types has been found to be much less in summer than in other seasons; at most times of year the scattering is much stronger from multiyear than from other ice types, but in early summer it is actually slightly weaker than that from first-year ice. Analysis of the measurements is continuing.

1.0 INTRODUCTION

The Remote Sensing Laboratory of the University of Kansas Center for Research, Inc., has acquired radar backscatter data from sea ice over a frequency range from 4-8 GHz. Little was known prior to this program about the ability of a C-band imager to monitor sea ice. A C-band system is a requirement for determining soil moisture and it was thought that it might be useful for sea ice measurements. Moreover, various domestic and foreign agencies are planning C-band spaceborne SARs. Numerous measurements of the radar backscatter from sea ice have been made in other frequency bands, but no data were available between 1.5 and 9 GHz. We proposed to obtain these data as part of cooperative agreement NCCI-51 with Langley Research Center. This work is continuing through a grant from NASA Headquarters (NAGW-334). The results of this research will be reported in the literature.

The value of all-weather, day-night reconnaissance radar has been well-established, particularly in the study of sea-ice scientific and in operational ice monitoring. This is particularly impressive since these studies and operational uses were made using radars which were not optimal for ice studies.

Many physical parameters important to the study of sea ice may be measured using radar as an observational tool, particularly if the radar's frequencies of operation, range of viewing angles, selection of antennae polarizations and resolution have been optimized. These may include: the fraction of a region that is covered by ice, the distribution of thickness categories, floe sizes, ridge and rubble patterns, leads, ice islands, ice motion, icebergs, ice surface roughness, ice physical properties, and the study of the seasonal advance and retreat of the seaward edge of the regional pack ice. This marginal ice zone is important in understanding the synoptic-scale air-sea-ice interactions. Synoptic images are also important in obtaining a continuous, long-term data set to be used for obtaining climatological averages and analyzing interannual variations.

Because the research and operational potential of space- or airborne radars has been clearly proven, the U.S. (NASA) and Canada (Department of Energy, Mines and Resources) have undertaken joint studies to define a future bilateral SAR satellite program. These studies (the Free-Flying Imaging Radar Experiment in the U.S. and the Radar Satellite Project in Canada), address the following requirements for supporting that SAR mission: science and operations in sea-ice-covered waters, oceanography, renewable and non-renewable resources. The work under this project was to help define the requirements for studying sea-ice-covered waters.

Before a research or operational SAR or RAR (Synthetic- or Real-Aperture Radar) can be built, an adequate knowledge of the backscatter coefficients of ice features of interest is necessary to define the radar parameters. Radar earth scene returns are described by a scattering coefficient (scattering cross-section per unit area) σ^o. Since the total cross-section, σ, of a pixel varies with the illuminated area, and this is determined by the geometric radar parameters (pulsewidth, beamwidth, etc.), σ^o was introduced to obtain a coefficient independent of these parameters.

The two major influences on radar earth returns are the radar-system and the earth-scene parameters. To describe the influence of the radar parameters, backscatter measurements are made as a function of radar frequency, viewing angle, and antenna polarization. The earth-scene parameters, examined directly or indirectly through ice characterization measurements, include:

(1) complex permittivity,

(2) roughness of surfaces and subsurfaces to depths where attenuation reduces the electromagnetic wave to negligible amplitude, and

(3) location and size of scattering centers.

Because the physical/electrical properties of ice are influenced by season, a seasonally dependent description of backscatter properties is necessary.

Backscatter coefficients are useful in many ways. Not only do they allow the specification of new remote sensors, but they also are a significant source of useful information in the interpretation of data products from existing and future sensors. Comprehensive backscatter measurement and ice characterization programs enhance our ability to understand and study the radar-ice interaction process. The modeling of this process is useful because it acts as an aid to insight. This assists in interpreting measurements and allows us to extrapolate the results. We may then judge the effects of variations in dielectric properties, the roughness of the surface, and the influence of scattering centers' size distribution.

The University of Kansas has made scatterometer measurements over a wide range of frequencies (L-, C-, X-, Ku-bands). In contrast, other investigations have been limited to one or two frequencies. What was known before the first measurements of this program was that frequencies above 9 GHz showed the ability to discriminate between different ice types, at least under winter and spring conditions, while frequencies below 1.5 GHz did not. No data were available at that time for the region between 1.5 and 9 GHz. The University of Kansas proposed a program to make C-band measurements to fill this gap. Since 9 GHz seemed to be the best frequency for discriminating ice types, while 1.5 GHz is unsatisfactory, an optimum frequency somewhere between 1.5 and 9 GHz might exist; the use of C-band was expected to give results more like the 9 GHz good results than the not-so-useable 1.5 GHz results. Since the character of the radar backscatter changes so much over this gap in frequency coverage (wavelength changes by a factor of 6!) additional measurements were needed to determine just where the ability to discriminate drops off as one goes down from 9 GHz.

Also unknown was the impact of summer conditions on the ability to discriminate ice types. The influence of the summer melt upon the discrimination capability at all frequencies (1.5 to 18 GHz) must be known to show whether an active remote sensor is useful in all seasons or whether seasons of ambiguities exist. It has been suggested that the longer wavelengths, such as C-band, may be influenced less by the effects of the melt season. Although the ability to discriminate at even the higher frequencies has not yet been adequately described, the potential all-season utility of a longer wavelength sensor needed to be determined. Only future analysis of our most recent experiments will yield answers to some of these questions.

Measurements were made as part of a joint U.S./Canadian experiment series. Backscatter data were acquired near Mould Bay, N.W.T., Canada, during October 1981. These measurements focused on the characteristics of multiyear and newly formed sea ice at the start of the growing season. Fresh-water ice in the St. Lawrence River was examined in February 1982, first-year and pancake ice in the North Atlantic in March 1982, and sea ice at Mould Bay again during June 1982. The June experiment focused on both first-year ice and multiyear ice during the melt season. Measurements were made over the 4-18 GHz range (4-8 GHz under this agreement and 8-18 GHz under ONR sponsorship) and in the latter two experiments at 1.5 GHz (ONR sponsorship). Viewing angles ranged from 10° to 70° from vertical and antenna polarizations included both like (VV and HH) and cross (VH). This series of experiments was coupled with extensive ice characterizations by Dr. Rene Ramseier of Atmospheric Environment Service/RadarSat Project Canada. Coincident passive measurements were made by Dr. Tom Grenfell of the University of Washington.

The purpose of our research was to acquire more information about backscatter properties of ice and about the radar methods for measuring its properties. The basic objectives of the research were, and remain:

(1) to establish the ability of radar to discriminate ice features;

(2) to identify optimum frequency(ies), polarization(s) and incidence angle(s) for discrimination; and

(3) to develop a better understanding -- theoretical, empirical, and experimental -- of radar-ice interactions.

2.0 ACCOMPLISHMENTS AND ACTIVITIES

One of the first tasks completed, before the measurement program could be undertaken, was the integration of a C-band channel into the University of Kansas helicopter-borne microwave active spectrometer (HELOSCAT) which was developed under ONR sponsorship. This system, originally designed to operate at frequencies between 8 and 18 GHz, used two antennas, 12- and 18-inch parabolic reflectors, allowing transmit-receive polarizations of VV, HH and HV. Angles of incidence ranged from 10° to 70° from vertical. Eighteen-inch and 24-inch antennas were acquired to accommodate the lower frequency range. The HELOSCAT system is shown in Figure 1 and specifications of the combined system in Table 1.

