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**MILLIMETER - WAVE RADAR  
SCATTERING FROM TERRAIN: DATA HANDBOOK  
VERSION 2**

Fawwaz T. Ulaby  
Thomas F. Haddock

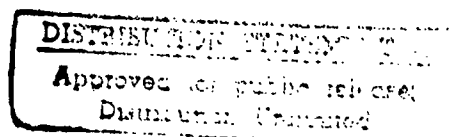
Radiation Laboratory  
University of Michigan  
Ann Arbor, Michigan



Technical Report 026247-3-T



September, 1990



**THE UNIVERSITY OF MICHIGAN**

Radiation Laboratory  
Department of Electrical Engineering  
and Computer Science  
Ann Arbor, Michigan 48109-2122  
USA

026247-3-T

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## I. INTRODUCTION

Version 1.0 of this Handbook provided plots of millimeter-wave (MMW) radar scattering data for terrain based on measurements made by the University of Michigan's Millimeter-Wave Polarimeter system at 35, 94, and 140 GHz. The present edition, Version 2.0, includes the University of Michigan data as well as data reported by The University of Massachusetts, The University of Kansas, Ohio State University, and data from other institutions.

Most of the data are presented in the form of plots of the backscattering coefficient  $\sigma^0$  versus the incidence angle  $\theta$ , measured relative to normal incidence, although some plots of  $\sigma^0$  versus time are included also. The radar data are augmented with photographs and close-up observations of the target whenever such information is available in the data source. In some cases, the original data were reported as a function of depression angle, instead of incidence angle, or in terms of  $\gamma$ , where

$$\gamma = \sigma^0 / \cos \theta.$$

For the sake of consistency and in order to make comparison of data more useful, all such data were converted to  $\sigma^0$  versus  $\theta$ .

No effort will be made in this handbook to provide any analysis of the radar data or to compare the data with model predictions. Instead, a list of relevant publications is given in the bibliography for the interested reader.

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## **PART I. UNIVERSITY OF MICHIGAN DATA**

The Millimeter-Wave Polarimeter is a truck-mounted radar system capable of making observations from a 20-m high platform at any incidence angle between 0° (normal incidence) and 80°. In some cases, however, because of truck-access considerations or signal-to-noise limitations, it was not possible to make observations over this entire angular range. Figure I-1 shows a photograph of the system in operation and Figure I-2 shows a close-up of the antenna platform. Table I-1 provides a summary of the system specifications.

The list below provides definitions for the quantities quoted in conjunction with the radar data presented in this part of the Handbook.

### **TERMINOLOGY**

**Average Leaf (or Needle) Dimensions** - the approximate main axis length of the individual leaves (or needles).

**Backscattering Coefficient** - radar cross-section per unit area averaged over the illuminated area of the radar footprint, expressed in dB. Also referred to as Sigma-zero or  $\sigma^0$ .

**Cut** - this term is applied to grasses when they have been cut, and no longer have the natural termination on their blades.

**Data set code** - the unique alphanumeric sequence describing each data set. Typically it is the date of the measurement, in the sequence YYMMDD, with a numeric suffix if required for uniqueness.

**Snow Density** - the mass/volume density of undisturbed samples taken from the snowpit.

**Snow Depth** - the distance from the average top level of the snow to the underlying ground.

**Ice Crystal Diameter** - the approximate semi-major axis of an individual scatterer. This is typically a statistical quantity, arrived at by examining a number of individual scatterers.

**Dry** - a material is called "dry" when its moisture content (in the case of soils and vegetations) or its liquid water content (in the case of snow) is within experimental uncertainty of 0 %.

**Snow Liquid Water Content (LWC)** - the quantity of liquid (non-frozen) water contained in snow, by weight (gravimetric), measured in percent.

**Metamorphosed** - snow crystals having extensively undergone the natural sublimation process that alters their shape from its original form toward the spherical.

**Moisture Content** - the percent of water, by mass, contained in a representative sample of soil or vegetation. The measurement consists of weighing a sample in its natural state, and again after drying it in an oven.

**Percent Ground Cover** - the percent of the ground covered by tree vegetation when viewed from above.

**Rough** - this term is applied to surfaces which are typically rougher than the natural state in which they are usually found. Often, in the case of soils or snow, it is used to describe a surface that has been artificially roughened.

**Smooth** - this term is applied to surfaces which are smooth compared to the natural state in which they are usually found. Sometimes it may be used to describe a surface which has been artificially smoothed.

**Surface RMS Height** - the root-mean-square deviation of the surface height relative to the mean surface

**Surface Temperature** - the temperature registered by a mercury-bulb thermometer with the bulb just covered by the top layer of the surface.

**Tree Density** - number of trees per unit area.

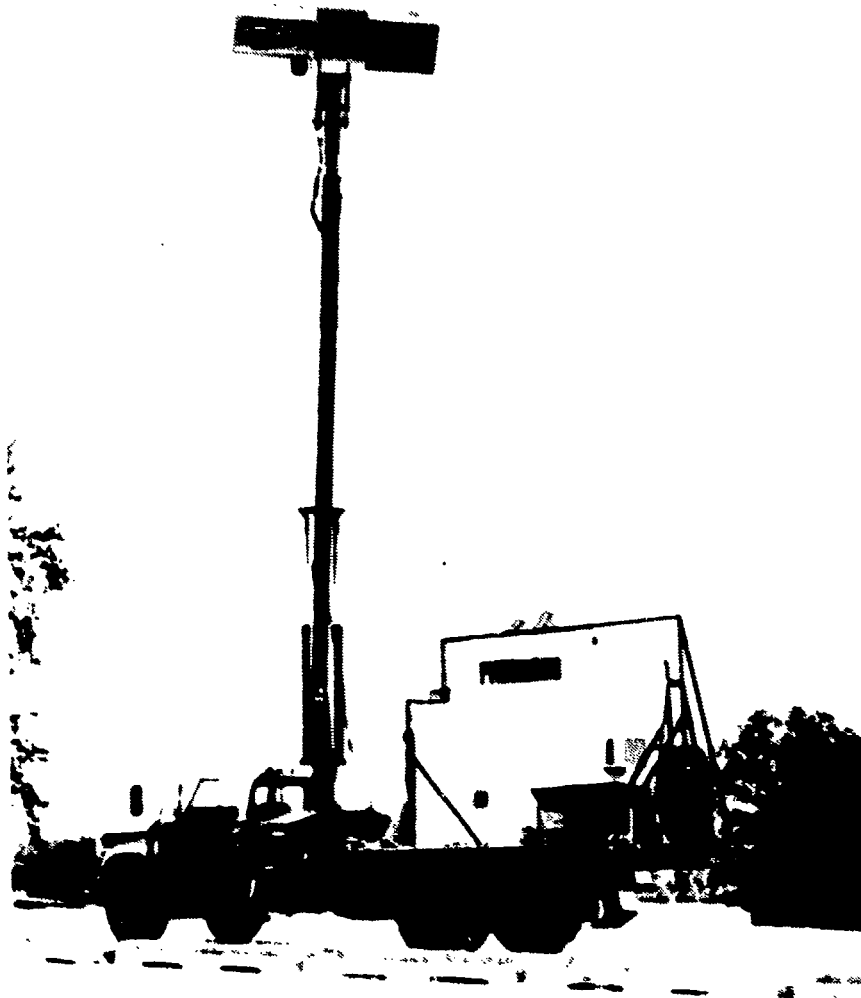


**Fig. 1-1** Photograph of the Millimeter-Wave Polarimeter system with the boom extended about half way.

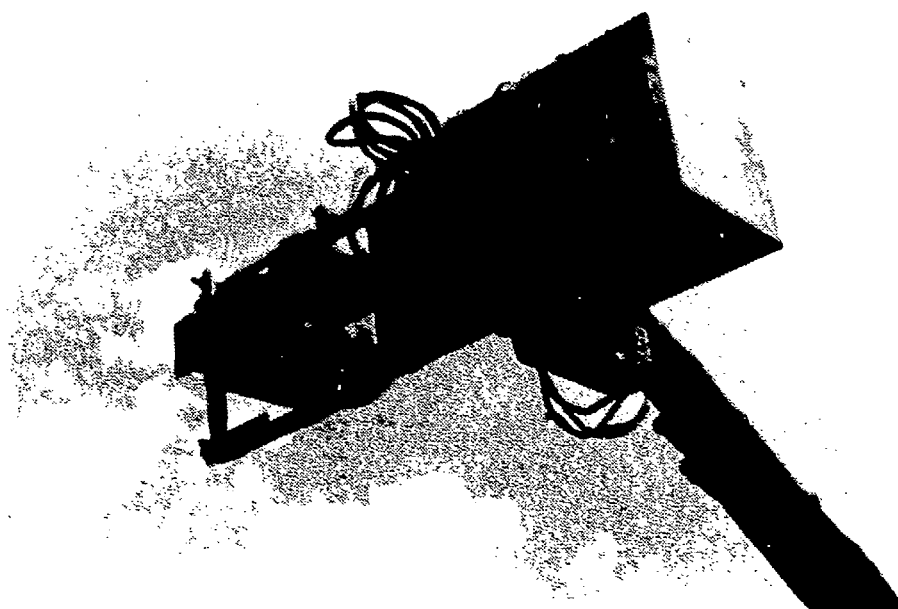


**Fig. 1-2.** Close-up view of the RF sections, showing the 35, 94, and 140 GHz radars on the right side, and radiometers at the same operating frequencies on the left side.

**Table I-1. Millimeter-wave Polarimeter system parameters.**

|                                                  |                                                                                                                          |                          |                |
|--------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|--------------------------|----------------|
| <b>FREQUENCIES:</b>                              | 35, 94, 140 GHz                                                                                                          |                          |                |
| <b>IF BANDWIDTH:</b>                             | 0 to 2.0 GHz                                                                                                             |                          |                |
| <b>TRANSMIT POWER:</b>                           | 35 GHz:                                                                                                                  | +3 dBm                   |                |
|                                                  | 94 GHz:                                                                                                                  | 0 dBm                    |                |
|                                                  | 140 GHz:                                                                                                                 | -4 dBm                   |                |
| <b>SWEEP RATE:</b>                               | 1 m-sec/freq., 51, 101, 201, 401 freq./sweep                                                                             |                          |                |
| <b>POLARIZATION:</b>                             | HH, HV, VV, VH                                                                                                           |                          |                |
| <b>INCIDENCE ANGLES:</b>                         | 0 to 70 degrees                                                                                                          |                          |                |
| <b>PLATFORM HEIGHT:</b>                          | 3 meters minimum, to 18 meters maximum                                                                                   |                          |                |
| <b>NOISE EQUIV. <math>\sigma^{\circ}</math>:</b> | 35 GHz:                                                                                                                  | -22 dB                   |                |
|                                                  | 94 GHz:                                                                                                                  | -28 dB                   |                |
|                                                  | 140 GHz:                                                                                                                 | -21 dB                   |                |
| <b>CROSSPOL ISOLATION:</b>                       | 35 GHz:                                                                                                                  | 23 dB                    |                |
|                                                  | 94 GHz:                                                                                                                  | 20 dB                    |                |
|                                                  | 140 GHz:                                                                                                                 | 10 dB                    |                |
| <b>PHASE STABILITY:</b>                          | 35 GHz:                                                                                                                  | -1 degree/hour           |                |
|                                                  | 94 GHz:                                                                                                                  | -1 degree/minute         |                |
|                                                  | 140 GHz:                                                                                                                 | -10 to 50 degrees/second |                |
| <b>NEAR FIELD DIST:</b>                          | 35 GHz:                                                                                                                  | 2.7 m                    |                |
|                                                  | 94 GHz:                                                                                                                  | 7.3 m                    |                |
|                                                  | 140 GHz:                                                                                                                 | 2.7 m                    |                |
| <b>BEAMWIDTH:</b>                                | 35 GHz:                                                                                                                  | R: 4.2 deg               | T: 4.2 deg     |
|                                                  | 94 GHz:                                                                                                                  | R: 1.4 deg               | T: 2.8 deg     |
|                                                  | 140 GHz:                                                                                                                 | R: 2.2 deg               | T: 11.8 deg    |
| <b>ANTENNA DIAMETER:</b>                         | 35 GHz:                                                                                                                  | R: 6 inches              | T: 6 inches    |
|                                                  | 94 GHz:                                                                                                                  | R: 6 inches              | T: 3 inches    |
|                                                  | 140 GHz:                                                                                                                 | R: 3 inches              | T: 0.36 inches |
| <b>SIGNAL PROCESSING:</b>                        | HP 8510A/8511A based                                                                                                     |                          |                |
| <b>OUTPUT PRODUCTS:</b>                          | -received power verses range<br>-received power verses frequency (at fixed R)<br>-phase and amplitude for each frequency |                          |                |

## 2. MMW DATA FOR DRY SNOW

Snow is a very complex target and many of the following data sets could be categorized in several ways. In the interests of simplifying the data organization, and facilitating its use by the reader, the data have been categorized into subsections by their most salient feature.

The following chart is included in order to give a more complete overview of the characteristics of the data:

|               | smooth surface | slightly rough surface | very rough surface | heavily metamorphosed | unmetamorphosed fresh | small crystal size | large crystal size |
|---------------|----------------|------------------------|--------------------|-----------------------|-----------------------|--------------------|--------------------|
| Data Set Code | A              | B                      | C                  | D                     | E                     | F                  | G                  |
| 880329 (S)    | x              |                        |                    | x                     |                       |                    | x                  |
| 880329 (SR)   |                | x                      |                    | x                     |                       |                    | x                  |
| 880329 (VR)   |                |                        | x                  | x                     |                       |                    | x                  |
| 890210        | x              |                        |                    | x                     |                       |                    | x                  |
| 890223        | x              |                        |                    |                       | x                     | x                  |                    |
| 890302 (SM)   | x              |                        |                    |                       | x                     | x                  |                    |
| 890302 (LG)   | x              |                        |                    |                       | x                     |                    | x                  |
| 890307 (RO)   |                | x                      |                    |                       | x                     |                    | x                  |
| 890307 (SM)   | x              |                        |                    |                       | x                     |                    | x                  |

# MMW DATA FOR DRY SNOW

## A. Smooth Surface

Dry snow

Data set code: 880329(S)

Depth: 20-30 cm

LWC: 0 %

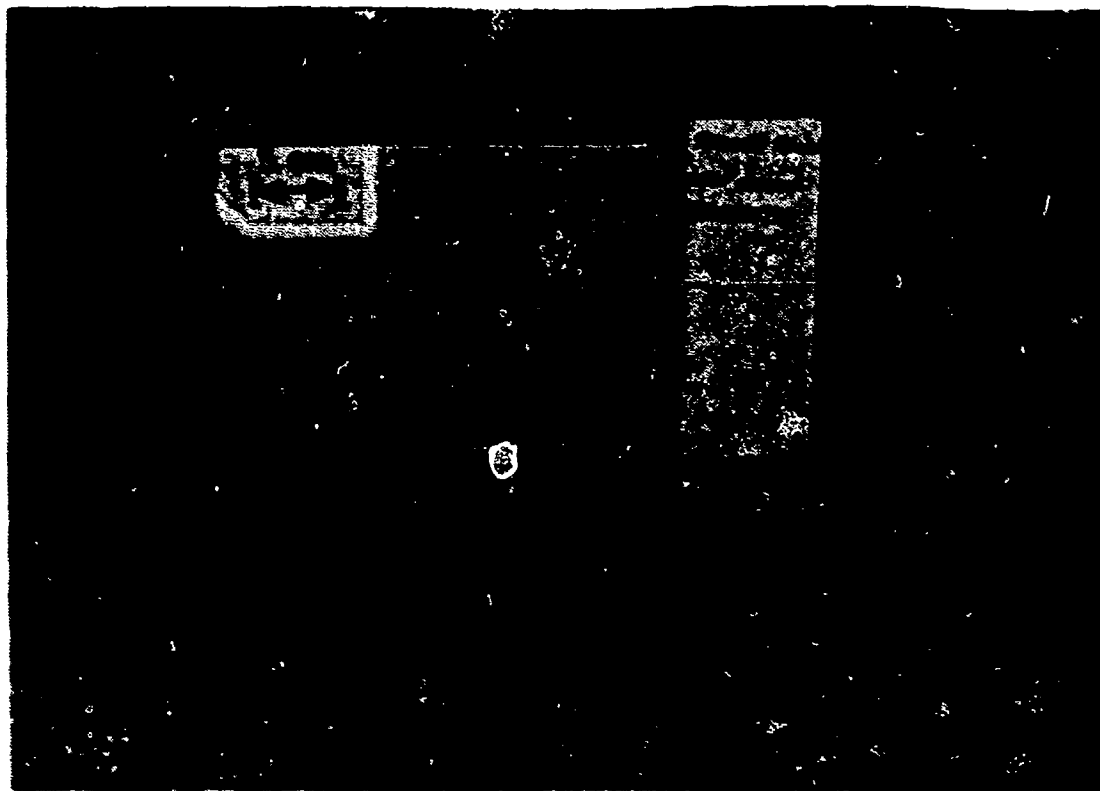
Surface RMS height: 1 cm

Density: 0.3 to 0.4 gm/cm<sup>3</sup>

Ice crystal diameter: 1 to 4 mm

Surface temperature: -2.0 C

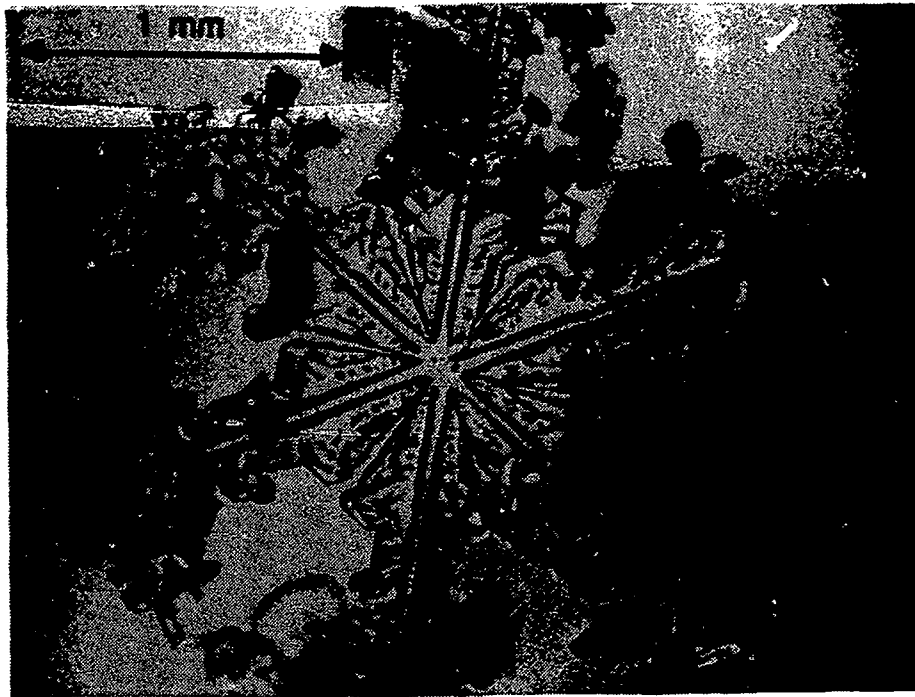
Description: smooth snow surface



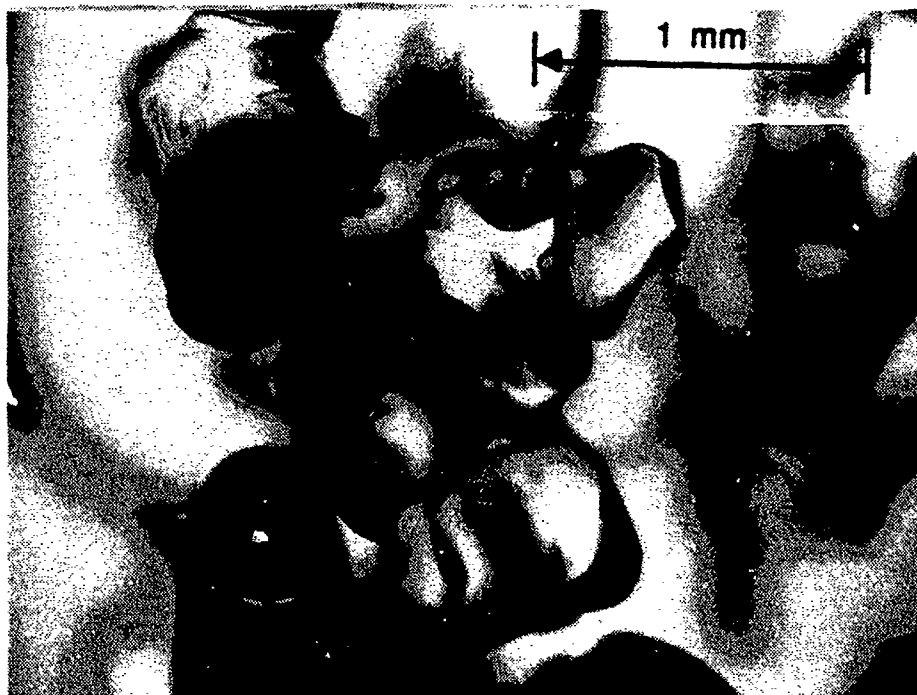
Surface roughness profile with 1 cm grid

# MMW DATA FOR DRY SNOW

880329(S)



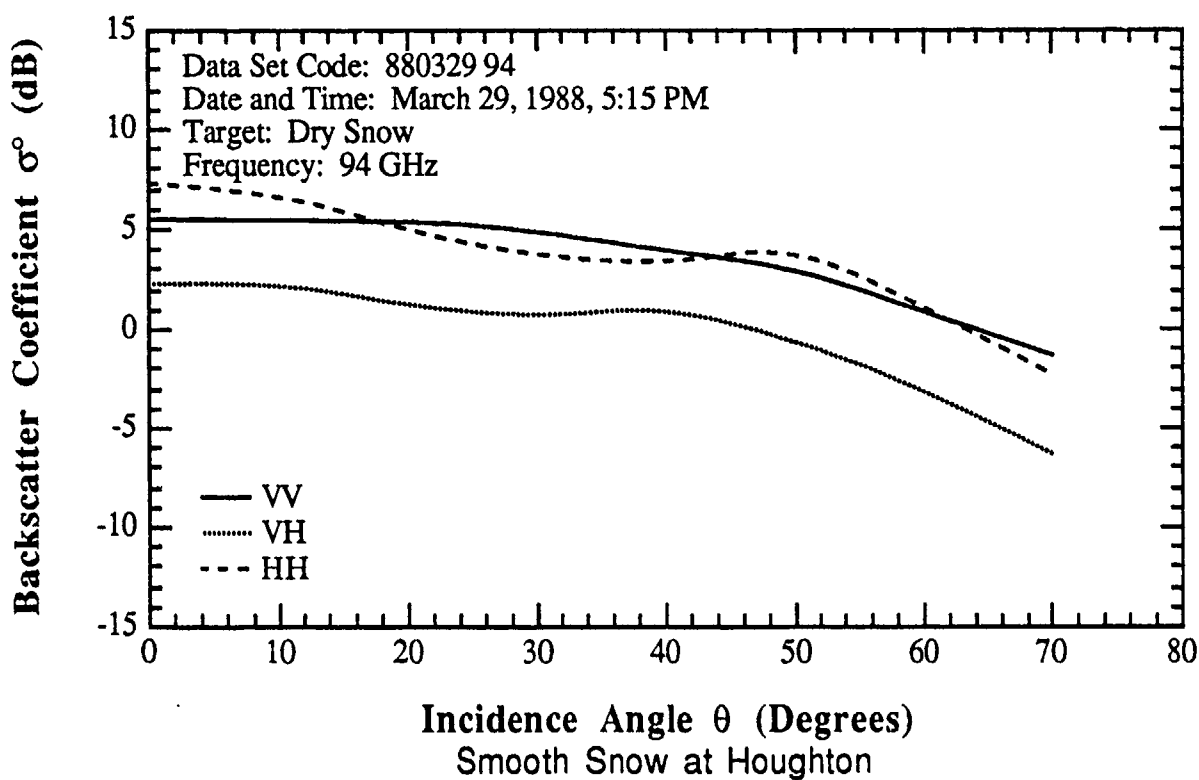
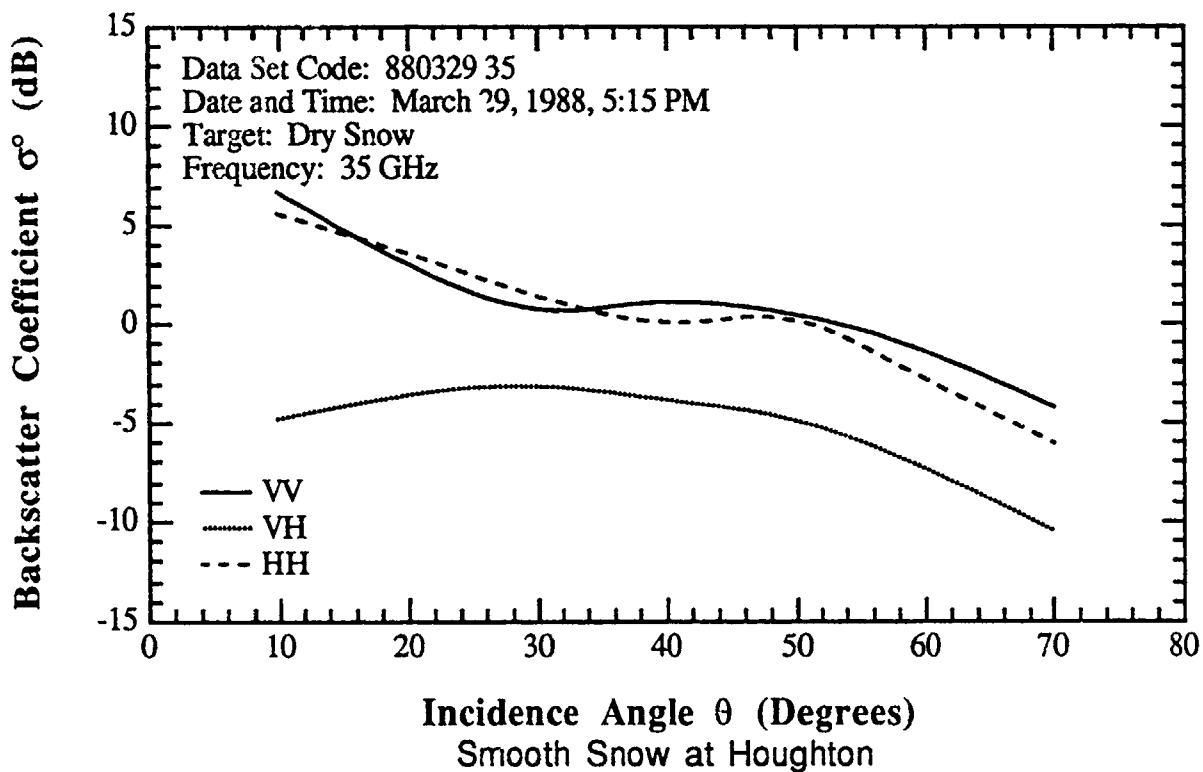
Snow crystal from surface



Metamorphosed crystal from middle of snowpack

# MMW DATA FOR DRY SNOW

880329(S)



## B. Slightly Rough Surface

Dry snow

Data set code: 880329 (SR)

Depth: 20 to 30 cm

LWC: 0%

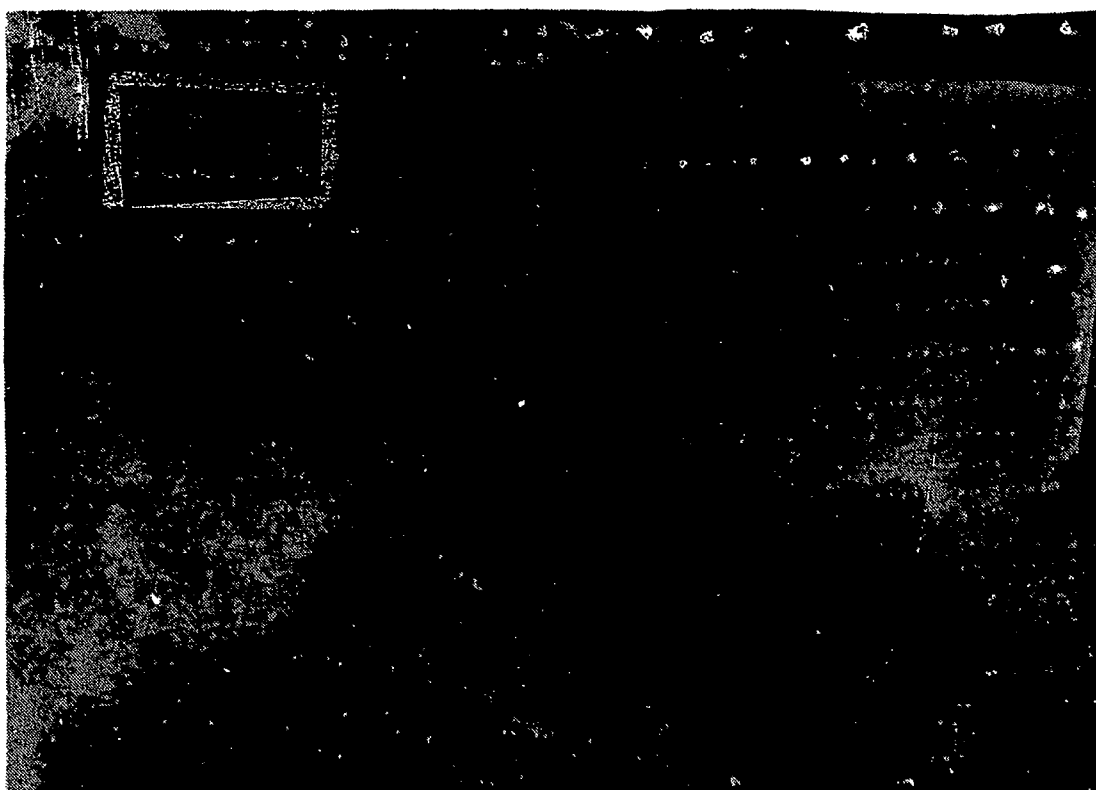
Surface RMS height: 1 cm

Density: 0.3 to 0.4 gm/cm<sup>3</sup>

Ice crystal diameter: 1 to 4 mm

Surface temperature: 0 C

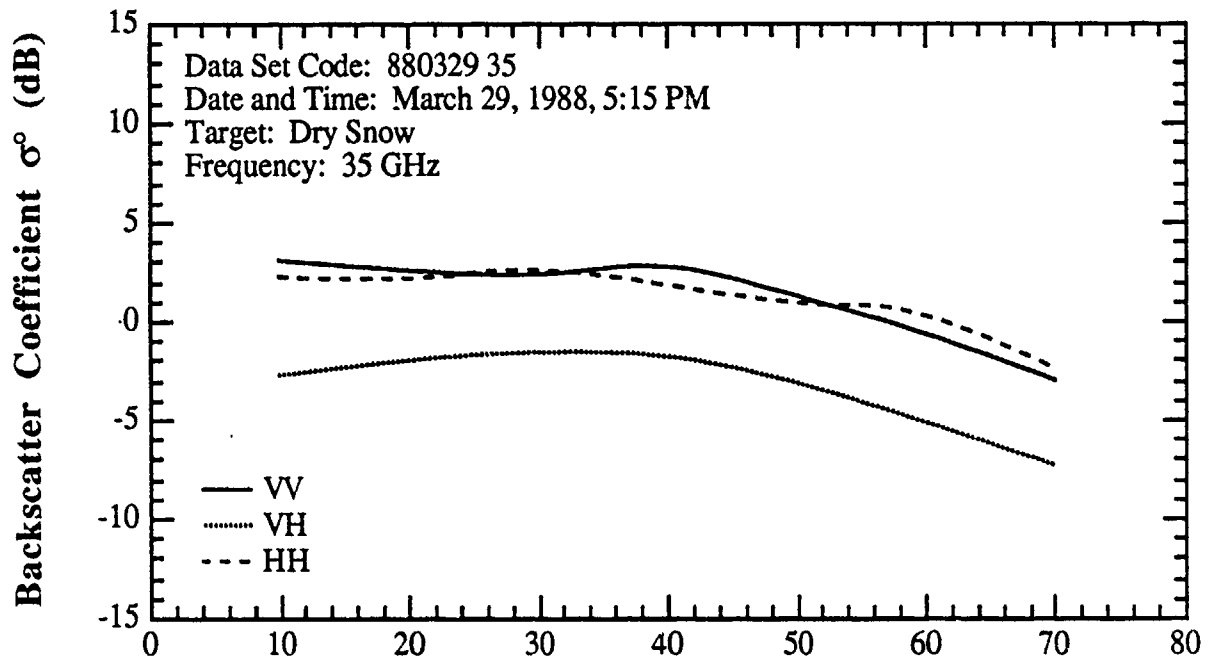
Description: snowpack of highly metamorphosed  
snow with a slightly rough surface



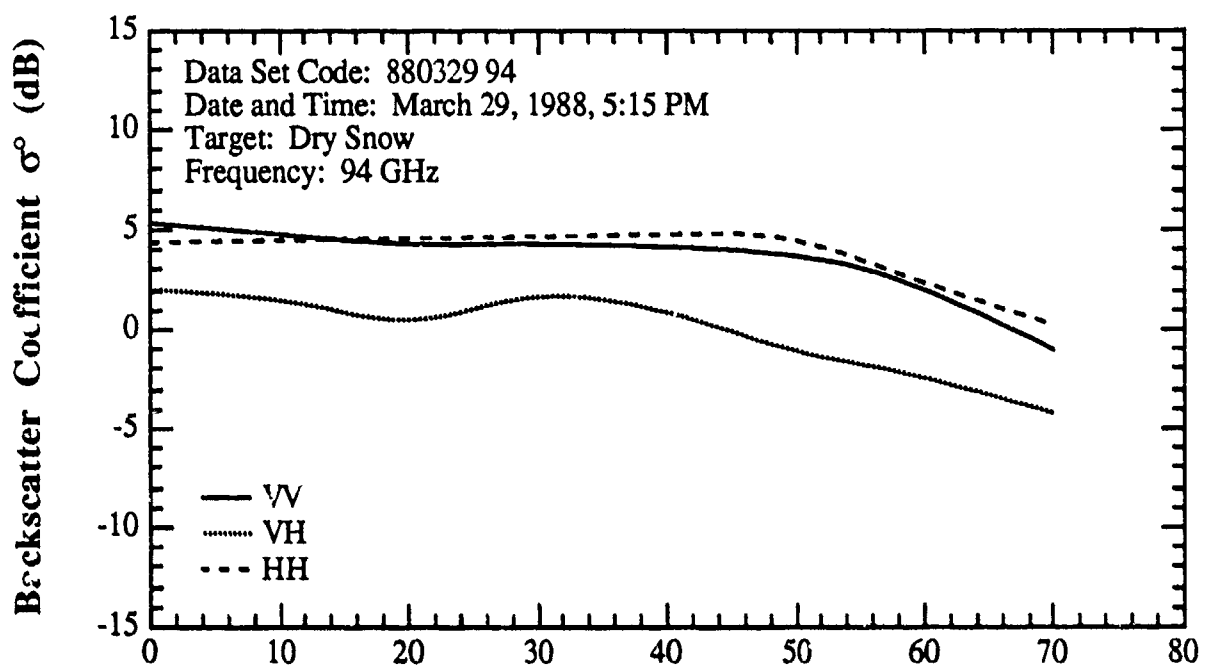
Surface roughness profile with 1 cm grid

# MMW DATA FOR DRY SNOW

880329(SR)



Incidence Angle  $\theta$  (Degrees)  
Slightly rough snow at Houghton



Incidence Angle  $\theta$  (Degrees)  
Slightly rough snow at Houghton

### C. Very Rough Surface

Dry snow

Data set code: 880329(VR)

Depth: 20 to 30 cm

LWC: 0%

Surface RMS height: 4 cm

Density: 0.3 to 0.4 gm/cm<sup>3</sup>

Ice crystal diameter: 1 to 4 mm

Surface temperature: 0 C

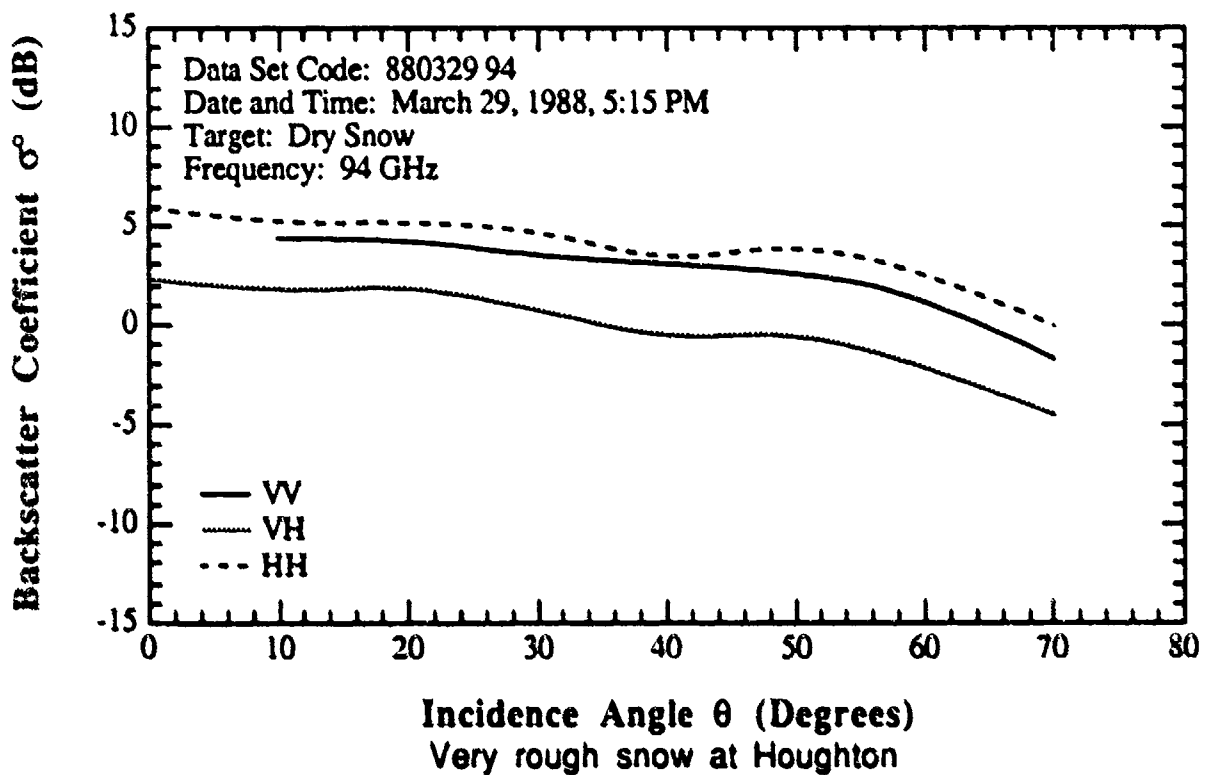
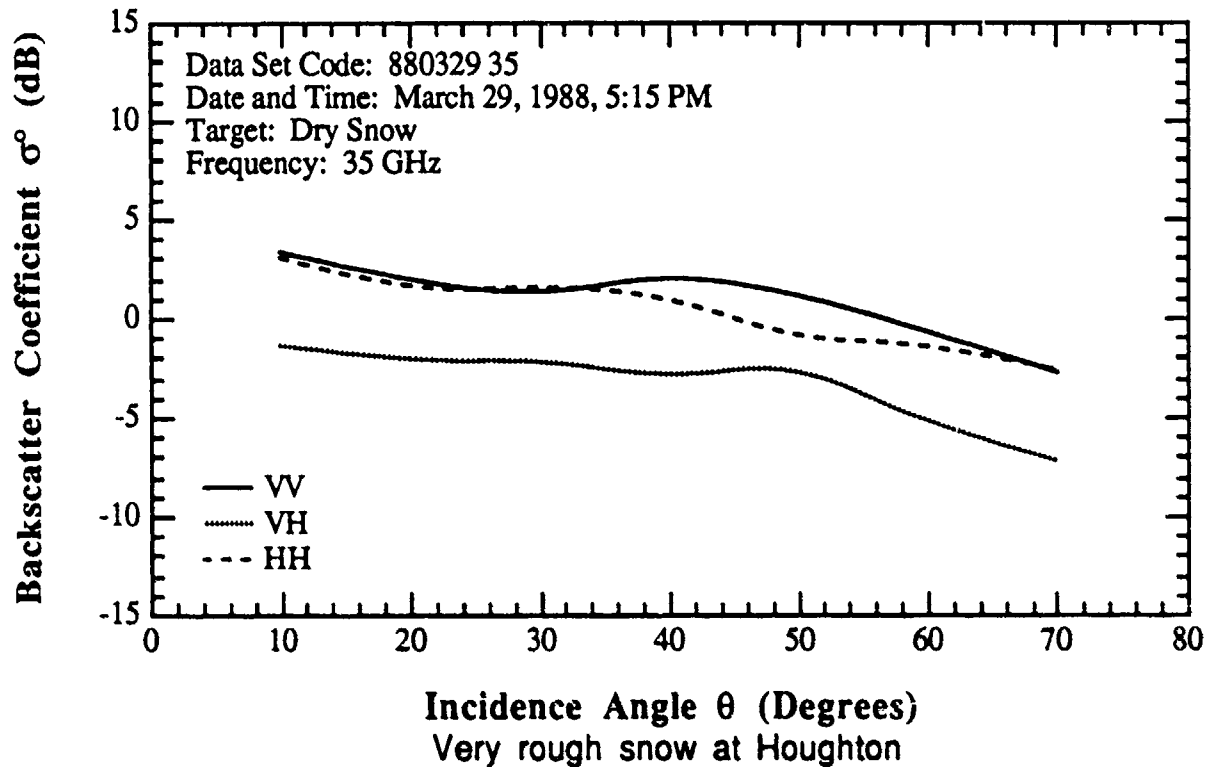
Description: snowpack of highly metamorphosed  
snow with a rough surface