The backscatter and ice characterization measurements, made in October 1981 in collaboration with Canadian experimenters led by Dr. Rene O. Ramseier of AES/RadarSat, were dedicated to combining an intensive ice characterization program with a backscatter measurement program. Both the helicopter-borne and a surface-based system were used in this experiment. Multiyear ice, a very large multiyear pressure ridge, first-year ice with varying degrees of surface roughness, gray ice, very old shorefast ice, and lake ice with and without snow cover were investigated with the airborne system. A frozen multiyear pond, a multiyear hummock, and first-year ice (with and without a snow cover) were investigated with the surface-based system, which allowed measurements up to 80° from vertical.

FIGURE 1: The Helicopter-Borne Scatterometer

TABLE 1
HELOSCAT III SYSTEM SPECIFICATIONS

Type	FM-CW
Frequency Range	4-18 GHz
Modulating Waveform	Triangular
FM Sweep	800 MHz
Transmitter Power	14-19 dBm
Intermediate Frequency	50 kHz
IF Bandwidth	13.5 kHz
Antennas:	Log-Periodic Feed Reflectors
Polarization	VV
Size	46 cm
Beamwidths	6.5°, 4.4°, 3.8° and 3.4° at 4.8, 7.2, 9.6 and 13.6 GHz
Polarization	Cross
Size	46 cm and 61 cm
Beamwidths	5.6°, 3.8°, 3.0° and 2.6° at 4.8, 7.2, 9.6 and 13.6 GHz
Incidence Angles	10° to 70° from nadir
Calibration:	
Internal	Signal Injection through Delay Line
External	Luneberg lens
Altitude	30 m for θ = 10° to 50° 15 m for θ = 60° and 70°

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A brief investigation of ice in the St. Lawrence River was made in February 1982. In this experiment, fresh water ice covered by a thick layered hard snowpack was investigated. Measurements were made of ice regions of different thicknesses. Just prior to this experiment the HELOSCAT system was certified (through the close cooperation of RadarSat) for operation in Canadian airspace.

Ice conditions along the Newfoundland Coast were investigated in March 1982. The original intent of this experiment was to study ice in the Labrador Sea, including the observation of icebergs. However, due to situations beyond control of the experiment team, only ice along the coast of Newfoundland was investigated. The HELOSCAT was operated in a sidelooking mode using the Sir John Franklin Icebreaker as a floating platform. Many categories of thin ice s well as thin first-year ice, were examined. The thinner ice included grease, frazil, new, slush, shuga, nilas, and pancake ice.

First-year and multiyear ice during the summer melt season were investigated during June 1982 at Mould Bay. This program was many-faceted and included coincident active/passive near-surface measurements; intensive ice characterization; ice microstructure work; lead dynamics; and AES Electra (RAR), CCRS CV-580 (SAR, scatterometer), and U.S. Navy P-3 (radiometer) aircraft overflights. To aid in our investigation of the radar-ice interaction, detailed ice surface roughness measurements were also made. These measurements produced a continuous profile of roughness for 4 sites of first-year ice which had small-scale surface roughness ranging from very smooth to rough. A measurement of loss at 13.9 GHz was made in the top 8 cm of the first-year ice sheet.

In addition, the radar return power spectra of first-year ice were recorded for future analysis. These data were obtained using the HELOSCAT radar to probe into the ice. These spectra will be used to study empirically the individual contributors to the radar-ice interaction process. Information sought from this data includes the contribution of the snow layer of surface roughness, and of volume scattering, as well as the location of significant scattering centers, and the determination of penetration depth.

3.0 PRELIMINARY RESULTS

The observations of sea ice made in October 1981 under fall growing conditions show a 4 dB spread in the average scattering cross-section of homogeneous first-year ice (Figure 2). This spread correlates with the bands of ice which ran parallel to the coast of Mould Bay. These bands exhibited small-scale surface roughness ranging from very smooth to rough. Multiyear ice frozen in gray ice was easily detected under fall conditions due to a 7 dB (at 5.6 and 9.6 GHz) or higher contrast (Figures 3 and 4). Contrast between multiyear and gray ice is less than between multiyear and first-year ice by about 2 dB due to a slightly higher cross-section for gray ice than for first-year ice. Many additional features may be identified in the flight-line profiles: multiyear melt ponds, blocks on the edge of the multiyear floes, fragments of multiyear ice near the main multiyear floe and rafting of homogeneous gray ice.

A family of theoretical radar cross-section curves (Figure 5) has been generated to illustrate results and to be used as an aid in interpreting the complex nature of the interaction of surface roughness and the volume scattering properties of the ice medium on angular response. Five possible mechanisms were considered: volume scatter alone, dominant <u>volume scatter</u> with a contribution of scatter from a slightly rough (compared with radar wavelength) surface, scatter from a <u>slightly rough surface</u> with some volume scatter, scatter from a <u>slightly rough surface</u> alone, and scatter from a nearly smooth surface. Using this family of curves as a