Surface roughness profile with 1 cm grid

# MMW DATA FOR DRY SNOW

880329(VR)



#### D. Heavily Metamorphosed Snow

Dry snow

Data set code: 890210

Depth: 27 cm

LWC: 0.0 %

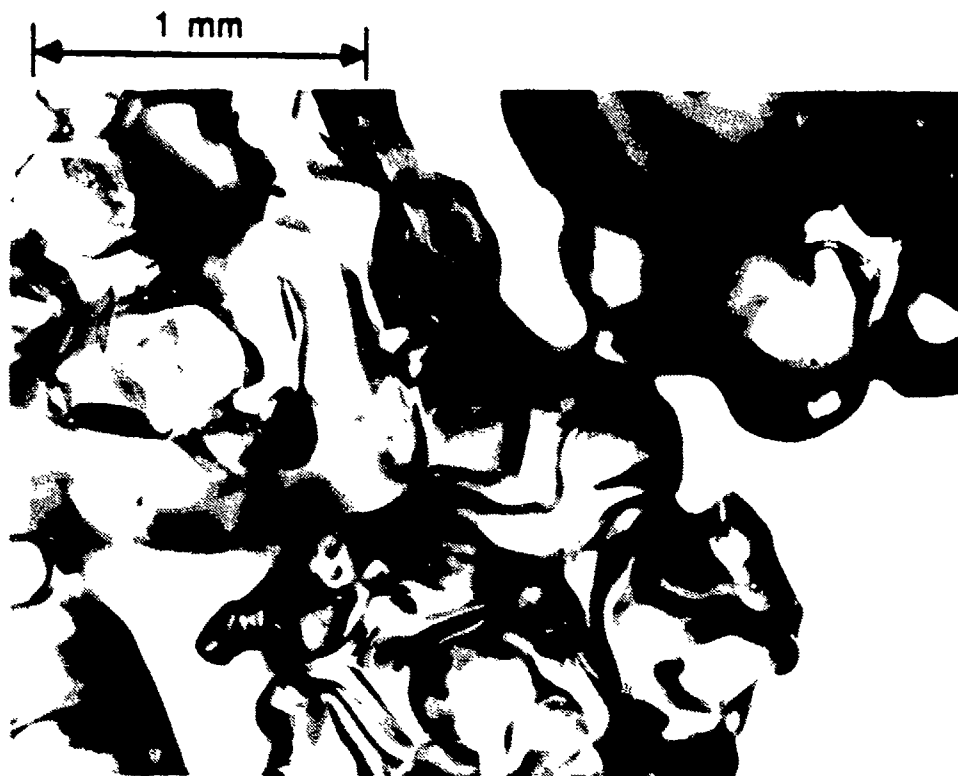
Surface RMS height: ~ 1 cm

Density: 0.5 gm/cm<sup>3</sup>

Ice crystal diameter: 2 to 4 mm

Surface temperature: -4.8 C

Description: heavily metamorphosed snow

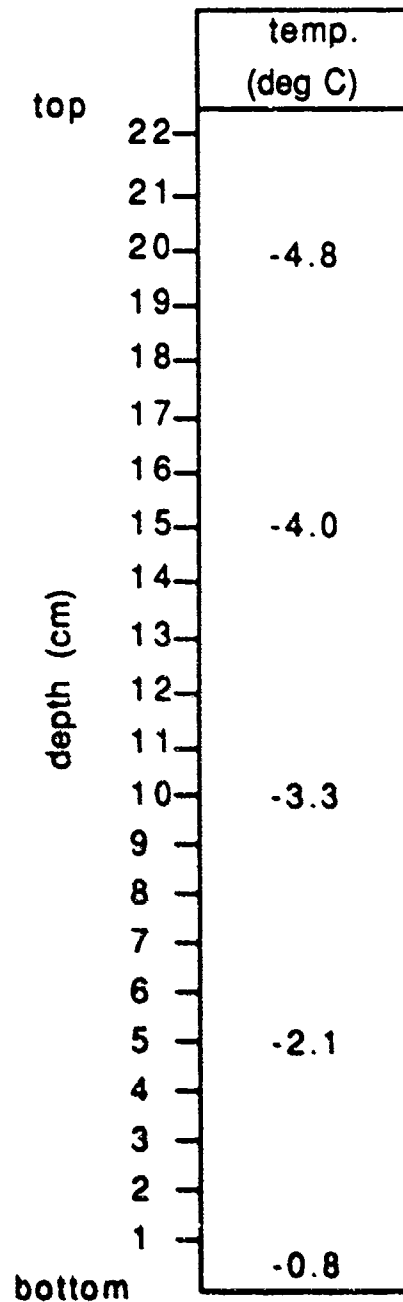


Metamorphosed crystal from top of the snowpack

# MMW DATA FOR DRY SNOW

890210

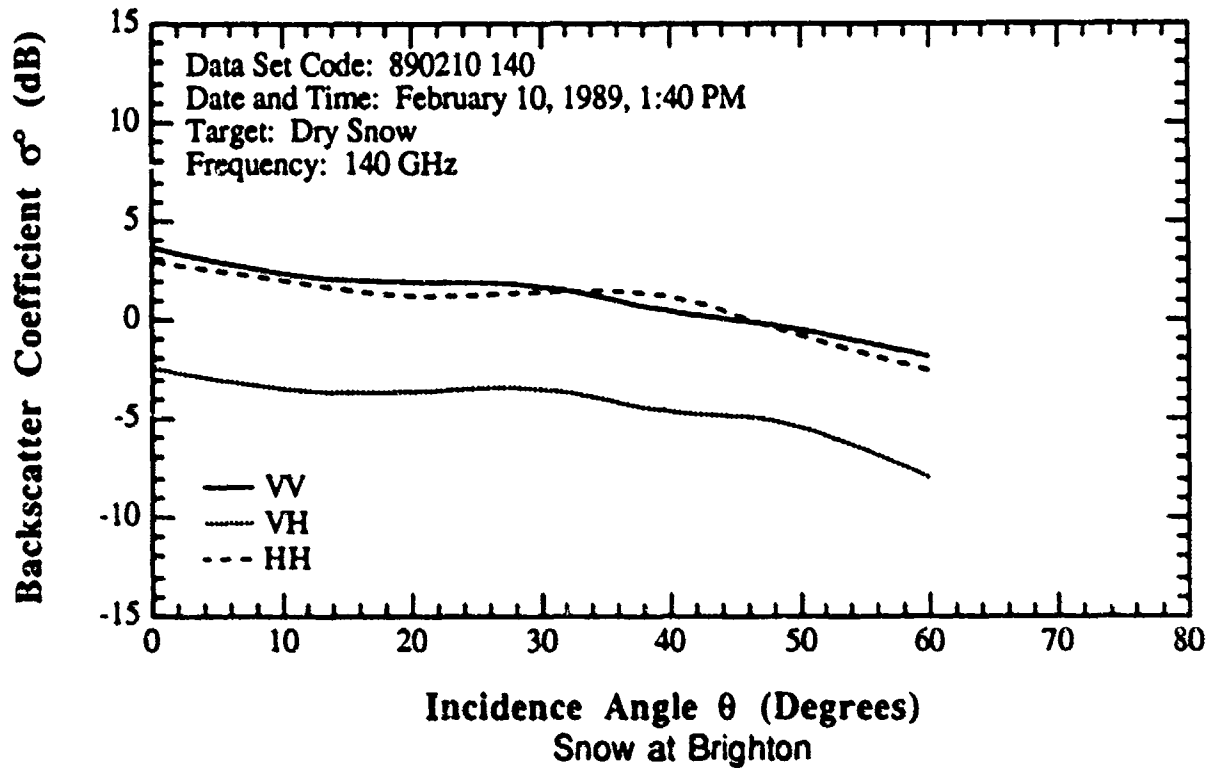
## SNOW PIT PROFILE FOR 890210



air temperature: -4.4 C

# MMW DATA FOR DRY SNOW

890210



## **E. Unmetamorphosed Fresh Snow**

Dry snow

Data set code: 890223

Depth: 12 cm

LWC (at 2:15 PM): 0 %

LWC (at 3:52 PM): 0 %

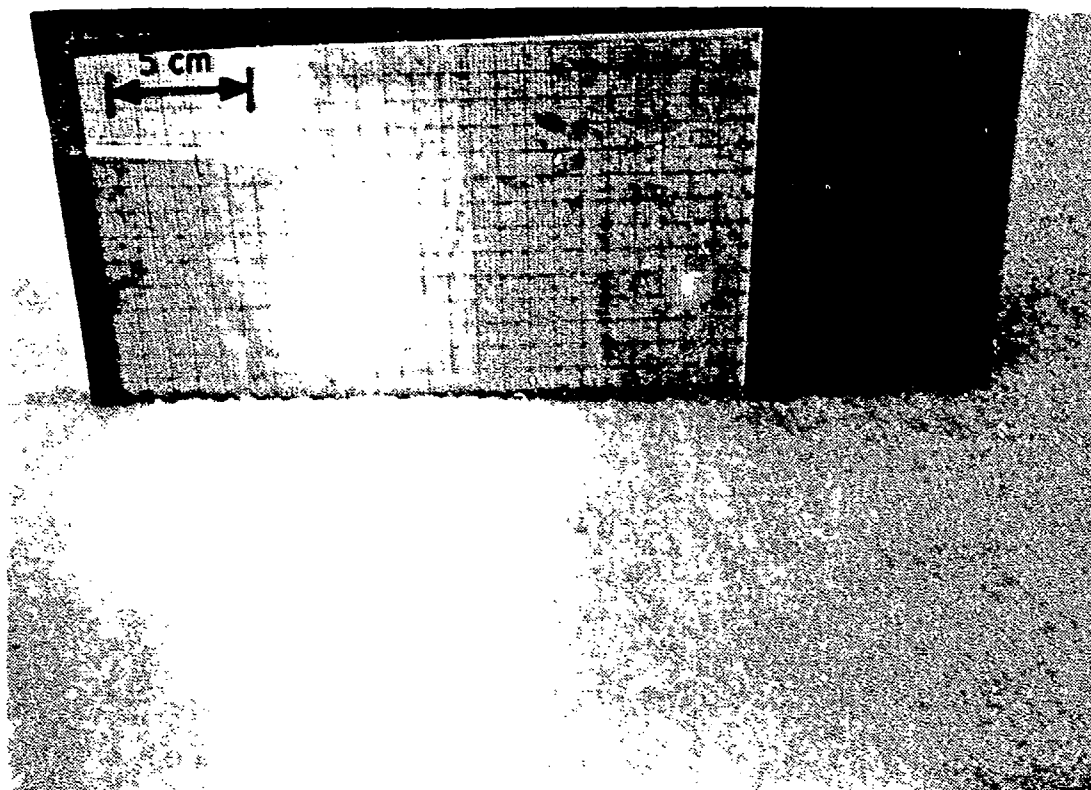
Surface RMS height: 1.4 mm

Density: 0.2 g/cm<sup>3</sup>

Ice crystal diameter: 1 to 2 mm

Surface temperature: -7 C

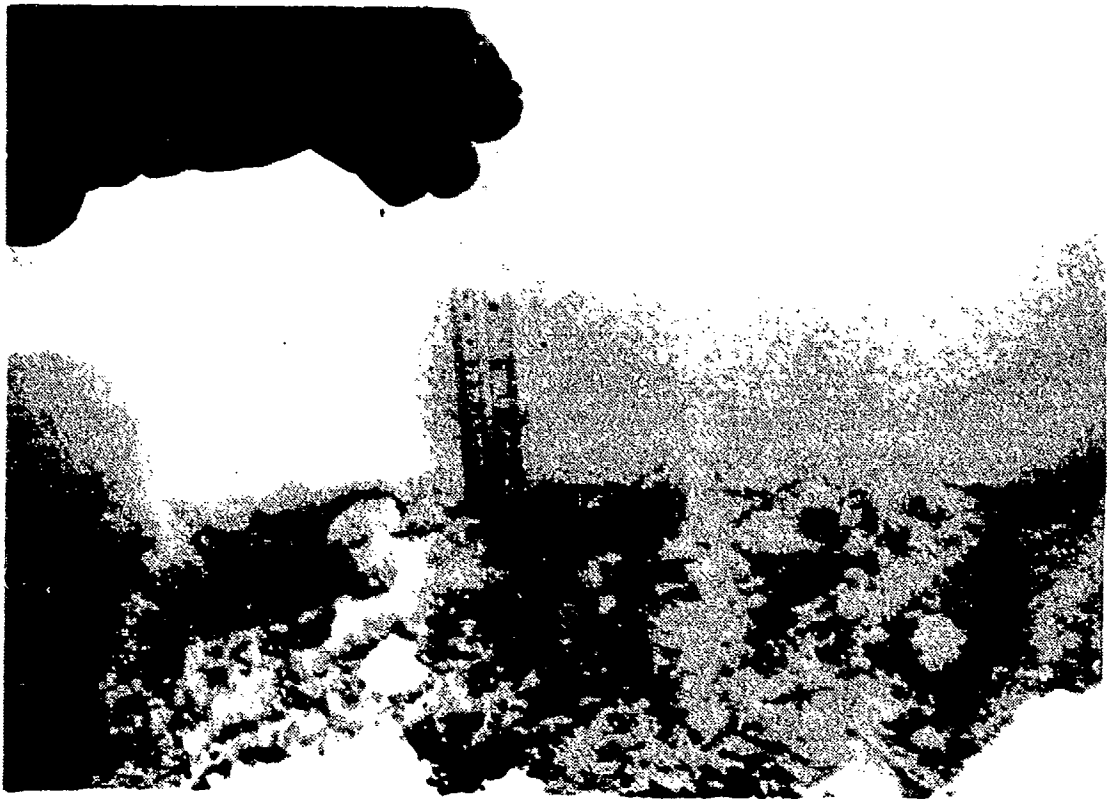
Description: dry unmetamorphosed snow



**Surface roughness profile with 1 cm grid**

# MMW DATA FOR DRY SNOW

890223



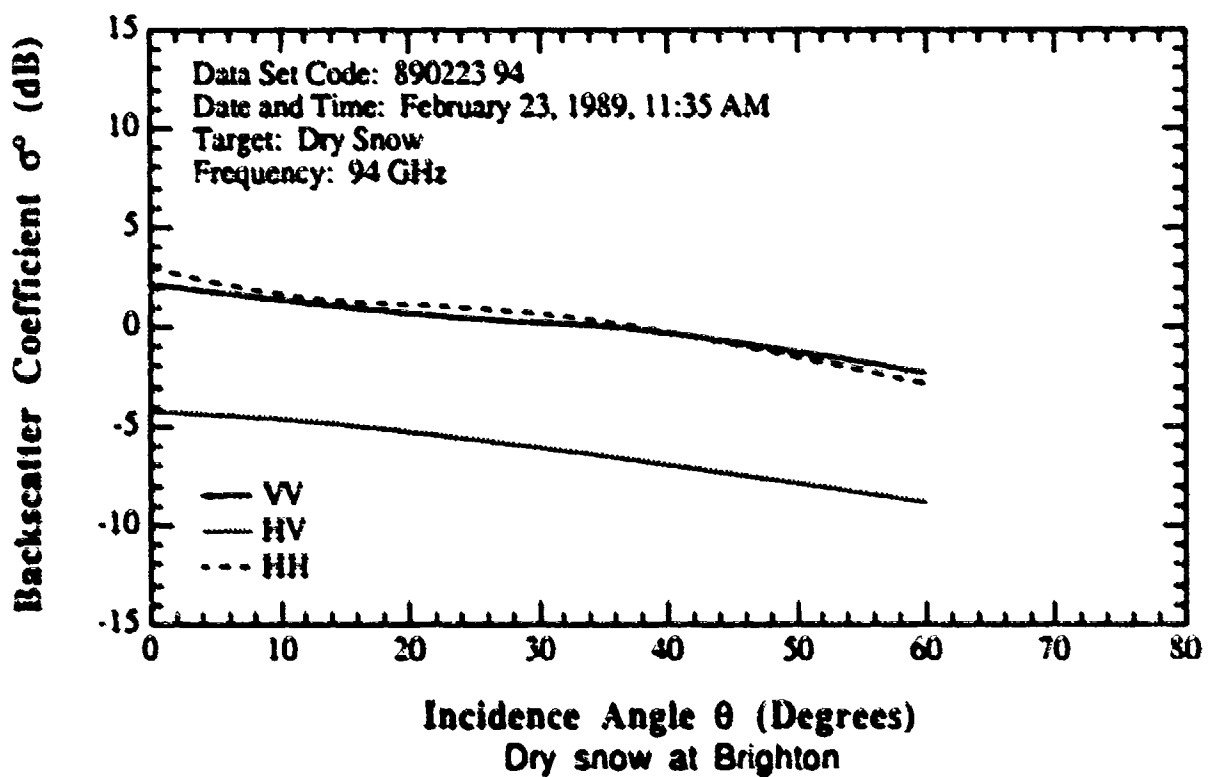
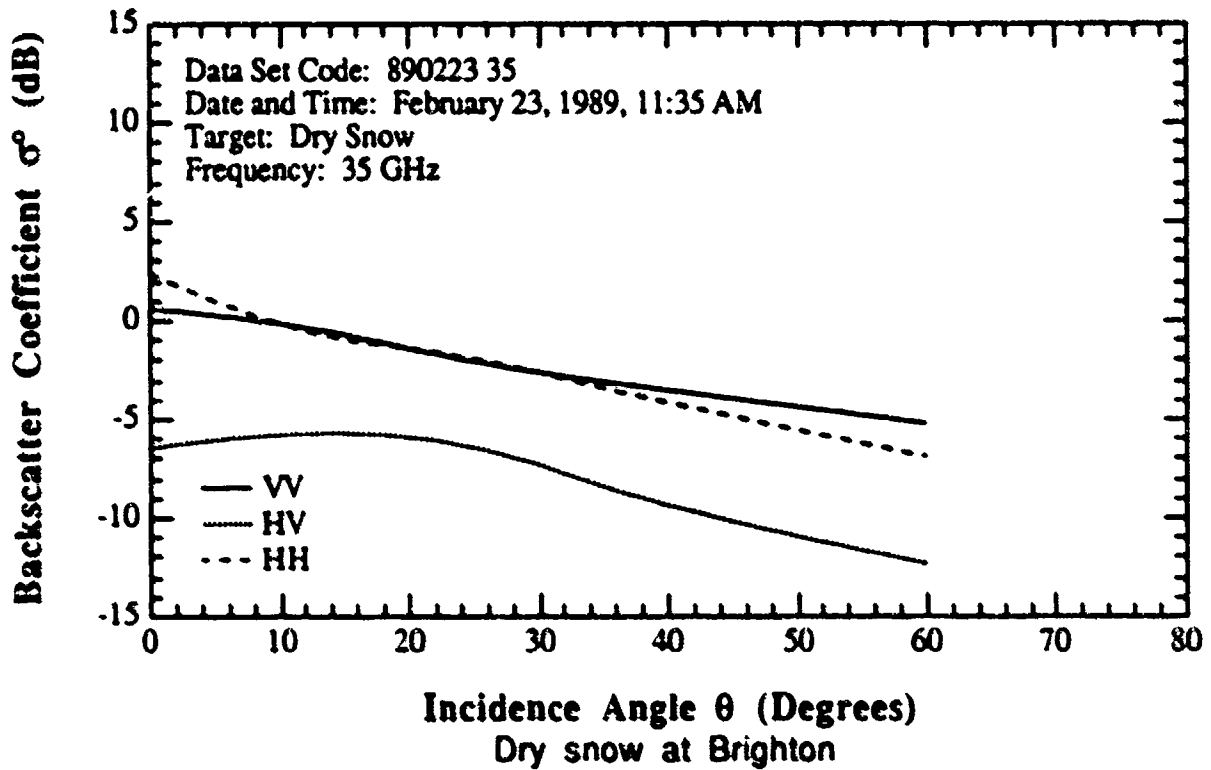
Snow pit



Data collection scene

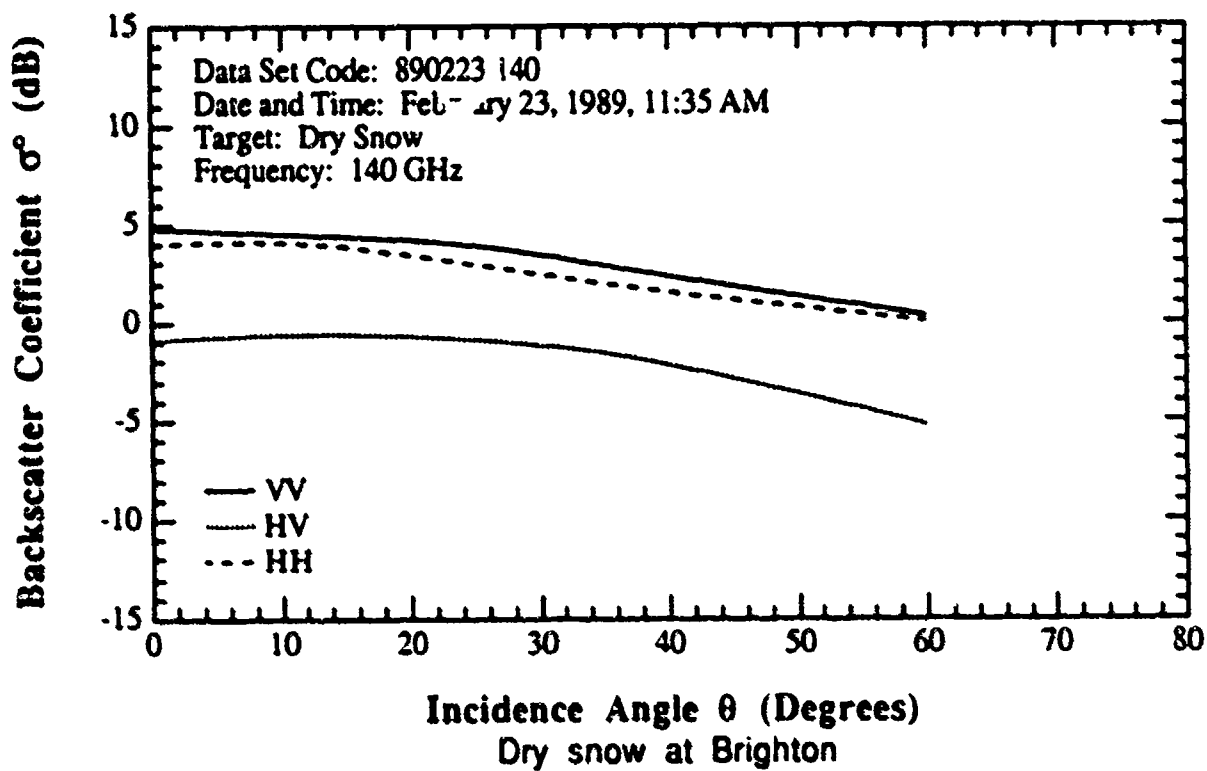
# MMW DATA FOR DRY SNOW

890223



# MMW DATA FOR DRY SNOW

890223



## **F. Small Crystal Size**

Dry snow

Data set code: 890302(sm)

Depth: 10 cm

LWC: 0 %

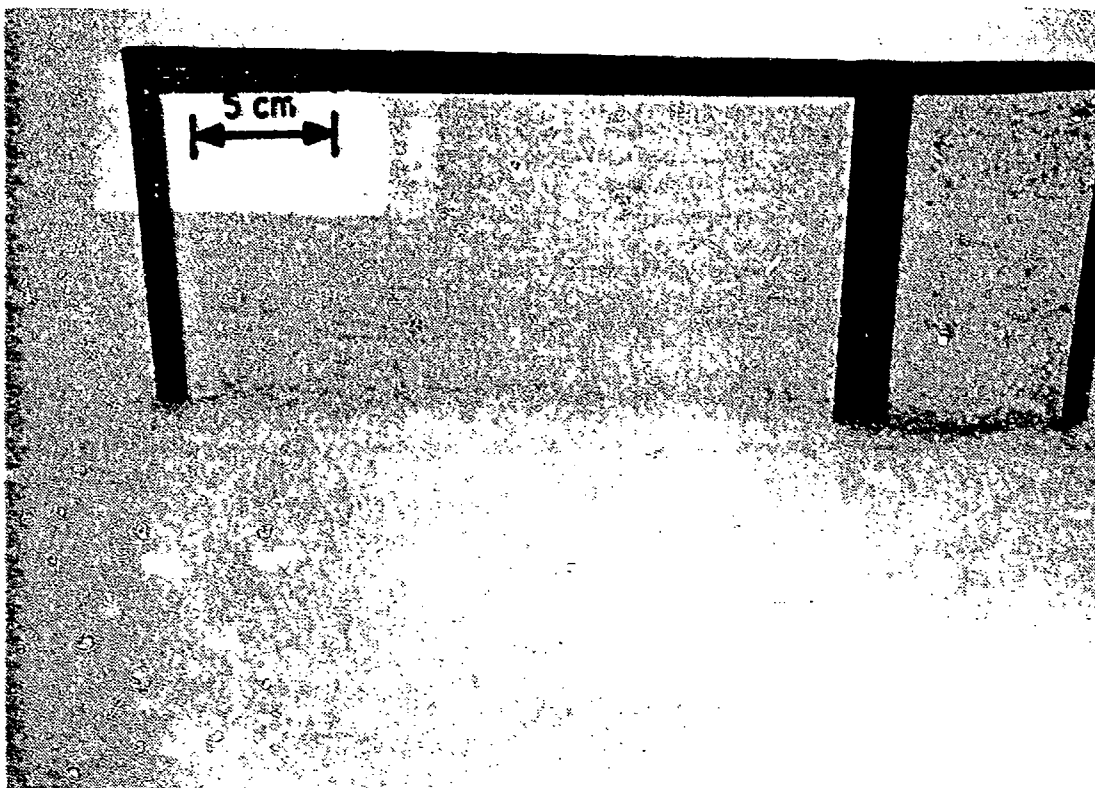
Surface RMS height: 0.15 cm

Density: 0.1 to 0.2 gm/cm<sup>3</sup>

Ice crystal diameter: 1 mm

Surface temperature: -5 C

Description: smooth snow surface



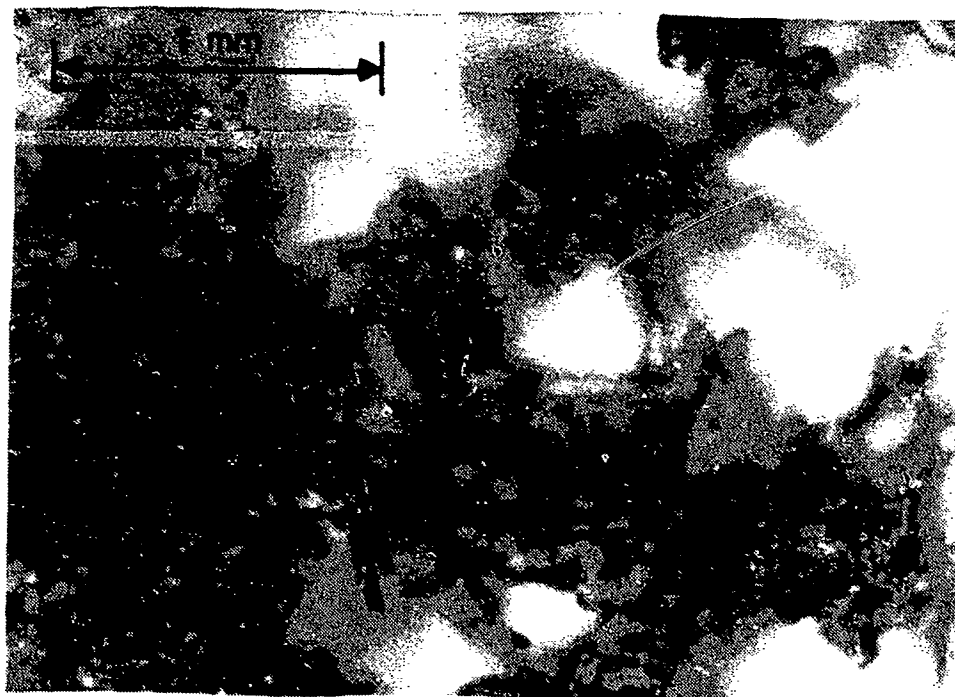
**Surface profile with 1 cm grid**

**MMW DATA FOR DRY SNOW**

**890302(SM)**



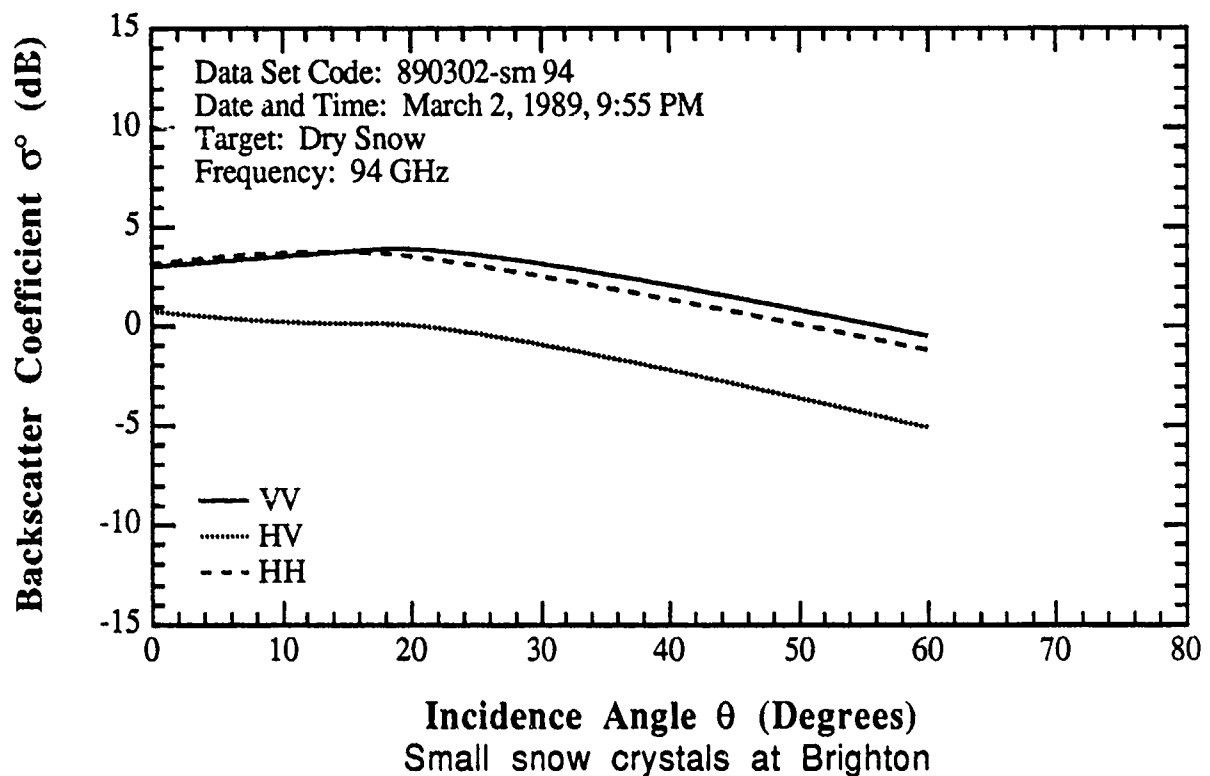
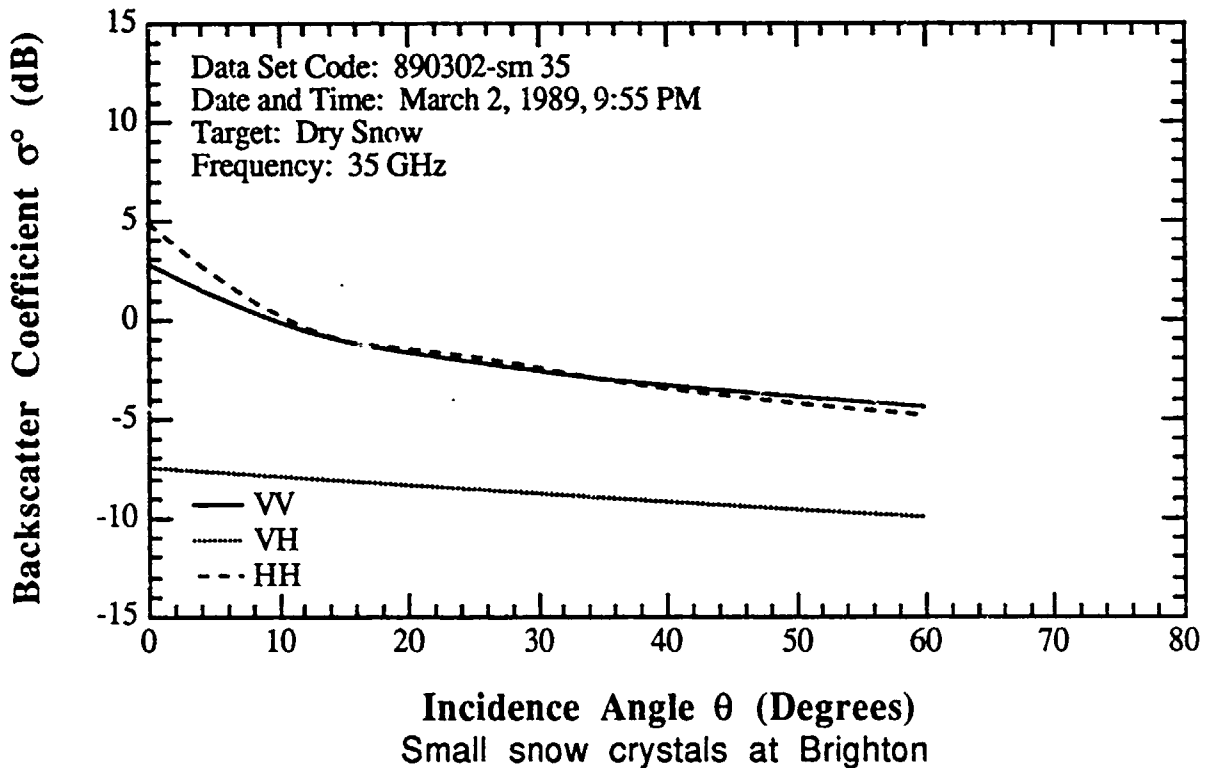
**Snow crystals from surface**



**Snow crystals from bottom of snowpack**

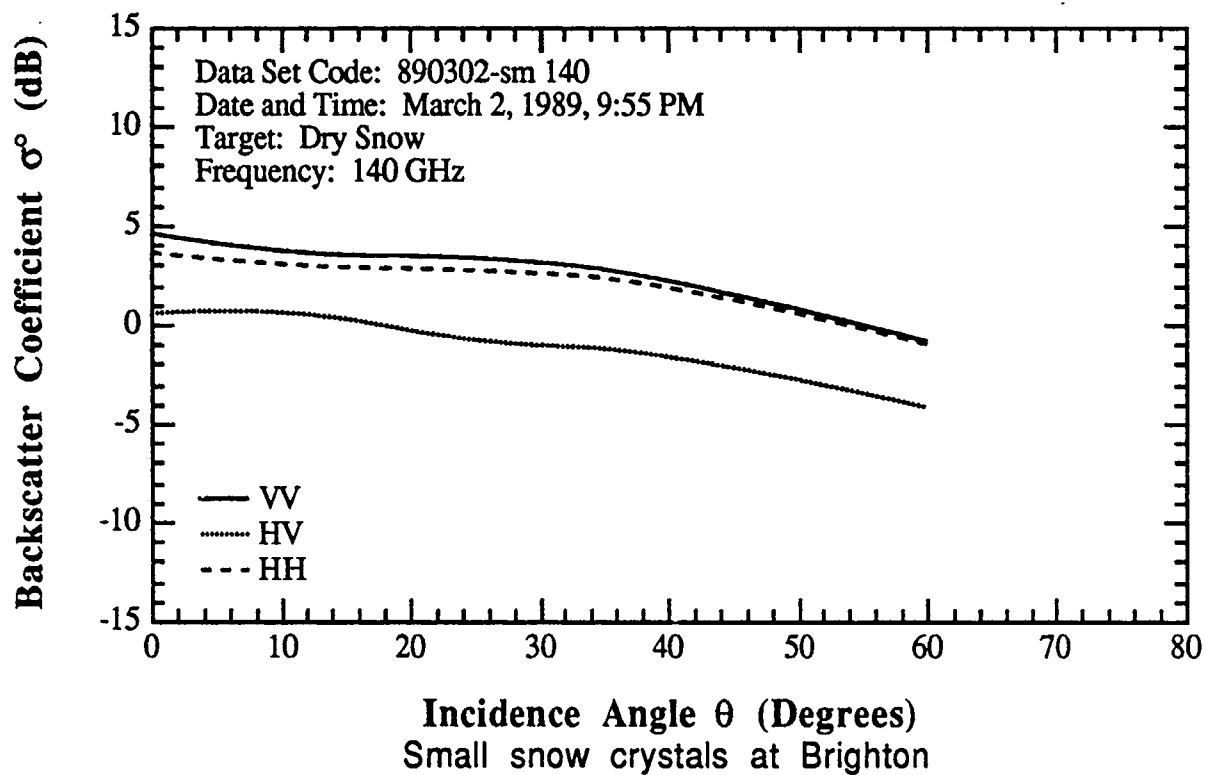
# MMW DATA FOR DRY SNOW

890302(SM)



# MMW DATA FOR DRY SNOW

890302(SM)



## G. Large Crystal Size

Dry snow

Data set code: 890302(Lg)

Depth: 10cm

LWC: 0%

Surface RMS height: 0.15cm

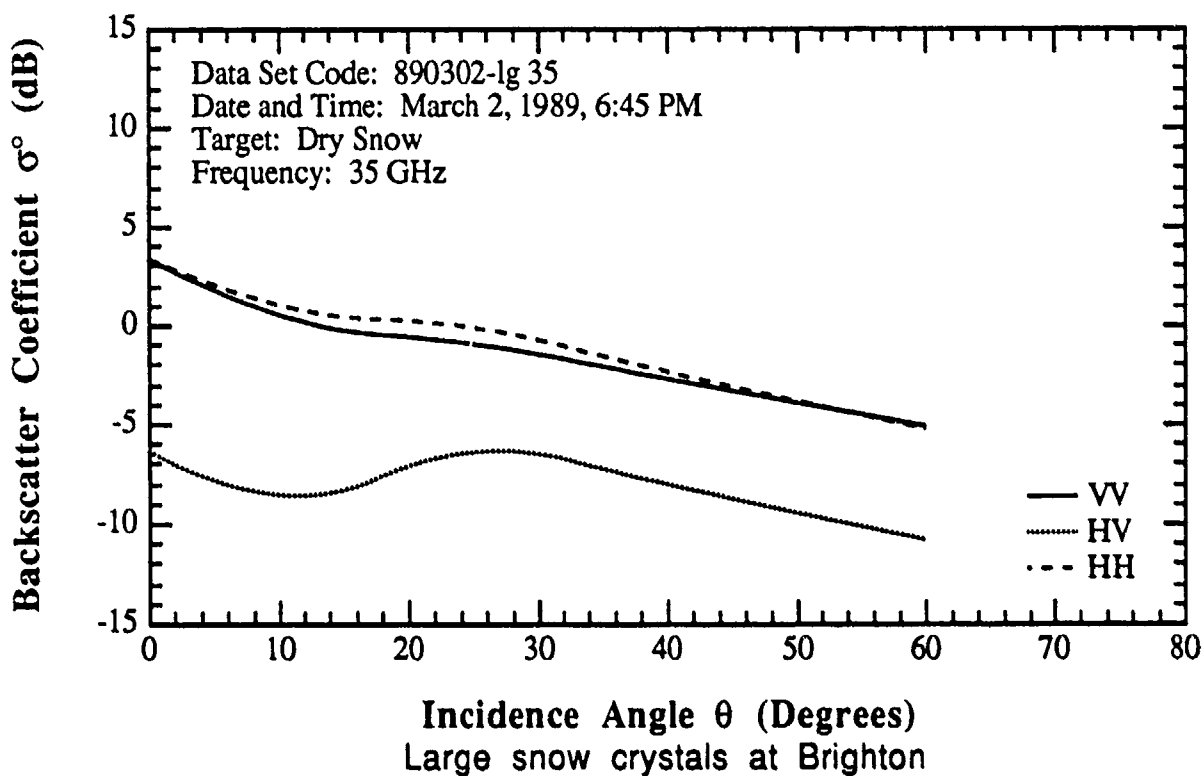
Density: 0.1 to 0.2 gm/cm<sup>3</sup>

Ice crystal diameter: 2 to 2.5 mm

Surface Temperature: -5 C

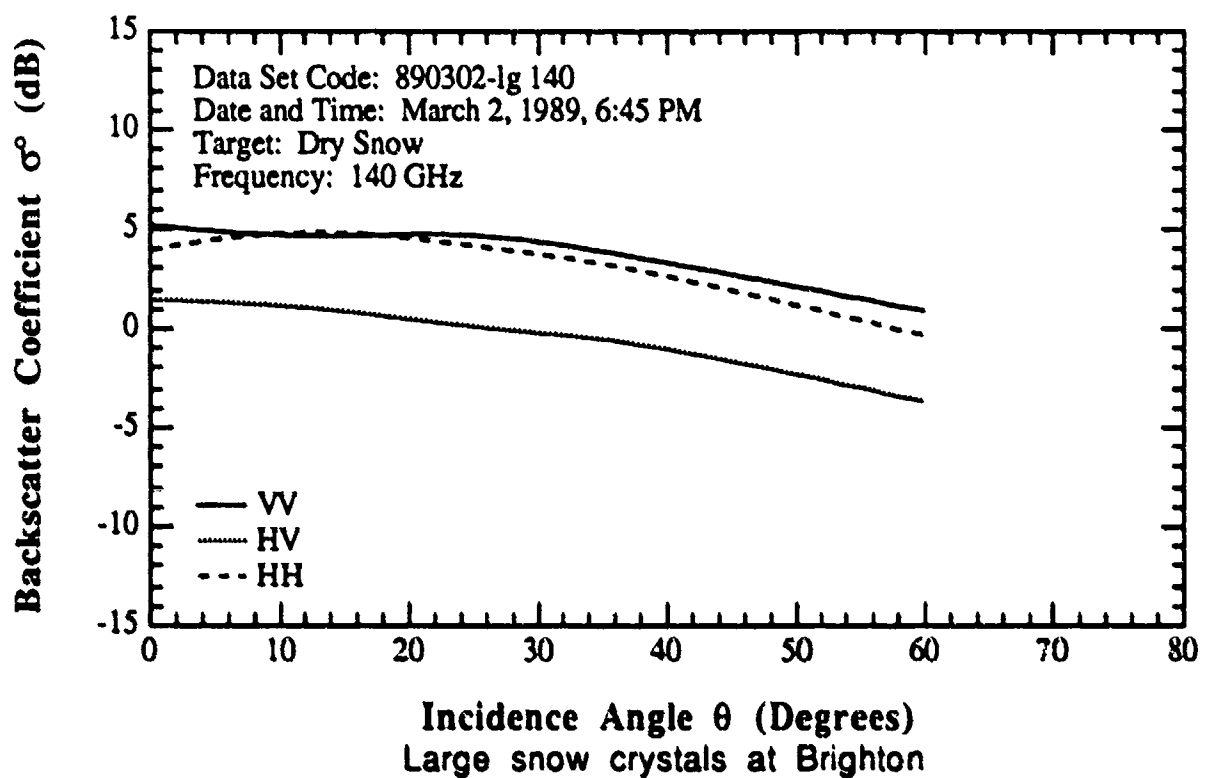
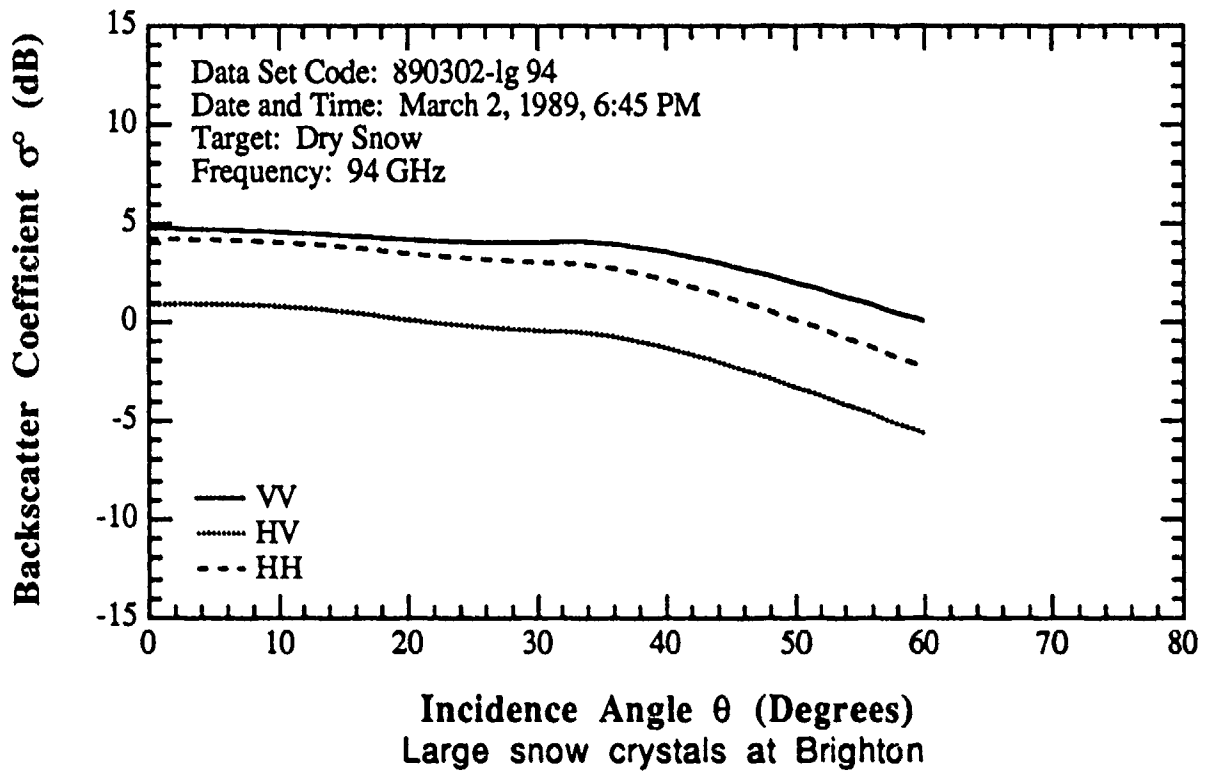
Description: fresh smooth snow surface

**890302(LG)**



# MMW DATA FOR DRY SNOW

890302(LG)



## H. Large Crystal Size with Rough Surface

Dry snow

Data set code: 890307(ro)

Depth: 10 cm

LWC: 0 %

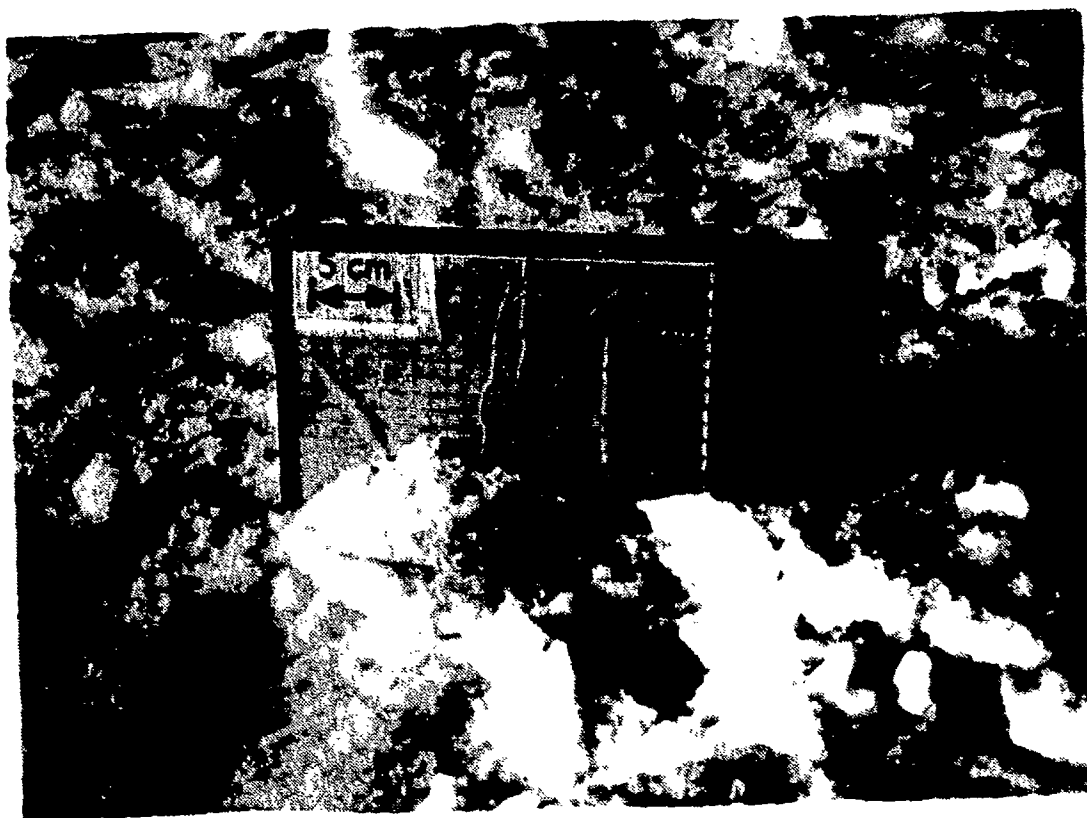
Surface RMS height: 1.17 cm

Density: 0.4 gm/cm<sup>3</sup>

Ice crystal diameter: 2 to 4 mm

Surface temperature: -10 to -12 C

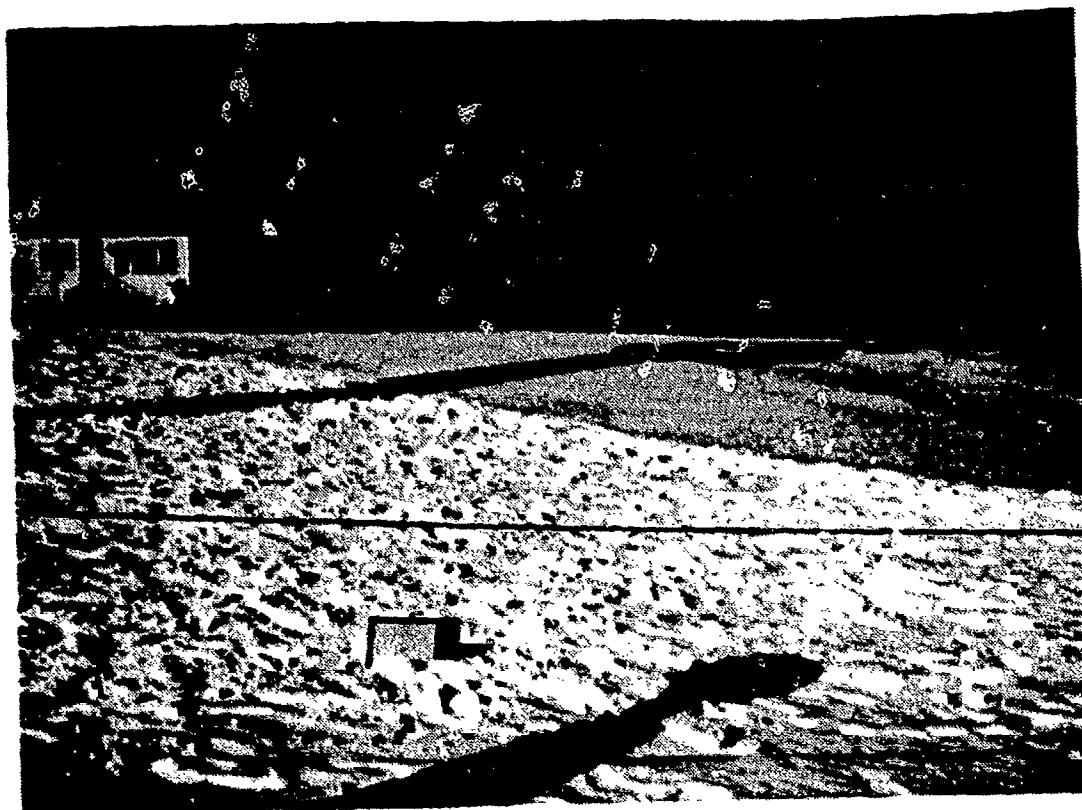
Description: dry, slightly metamorphosed snow



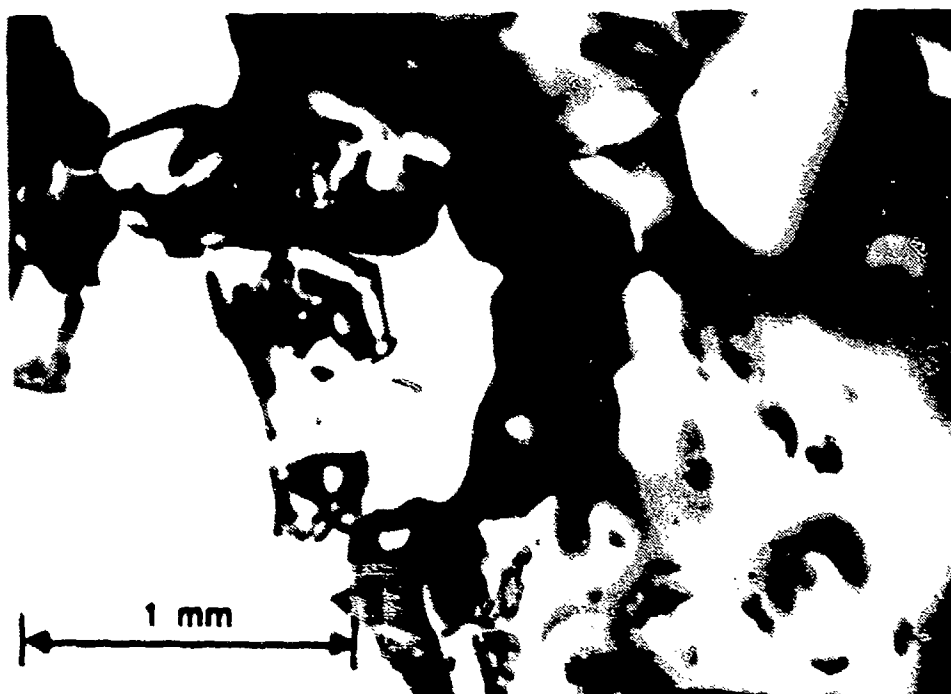
Surface roughness profile with 1 cm grid

# MMW DATA FOR DRY SNOW

890307(RO)



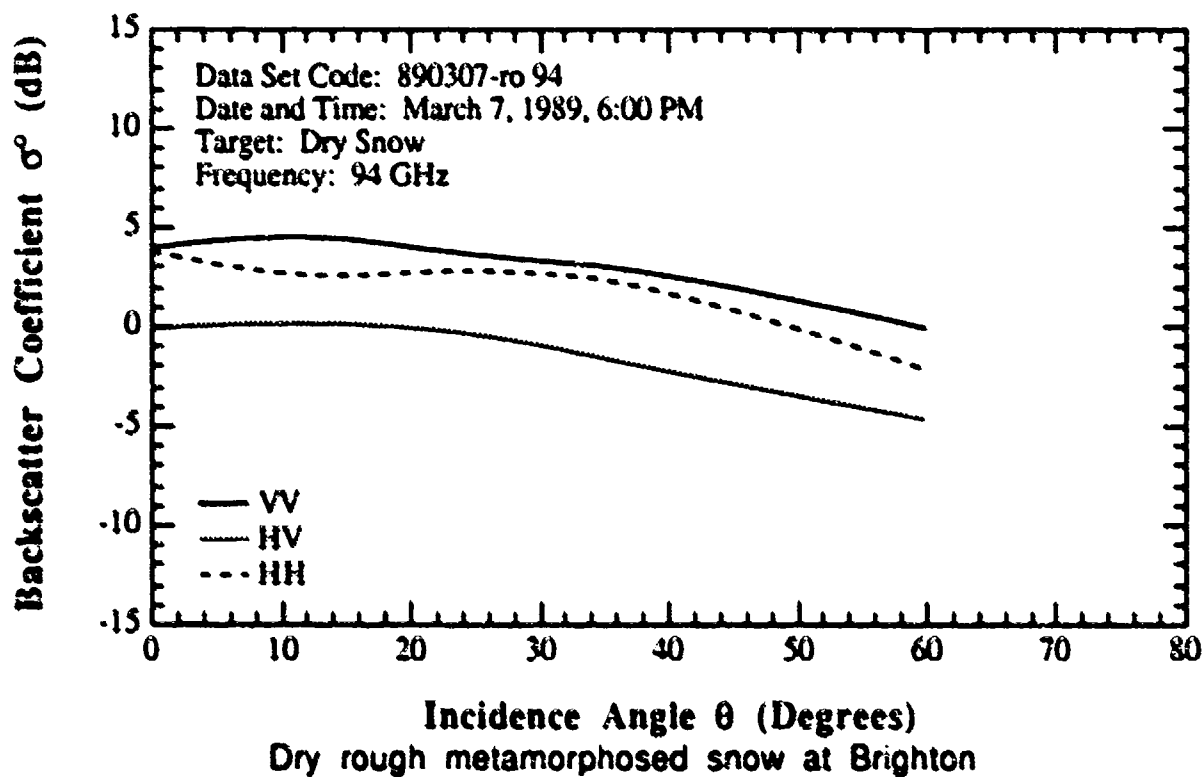
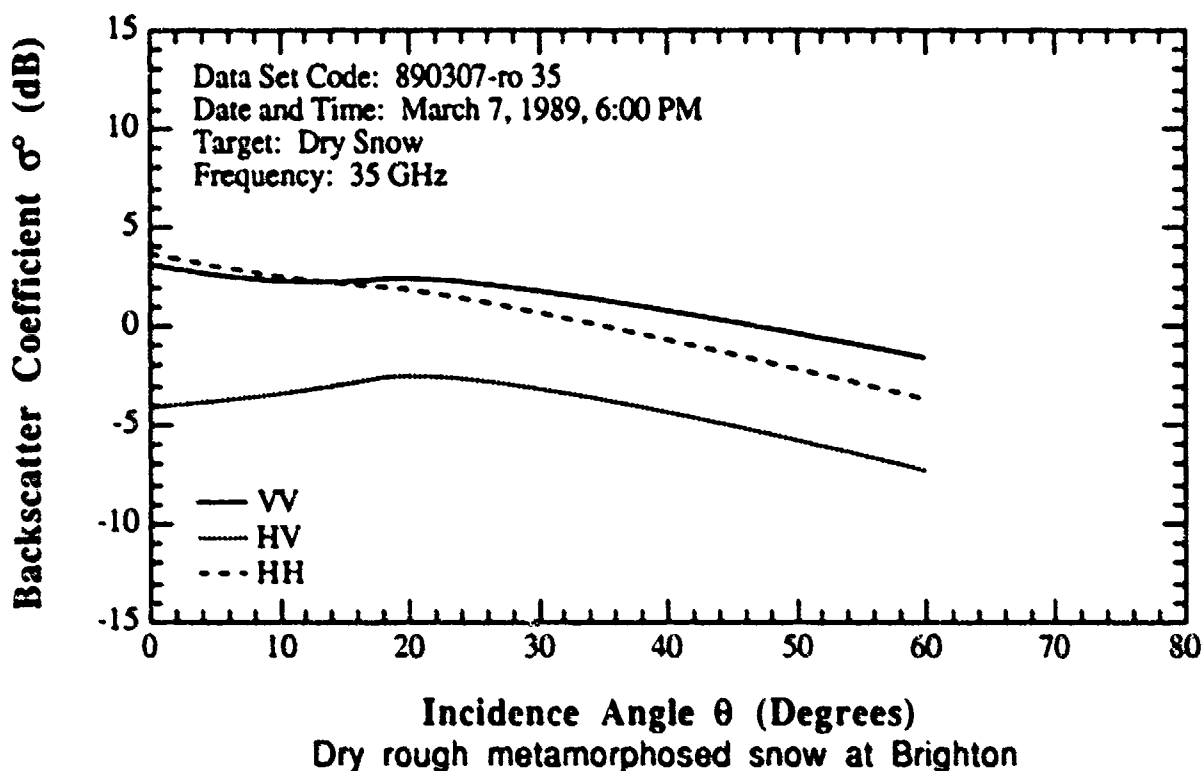
Data collection scene



Snow crystals from surface

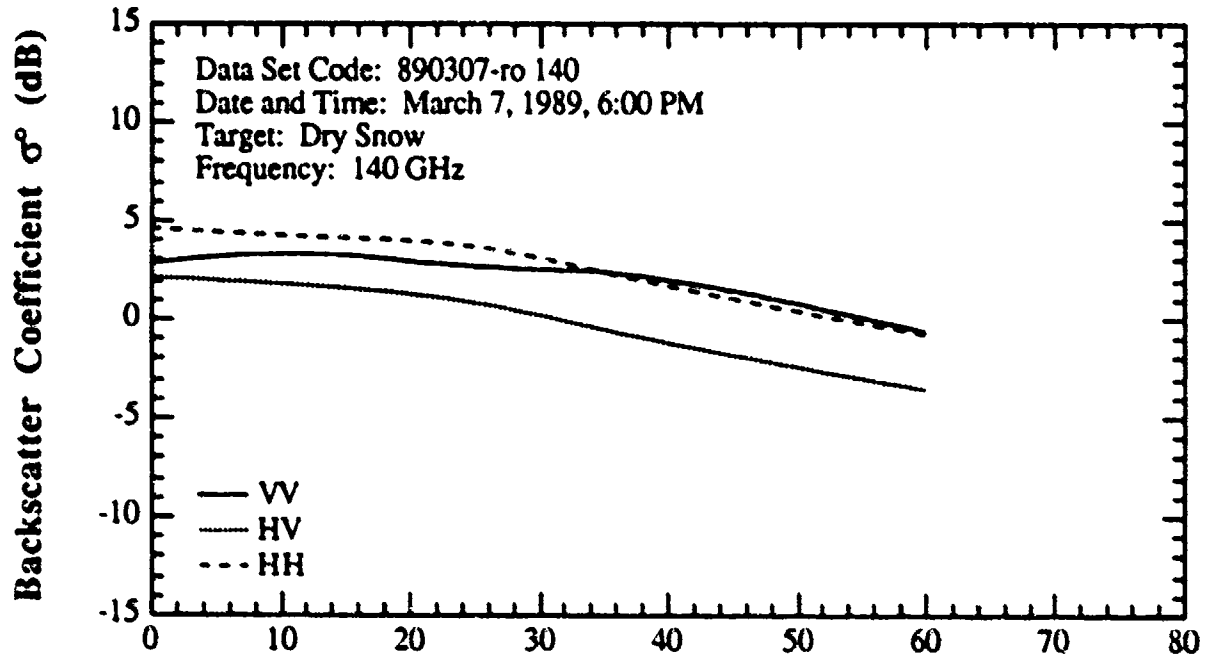
# MMW DATA FOR DRY SNOW

890307(RO)



# MMW DATA FOR DRY SNOW

890307(RO)



Dry rough metamorphosed snow at Brighton

## MMW DATA FOR DRY SNOW

### 1. Large Crystal Size with Smooth Surface

Dry snow

Data set code: 890307 (Sm)

Depth: 10 cm

LWC: 0 %

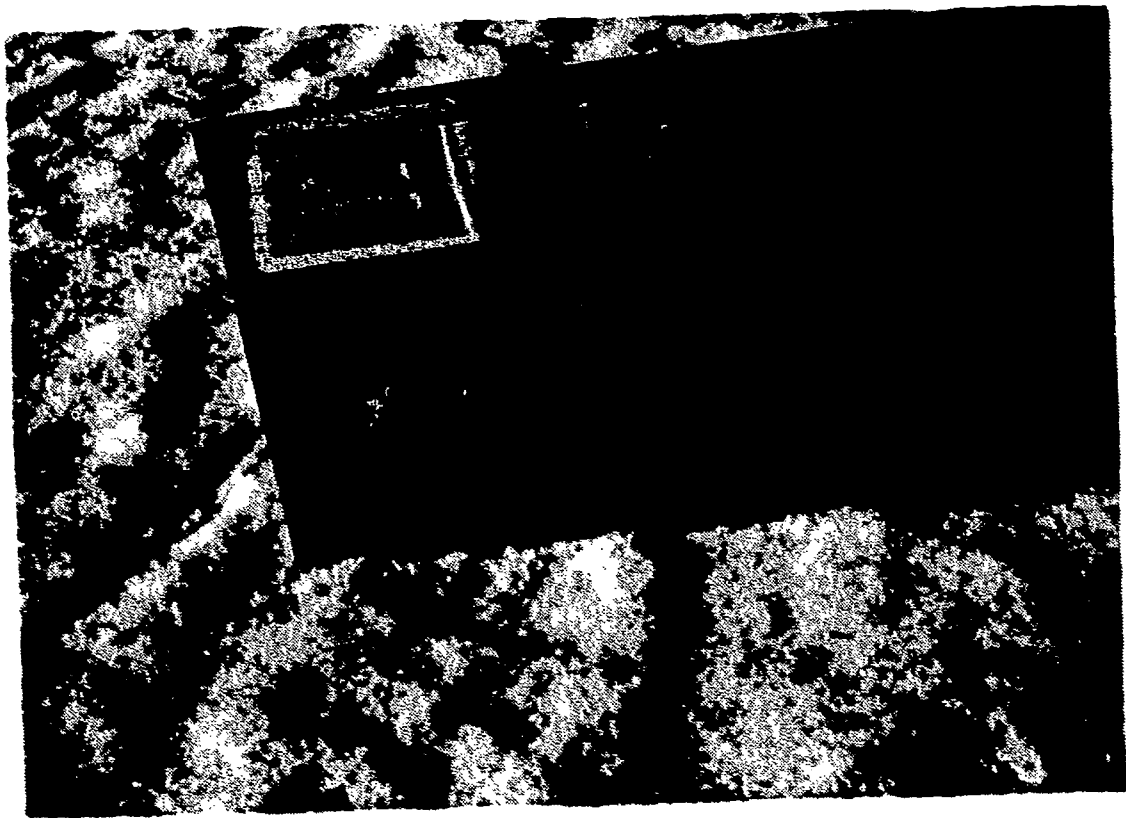
Surface RMS height: 0.28 cm

Ice crystal diameter: 2 to 4 mm

Density: 0.4 gm/cm<sup>3</sup>

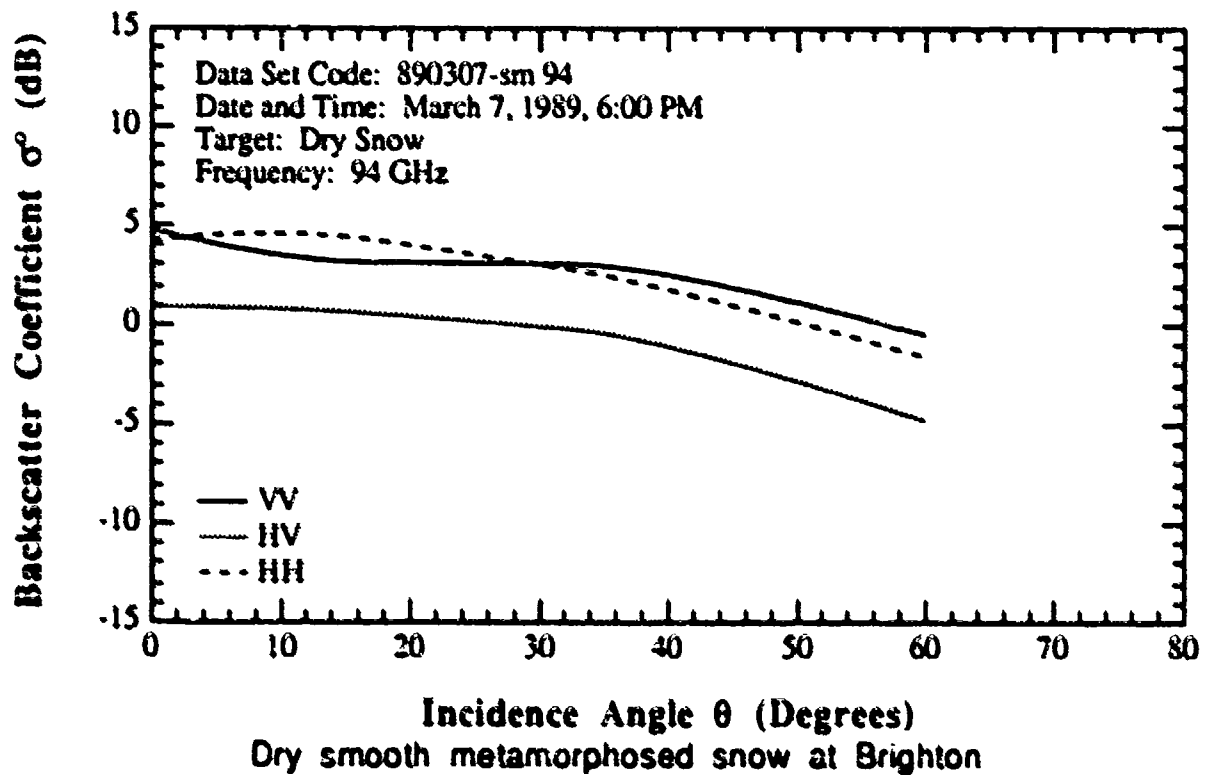
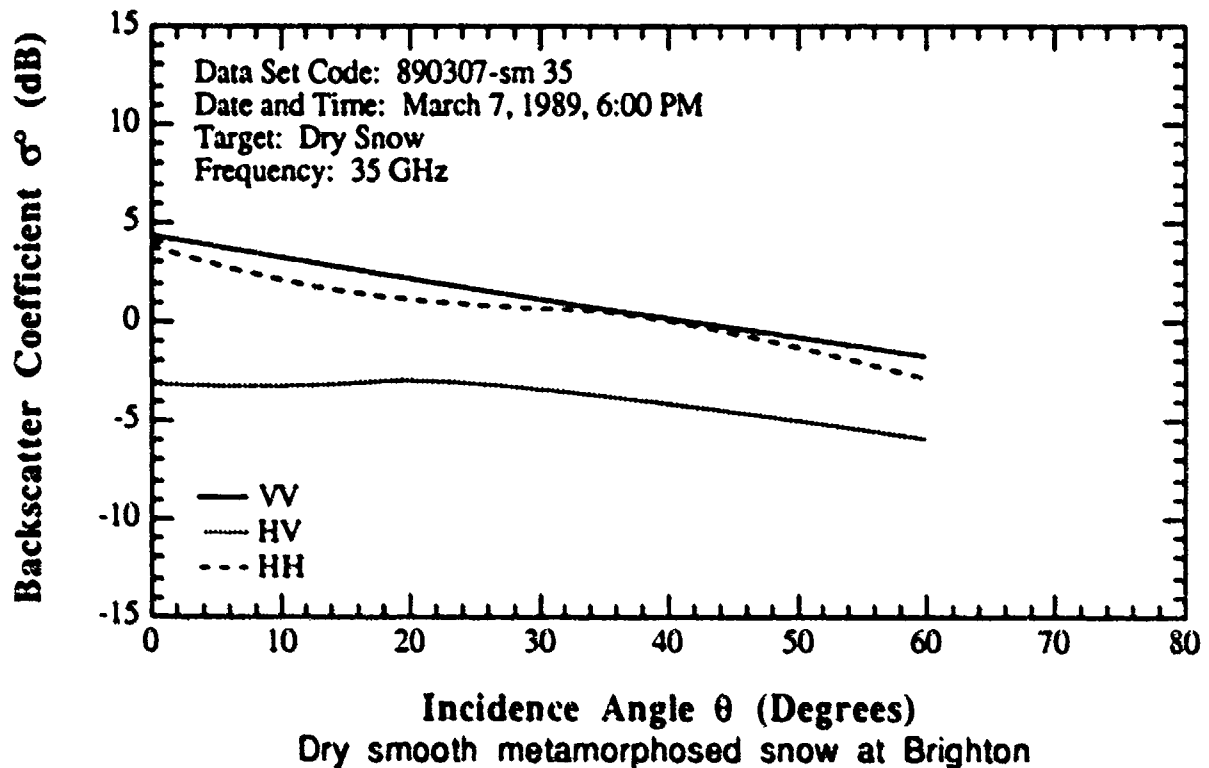
Surface temperature: -10 to -12 C

Description: dry slightly metamorphosed snow



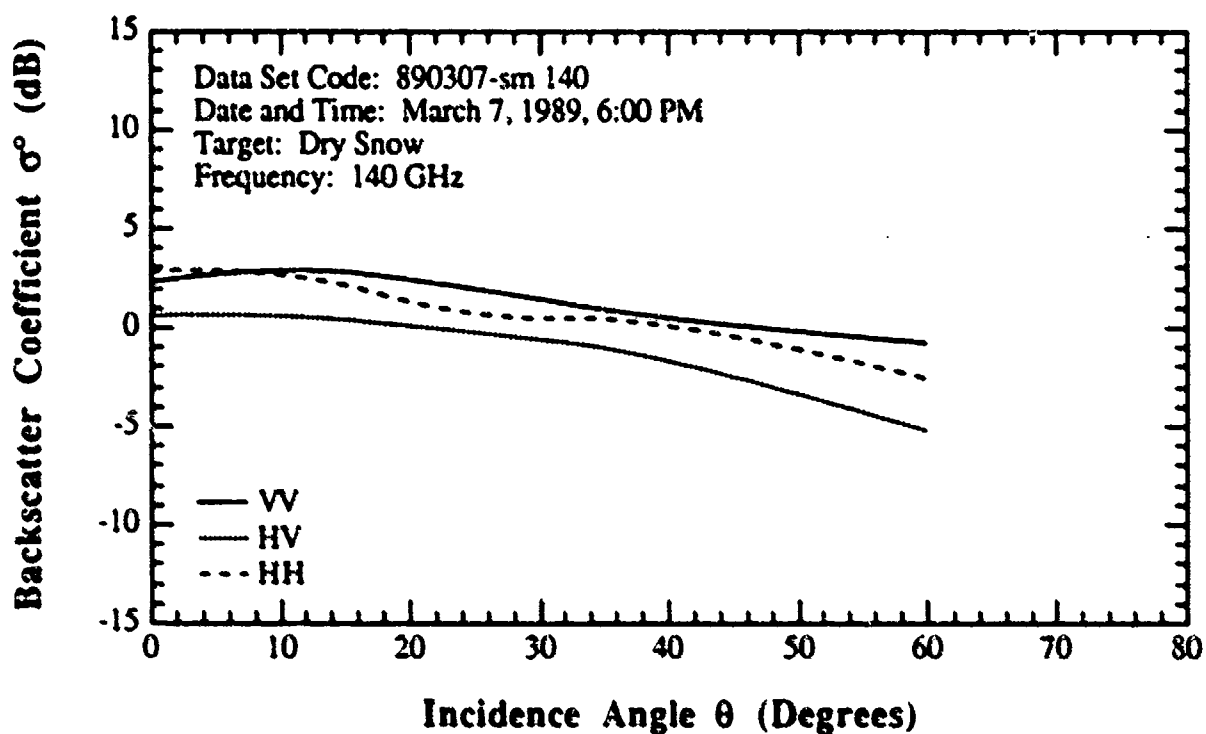
# MMW DATA FOR DRY SNOW

890307(SM)



# MMW DATA FOR DRY SNOW

890307(SM)



Dry Smooth metamorphosed snow at Brighton

### 3. MMW DATA FOR WET SNOW

As in the previous chapter on Dry Snow, the following chart is included in order to give a more complete overview of the characteristics of the data:

|                   | manmade wet | slightly wet with<br>smooth surface | wet w/ smooth surface | very wet with<br>rough surface | very wet with<br>smooth surface |
|-------------------|-------------|-------------------------------------|-----------------------|--------------------------------|---------------------------------|
| Data Set Code     | A           | B                                   | C                     | D                              | E                               |
| 890220            |             | x                                   |                       |                                |                                 |
| 890309 (vw w/ rs) |             |                                     |                       | x                              |                                 |
| 890221            |             |                                     | x                     |                                |                                 |
| 890309 (vw w/ ss) |             |                                     |                       |                                | x                               |
| 890215            | x           |                                     |                       |                                |                                 |