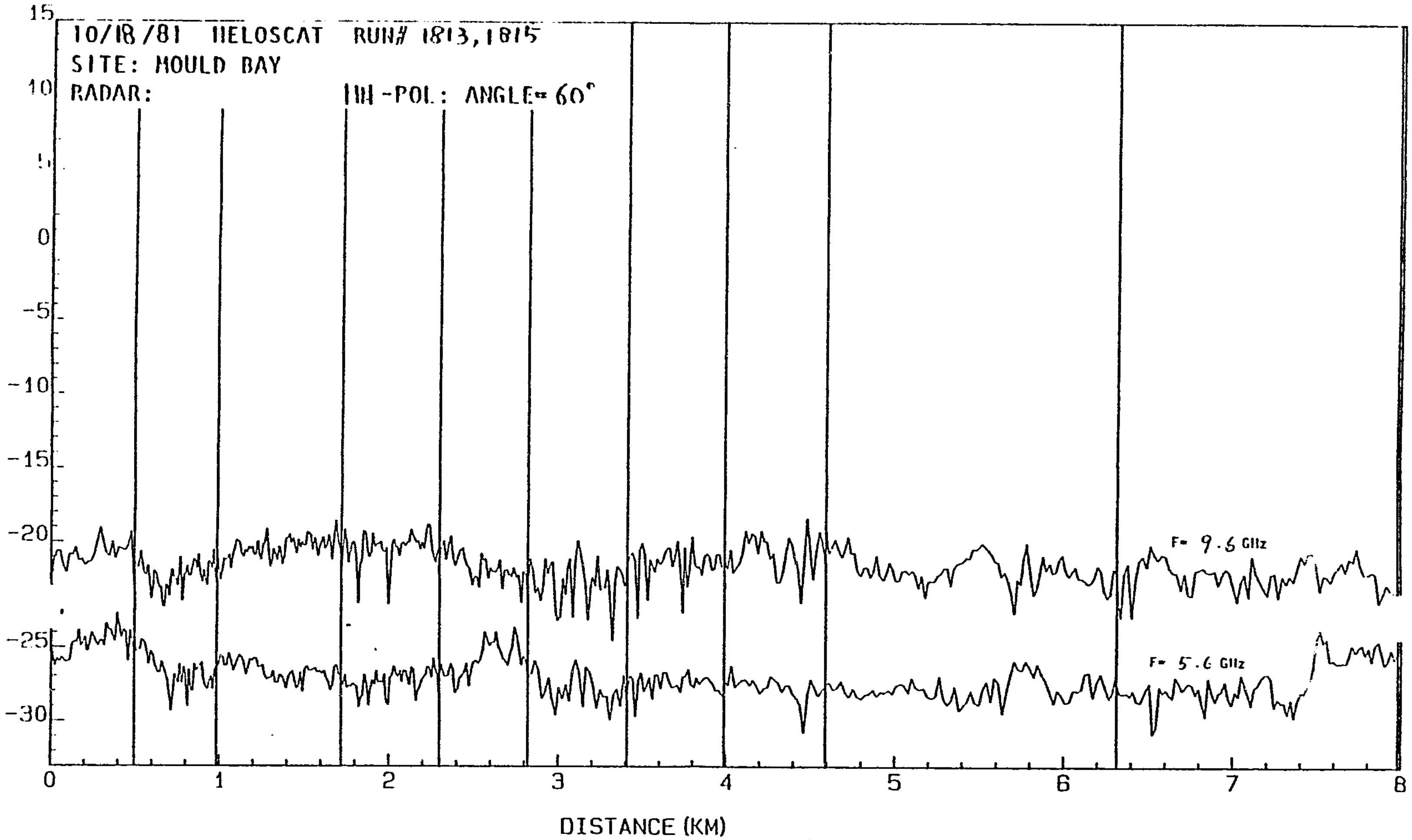

FIGURE 2: Scattering Cross-Sections of First-Year Ice (30-40 cm) with Varying Degrees of Small-Scale Surface Roughness at 60°, HH-Polarization, and 5.6 and 9.6 GHz. (Mould Bay, 1981 -- HELOSCAT)

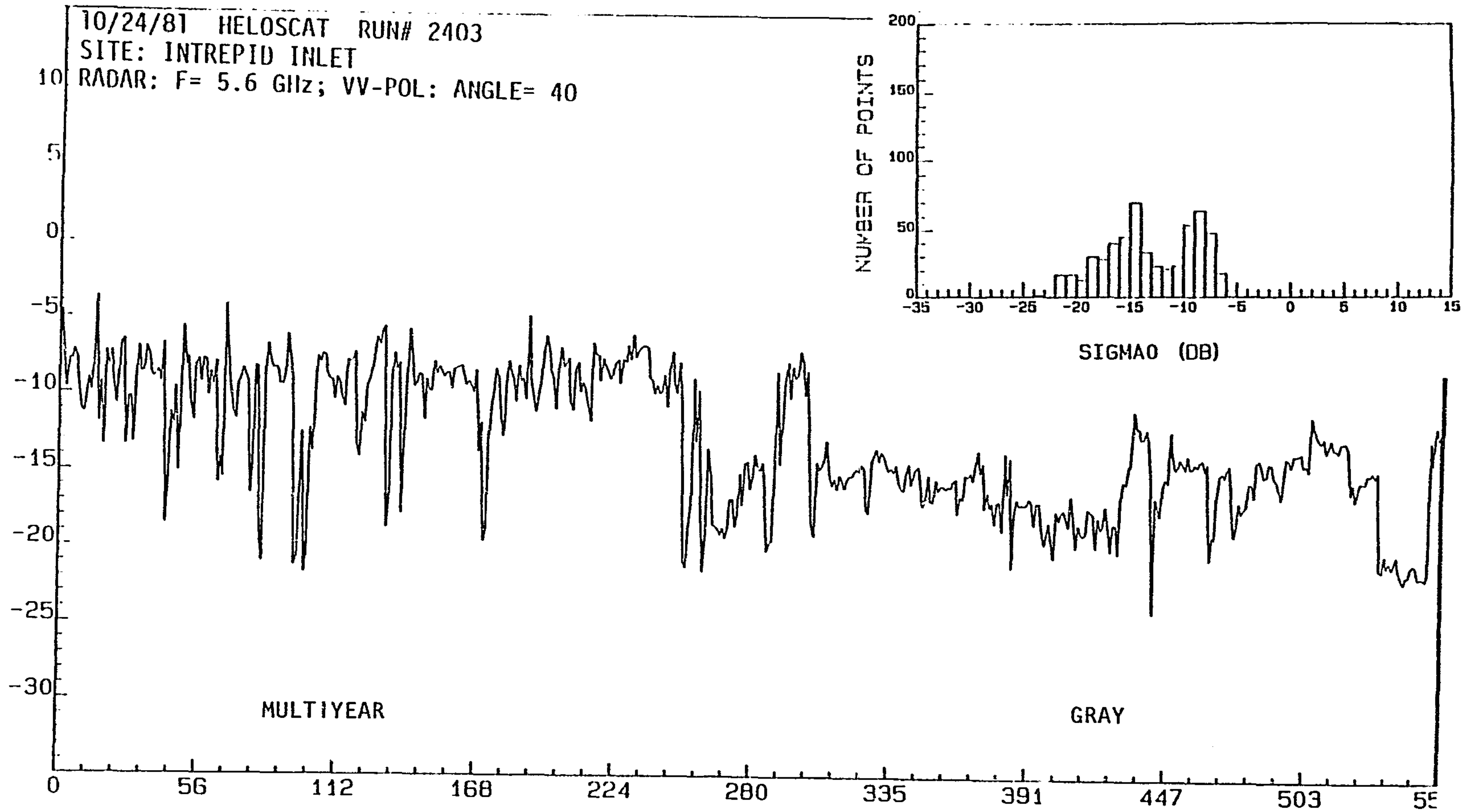

FIGURE 3: Scattering Cross-Sections of Multiyear and Grey Ice (15 cm) at 40°, HH-Polarization and 5.6 GHz. (Mould Bay 1981 -- HELOSCAT).