## MMW DATA FOR WET SNOW

### A. Manmade Wet Snow

Wet snow

Data set code: 890215

Depth: 27 cm

LWC: (at 3:25 PM): 8.82 %

Surface RMS height: 1.6 cm

Density: 0.48 gm/cm<sup>3</sup>

Ice crystal diameter: 2 to 4 mm

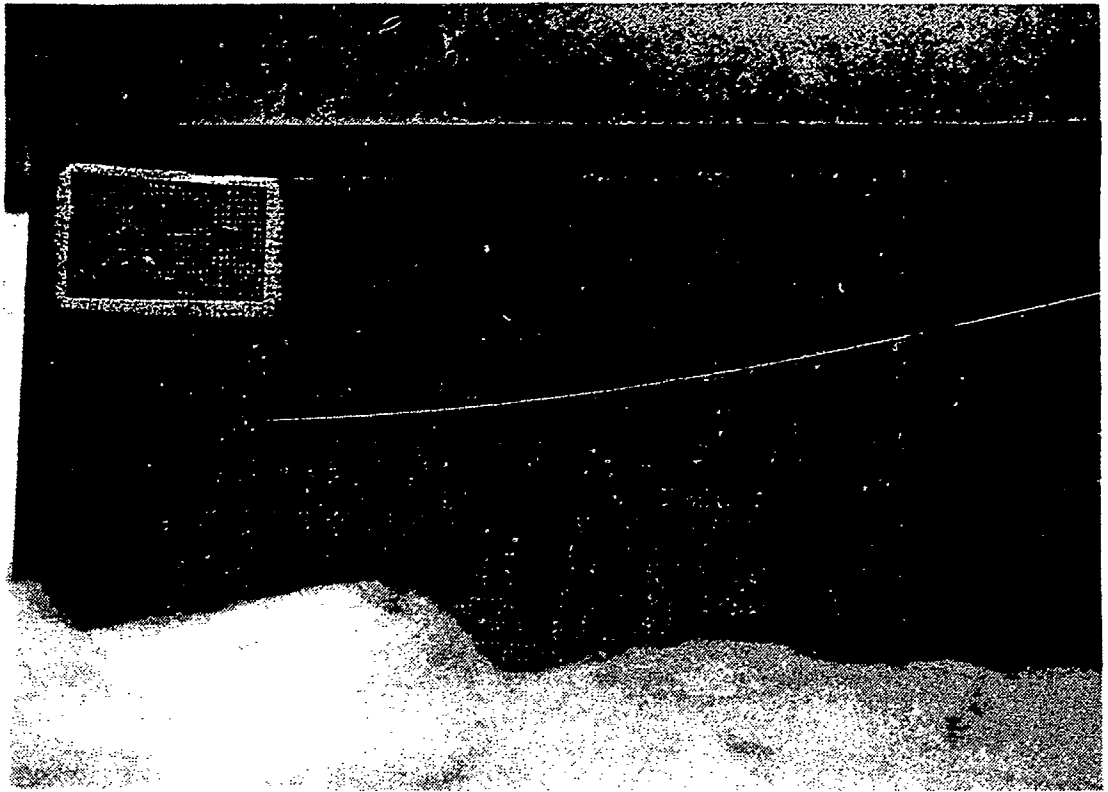
Surface temperature: 0.0 C

Description: manmade wet snow



Snowmaking scene

# MMW DATA FOR WET SNOW



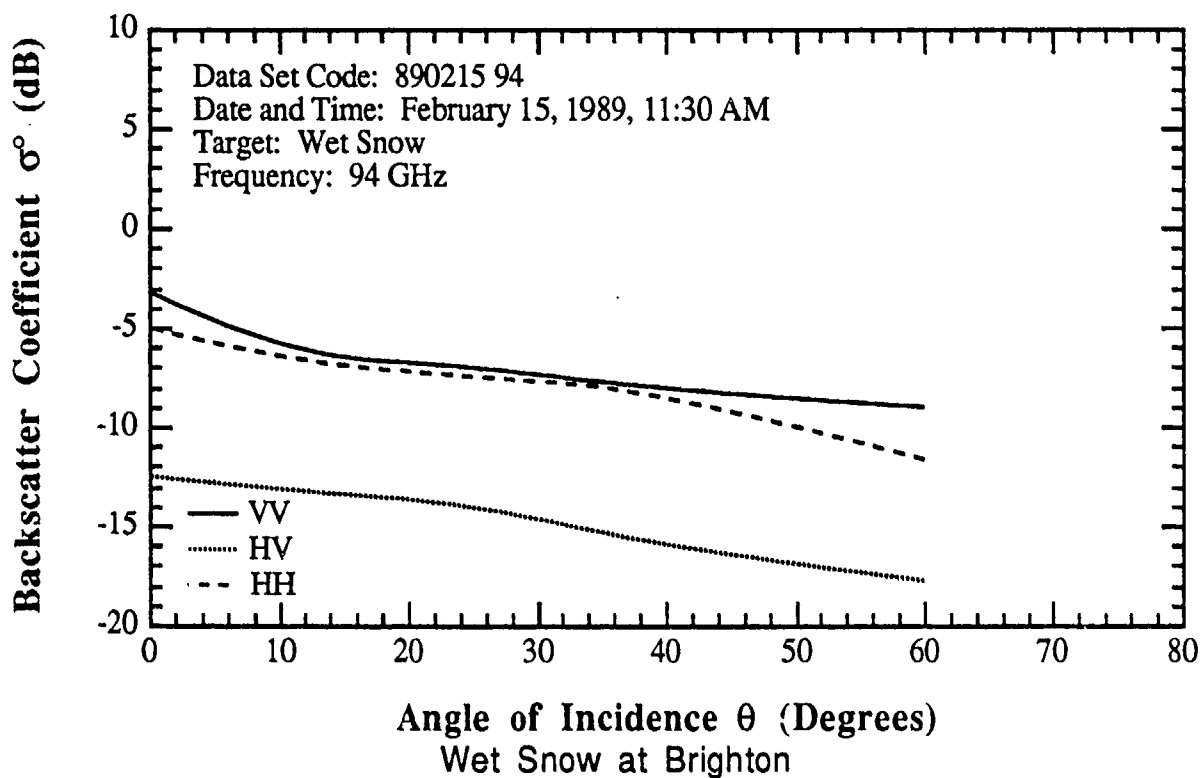
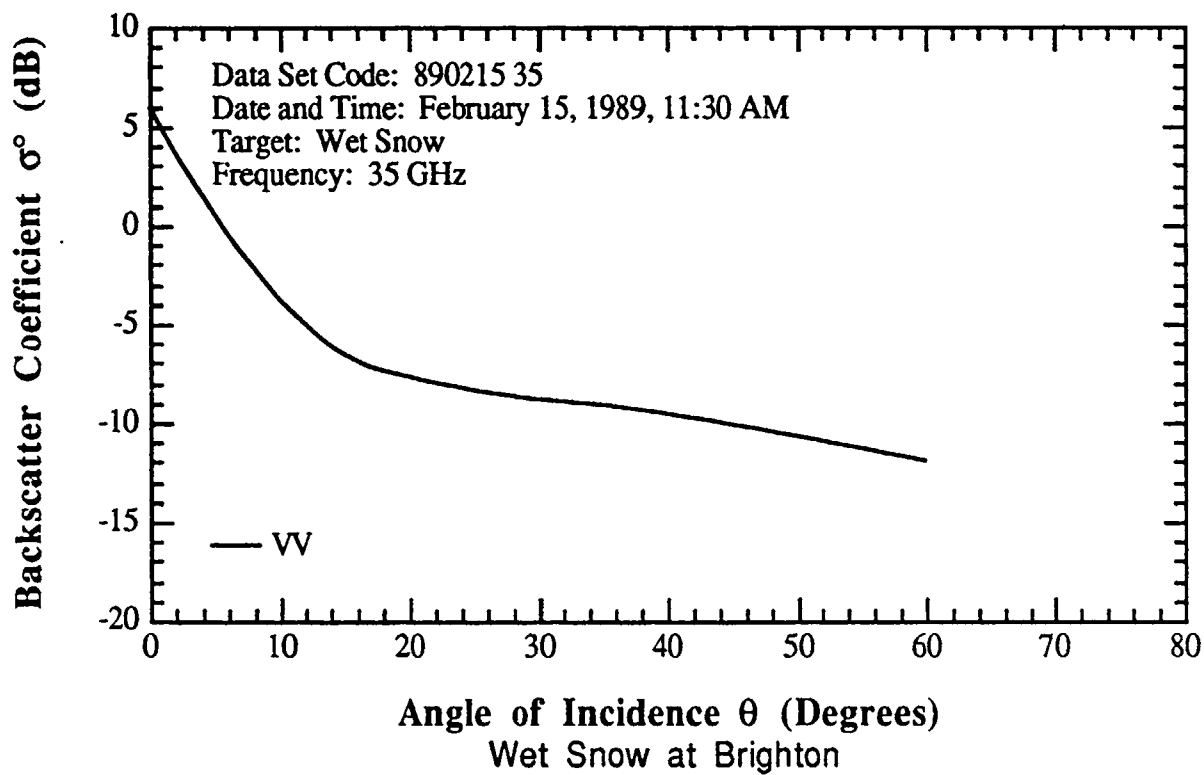
Surface roughness profile with 1 cm grid



Data collection scene

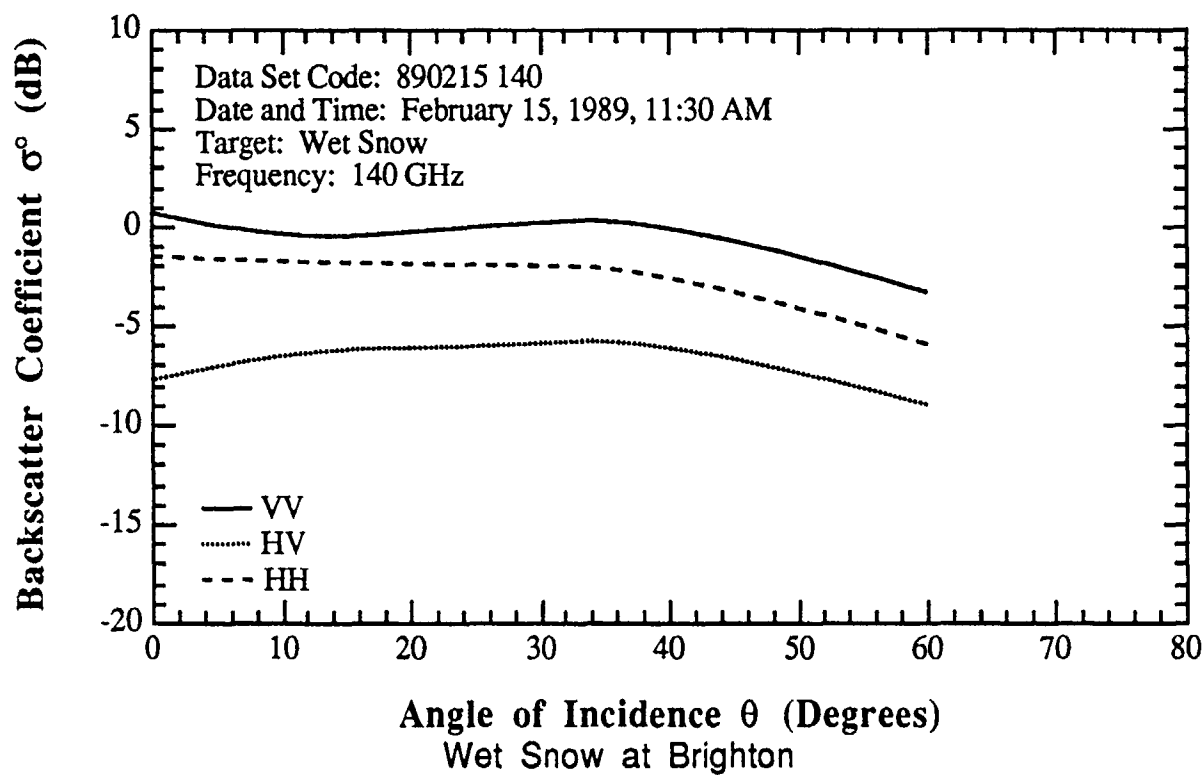
# MMW DATA FOR WET SNOW

890215



# MMW DATA FOR WET SNOW

890215



## B. Slightly Wet Snow with Smooth Surface

Data set code: 890220

Depth: 6.5 cm

Liquid Water Content: 1.9%

Surface RMS height: 0.11 cm

Density: 0.1 to 1.0 gm/cm<sup>3</sup>

Ice crystal diameter: 1 to 2 mm

Surface temperature: 0.0 C

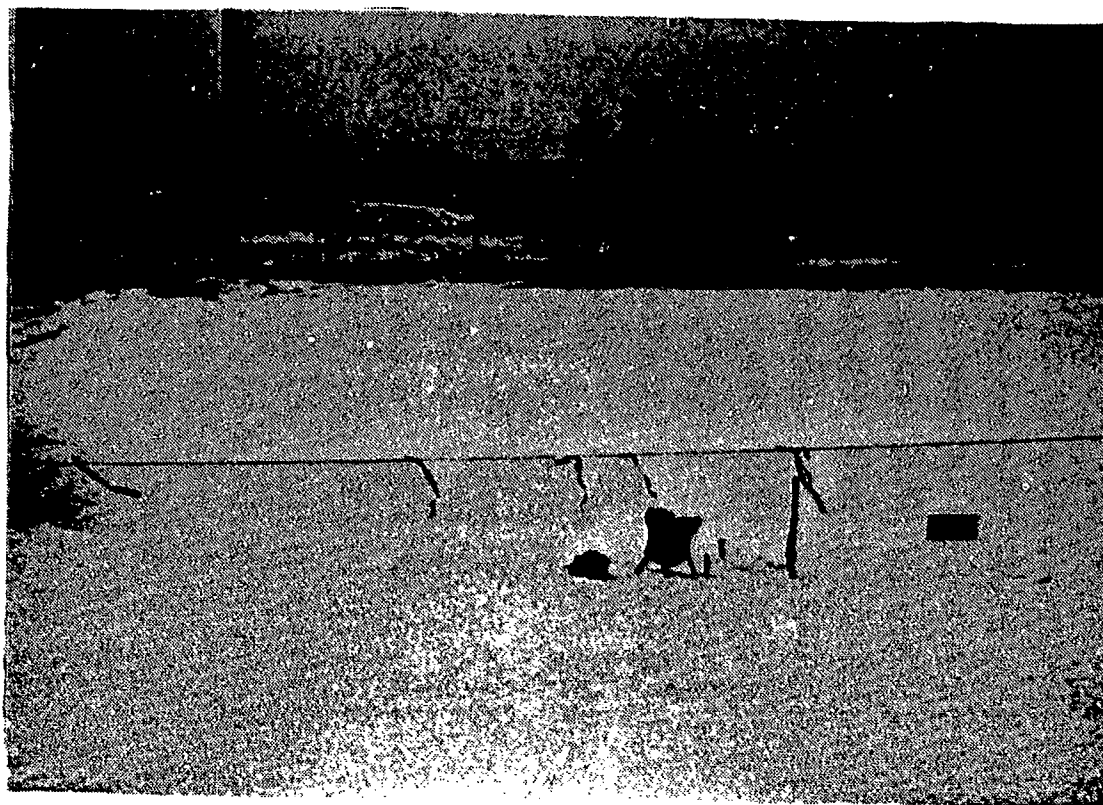
Description: smooth, wet natural snow

### SNOW PIT PROFILE FOR 890220

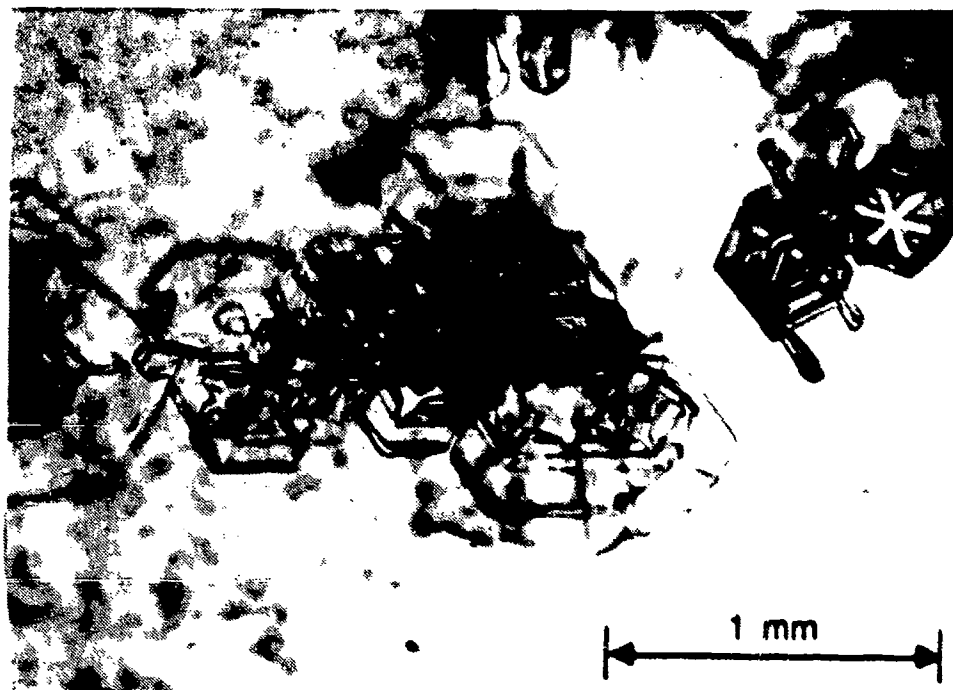
| top        | 6.5 | temp.<br>(deg C) | density<br>(g/cm3) |
|------------|-----|------------------|--------------------|
|            |     |                  |                    |
| depth (cm) | 6   | 0.0              | 0.113              |
|            | 5   |                  |                    |
|            | 4   | -0.25            | 0.237              |
|            | 3   |                  |                    |
| bottom     | 2   | -0.25            |                    |
|            | 1   |                  | 0.958 (ice)        |

air temperature: 1.1 C

# MMW DATA FOR WET SNOW



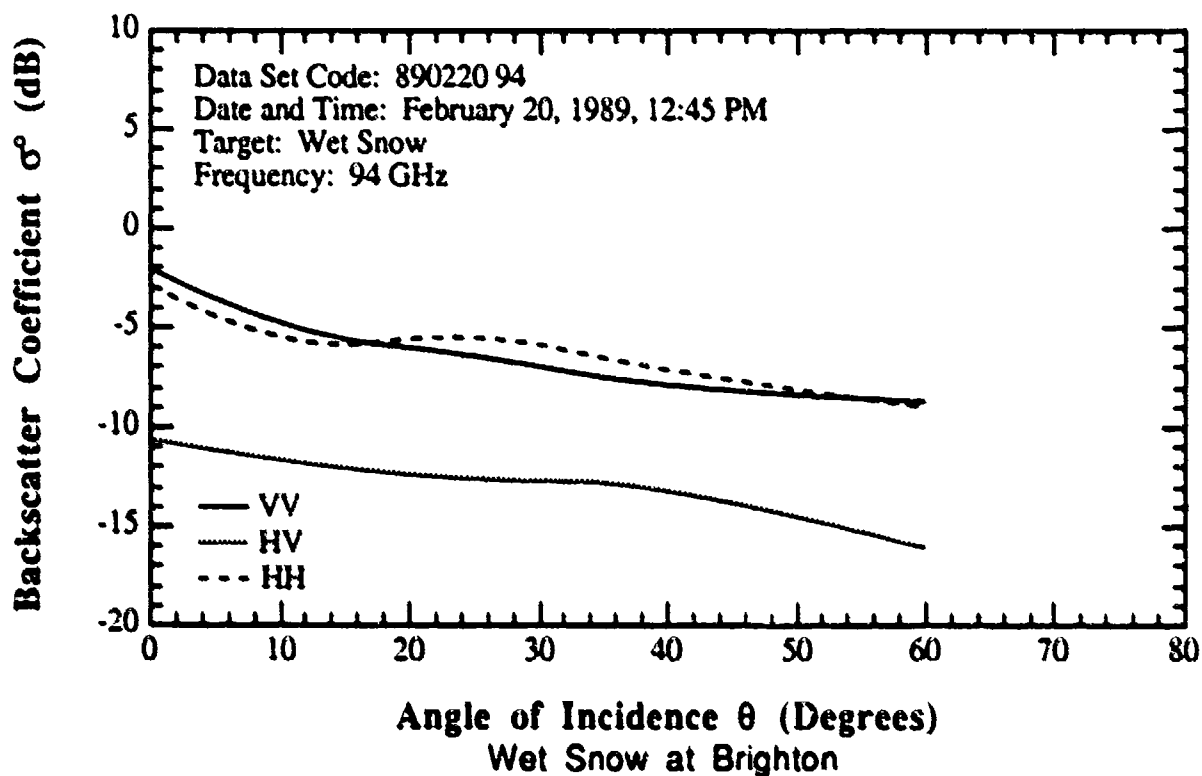
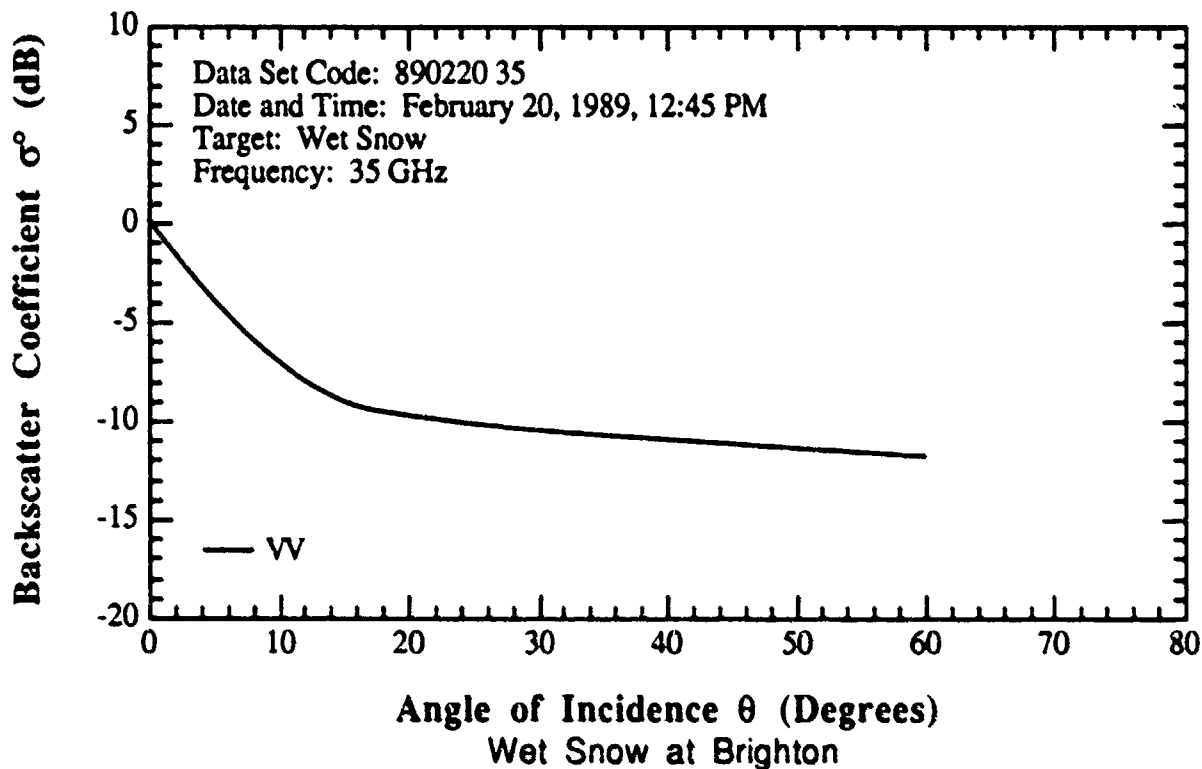
Data collection scene



Snow crystals from surface

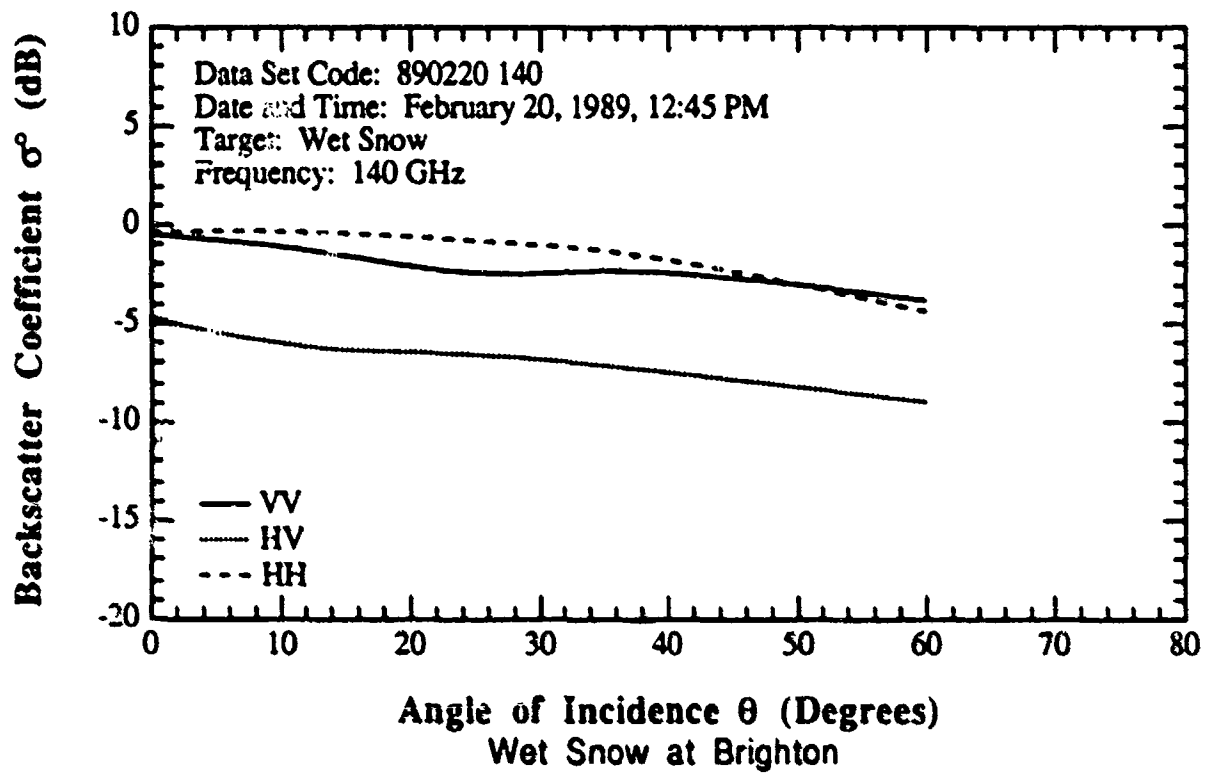
# MMW DATA FOR WET SNOW

890220



# MWW DATA FOR WET SNOW

890220



**C. Wet Snow with Smooth Surface**

Wet snow

Data set code: 890221

LWC (at 12:48 PM): 4.53 %

LWC (at 1:20 PM): 5.50 %

LWC (at 3:08 PM): 6.57 %

Depth: 13.5 cm

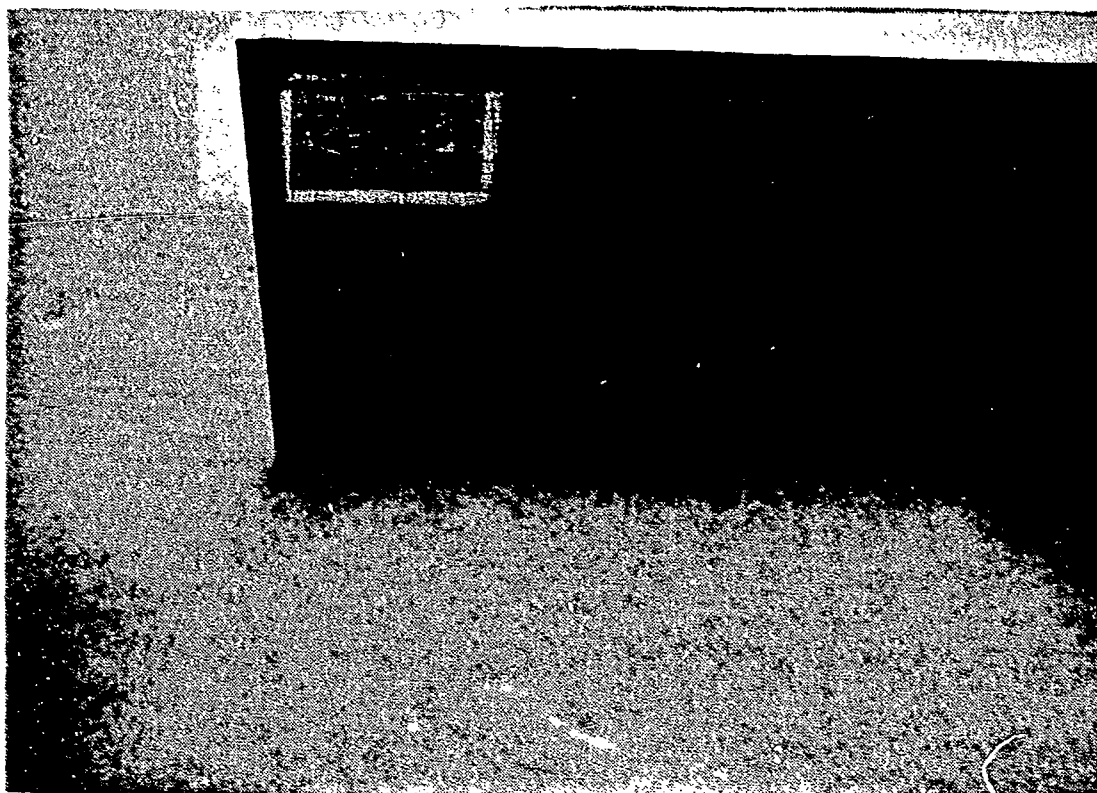
Surface RMS height: 0.22 cm

Ice crystal diameter: 1 mm

Density: 0.13 gm/cm<sup>3</sup>

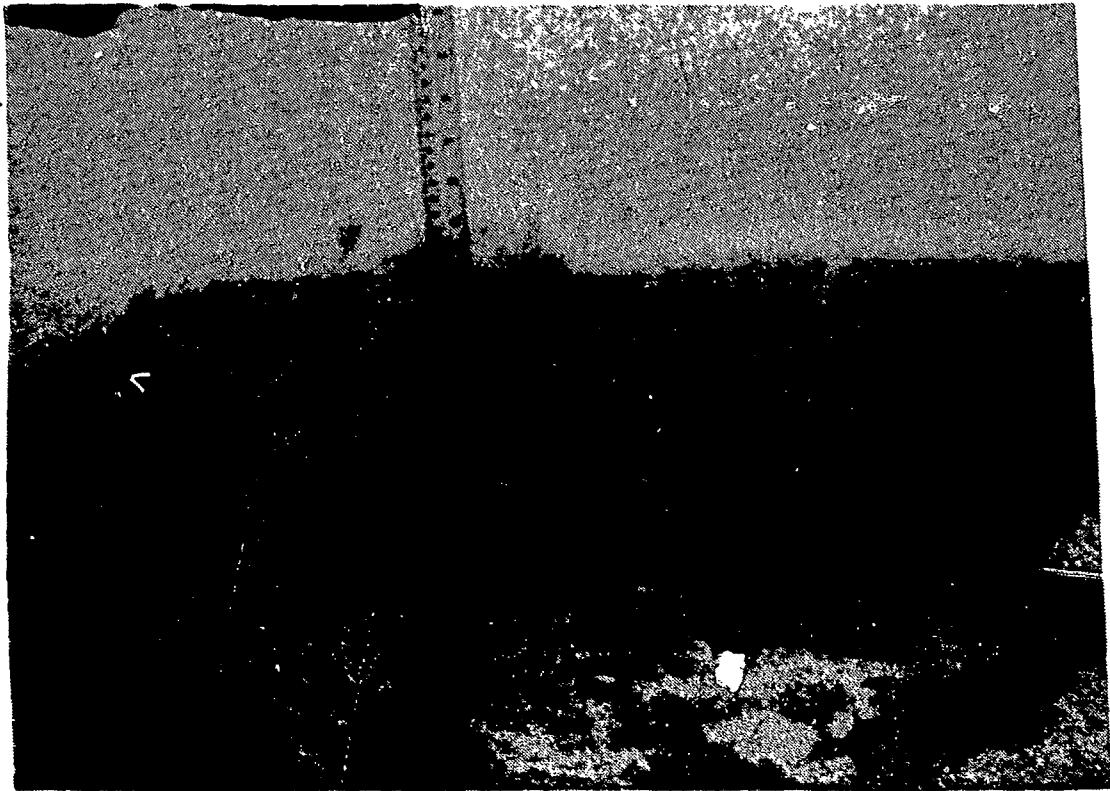
Surface temperature: 1.0 C

Description: smooth, wet natural snow



Surface roughness profile with 1 cm grid

# MMW DATA FOR WET SNOW



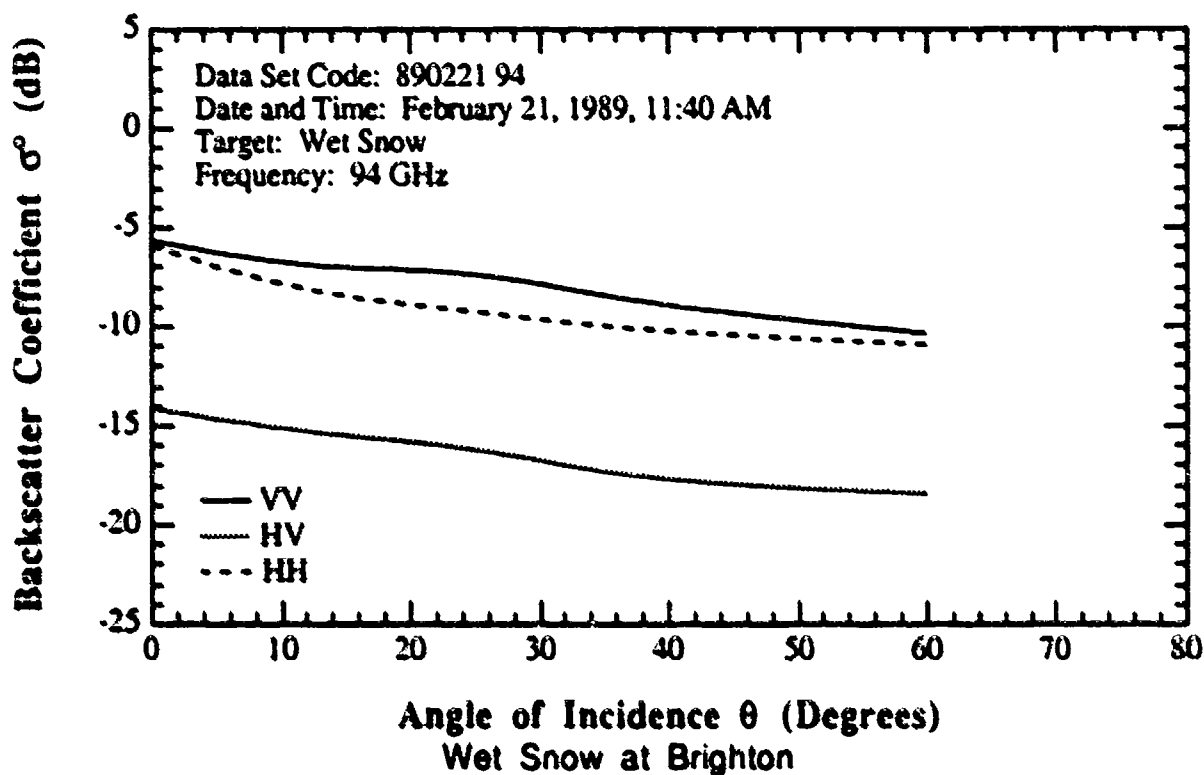
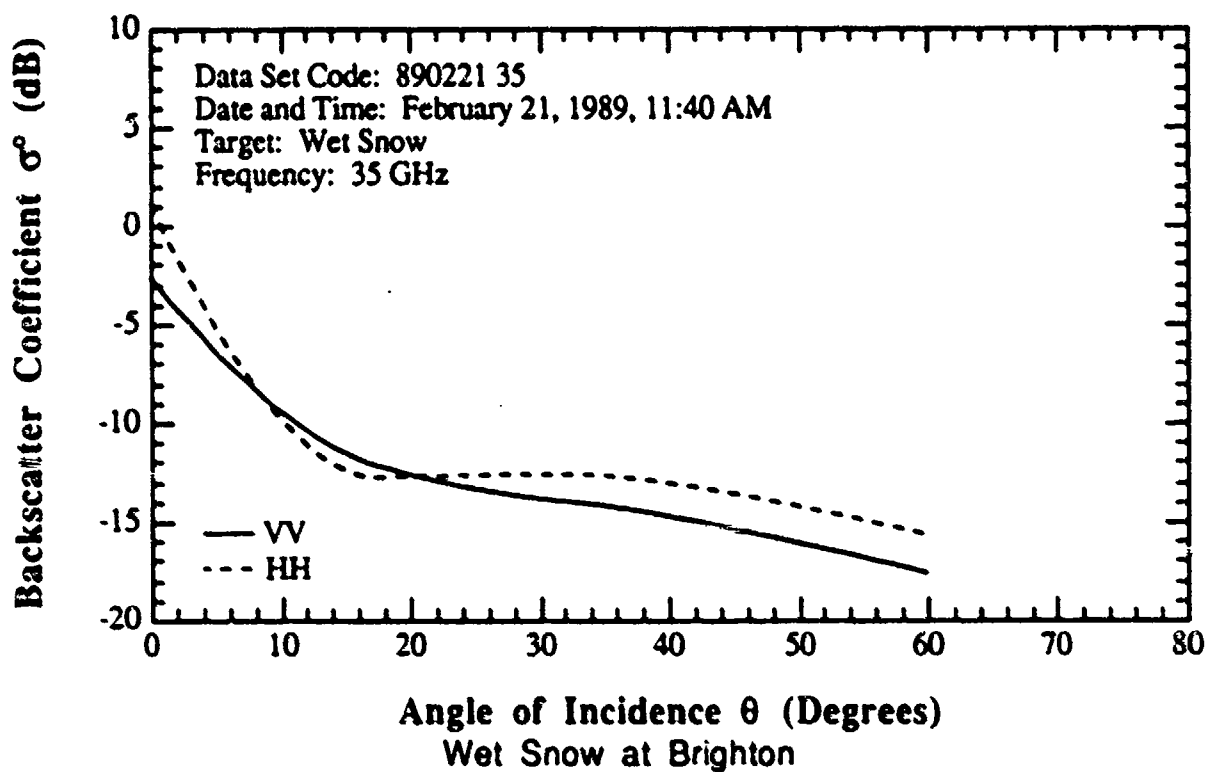
Snow pit



Data collection scene

# MMW DATA FOR WET SNOW

890221



### G. Very Wet Snow with Rough Surface

Wet snow

Data set code: 890309(RO)

Depth: 4.0 cm

LWC (at 2:30 PM): 16.89 %

LWC (at 3:09 PM): 15.47%

Surface RMS height (sample 1): 1.36 cm

Surface RMS height (sample 2): 1.78 cm

Surface RMS height (sample 3): 1.79 cm

Surface RMS height (sample 4): 2.29 cm

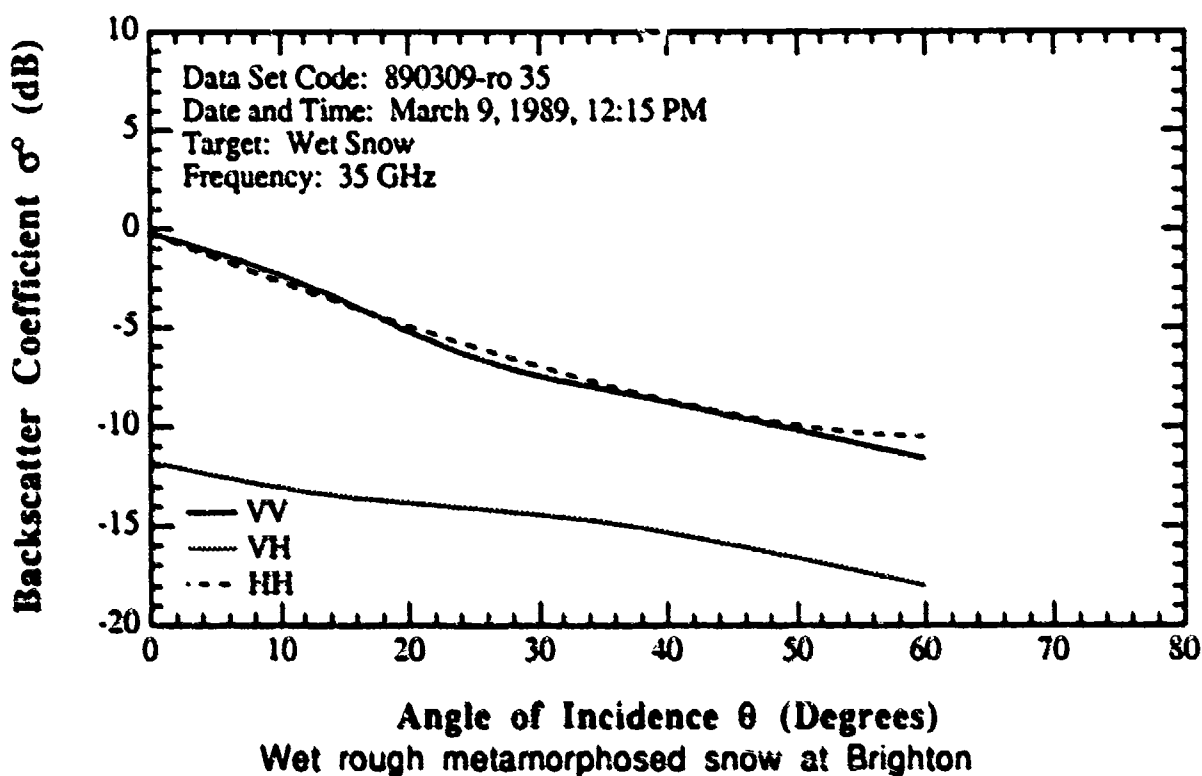
Density: 0.42 gm/cm<sup>3</sup>

Ice crystal diameter: 2 to 4 mm

Surface temperature: 4 to 6 C

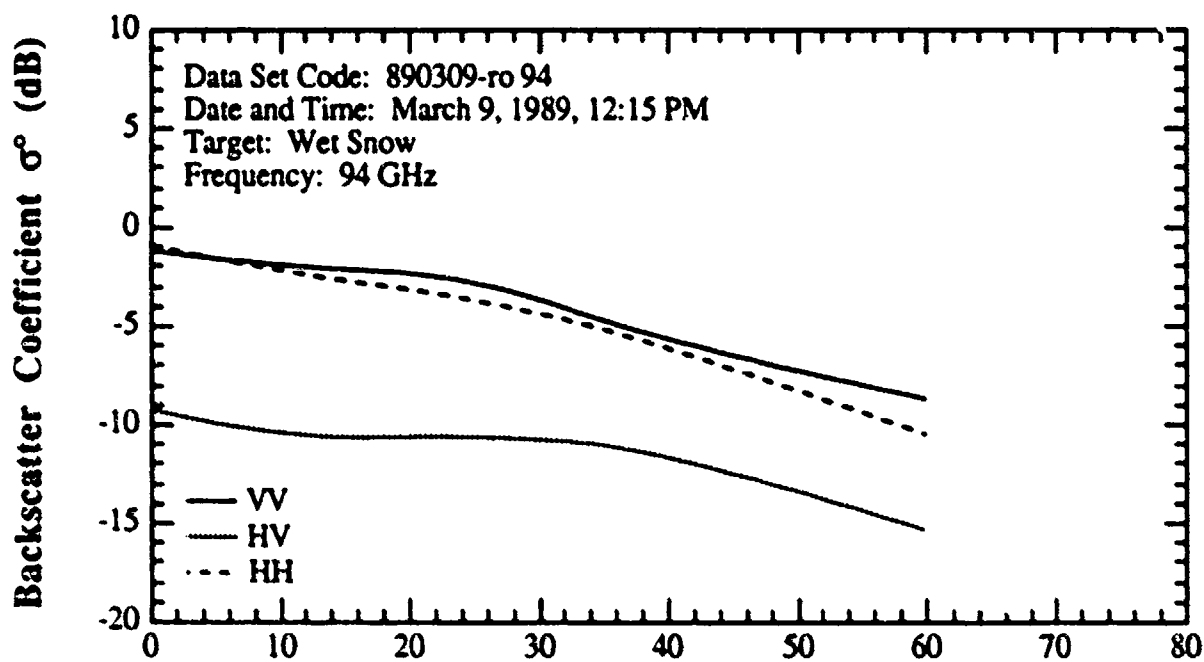
Description: rough, wet snow

890309(RO)