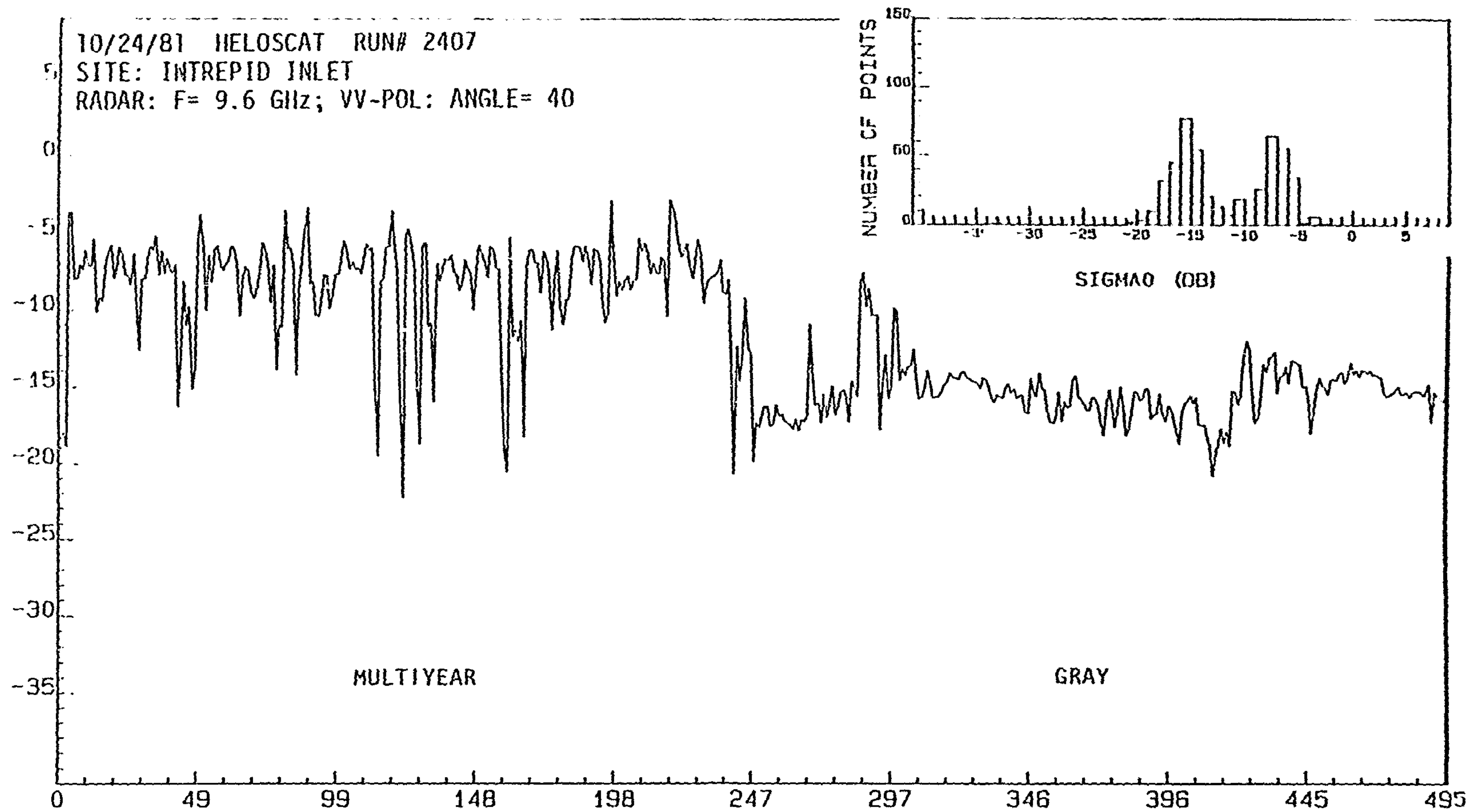

FIGURE 4: Scattering Cross-Sections of Multiyear and Grey Ice (15 cm) at 40°, HH-Polarization and 9.6 GHz. (Mould Bay 1981 -- HELOSCAT).

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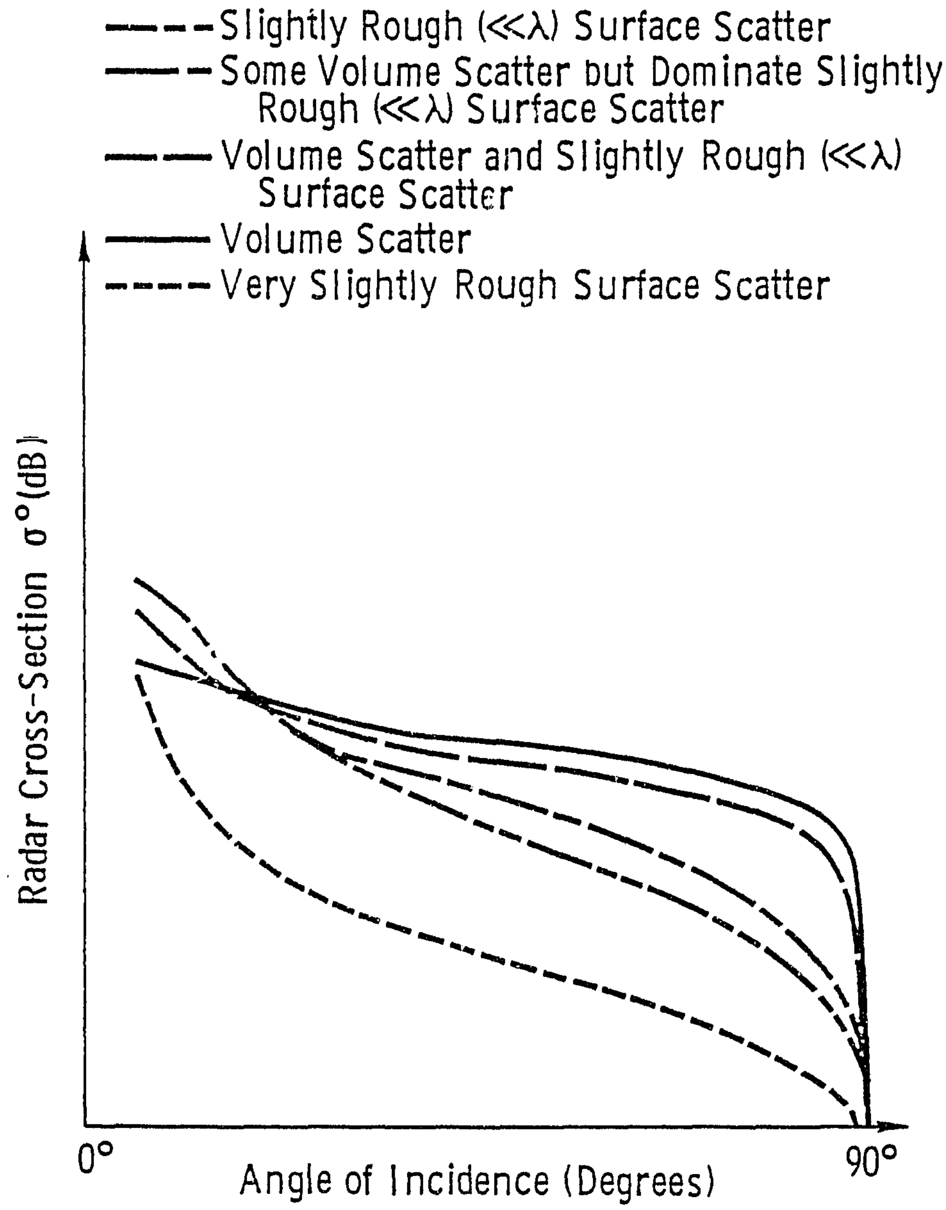

FIGURE 5: A Family of Radar Cross-Sections Which Illustrate the Interaction of Surface Roughness and the Volume Scatter Properties of Ice.

reference, the following discussion describes the backscatter properties of ice.

Scatter from multiyear ice (Figures 6-8) shows a slow rate of decay with incidence angle, and the same high backscatter level that was found under winter and spring conditions. This suggests that multiyear ice returns under fall conditions are greatly influenced by the contribution of volume scattering resulting from penetration of the electromagnetic energy into the snow and ice.

First-year and gray-ice scatter seems to be more surface-dominated. Although multiyear and gray/first-year ice can be discriminated at all angles, the contrast is greatest at larger angles of incidence. Results from the surface-based radar show that return-signal strength decreased by at least 10 dB as the viewing angle changed from 70° to 83°. This shows the rapid variation of scattering coefficient at small grazing angles.

A large, old, pressure ridge on a multiyear floe was studied for its frequency response at 40° and HH-polarization. Little difference in radar cross-section was found between the flat multiyear ice background and the large pressure ridge. This ridge was also imaged by the RAR on the AES Electra (10 GHz-HH) and the linear ice feature was detectable but not strikingly so. The large variation in return power along this feature proved useful in its detection.

Under fall conditions, discrimination among ice types was found to be better at Ku-X-band frequencies than at C band (Figure 9). The overall impression of C band is that it is more like X band than like L band in its ability to discriminate ice types,

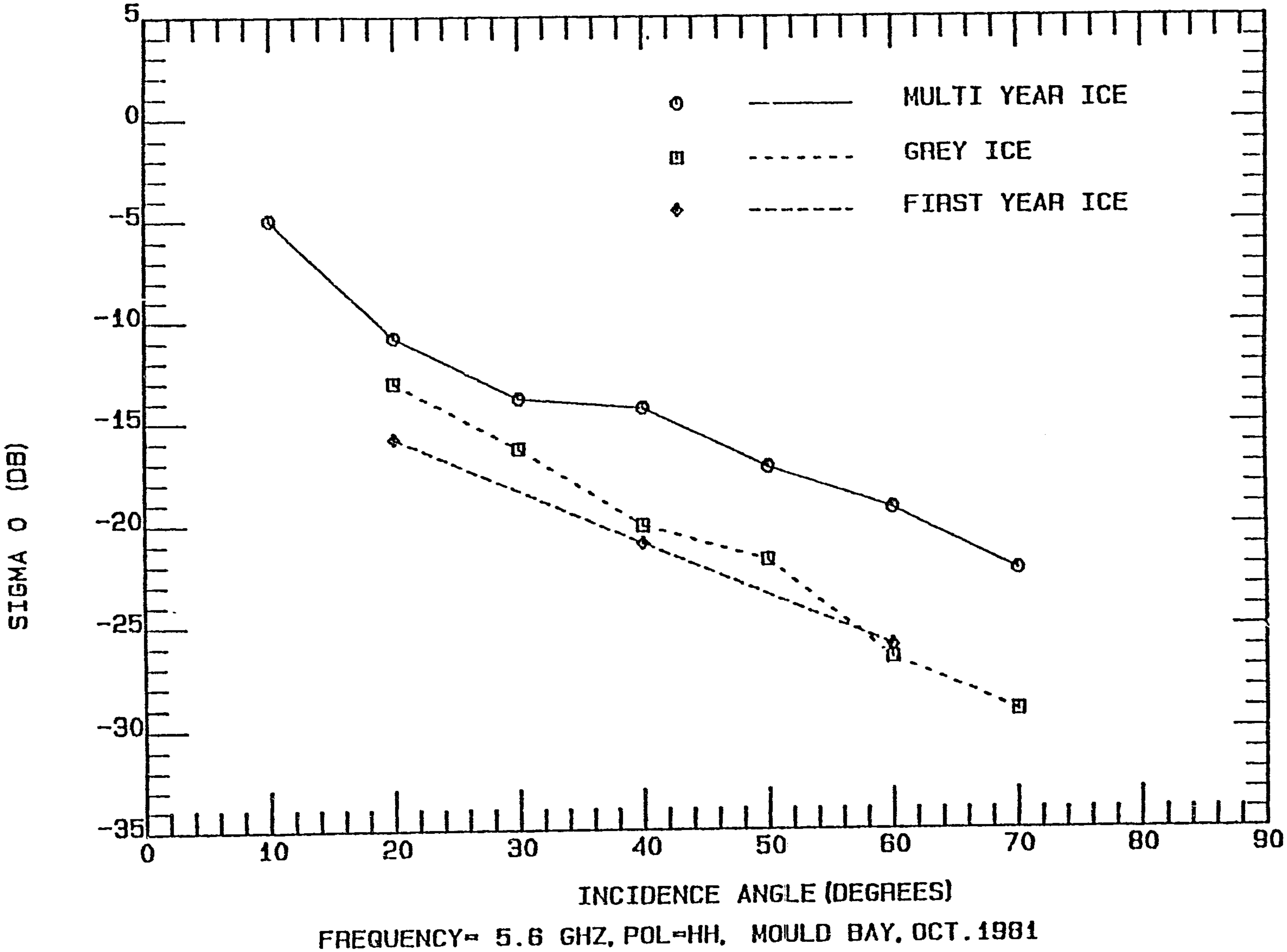

FIGURE 6: Scattering Cross-Sections of Multiyear, First-Year, and Grey Ice at 5.0 GHz and HH-Polarization (Mould Bay 1981 -- HELOSCAT).