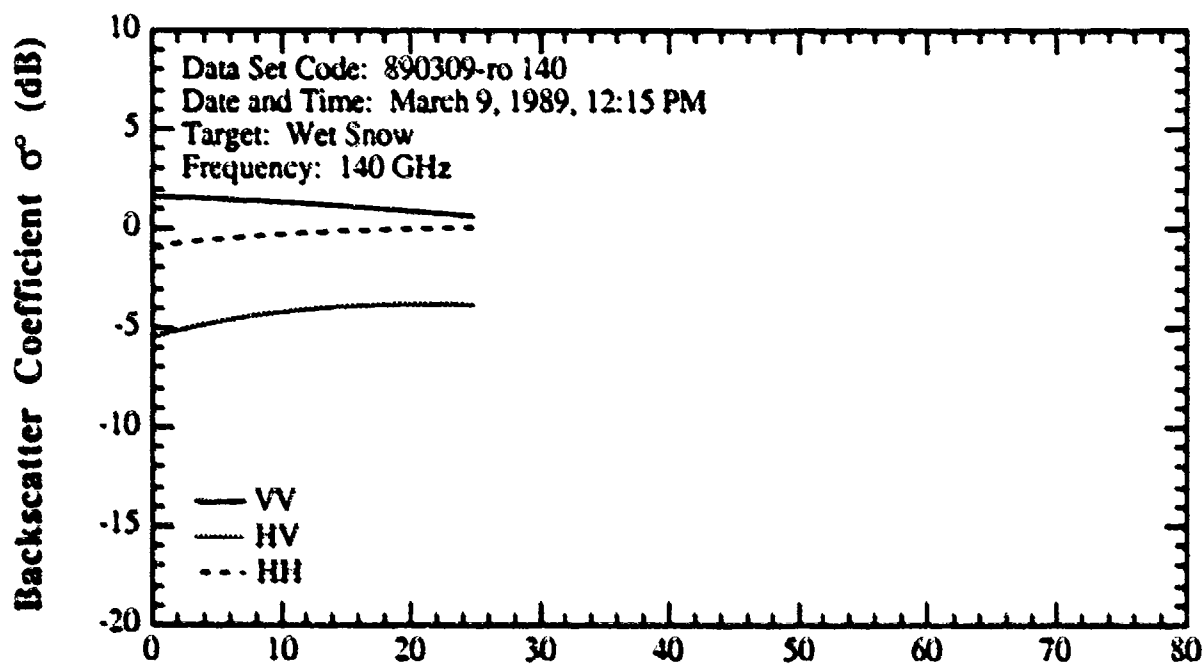


# MMW DATA FOR WET SNOW

890309(RO)



Wet rough metamorphosed snow at Brighton

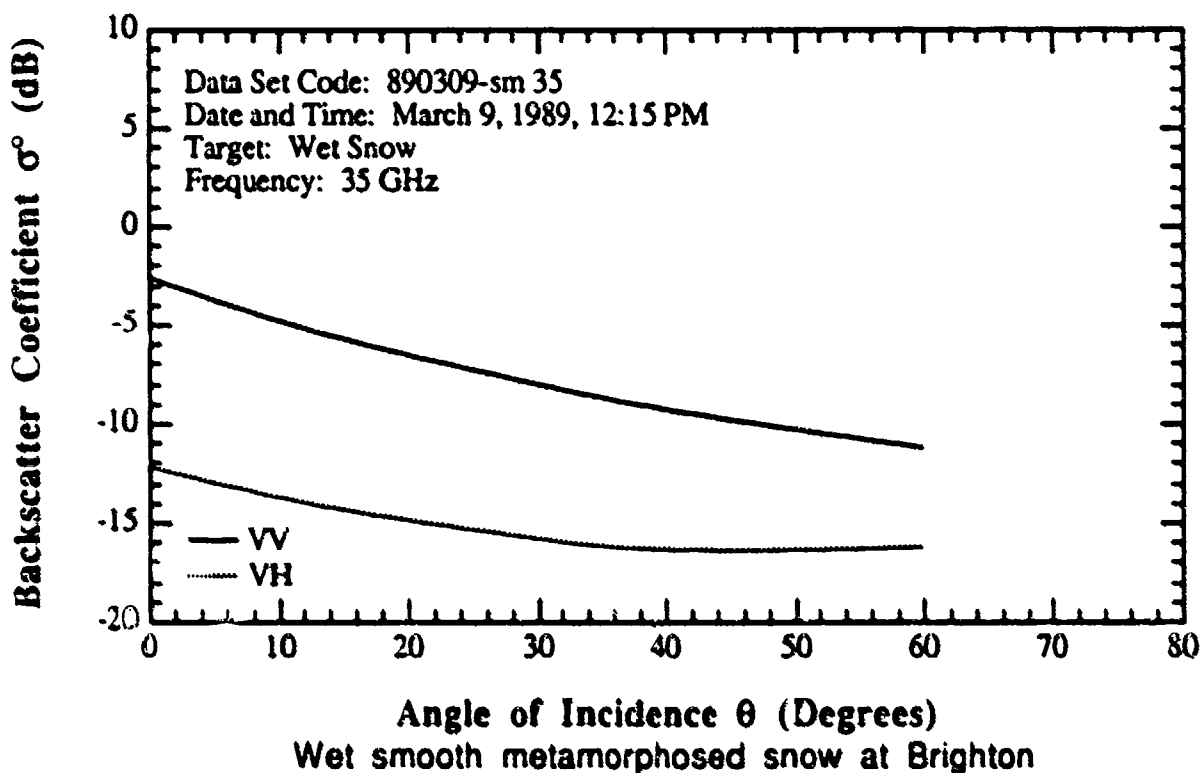


Wet rough metamorphosed snow at Brighton

### E. Very Wet Snow with Smooth Surface

Data set code: 890309(SM)  
Depth: 4.0 cm  
LWC (at 2:30 PM): 16.89 %  
LWC (at 3:09 PM): 15.47 %  
Surface RMS height: 0.30 cm  
Density: 0.42 gm/cm<sup>3</sup>  
Ice crystal diameter: 2 to 4 mm  
Surface temperature: 4 to 6 C  
Description: wet, smooth snow

890309(SM)



#### 4. MMW DIURNAL DATA FOR SNOW

A. 31 March 1988

Snow

Data set code: 880331

Depth: ~ 71 cm

LWC: 0 to 10.2 %

Smooth surface RMS height: 0.49 cm

Slightly rough surface RMS height: 0.88 cm

Very rough surface RMS height: 1.98 cm

Density: surface: 0.39

15 cm depth: 0.50 gm/cm<sup>3</sup>

30 cm depth: 0.54 gm/cm<sup>3</sup>

45 cm depth: 0.53 gm/cm<sup>3</sup>

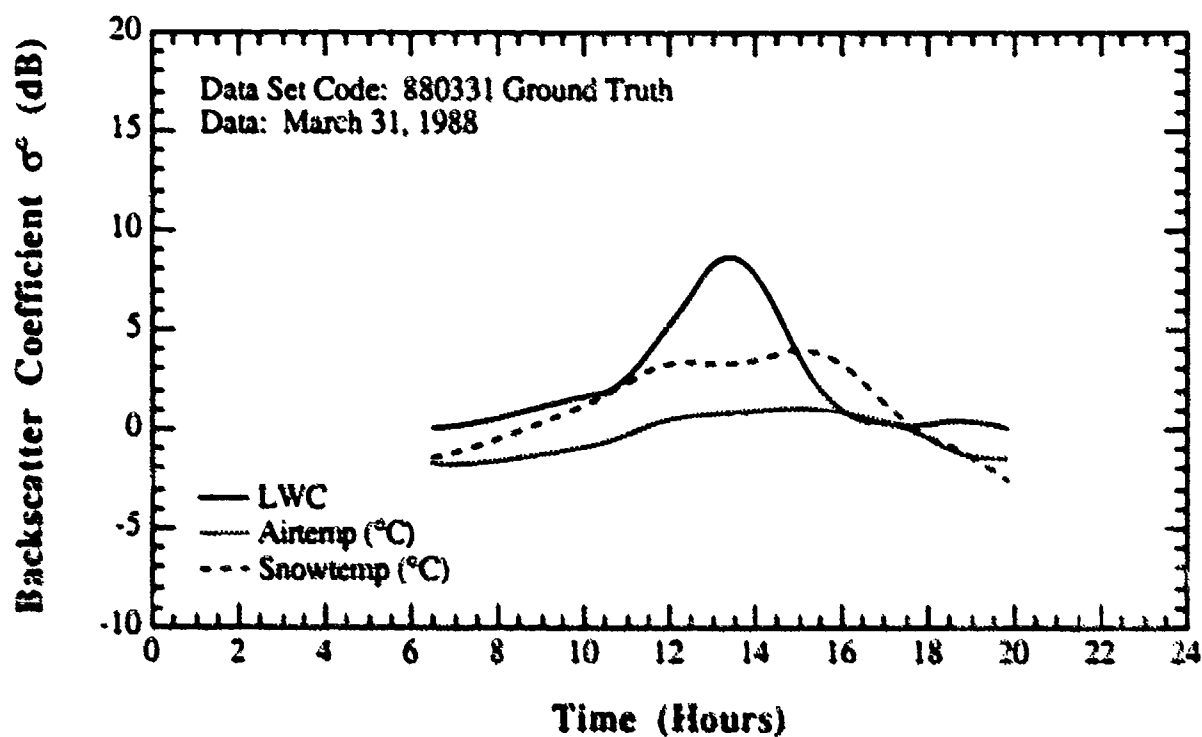
60 cm depth: 0.58 gm/cm<sup>3</sup>

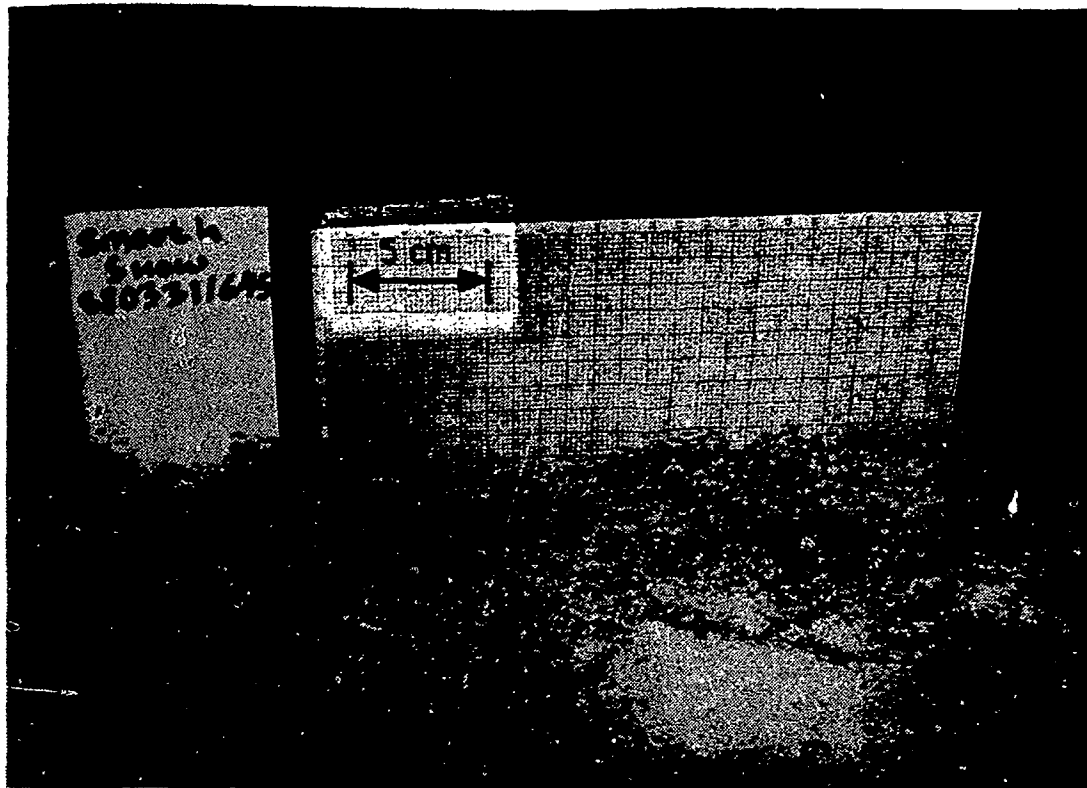
71 cm depth (ground): 0.65 gm/cm<sup>3</sup>

Ice crystal diameter: 0.5 to 1mm

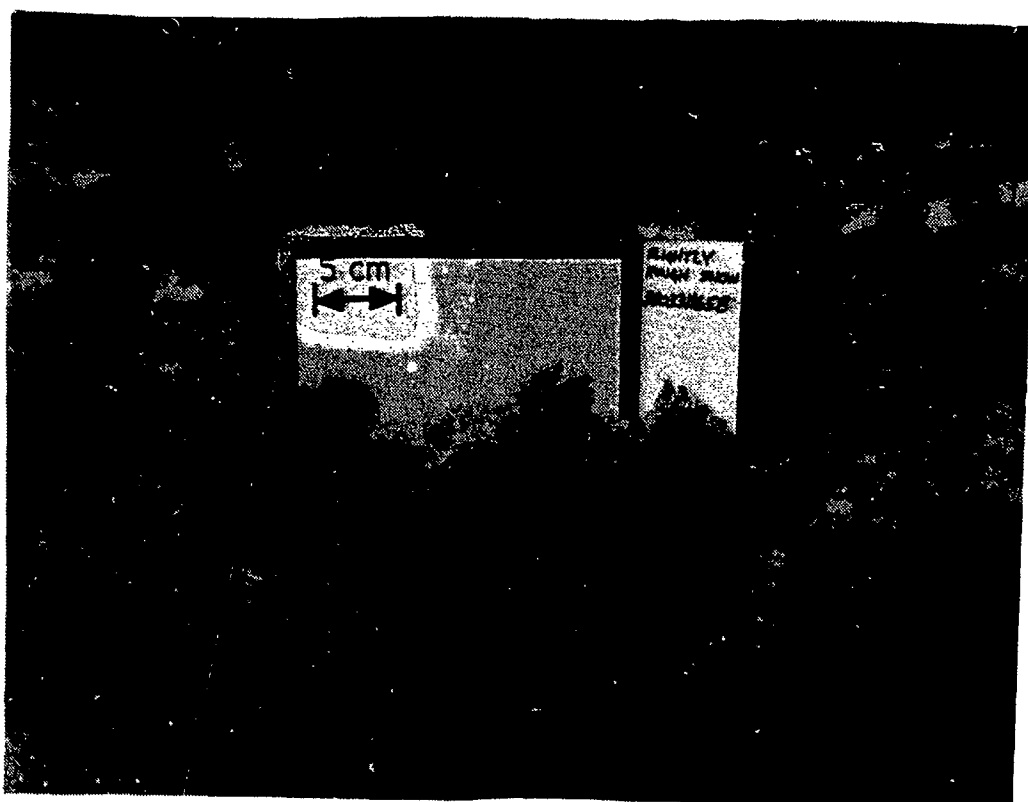
Surface temperature: -2.7 C to 4.5 C

Description: metamorphosed snow divided into three sections, one natural surface (smooth), and two with roughened surfaces.

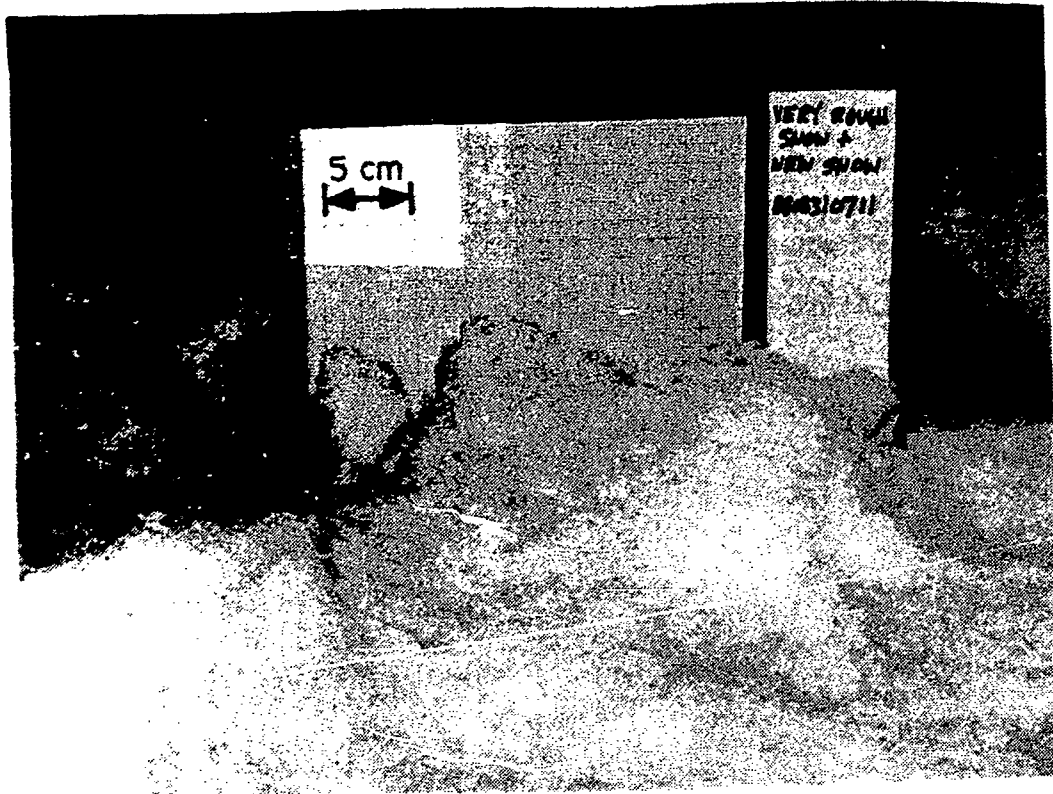




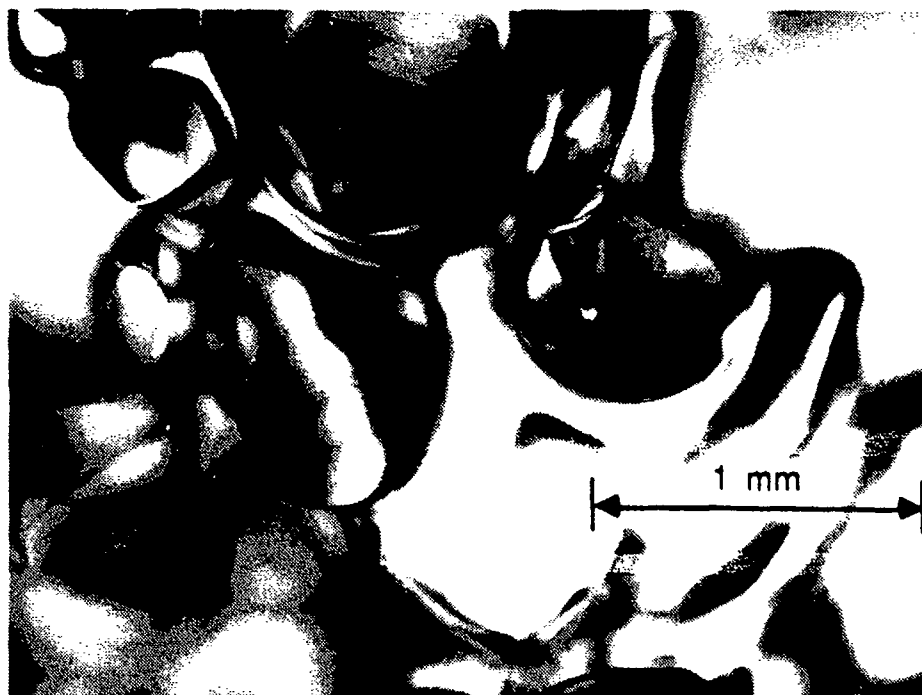
Surface roughness profile of smooth snow with 1 cm grid



Surface roughness profile of slightly rough snow with 1 cm grid



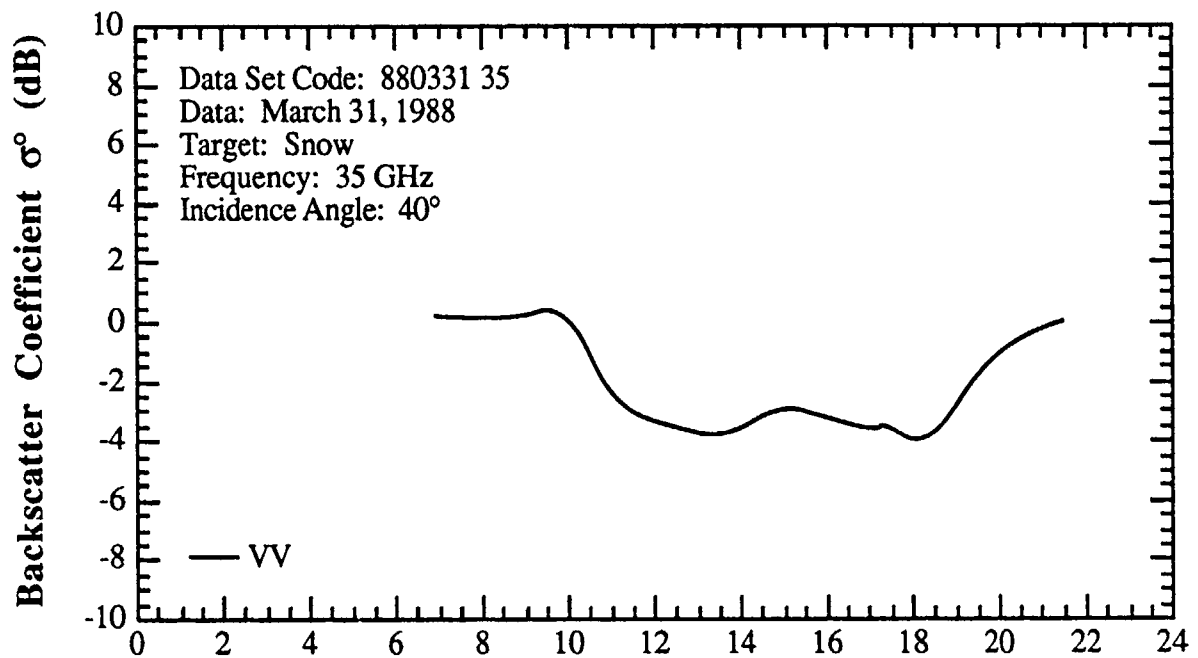
Surface roughness profile of very rough snow with 1 cm grid



Snow crystals from surface

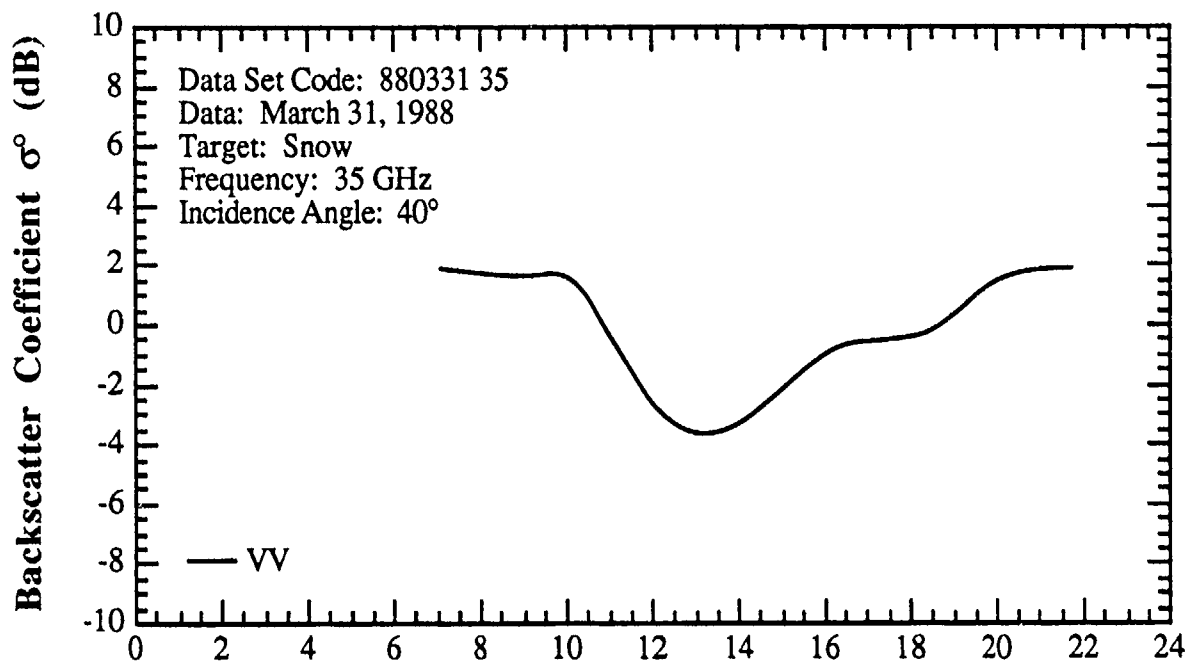
# MMW DIURNAL DATA FOR SNOW

880331



Time (Hours)

Houghton snow with smooth surface

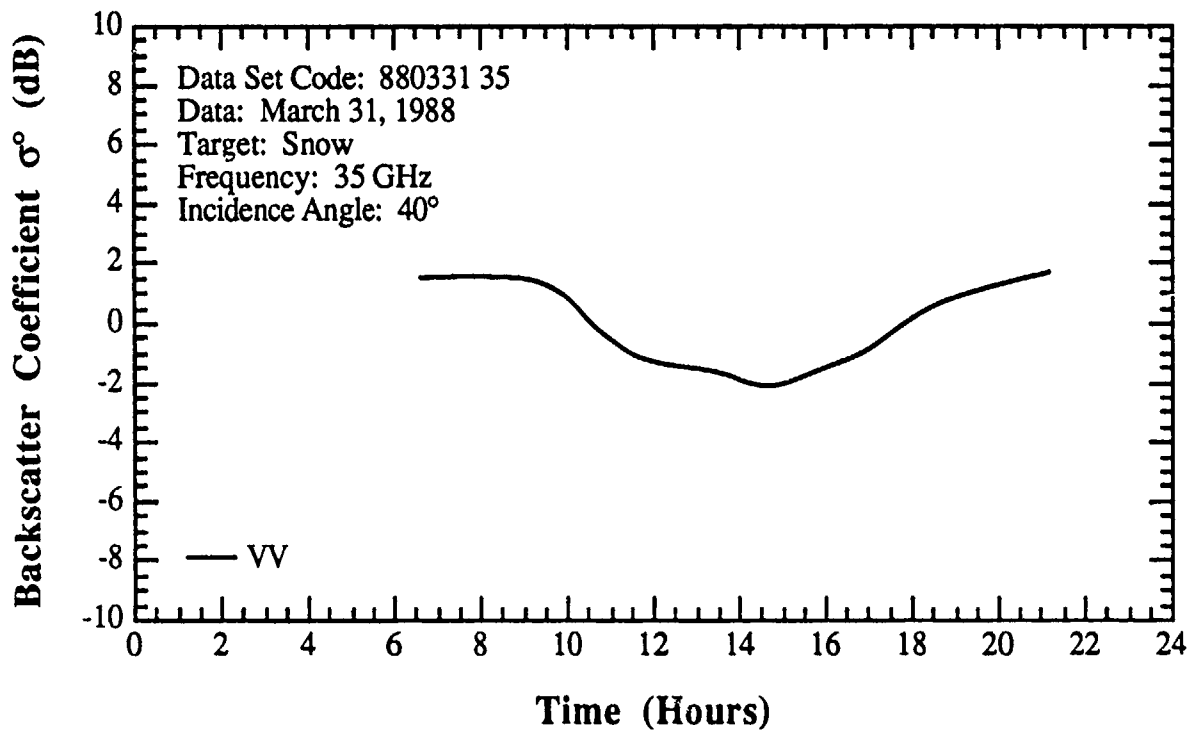


Time (Hours)

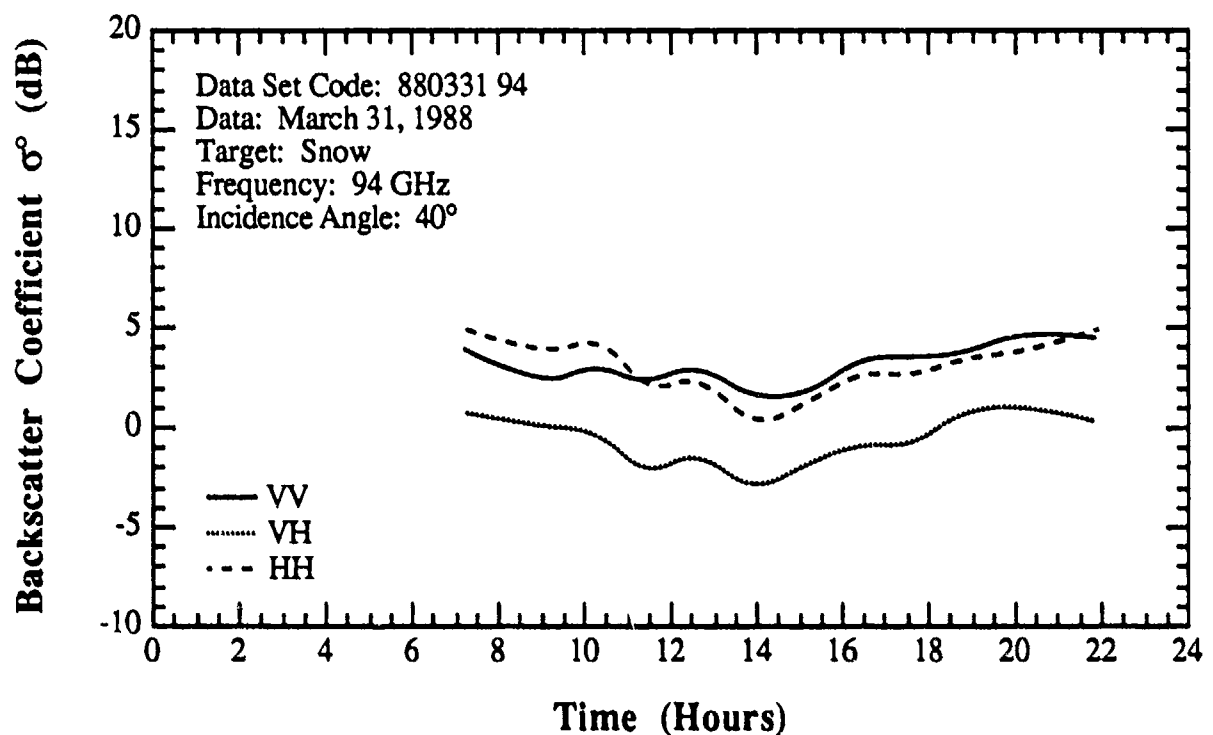
Houghton snow with slightly rough surface

# MMW DIURNAL DATA FOR SNOW

880331



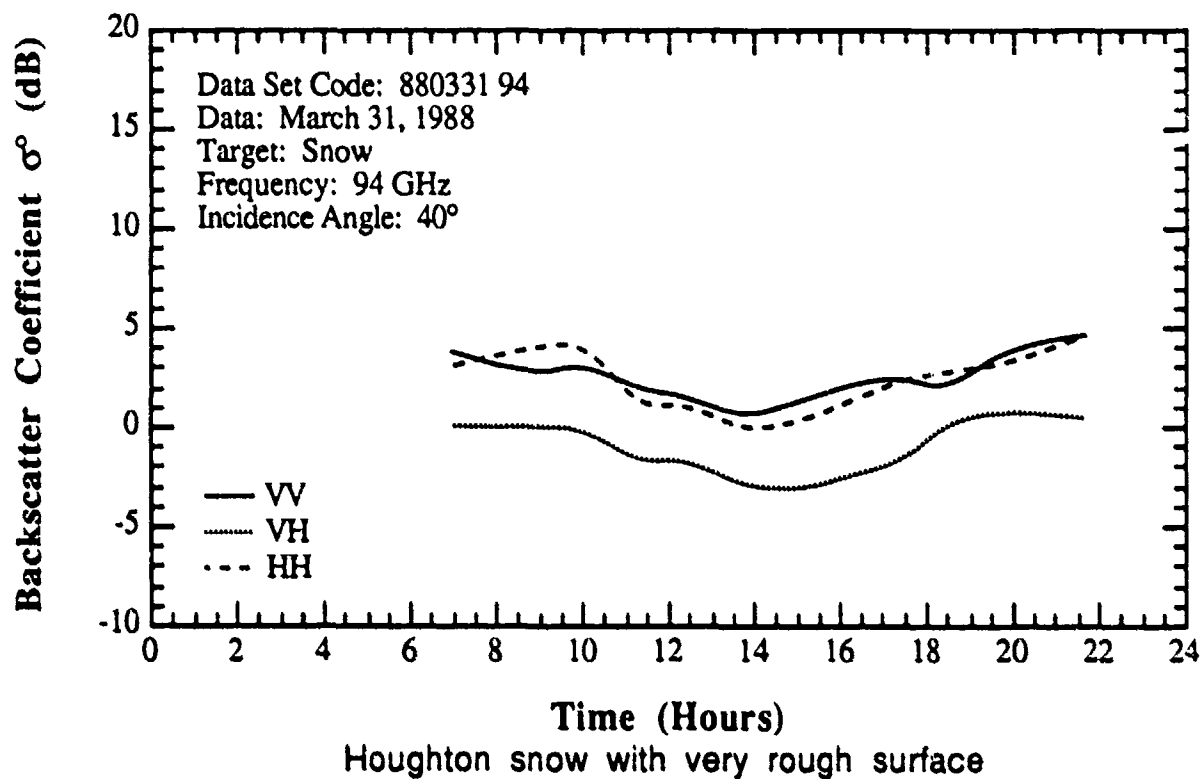
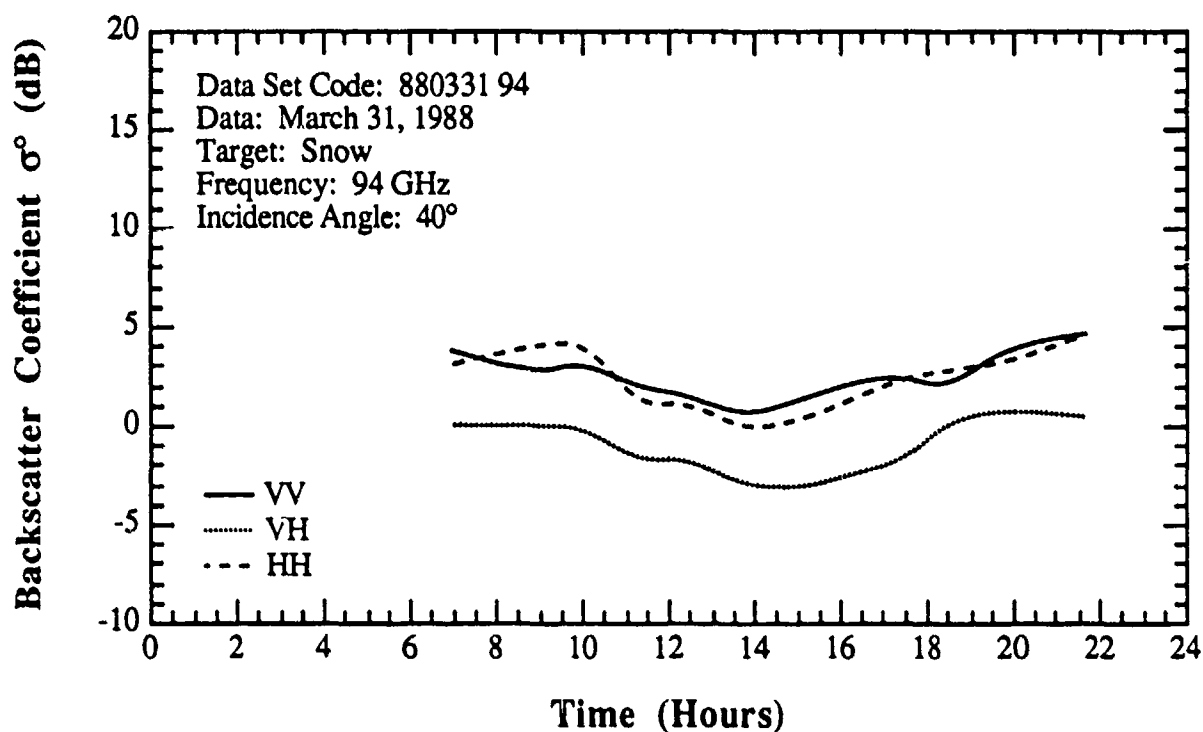
Houghton snow with very rough surface



Houghton snow with smooth surface

# MMW DIURNAL DATA FOR SNOW

880331



B. 27 February, 1989

Snow

Data set code: 890227/28

Depth: 9.5 cm

LWC: 0 to 5 %

Surface RMS height: 0.1 cm

Density: 0.31 gm/cm<sup>3</sup>

Ice crystal diameter: 1 mm

Surface temperature: 0.0 C to -9.0 C

Description: partially metamorphosed snow

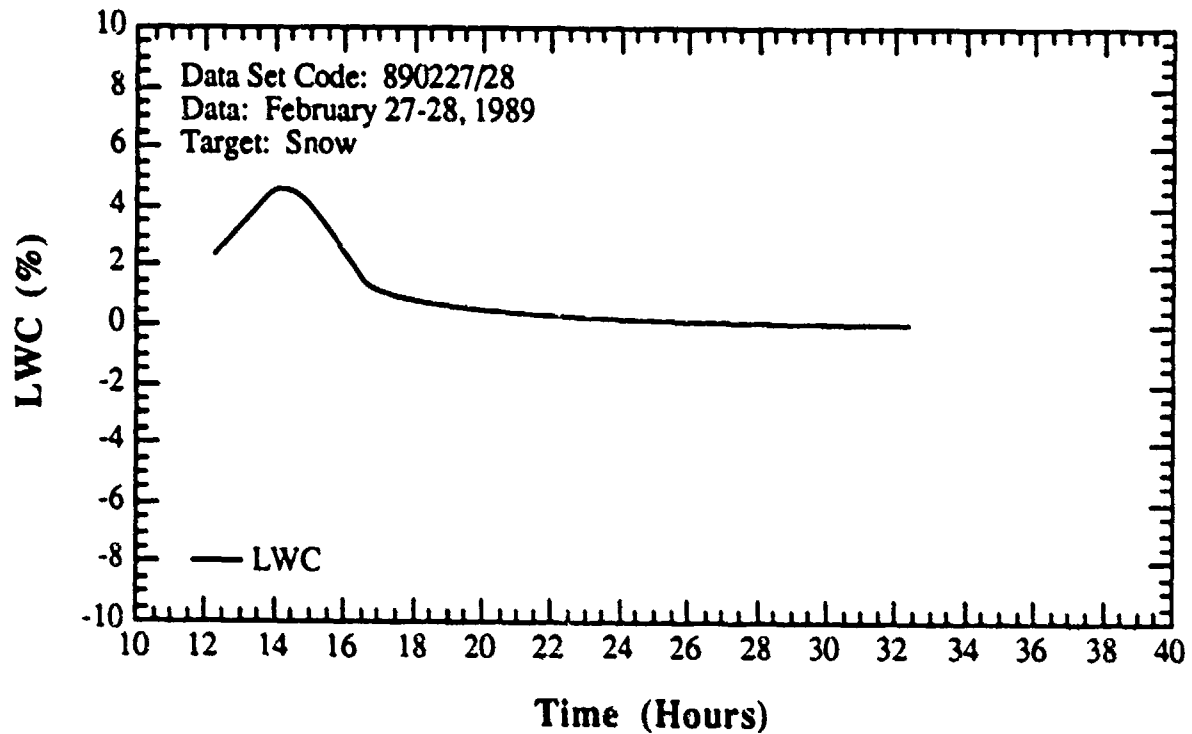
890227/28

SNOW PIT TEMPERATURE PROFILE (°C)