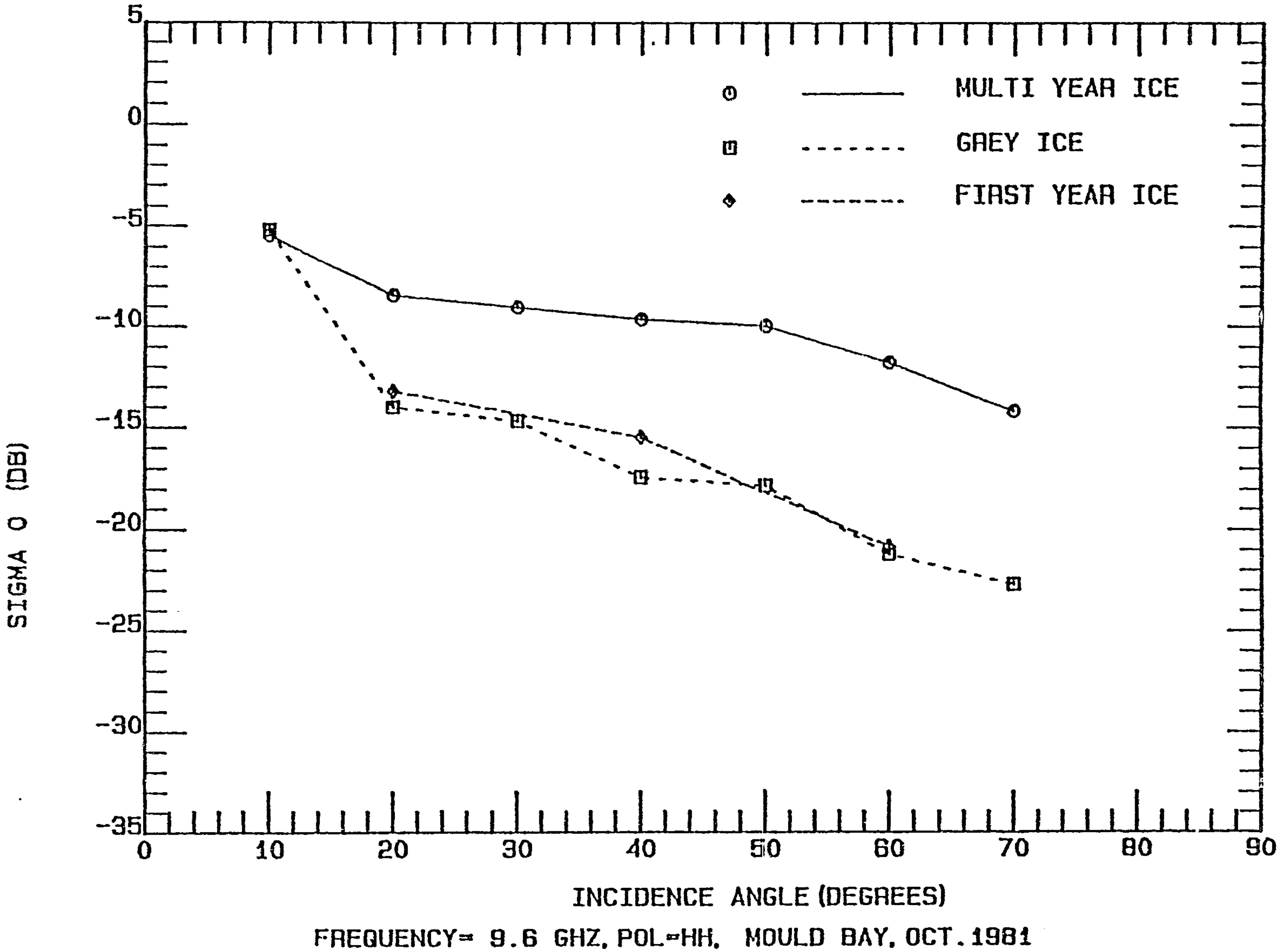

FIGURE 7: Scattering Cross-Sections of Multiyear, First-Year, and Grey Ice at 9.6 GHz and HH-Polarization (Mould Bay 1981 -- HELOSCAT).

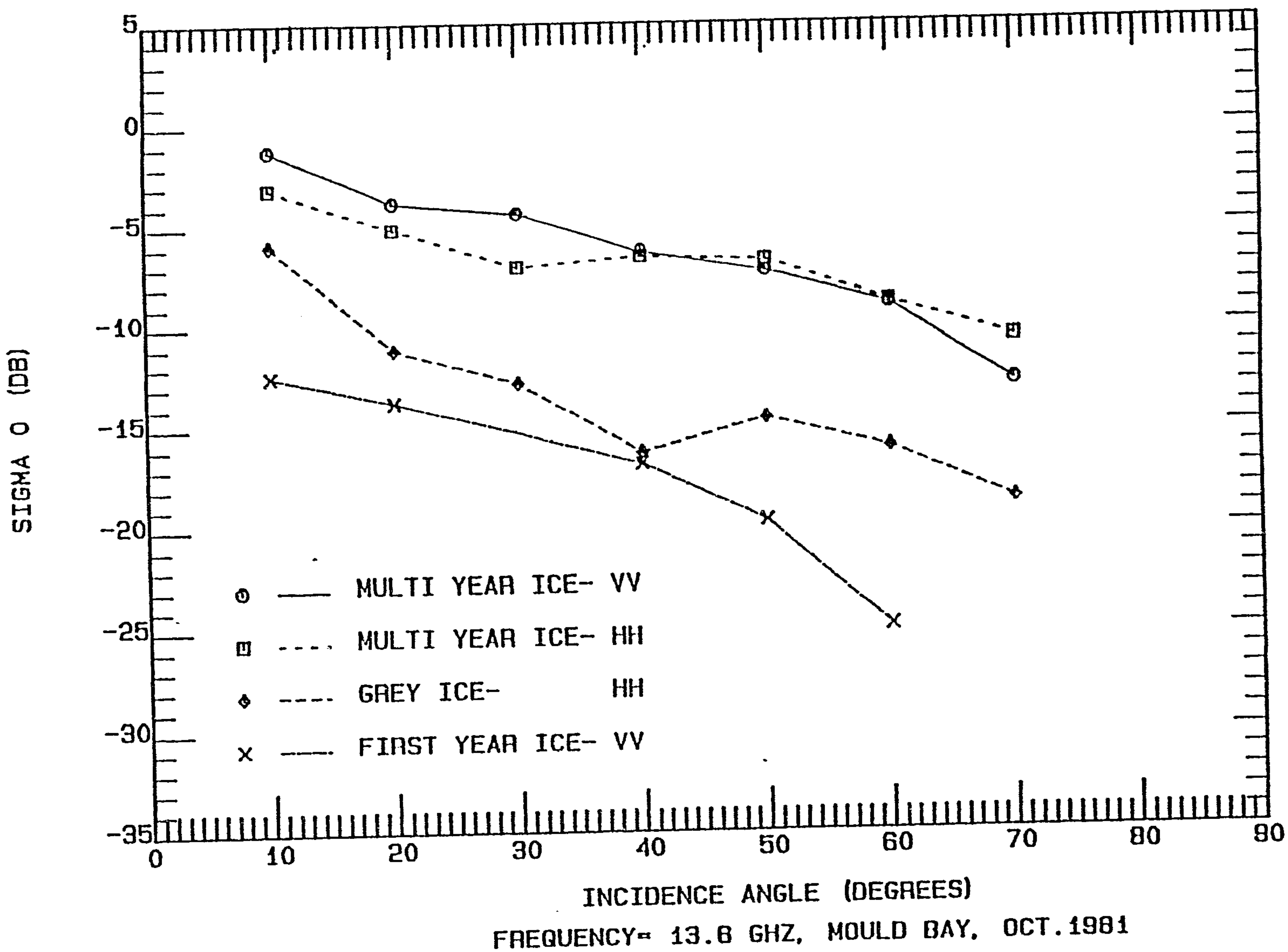

FIGURE 8: Scattering Cross-Sections of Multiyear, First-Year and Grey Ice at 13.6 GHz and HH- or VV-Polarization (Mould Bay 1981 -- HELOSCAT)

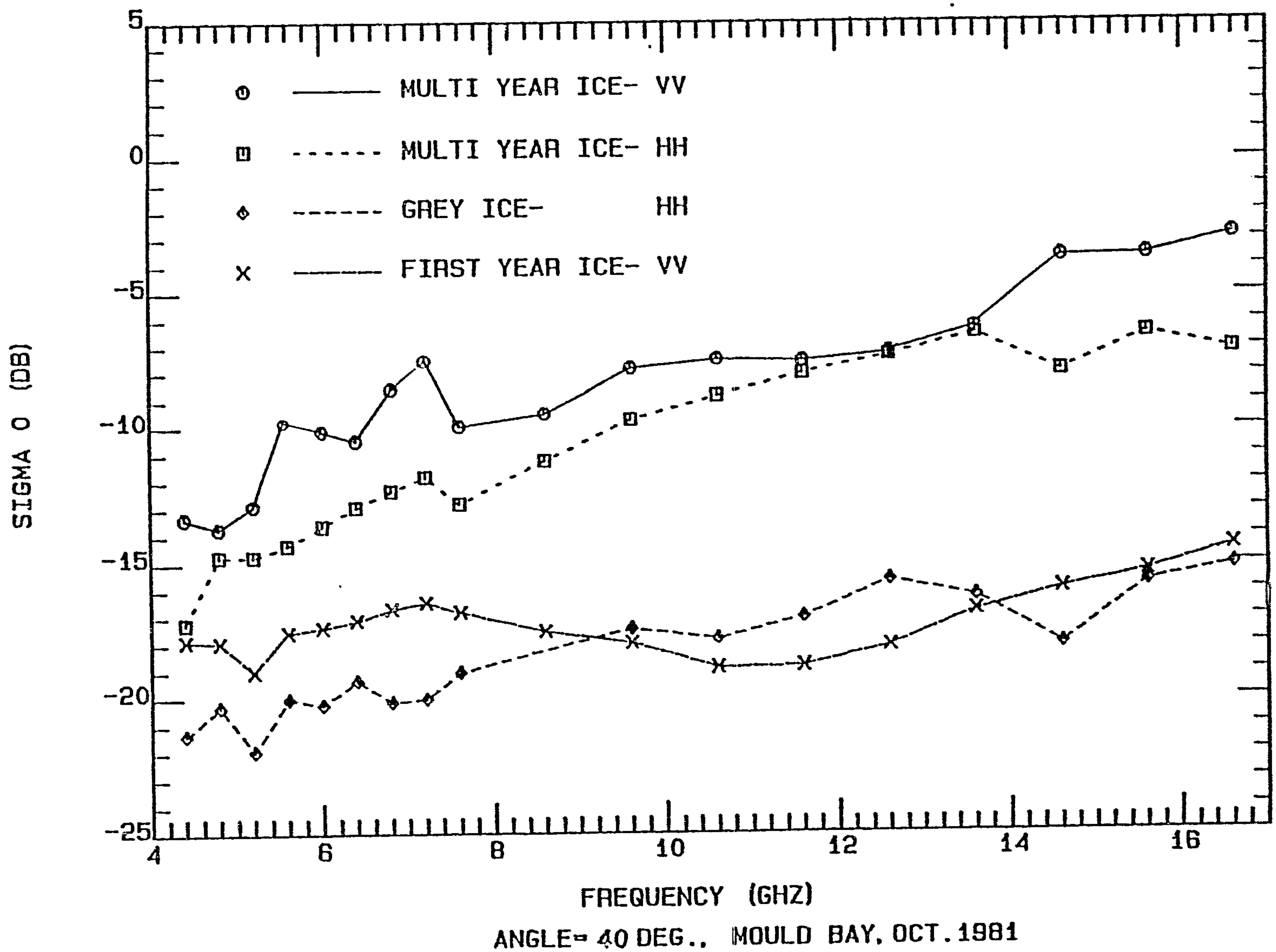

FIGURE 9: Scattering Cross-Section Frequency Response of Multiyear, First-Year and Grey Ice at 40° and HH- or VV-Polarization (Mould Bay 1981 -- HELOSCAT).

but with a poorer contrast between ice types than that for the higher frequencies.

Analysis of the Thousand Island and North Atlantic data has not progressed to the point of reportable preliminary results.

The data acquired during the summer melt season have proven to be quite interesting. During the experiment much was learned about the transitions that ice undergoes during the early and middle part of the melt season. These transitions were expected to affect the microwave properties of the ice. In Figures 10 and 11, the scattering cross-section profiles of first-year and multiyear ice are shown for 5.2 and 9.6 GHz under fall, early summer and middle summer conditions.

Preliminary results show a general trend emerging. During the early part of the summer, the surface of the first-year ice becomes rougher due to thaw-and-freeze-cycle effects and has a free-water layer which combines to cause the 2-3 dB increase in cross-section for this ice. Multiyear ice has a wet layer near the surface, which reduces the ability of the radar to penetrate into the ice. The result is a merging of scattering coefficients to similar values for first-year and multiyear ice. The first-year ice has a slightly higher scattering coefficient than the multiyear ice (unlike winter conditions). Note that these are well averaged cross-sections; because of fading and the overlapping of distributions of cross-sections, differences in mean cross-sections do not truly describe the ability to discriminate ice types. Further analysis is necessary to learn the significance of this difference.