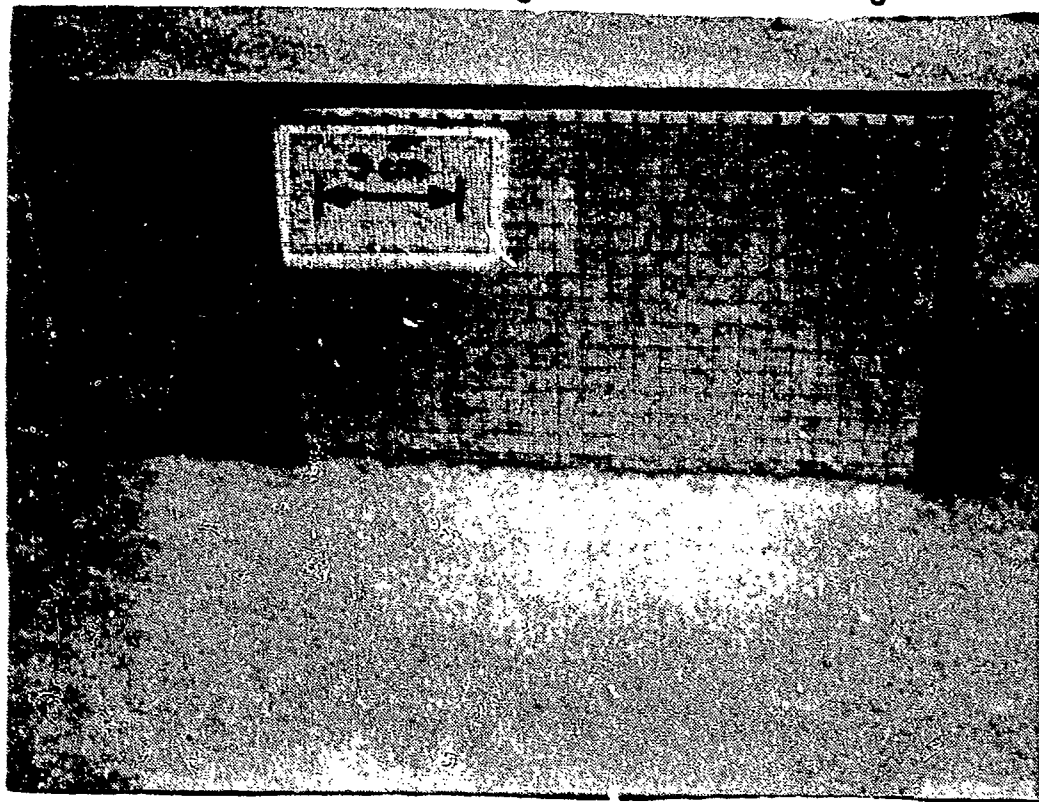
| Time     | 1400 | 1445 | 1540 | 1655 | 1800 | 1900 | 2100 | 2302 | 0100 | 0300 | 0500 | 0605 | 0803 |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Top 9.5  |      |      | 0.0  | -2.0 | -4.0 | -3.5 | -6.5 | -6.5 | -6.3 | -3.5 | -9.0 | -7.5 | -7.0 |
| 9        |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 8        | 0.0  | 0.0  |      |      |      |      |      |      |      |      |      |      |      |
| 7        |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 6        |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 5        | -0.6 | -0.3 | -0.3 | -0.5 | -1.1 | -4.0 | -5.5 | -5.5 | -4.0 | -5.0 | -6.5 | -4.5 | -5.7 |
| 4        |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 3        |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 2        |      |      |      |      |      |      |      |      |      |      |      |      |      |
| 1        |      |      |      |      |      |      |      |      |      |      |      |      |      |
| bottom   | -0.6 | -0.7 | -0.6 | -1.0 | -0.6 | -3.6 | -4.0 | -4.0 | -3.5 | -4.5 | -5.5 | -3.5 | -3.8 |
| air temp | -3.5 | -3.3 | -3.0 | -3.2 | -5.1 | -8.5 | -8.0 | -6.8 | -6.5 | -10. | -11. | -9.2 | -7.0 |

# MMW DIURNAL DATA FOR SNOW

890227/28



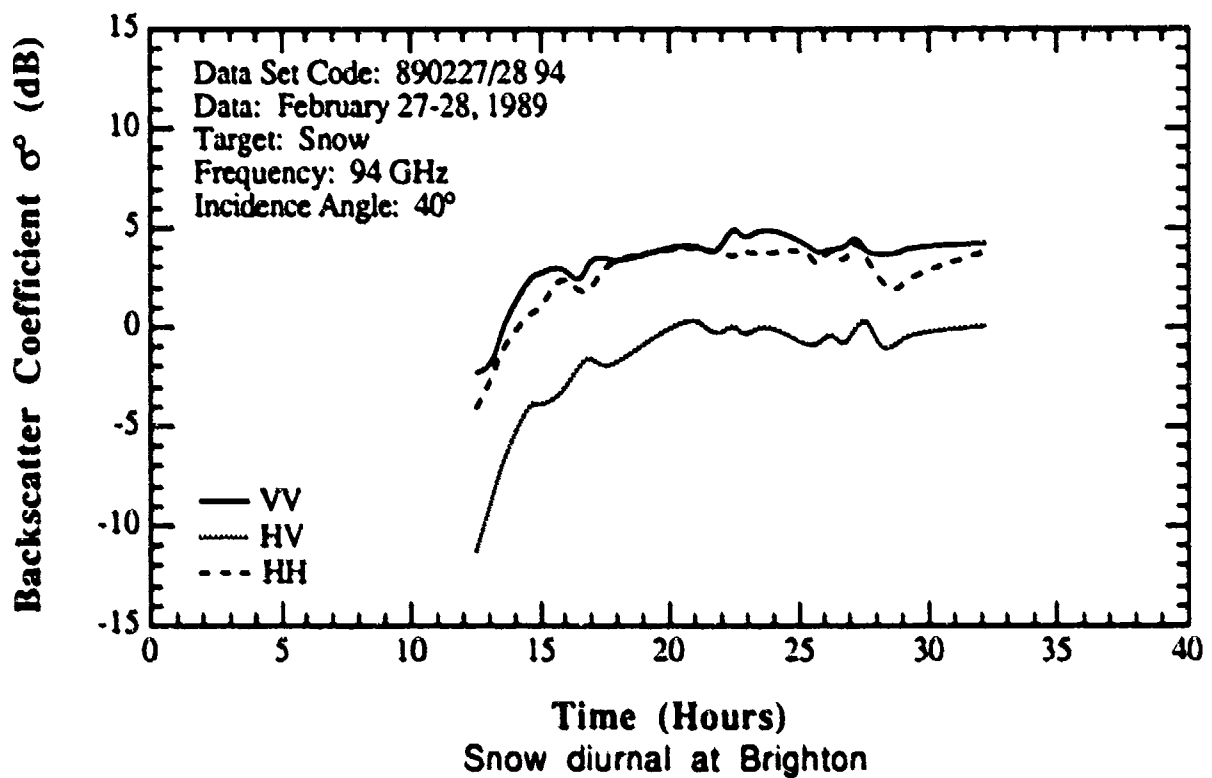
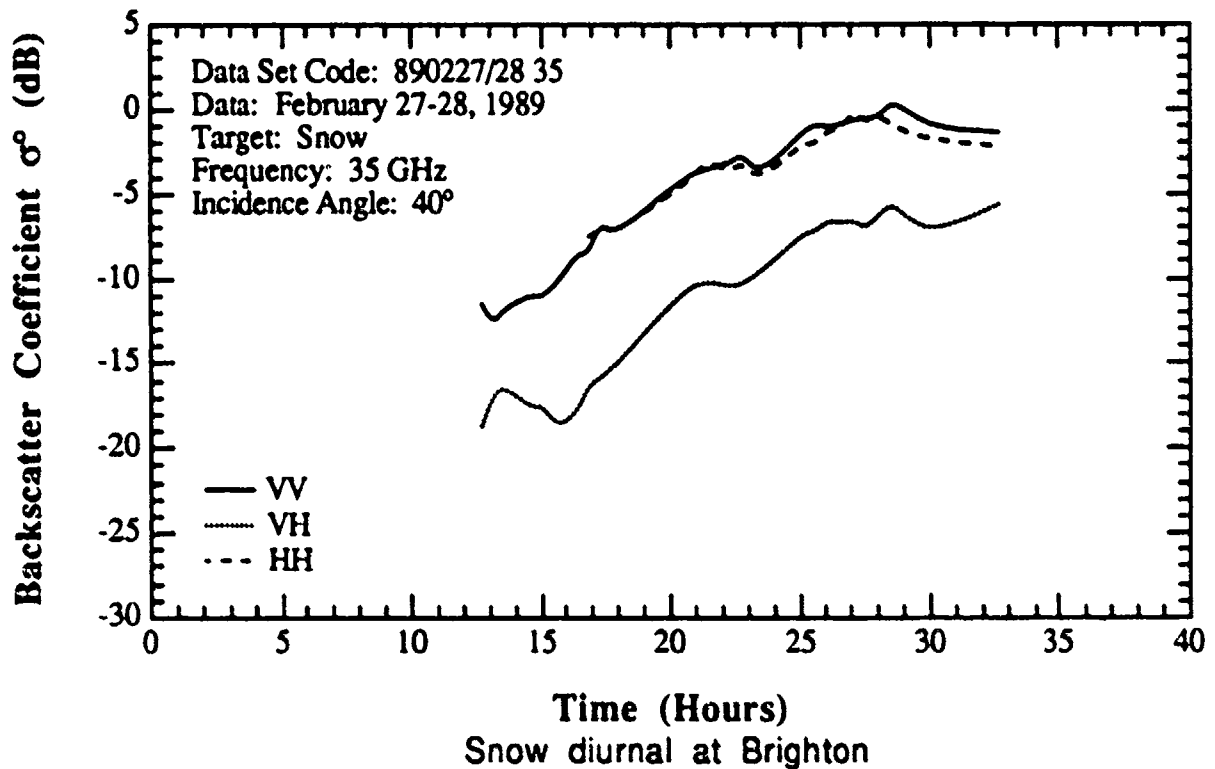
Liquid water content during snow diurnal at Brighton



Surface roughness profile with 1 cm grid

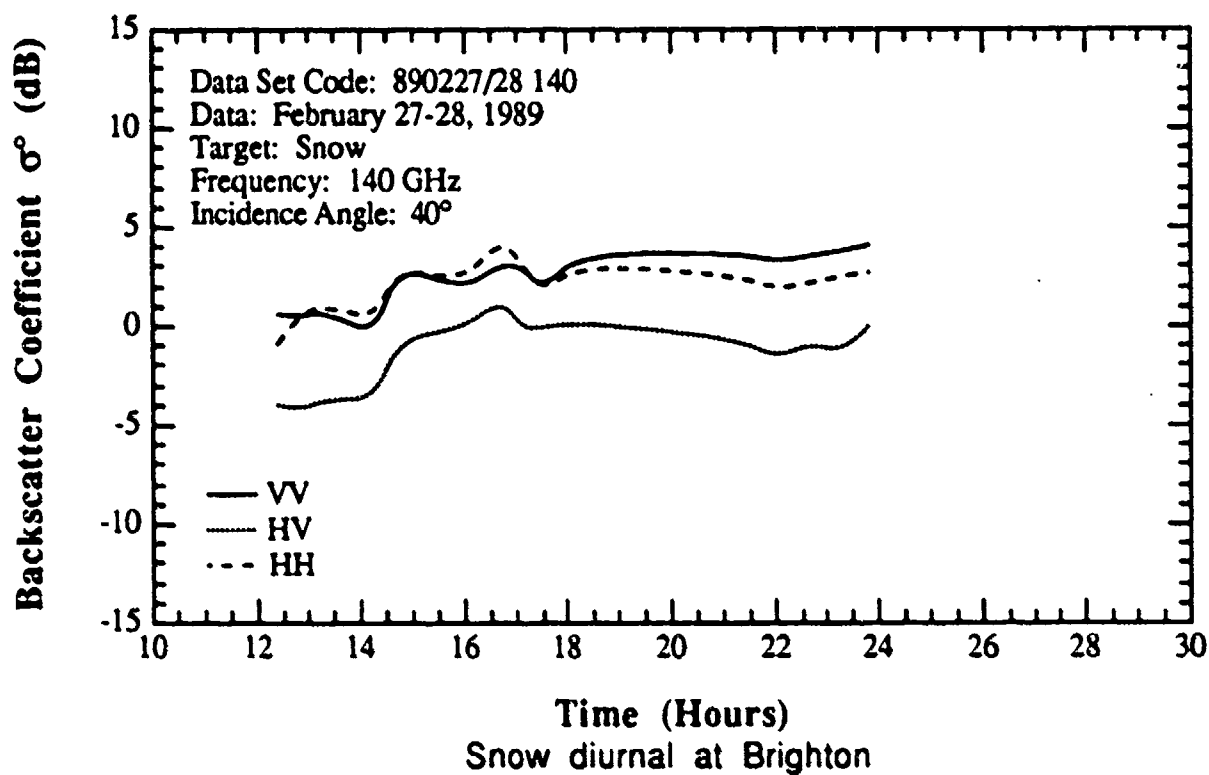
# MMW DIURNAL DATA FOR SNOW

890227/28



# MMW DIURNAL DATA FOR SNOW

890227/28



C. 2 March, 1989

Snow

Data Set code: 890302

Depth: 10 cm

LWC: 0%

Surface RMS height: 0.15 cm

Density: 0.1 to 0.2 gm/cm<sup>3</sup>

Ice crystal diameter: 2 to 2.5 mm

Surface temperature: -4 C to -5 C

Description: partially metamorphosed snow

# SNOW PIT TEMPERATURE PROFILE (°C)

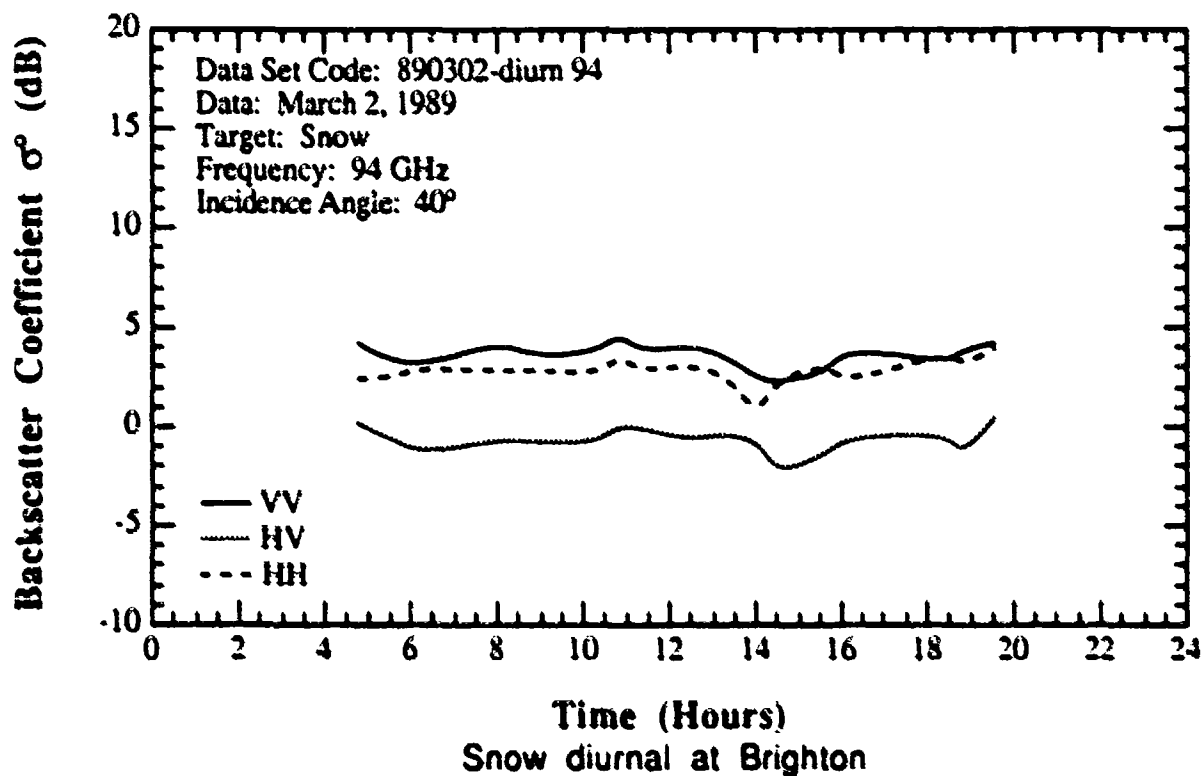
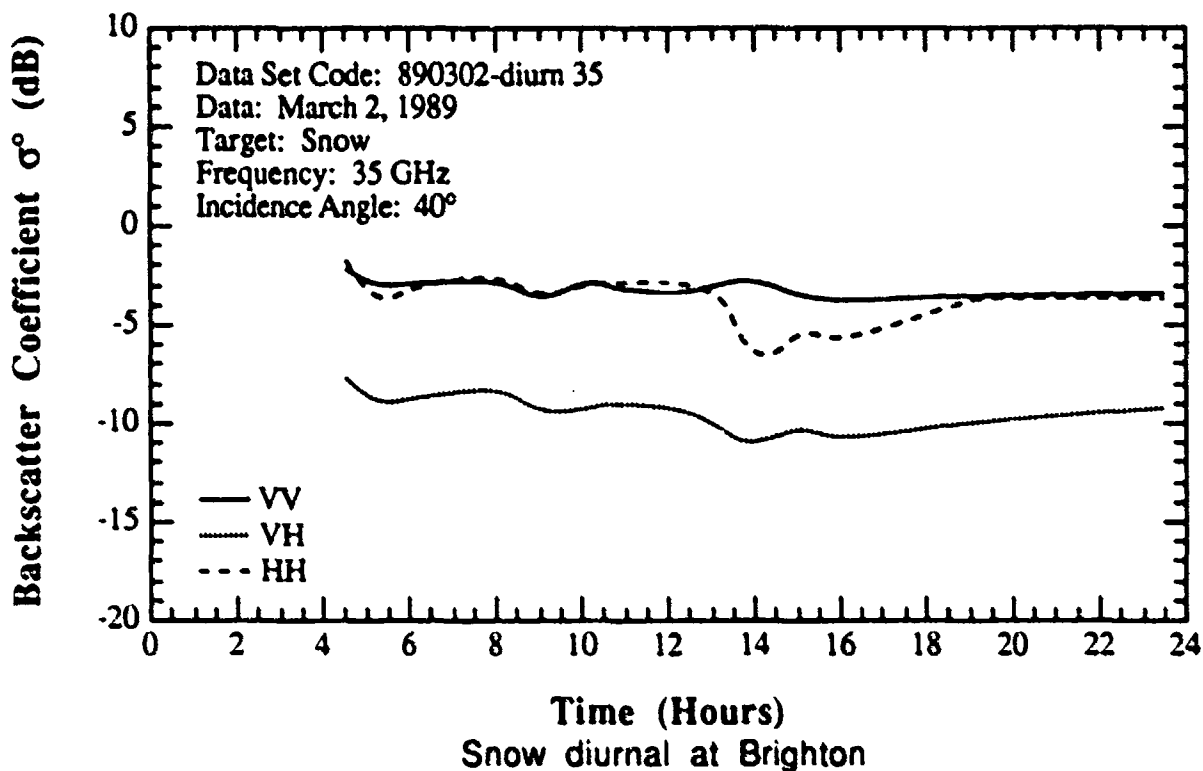
| Time       |        | 0400  | 0500  | 0600  | 0700  | 0800  | 0900 | 1000 | 1100 | 1200 | 1300 | 1400 | 1500 | 1600 |
|------------|--------|-------|-------|-------|-------|-------|------|------|------|------|------|------|------|------|
| depth (cm) | Top 10 | -4.0  | -5.0  | -5.0  | -5.0  | -5.0  | -4.0 | -4.0 | -3.0 | -3.0 | -2.0 | -2.0 | -2.0 | -1.9 |
|            | 9      |       |       |       |       |       |      |      |      |      |      |      |      |      |
|            | 8      |       |       |       |       |       |      |      |      |      |      |      |      |      |
|            | 7      |       |       |       |       |       |      |      |      |      |      |      |      |      |
|            | 6      |       |       |       |       |       |      |      |      |      |      |      |      |      |
|            | 5      | -7.0  | -7.0  | -6.0  | -6.0  | -6.0  | -5.0 | -4.0 | -3.0 | -3.0 | -1.5 | -1.0 | -1.8 | -1.7 |
|            | 4      |       |       |       |       |       |      |      |      |      |      |      |      |      |
|            | 3      |       |       |       |       |       |      |      |      |      |      |      |      |      |
|            | 2      |       |       |       |       |       |      |      |      |      |      |      |      |      |
|            | 1      |       |       |       |       |       |      |      |      |      |      |      |      |      |
| bottom     |        | -13.0 | -11.0 | -10.0 | -10.0 | -8.5  | -6.0 | -4.0 | -1.0 | -1.0 | -0.5 | -0.0 | -1.5 | -1.5 |
| air temp   |        | -15.0 | -13.5 | -13.0 | -12.0 | -10.0 | -6.0 | -5.0 | -5.0 | -5.0 | -3.5 | -4.0 | -4.5 | -5.0 |

| Time       |        | 1700 | 1800 | 1900 | 2100 | 1400 | 1500 | 1600 | 1700 | 1800 | 1900 | 2100 |
|------------|--------|------|------|------|------|------|------|------|------|------|------|------|
| depth (cm) | Top 10 | -2.8 | -3.7 | -4.0 | -5.0 | -2.0 | -2.0 | -1.9 | -1.9 | -3.7 | -4.0 | -5.0 |
|            | 9      |      |      |      |      |      |      |      |      |      |      |      |
|            | 8      |      |      |      |      |      |      |      |      |      |      |      |
|            | 7      |      |      |      |      |      |      |      |      |      |      |      |
|            | 6      |      |      |      |      |      |      |      |      |      |      |      |
|            | 5      | -2.3 | -2.7 | -3.1 | -3.5 | -1.0 | -1.8 | -1.7 | -1.7 | -2.7 | -3.1 | -3.5 |
|            | 4      |      |      |      |      |      |      |      |      |      |      |      |
|            | 3      |      |      |      |      |      |      |      |      |      |      |      |
|            | 2      |      |      |      |      |      |      |      |      |      |      |      |
|            | 1      |      |      |      |      |      |      |      |      |      |      |      |
| bottom     |        | -1.8 | -2.0 | -2.2 | -2.5 | -0.0 | -1.5 | -1.5 | -1.5 | -2.0 | -2.2 | -2.5 |
| air temp   |        | -5.5 | -6.0 | -6.5 | -7.5 | -4.0 | -4.5 | -5.0 | -5.0 | -6.0 | -6.5 | -7.5 |

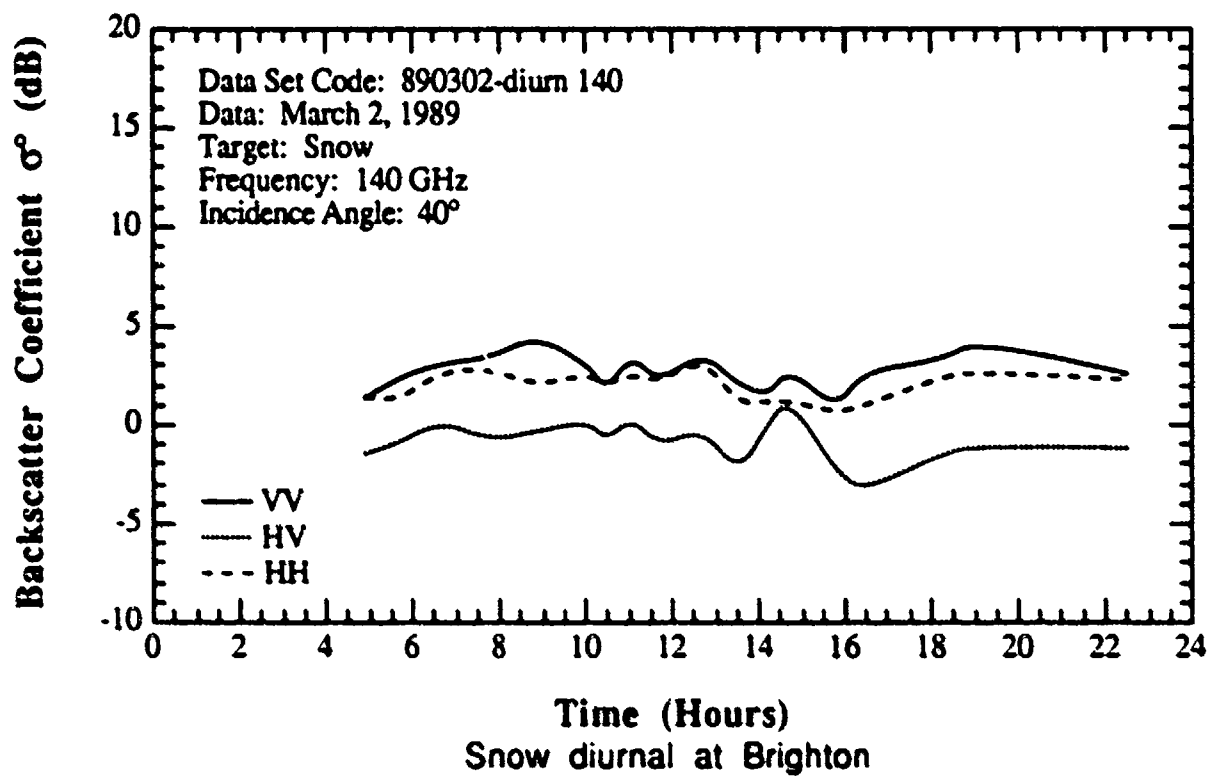
# MMW DIURNAL DATA FOR SNOW

890302



# MMW DATA FOR SNOW

890302



## 5. MMW DATA FOR ICE-COVERED GROUND

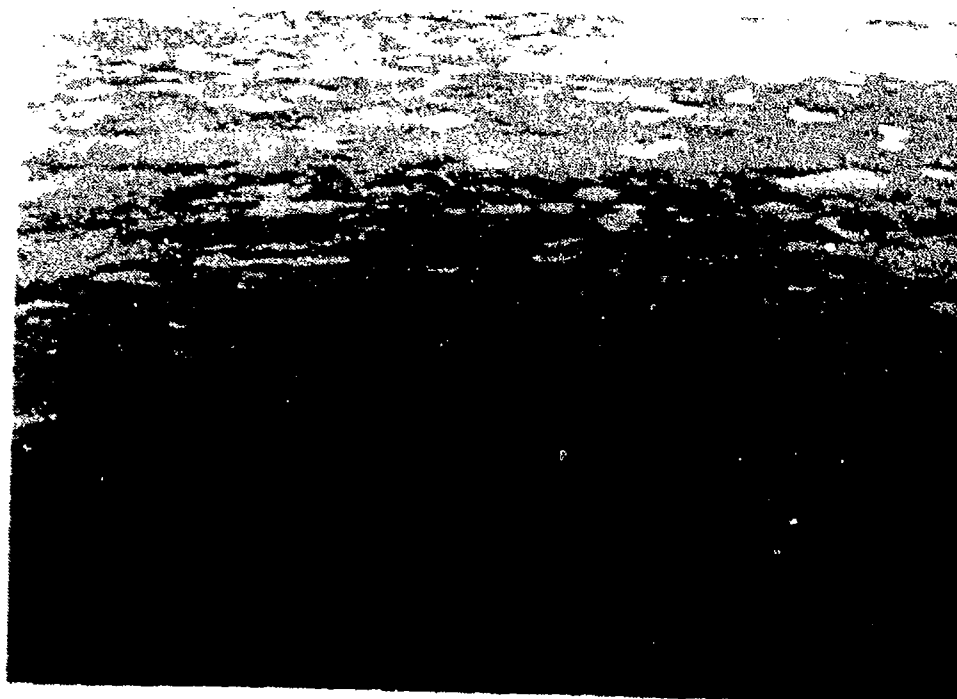
Data set code: 880308

Depth: 3 to 10 cm

Surface RMS height: 1 mm

Surface temperature: 0 C

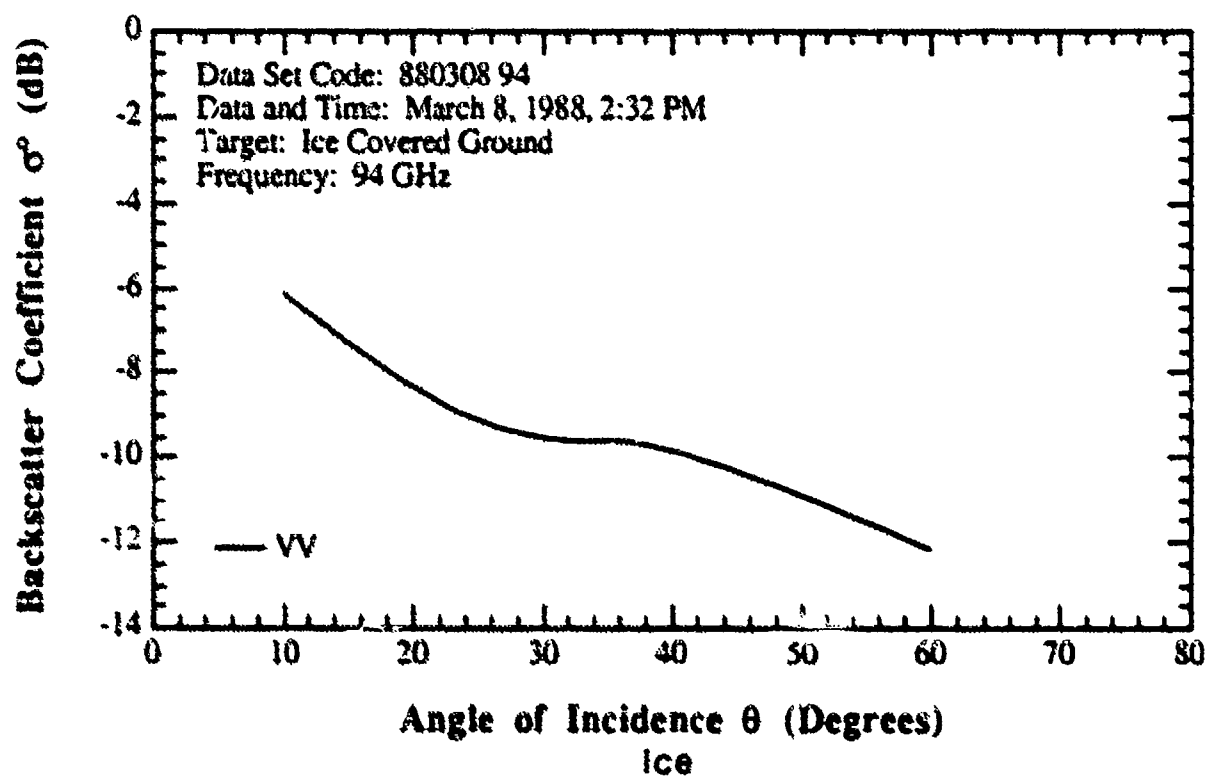
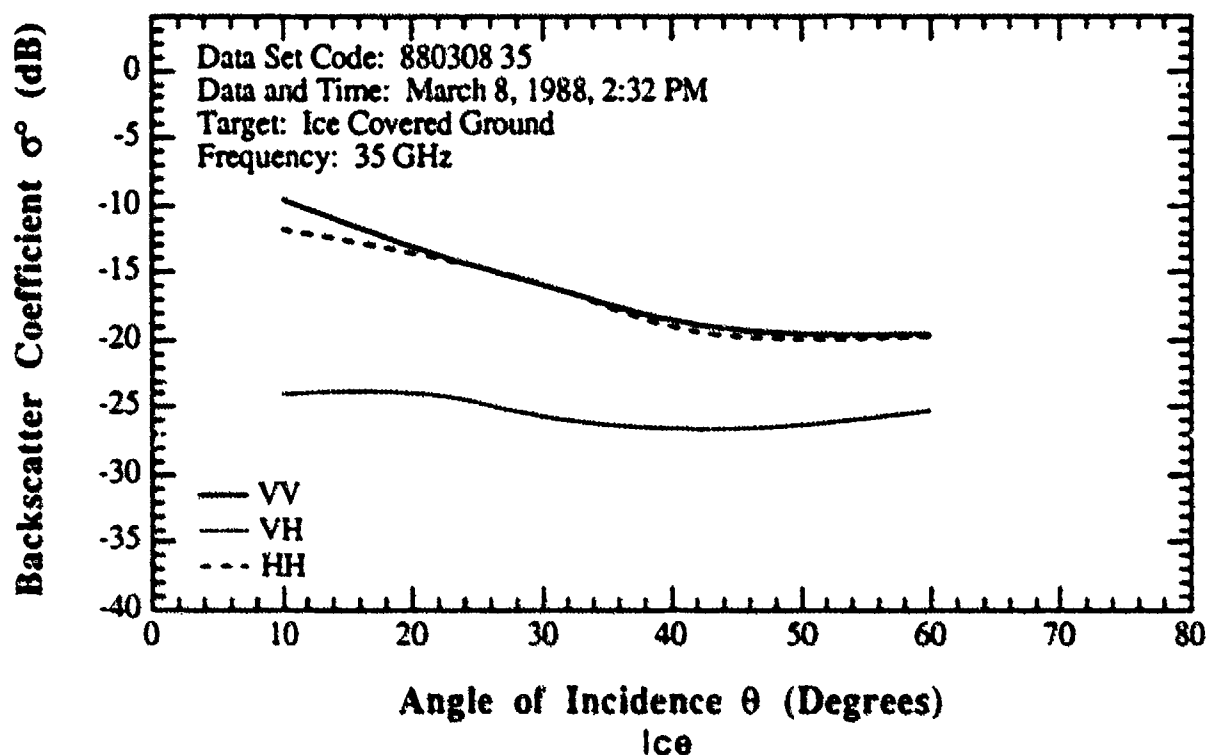
Description: ice formed by the freezing of sheet-flooded terrain, about 10% of the surface was covered by pools of water



Ice covered ground

# MMW DATA FOR ICE-COVERED GROUND

- 880308



## 6. MMW DATA FOR TREE CANOPIES

### A. Cedar Trees

Cedar trees -

Data set code: 871111

Tree density: 0.07 trees/m<sup>2</sup>

Average leaf (or needle) dimensions: ~ 2 to 3 cm

Leaf moisture content: ~ 70 %

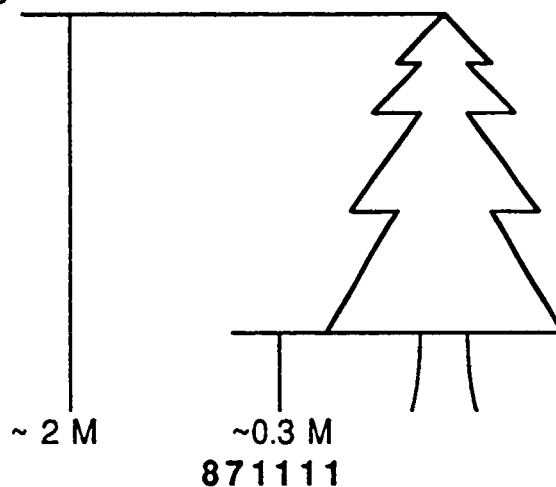
Ground cover moisture content: ~ 35 %

Percent vegetation cover: 90 %

Percent cover of undergrowth: 100%

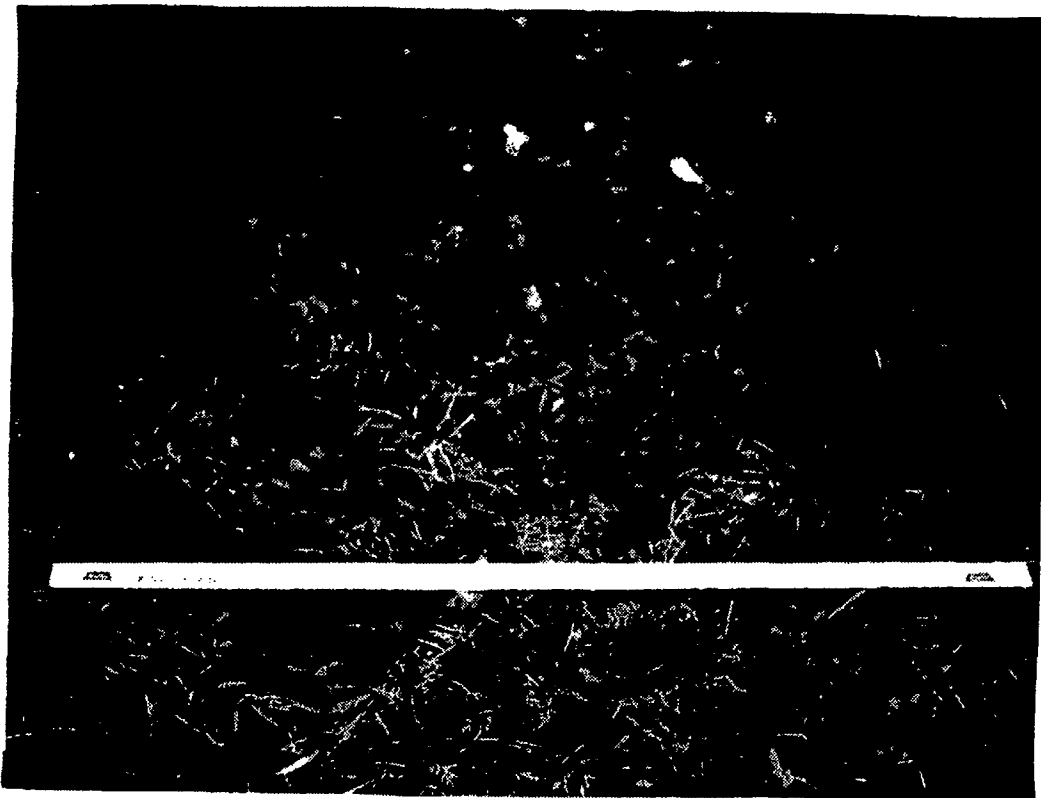
Moisture content of undergrowth: 35%

Description: Stand of mature oak trees over low ground cover





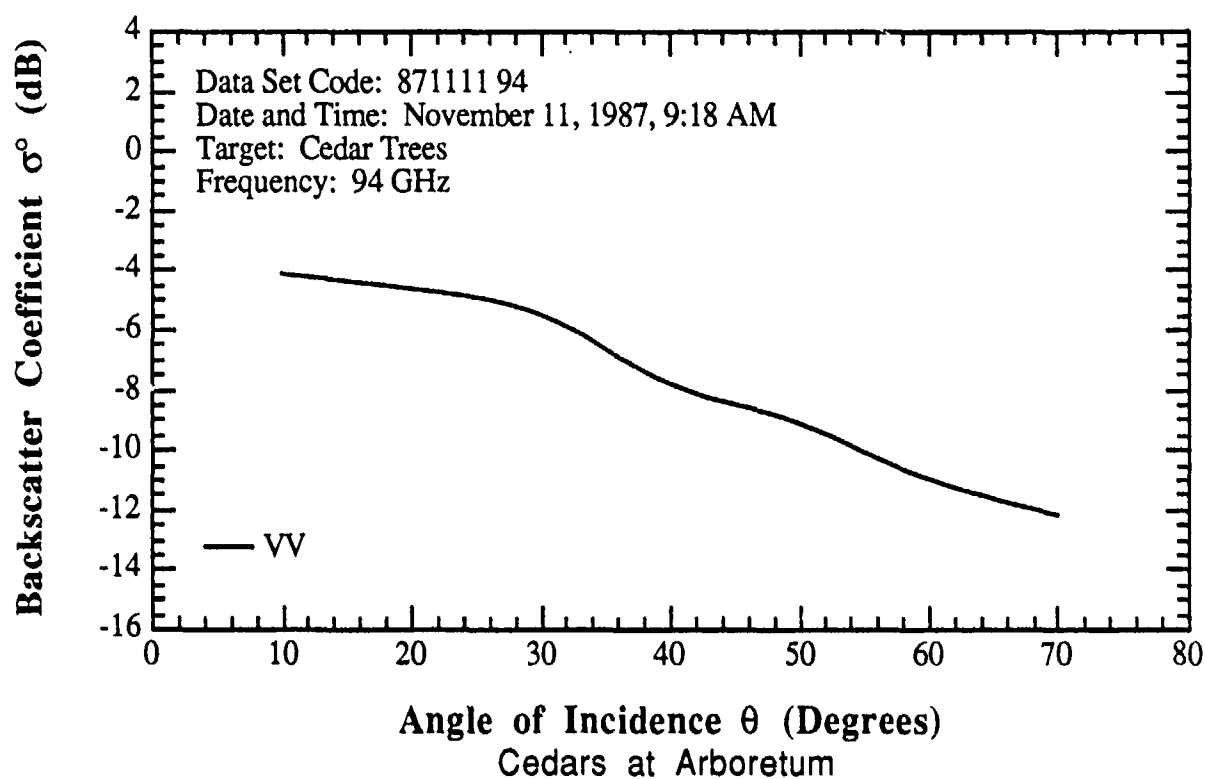
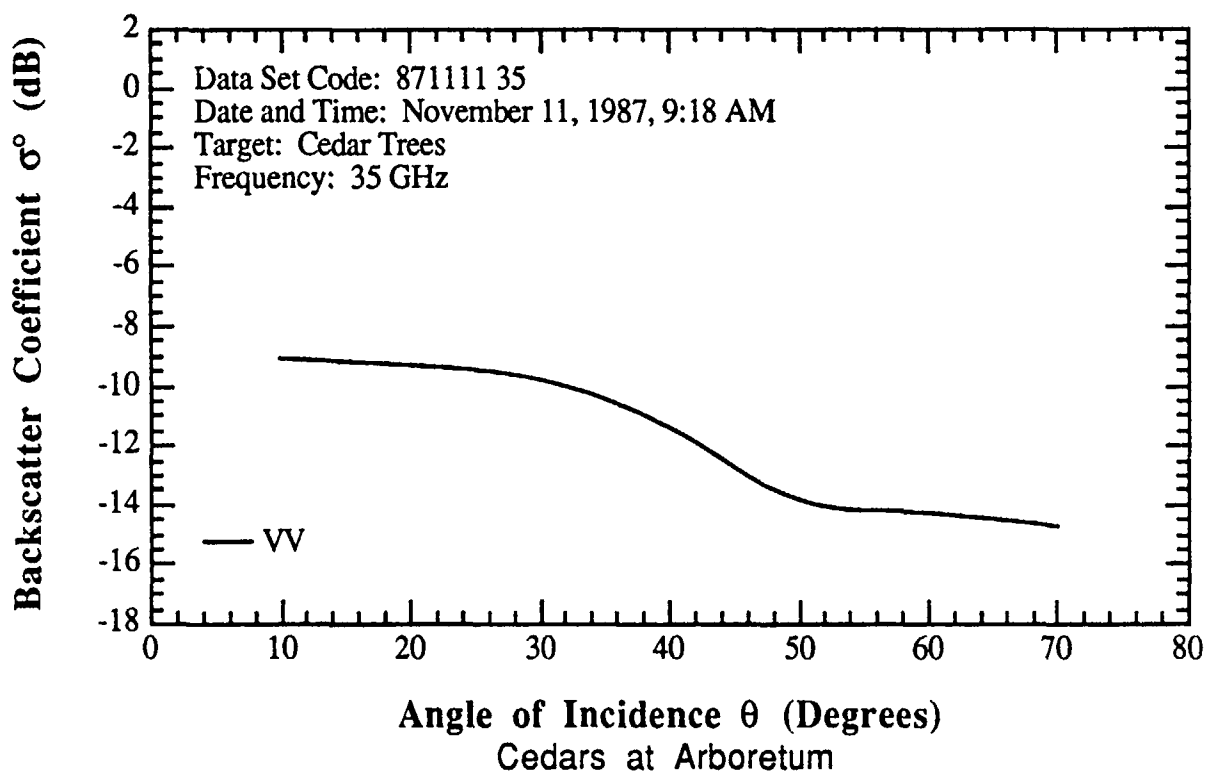
Needles of Cedar trees