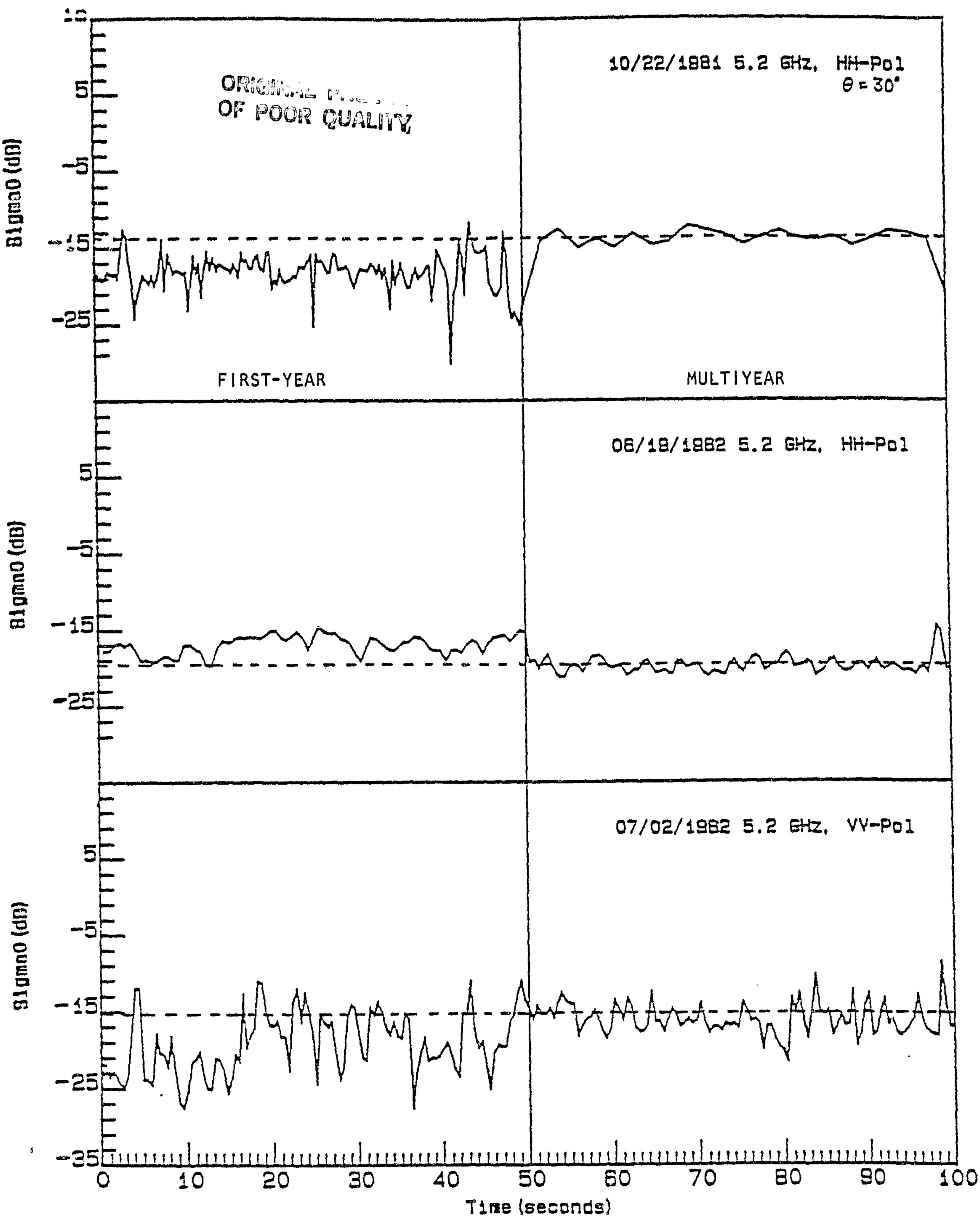

FIGURE 10: Scatterometer Tracks for First-Year and Multiyear Ice Taken Under Fall, Early Summer, and Late Summer Conditions at 5.2 GHz and HH-Polarization (Mould Bay 1981 and 1982 -- HELOSCAT).

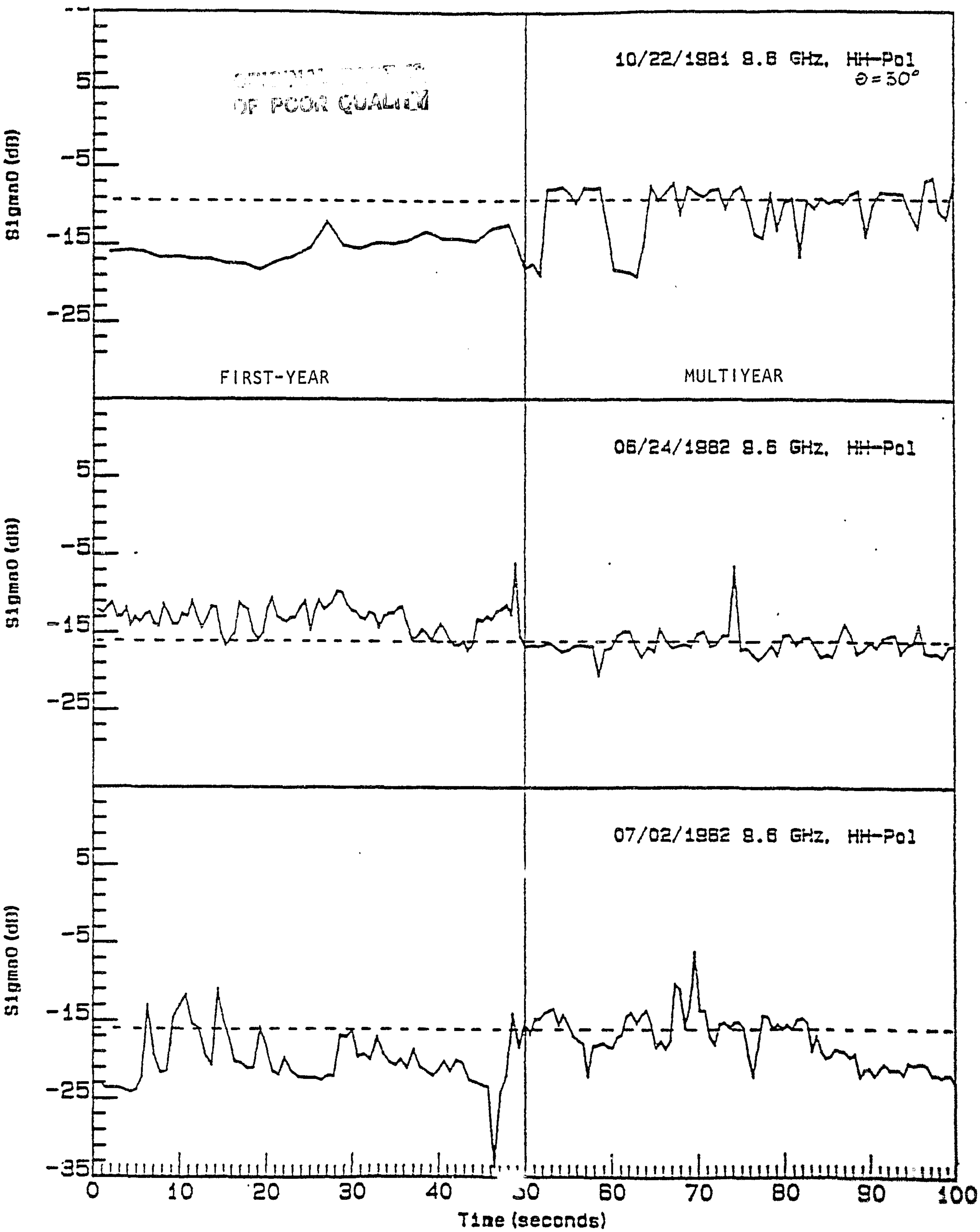

FIGURE 11: Scatterometer Tracks for First-Year and Multiyear Ice Taken Under Fall, Early Summer, and Late Summer Conditions at 9.6 GHz and HH-Polarization (Mould Bay 1981 and 1982 -- HELOSCAT).

In later summer, the trends seem to be similar to those in winter, but this is somewhat misleading. Under late summer conditions the snow layer has all but disappeared. Only crystallized ice mounds and large or small pools of free water are present on the first-year ice. In the mornings these pools are capped with a thin layer of ice. Multiyear ice exhibits similar features, but with a smaller portion covered by melt-pools and with prominent mounds of solid ice (hummocks). Melt-pools and ice seem readily identifiable in the data. Examination of the mean scattering coefficients of the two ice types suggests that the contrast between first-year and multiyear ice has returned in some fashion, with the level of multiyear ice being higher than that of first-year ice. What is being detected by the radar (at all frequencies), however, is the difference between ice and water. First-year ice has a greater frequency of melt-pools, so it has a lower mean cross-section because of low backscatter from the pools. At present, one frequency seems to have little advantage over the other during the summer season.

4.0 CONCLUSIONS

The extension of the frequency coverage of the HELOSCAT radar spectrometer into the 4-8 GHz band has allowed preliminary estimation of the relative usefulness of C band and X/Ku bands for ice discrimination with radar. Outside the summer melt season discrimination between first-year and multiyear ice is possible at C band, unlike the situation at L band, but it is not as good as at X band or Ku band. During the early part of the summer melt season the ability to discriminate is almost lost, with the usually much weaker first-year ice signal sometimes exceeding the usually stronger multiyear-ice signal. This apparently occurs because the wetness of the multiyear-ice surface during the melt season precludes signal penetration into regions that contribute a strong volume-scatter component to the radar signal at other times of year. Analysis of the data is continuing.