Ground cover beneath Cedar trees

# MMW DATA FOR TREE CANOPIES

871111



## B. Red Pine

5 -11 November, 1987

Data set code: 871105

Tree density: 0.14 trees/m<sup>2</sup>

Average leaf (or needle) dimensions: 10 to 15 cm

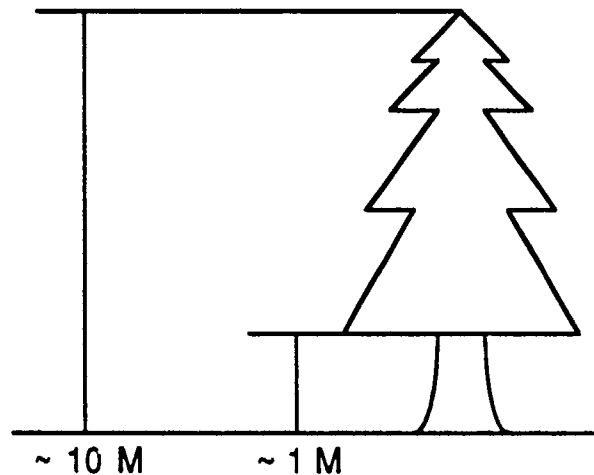
Leaf moisture content: ~70 %

Percent vegetation cover: 90 %

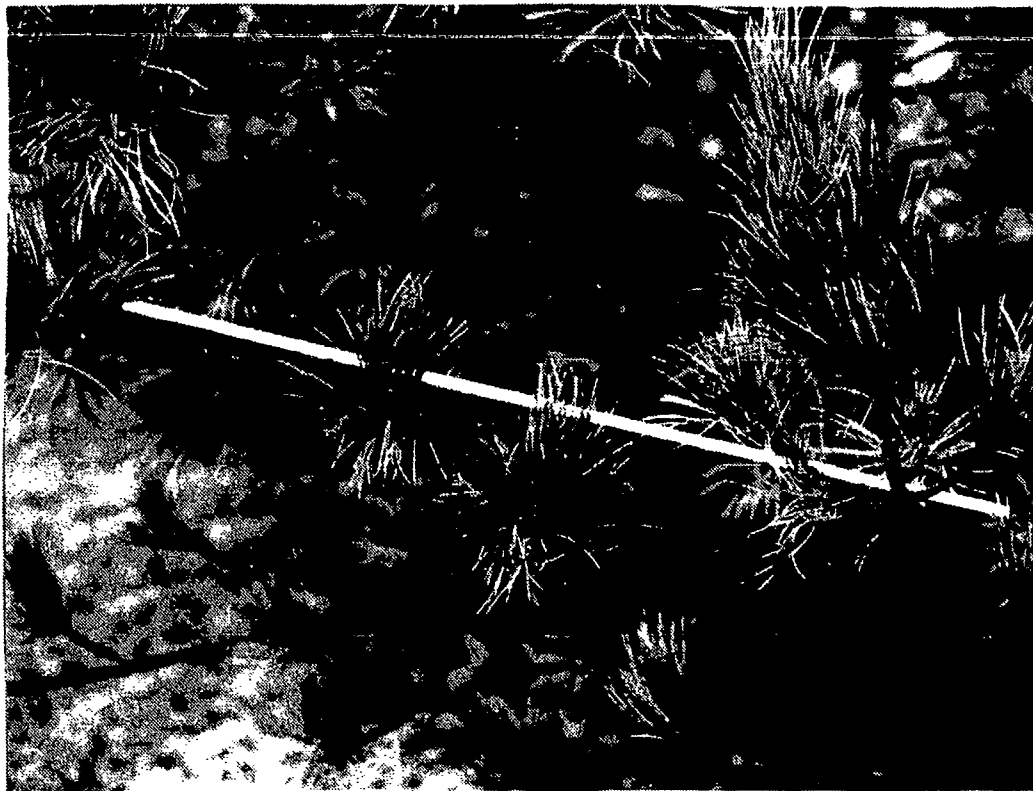
Percent cover of undergrowth: 100%

Moisture content of undergrowth: 35%

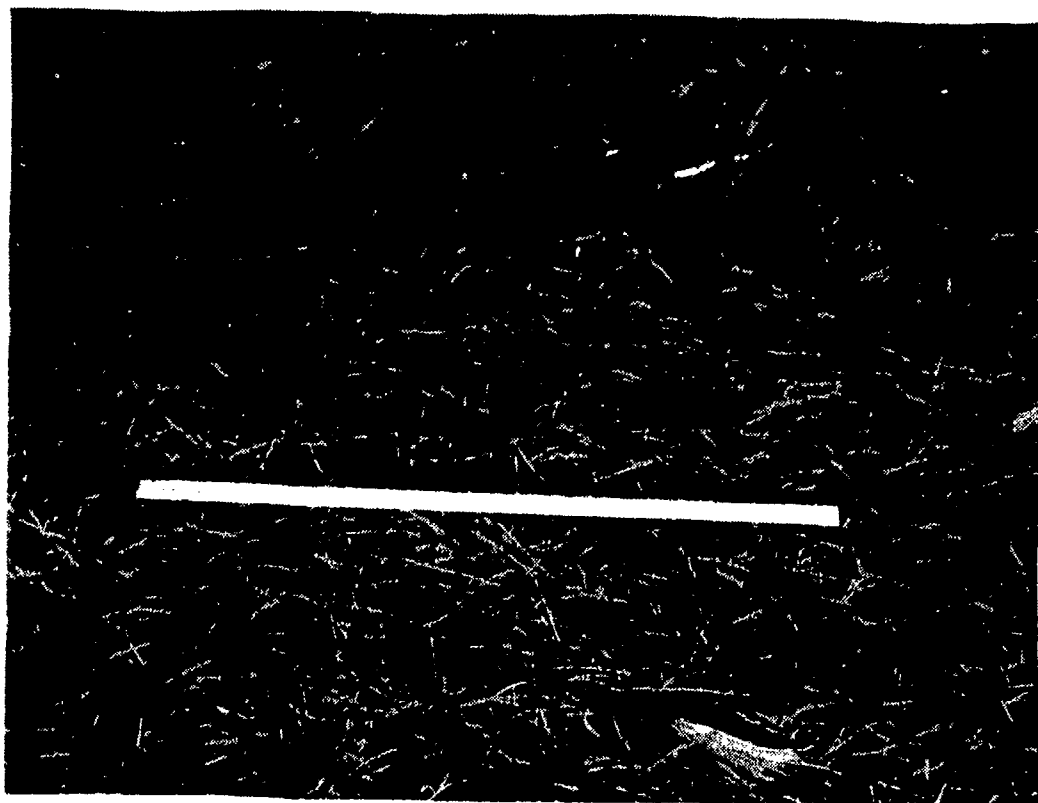
Description: Stand of mature red pines over dry, fallen needles



Red pines



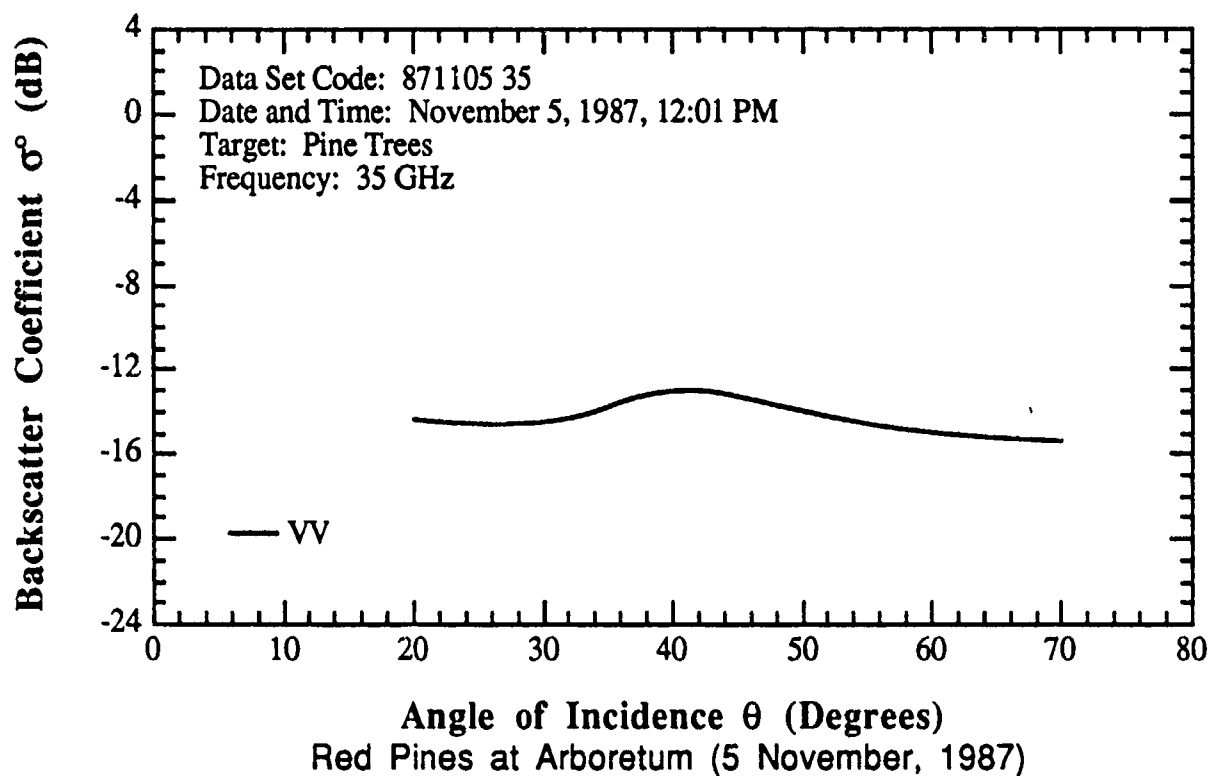
Needles of Red Pines



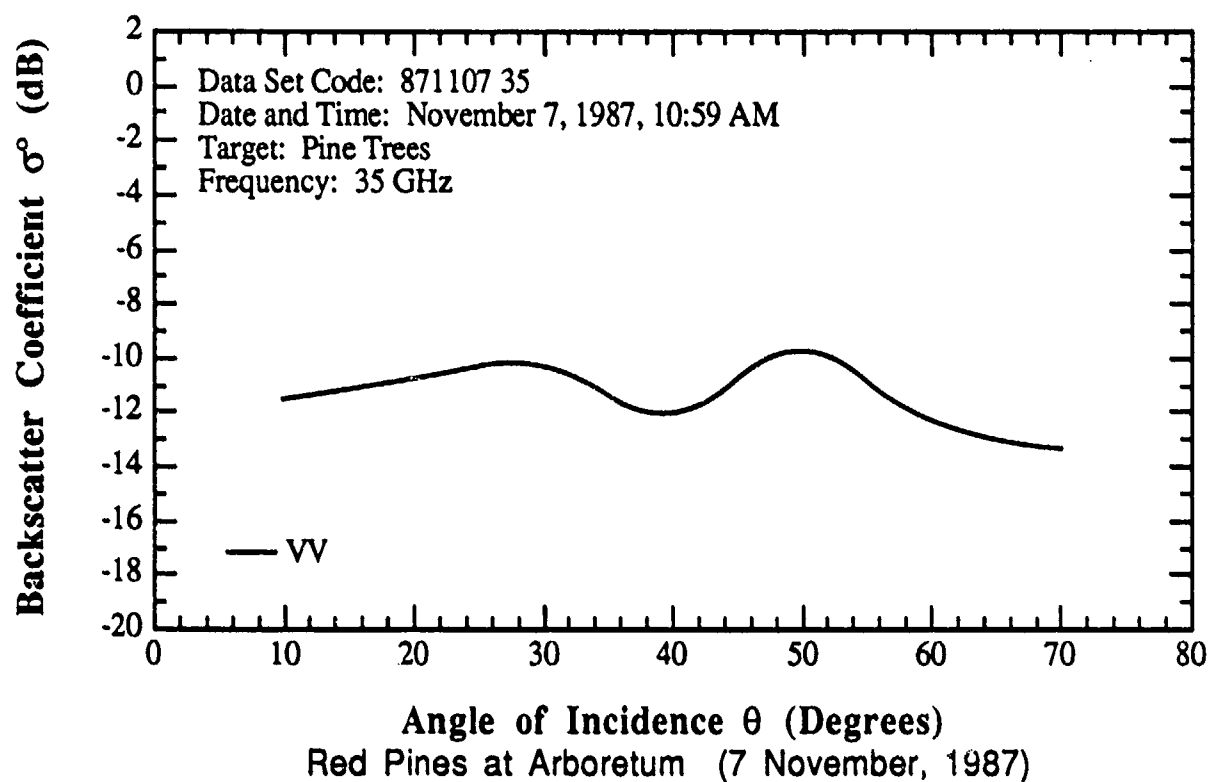
Ground cover beneath Red Pines

# MWW WAVE DATA FOR TREE CANOPIES

871105

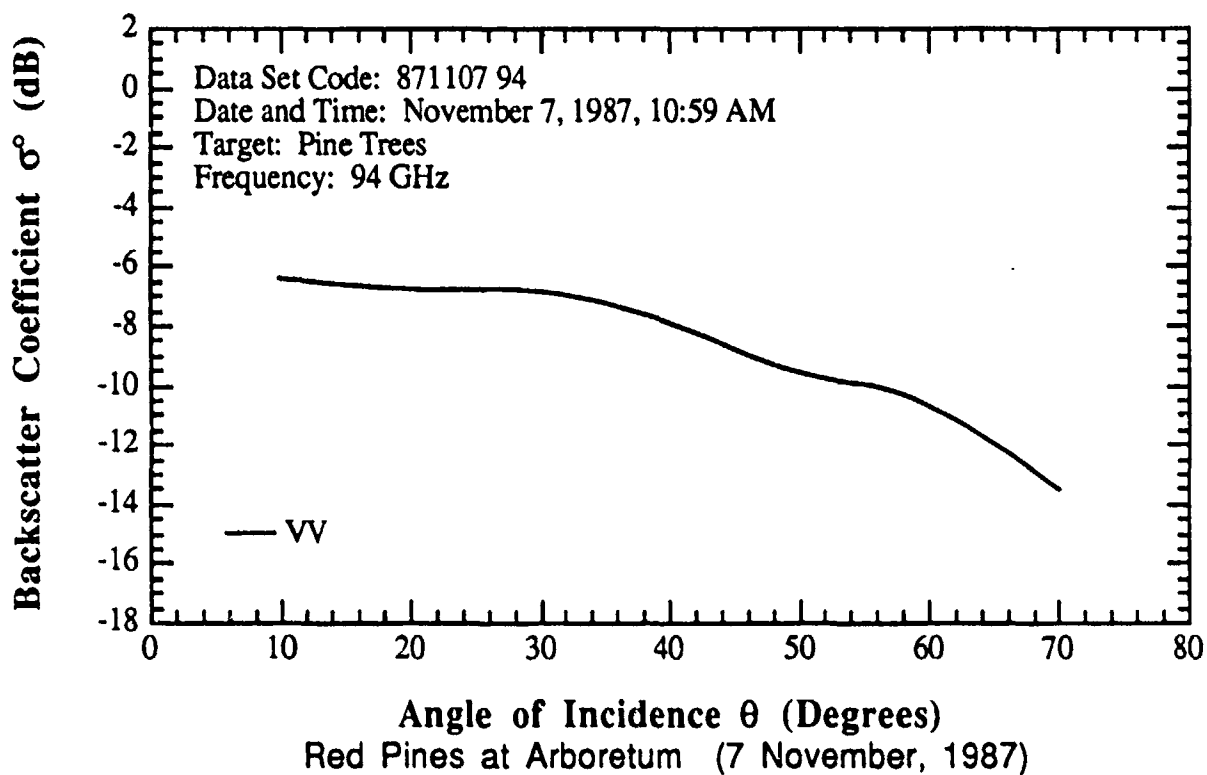


871107

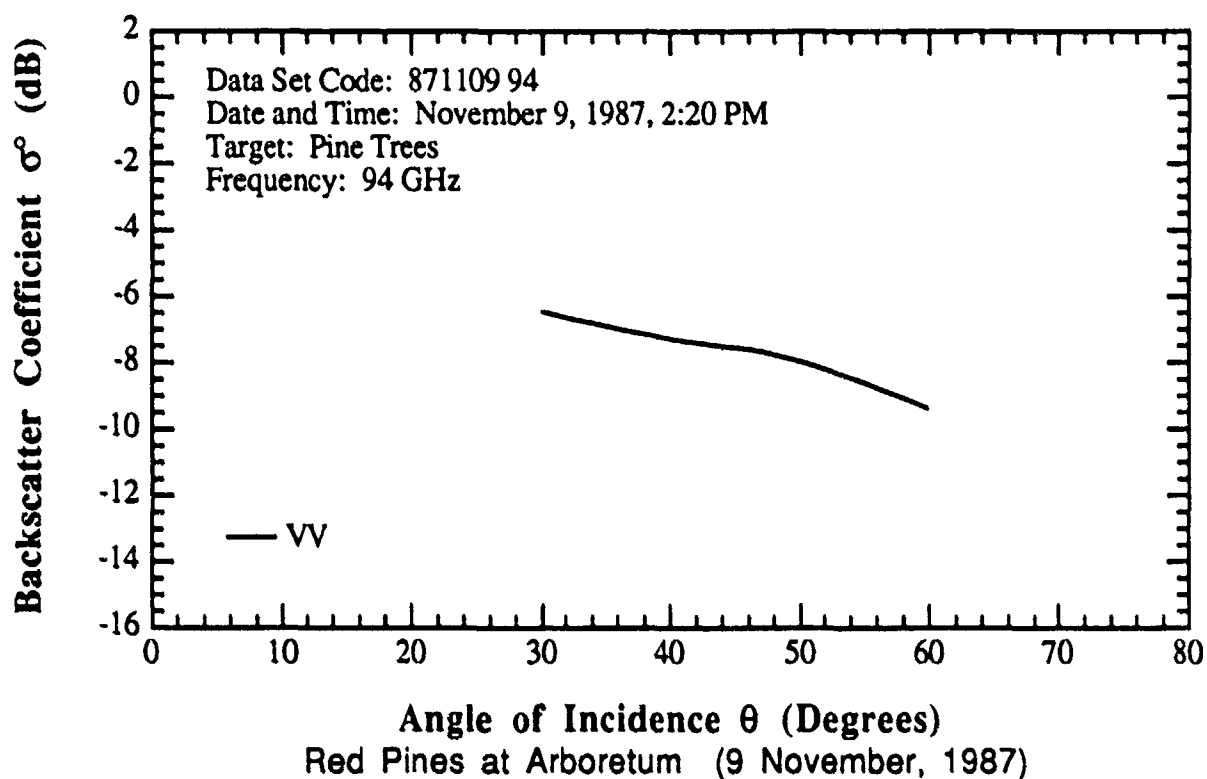


# MMW DATA FOR TREE CANOPIES

871107

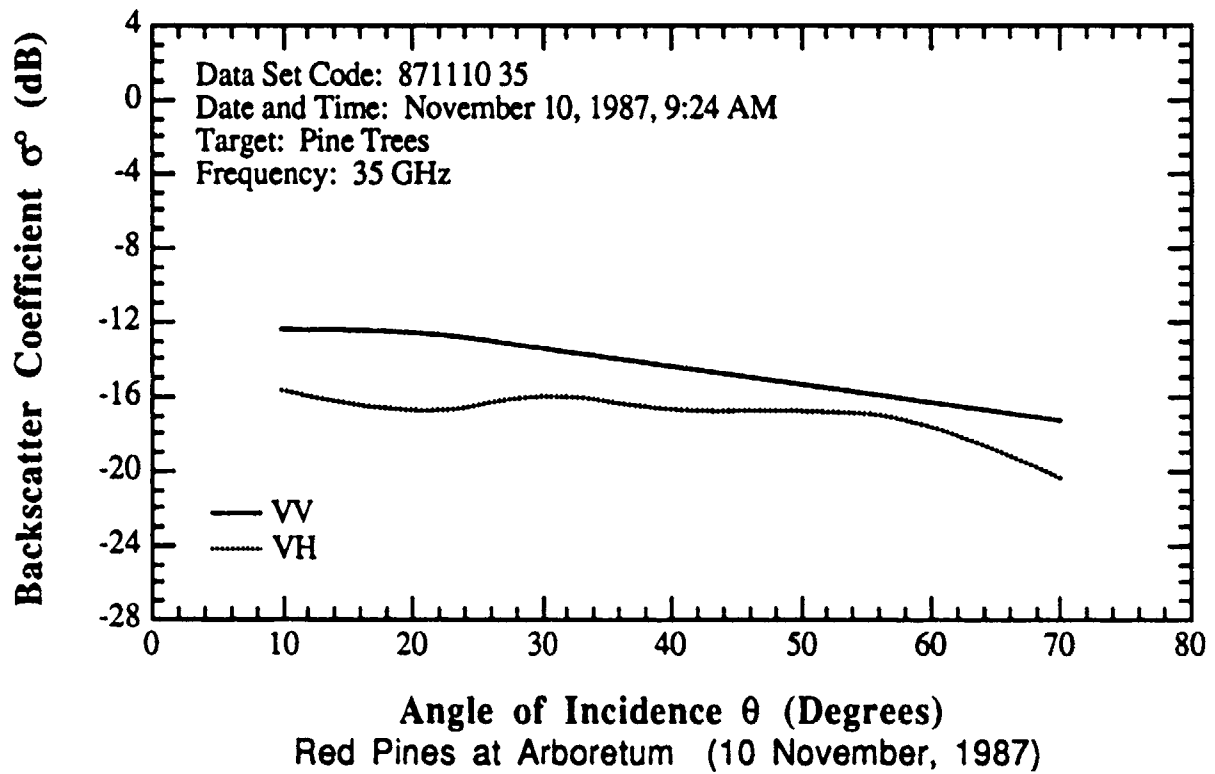


871109

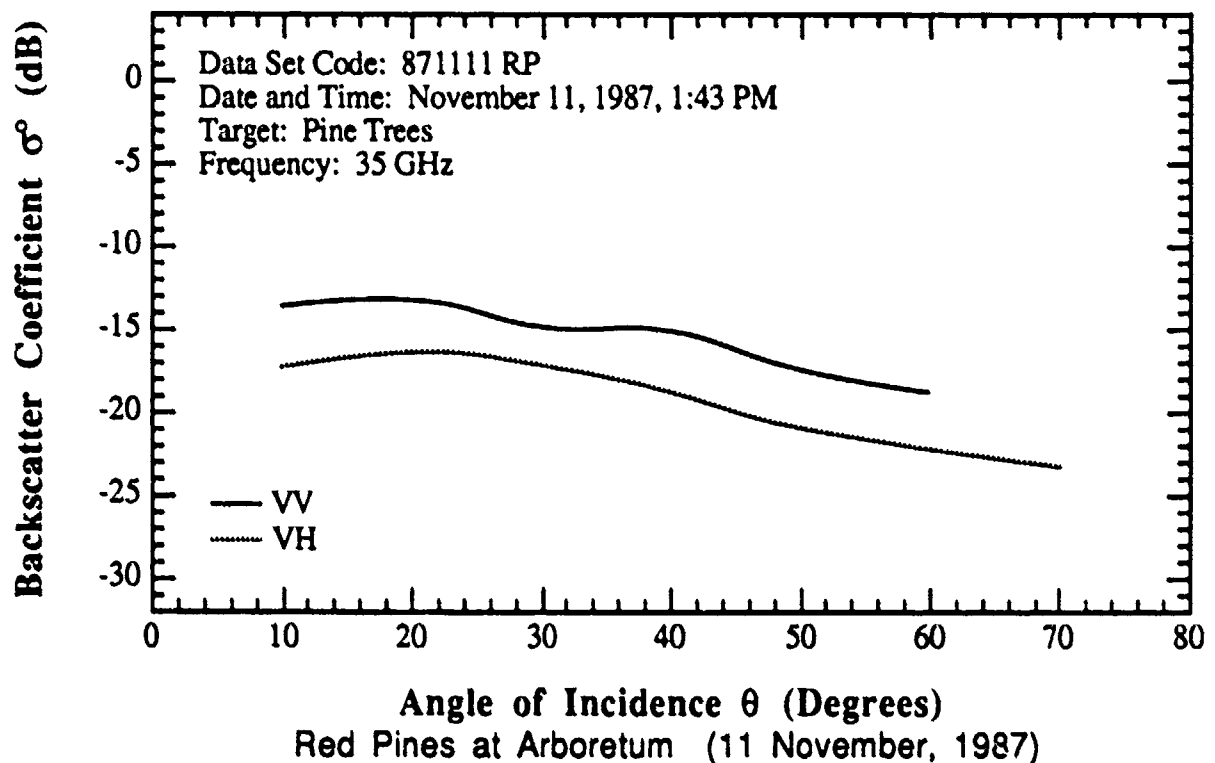


# MMW DATA FOR TREE CANOPIES

871110



871111



### C. Apple Trees

Data set code: 880811

Tree density: 0.1 trees/m<sup>2</sup>

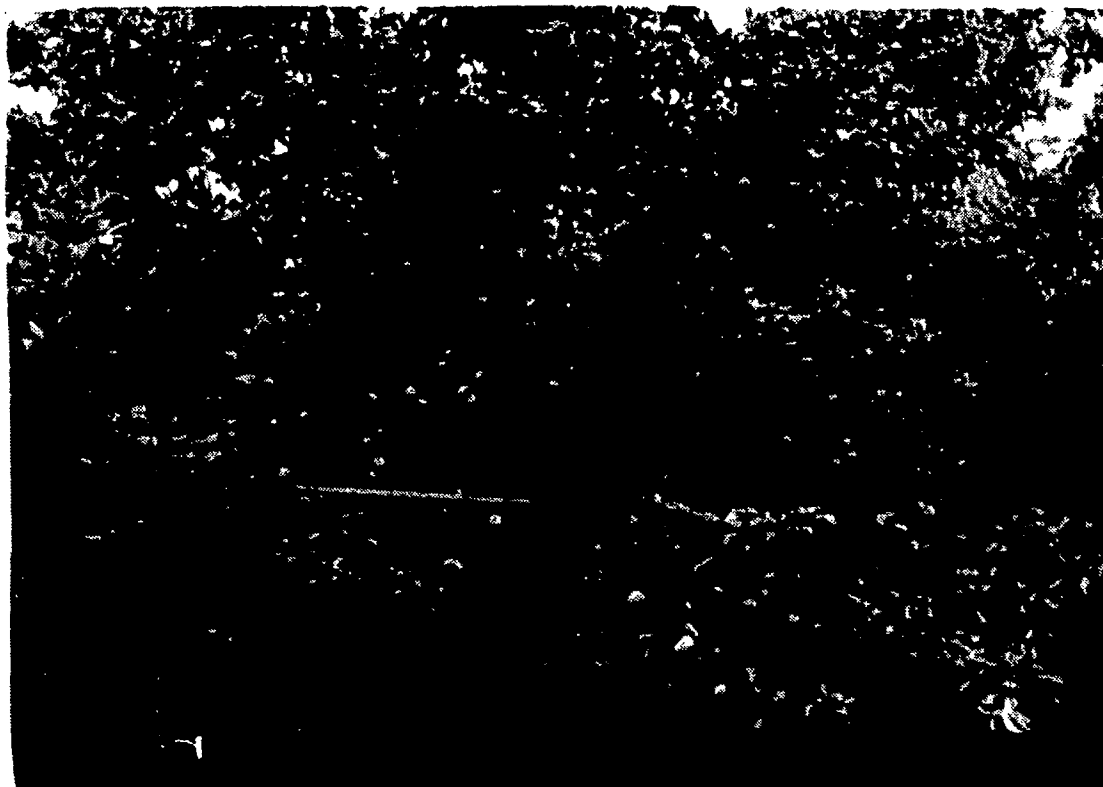
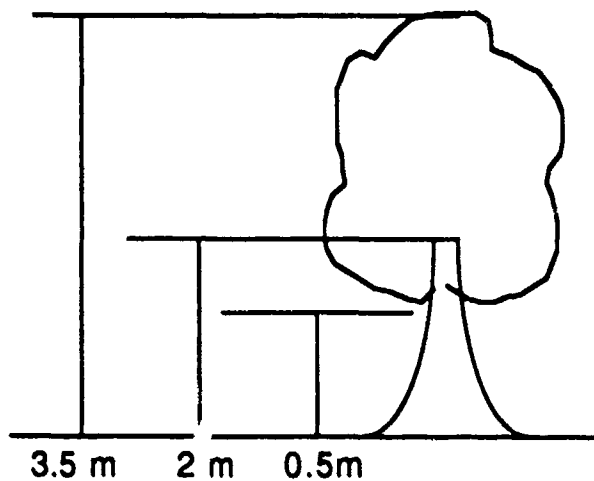
Average leaf (or needle) dimensions: 4 by 8 cm

Leaf moisture content: ~80 %

Percent vegetation cover: 90%

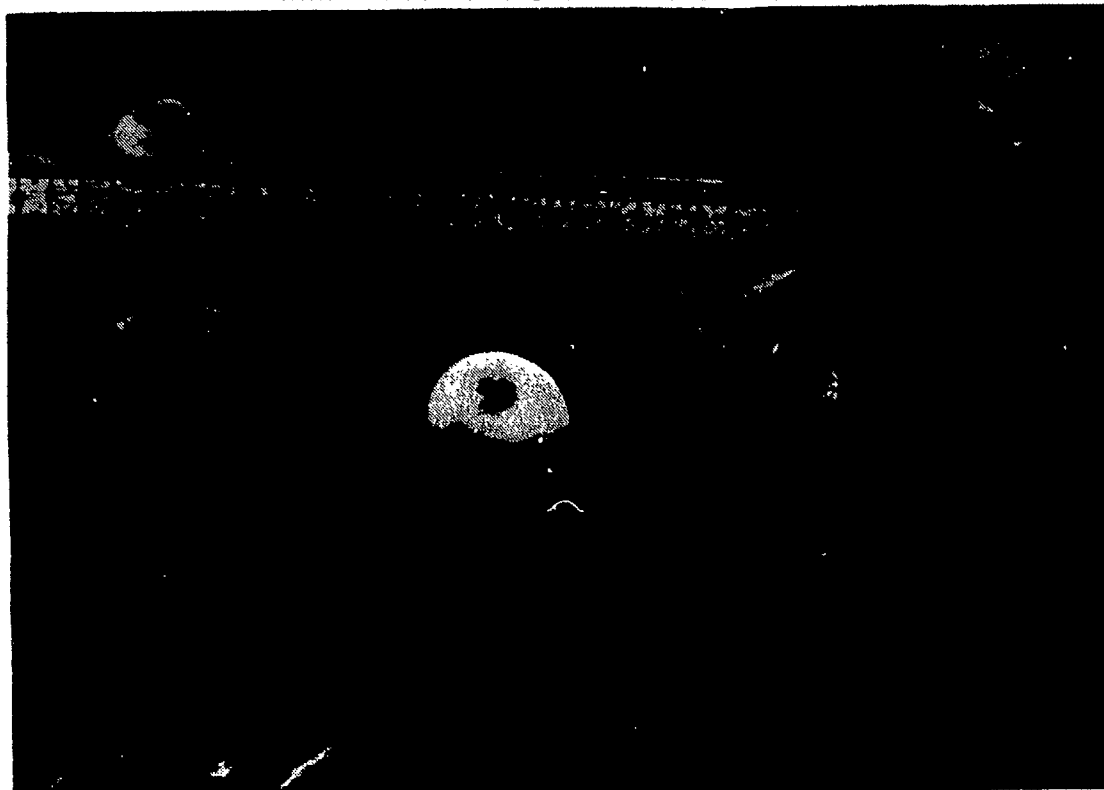
Percent cover of undergrowth: 100%

Moisture content of undergrowth: 80%



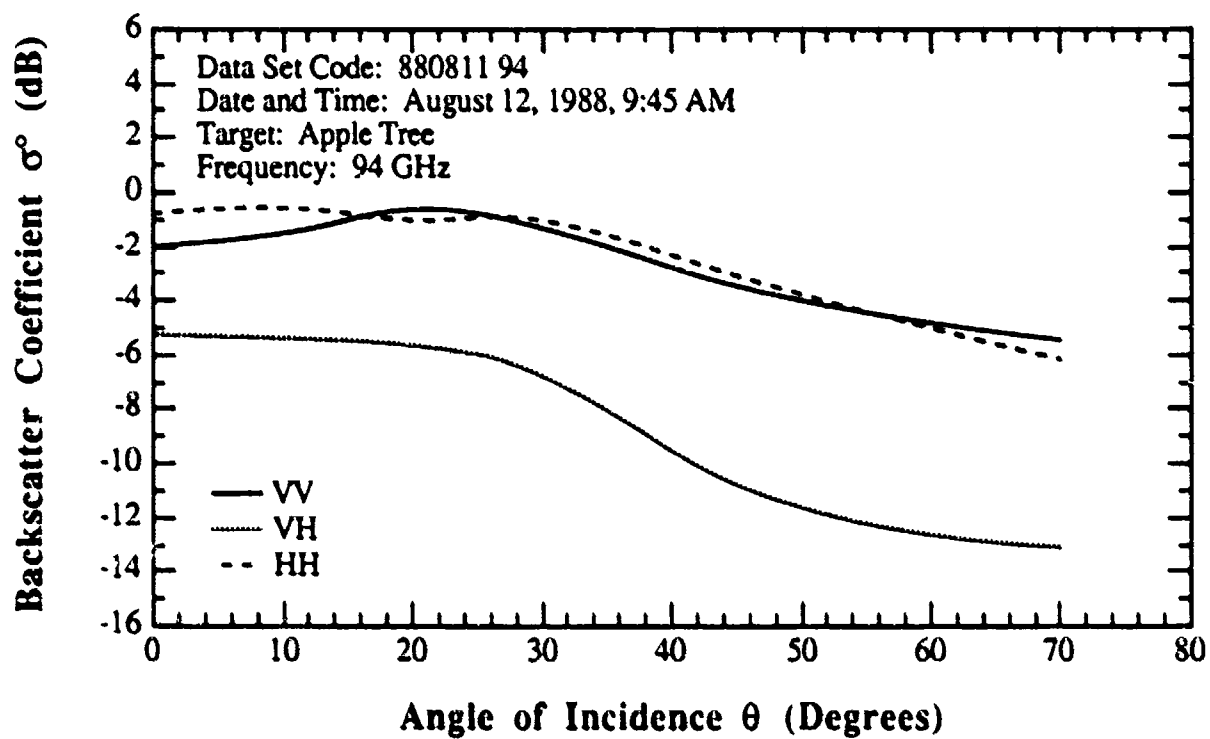
Apple tree

# MMW DATA FOR TREE CANOPIES



Leaves of Apple Tree

880811



#### D. Bur Oak

Bur Oak (*Quercus macrocarpa*)

Data set code: 880930-1027

Tree density: 0.09 trees/m<sup>2</sup>

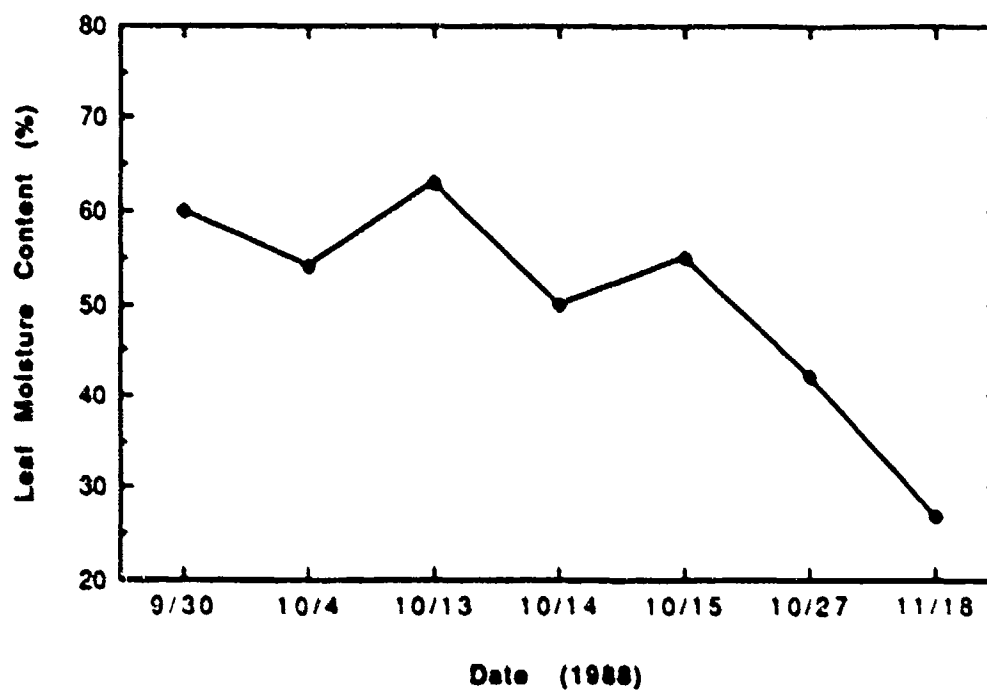
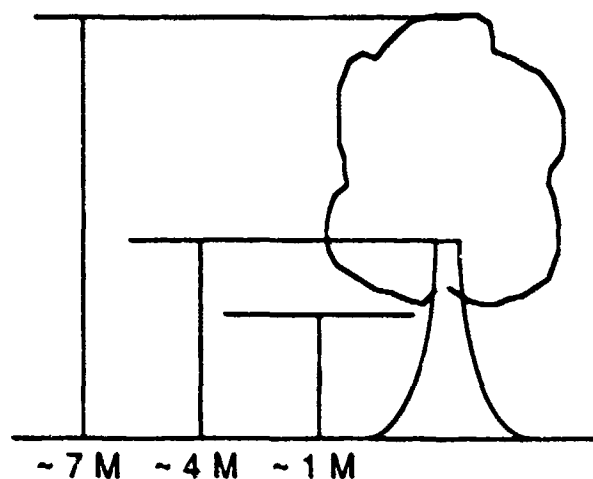
Average leaf (or needle) dimensions: 8 by 12 cm

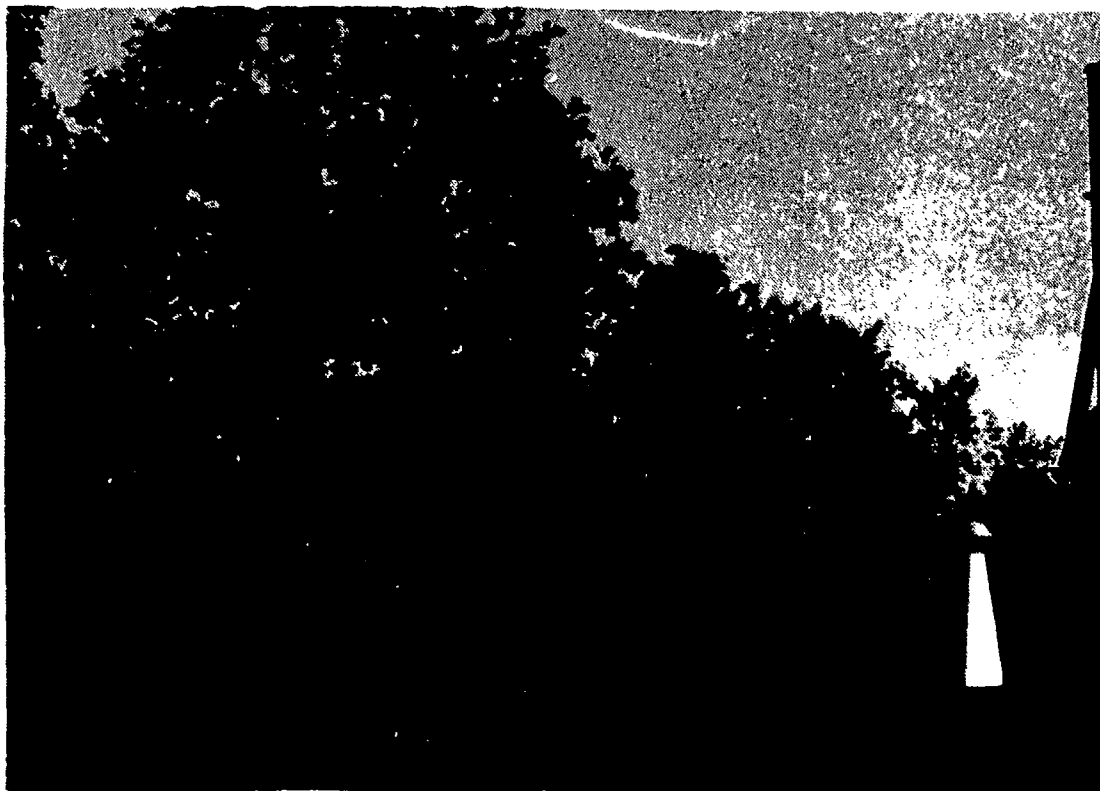
Moisture content of undergrowth: ~ 70%

Percent cover of undergrowth: 100%

Percent vegetation cover: 95%

Description: Stand of mature oak trees over low ground cover



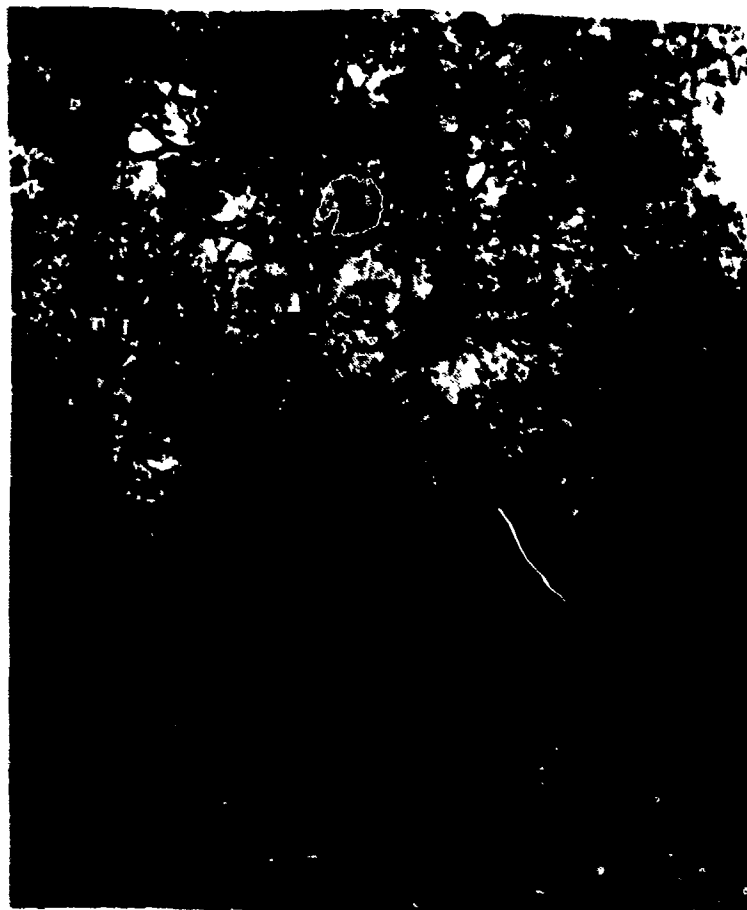


Bur oaks at Botanical Gardens -- 880930



Leaves of Bur oaks at Botanical Gardens -- 880930

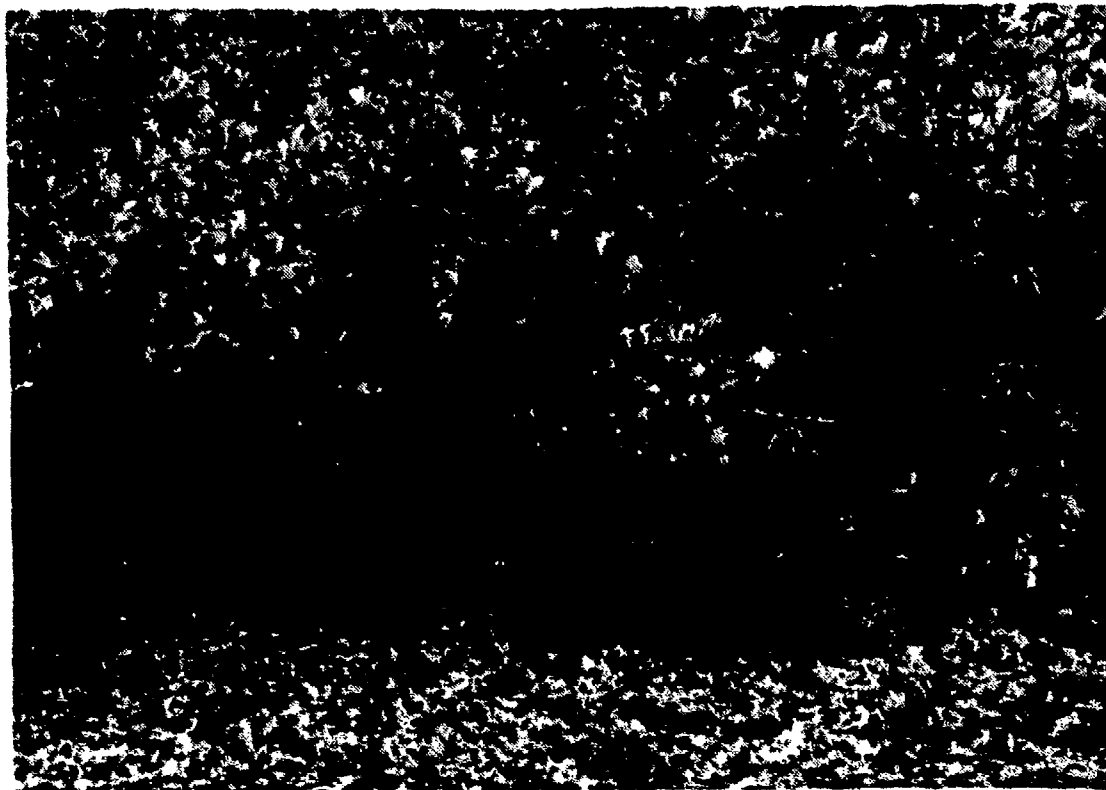
**MMW DATA FOR TREE CANOPIES**



**Bur oaks at Botanical Gardens -- 881007**



**Leaves of Bur oaks at Botanical Gardens -- 881007**

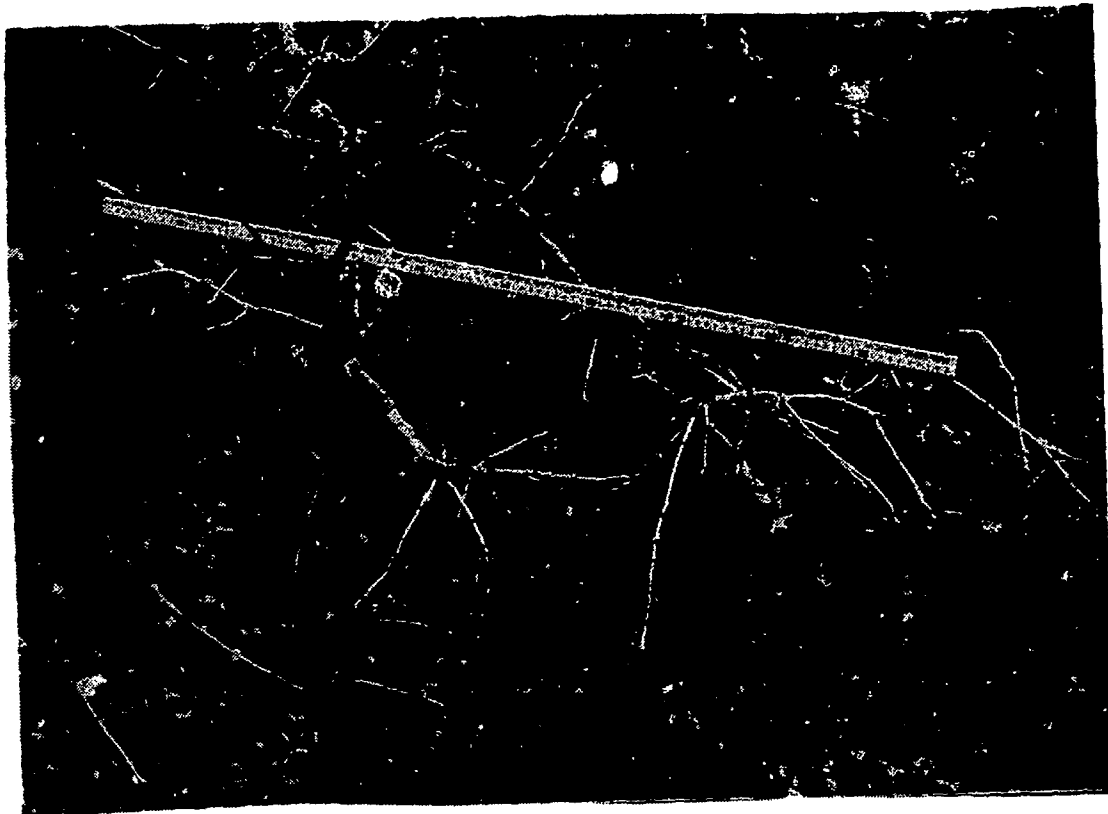


Bur oaks at Botanical Gardens -- 881015

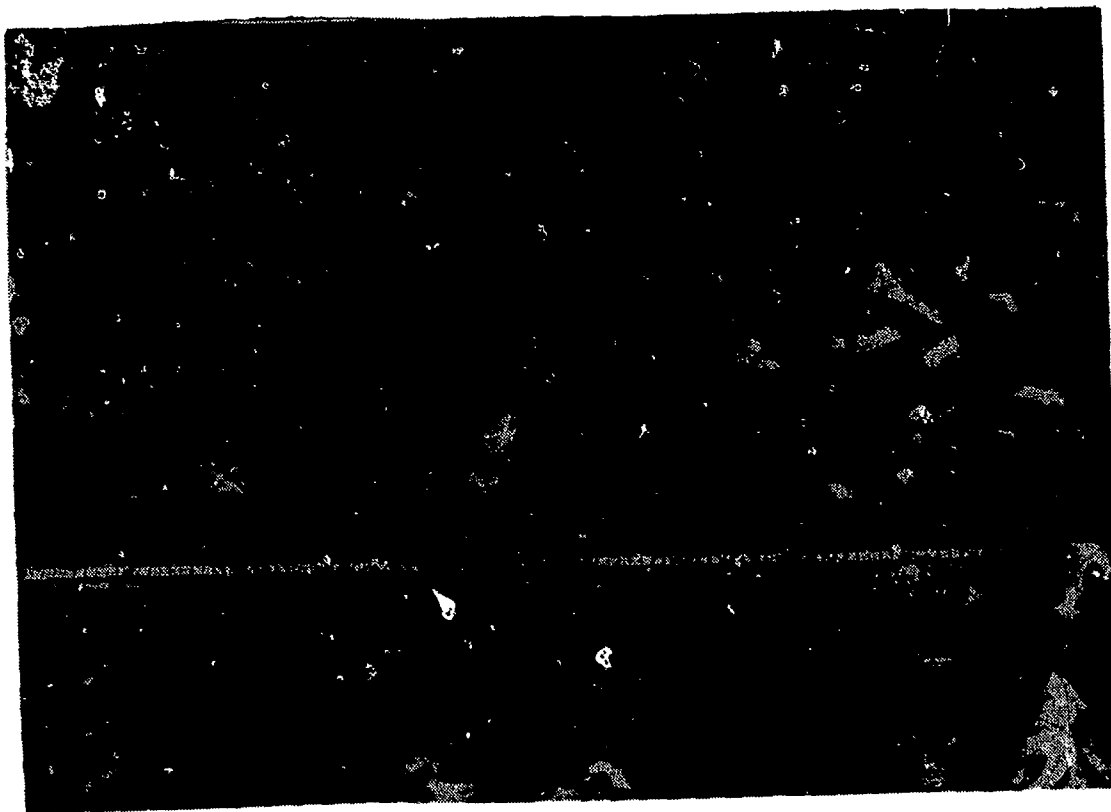


Leaves of Bur oaks at Botanical Gardens -- 881015

MMW DATA FOR TREE CANOPIES



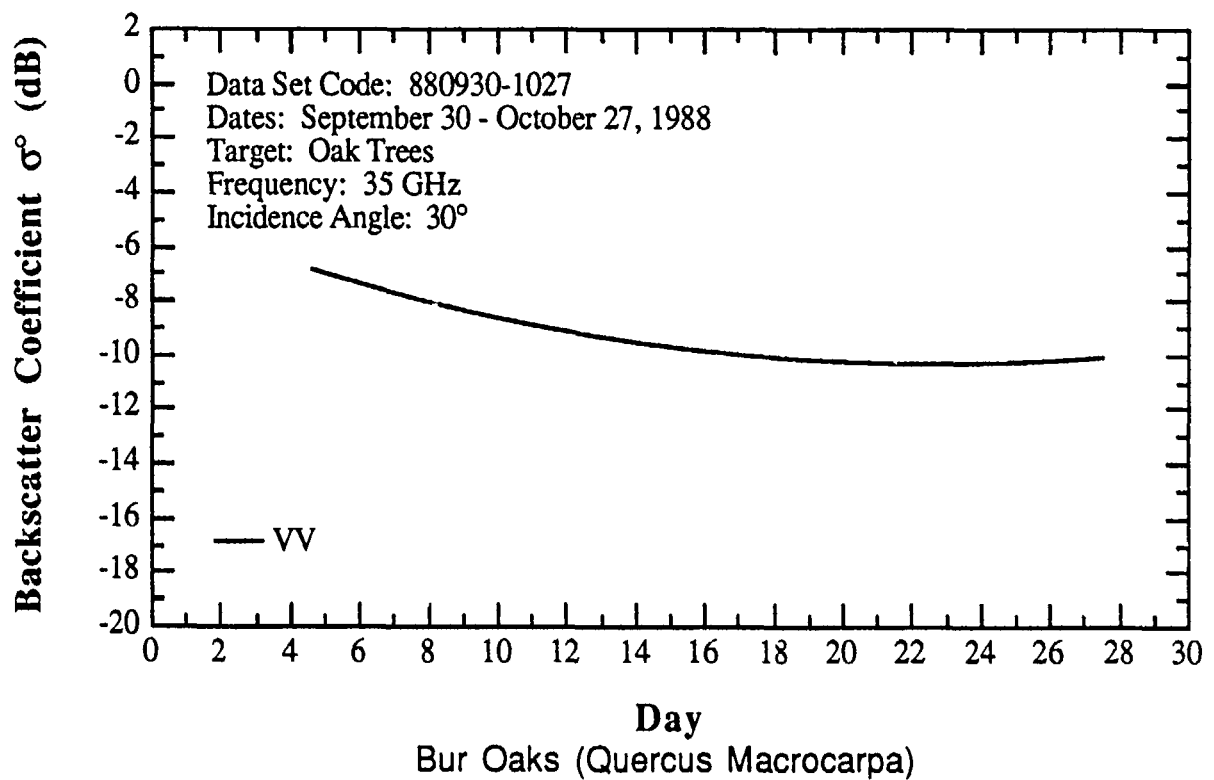
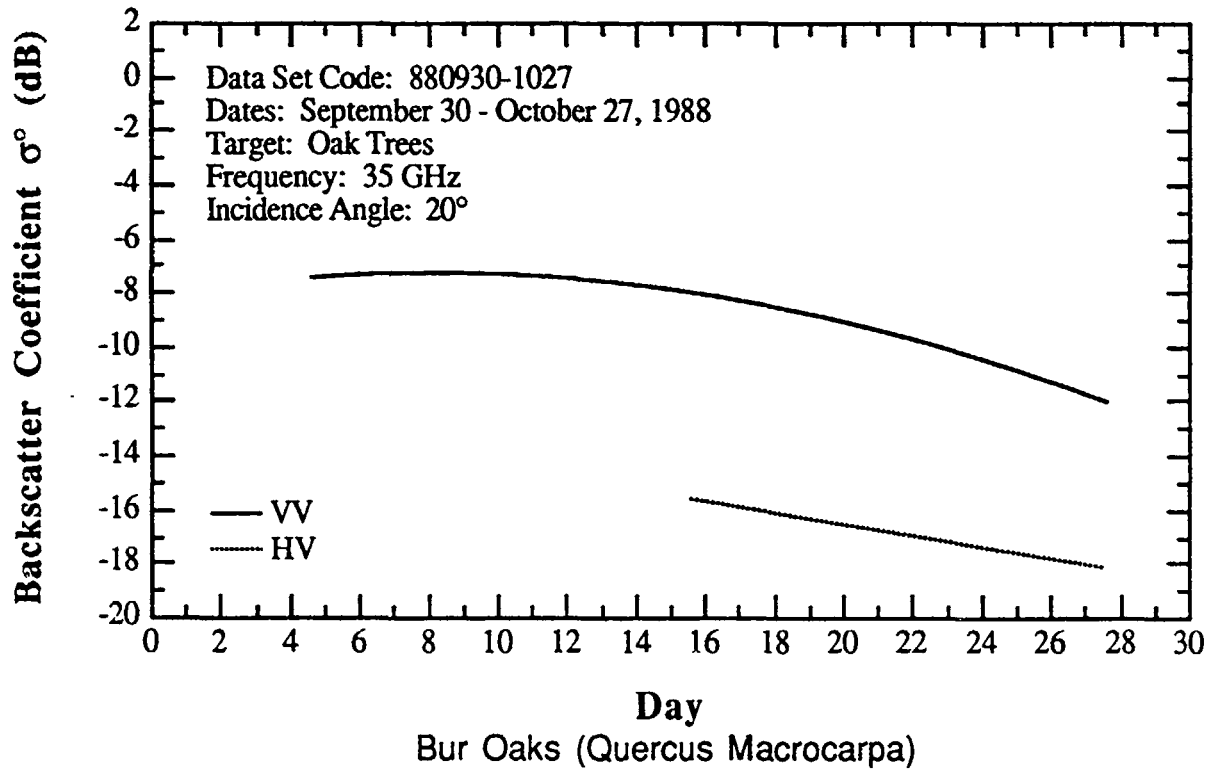
Leaves of Bur oaks at Botanical Gardens -- 881027



Ground cover beneath Bur oaks at Botanical Gardens -- 881027

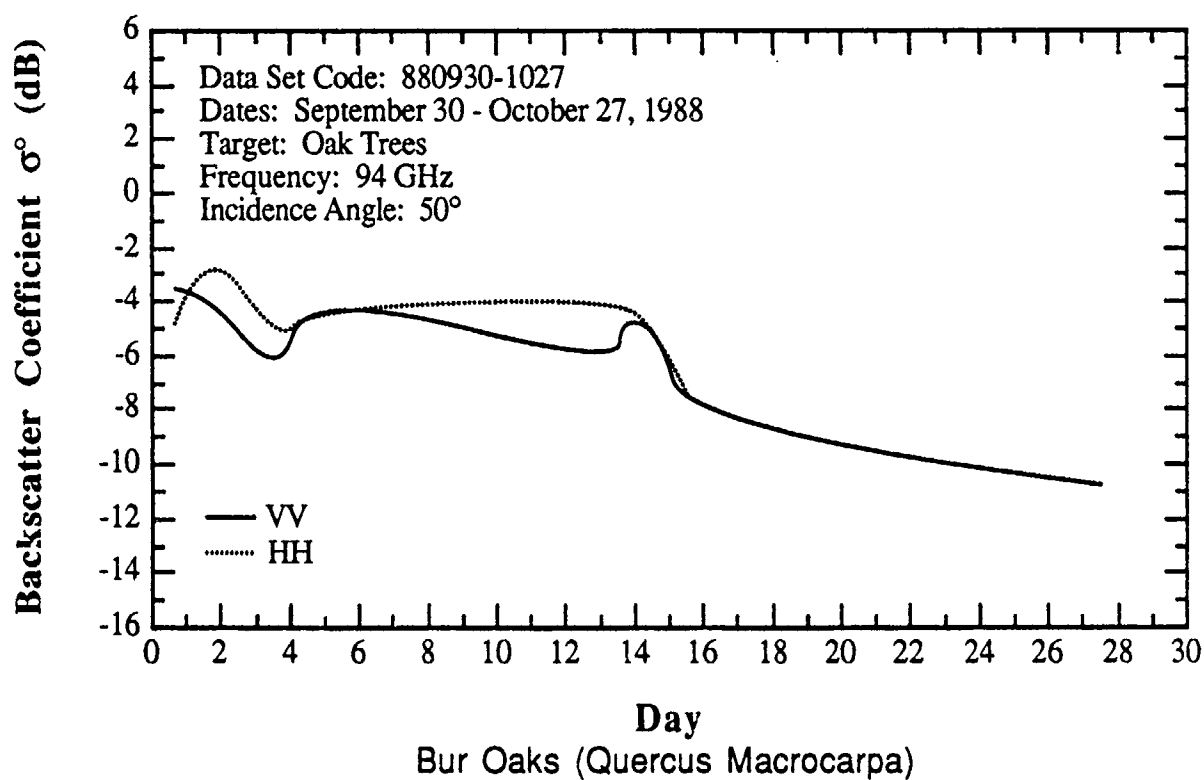
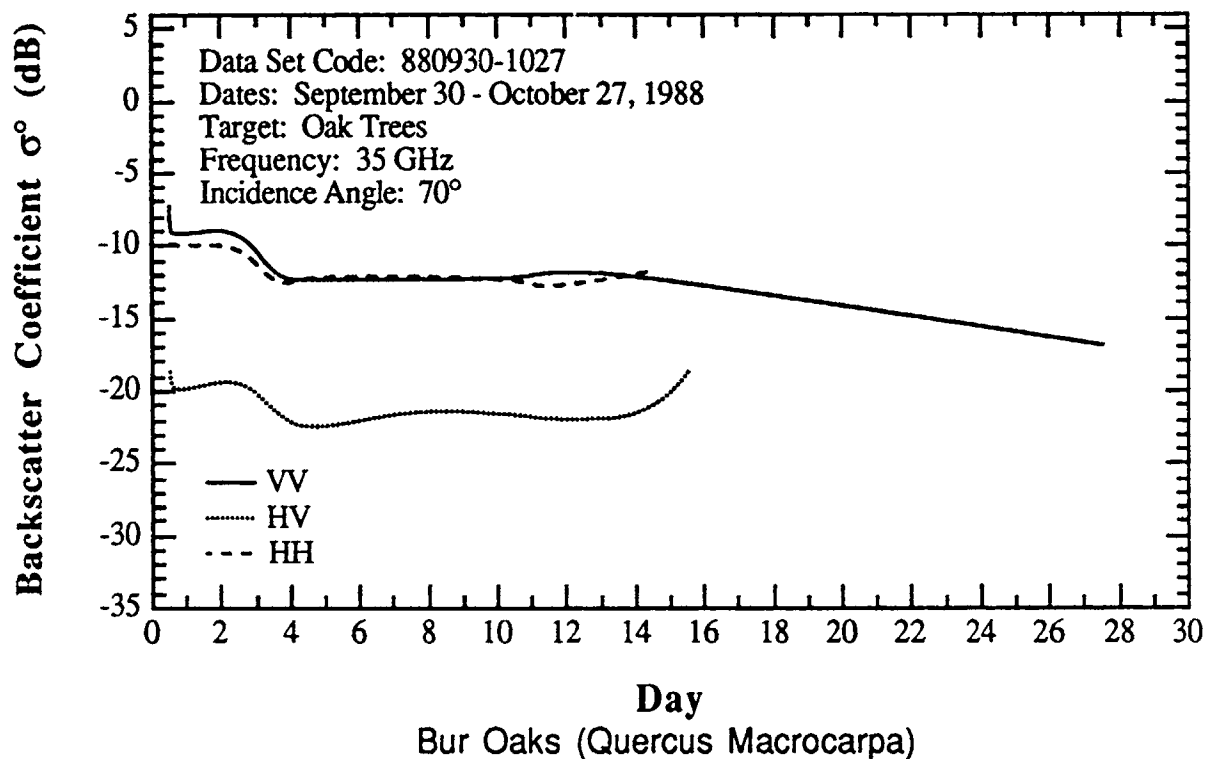
# MMW DATA FOR TREE CANOPIES

880930-1027



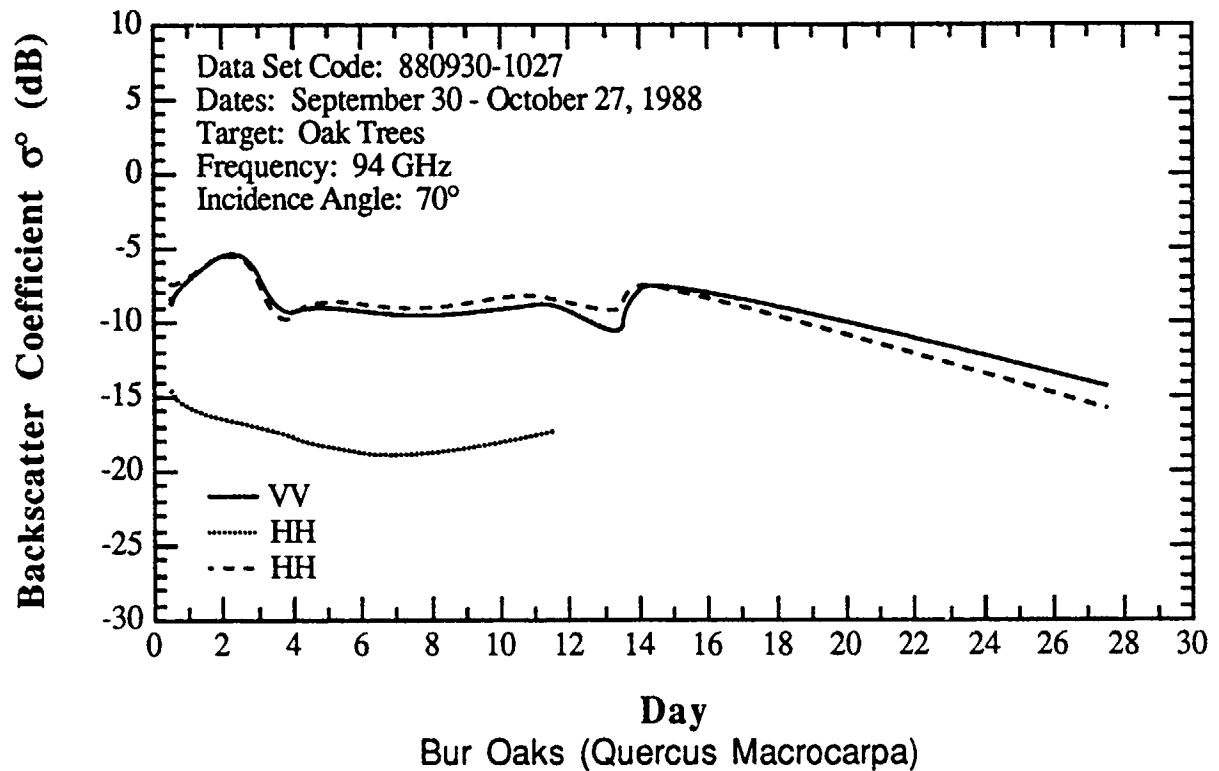
# MMW DATA FOR TREE CANOPIES

880930-1027

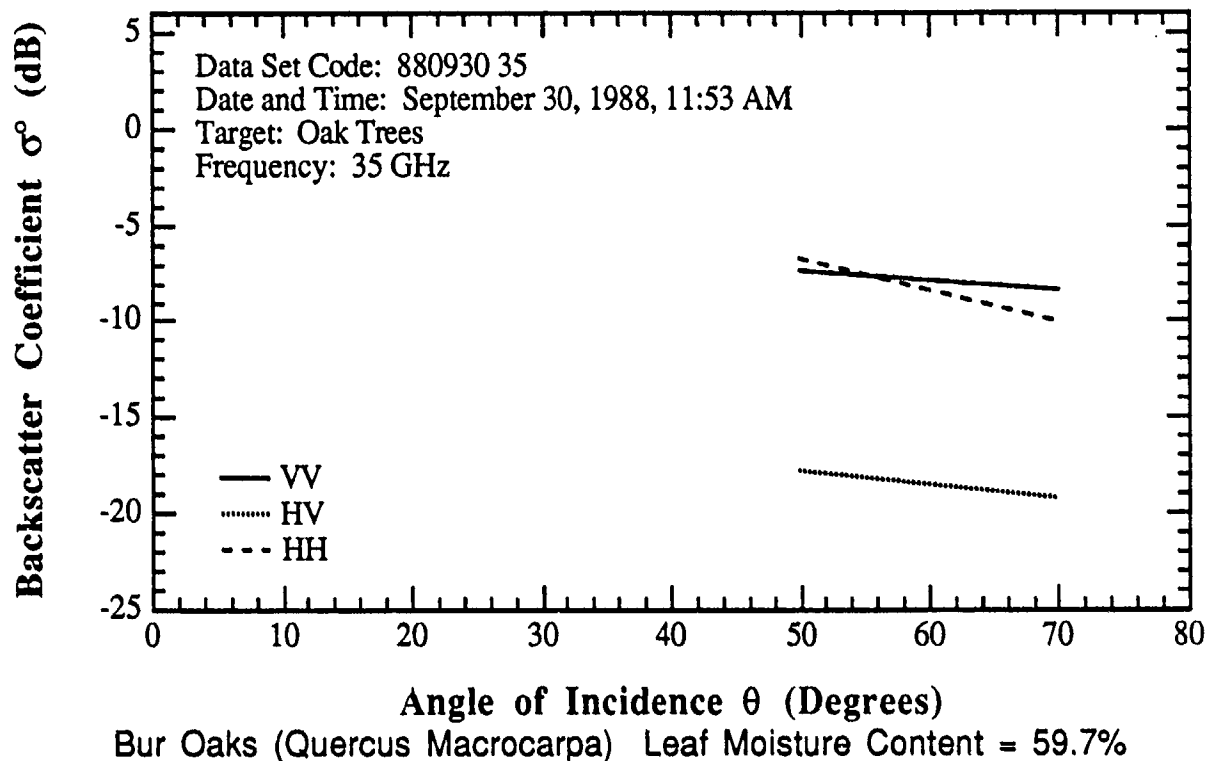


# MMW WAVE DATA FOR TREE CANOPIES

880930-1027

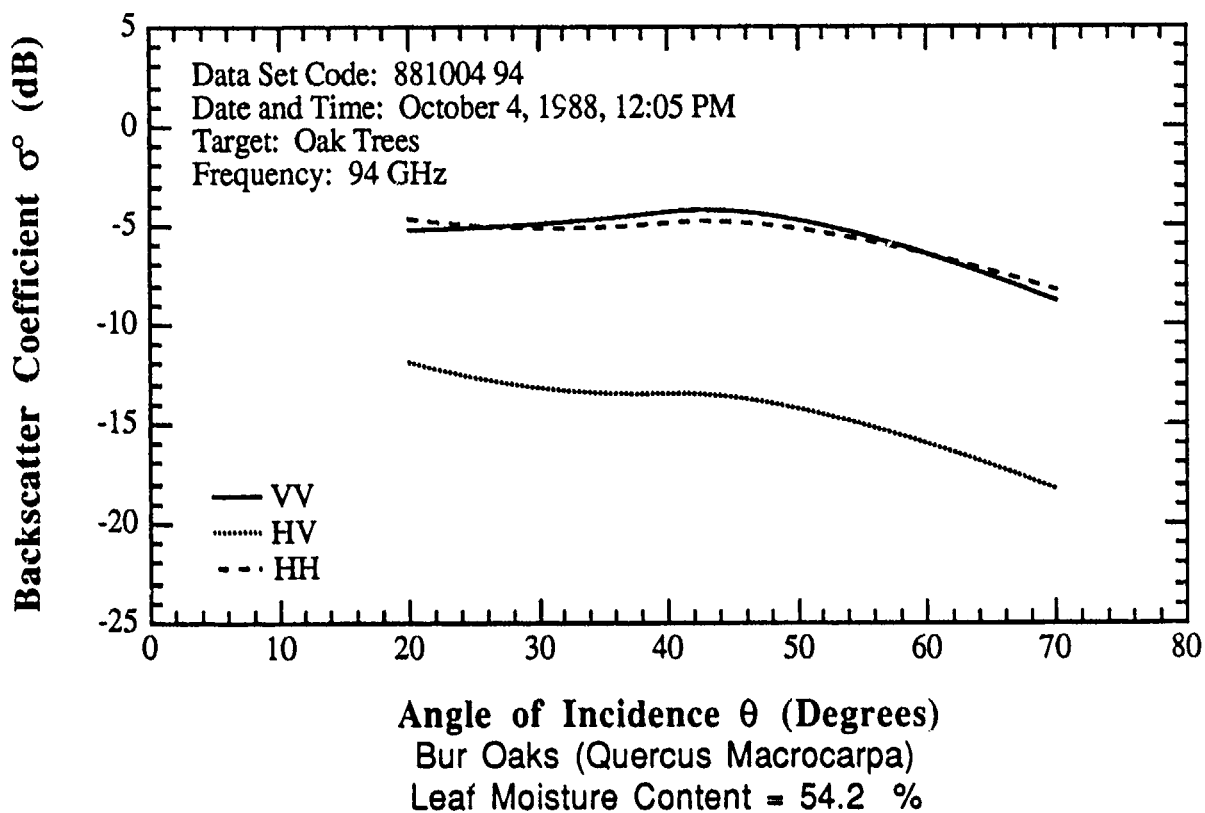
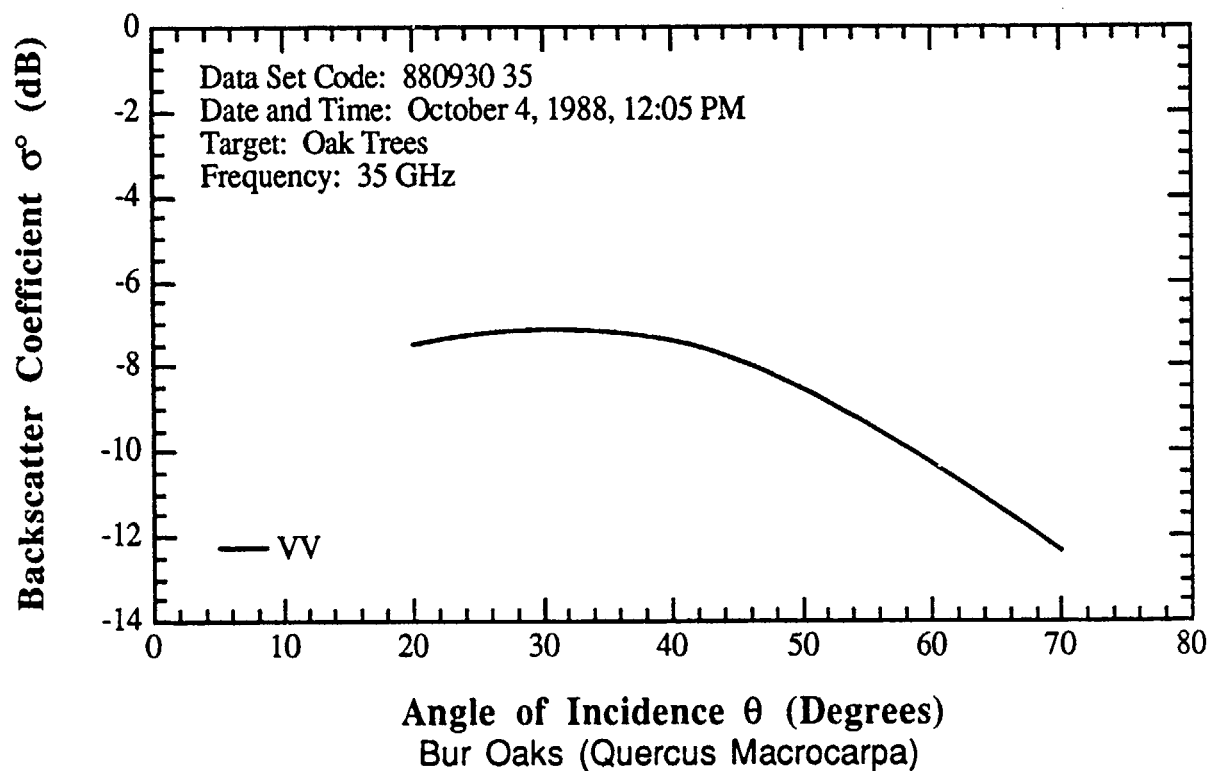


880930



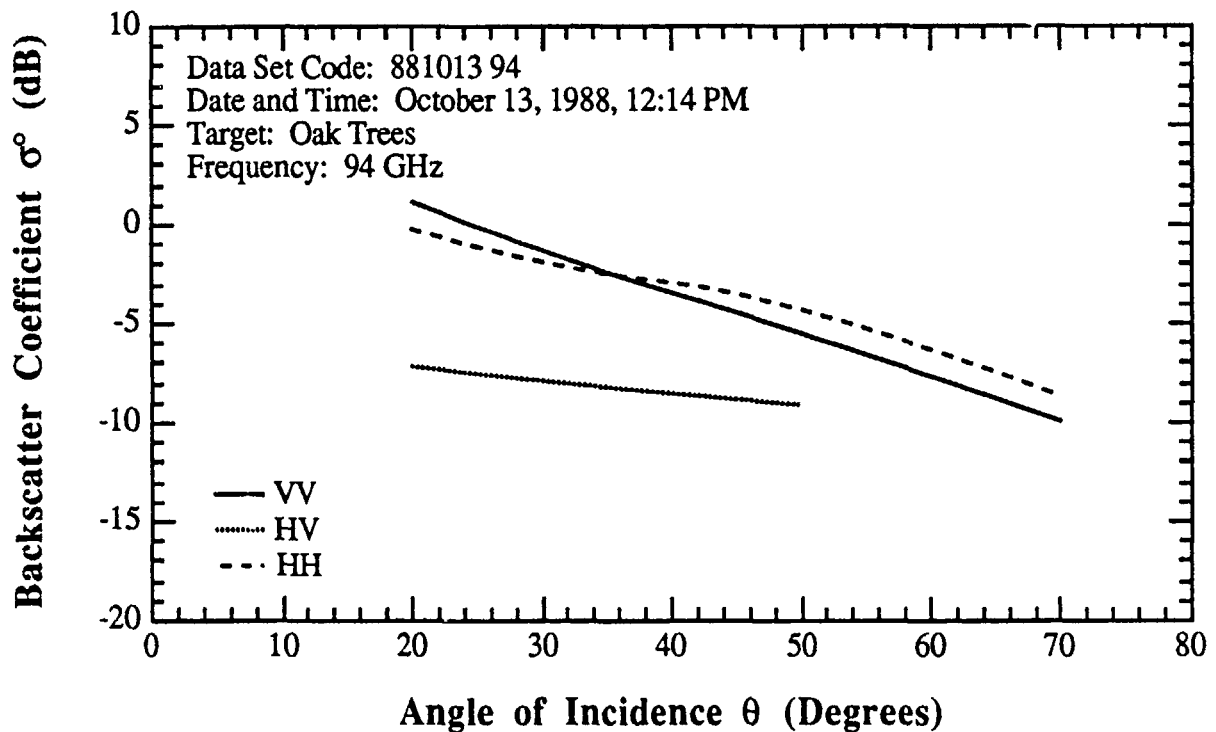
# MMW WAVE DATA FOR TREE CANOPIES

881004



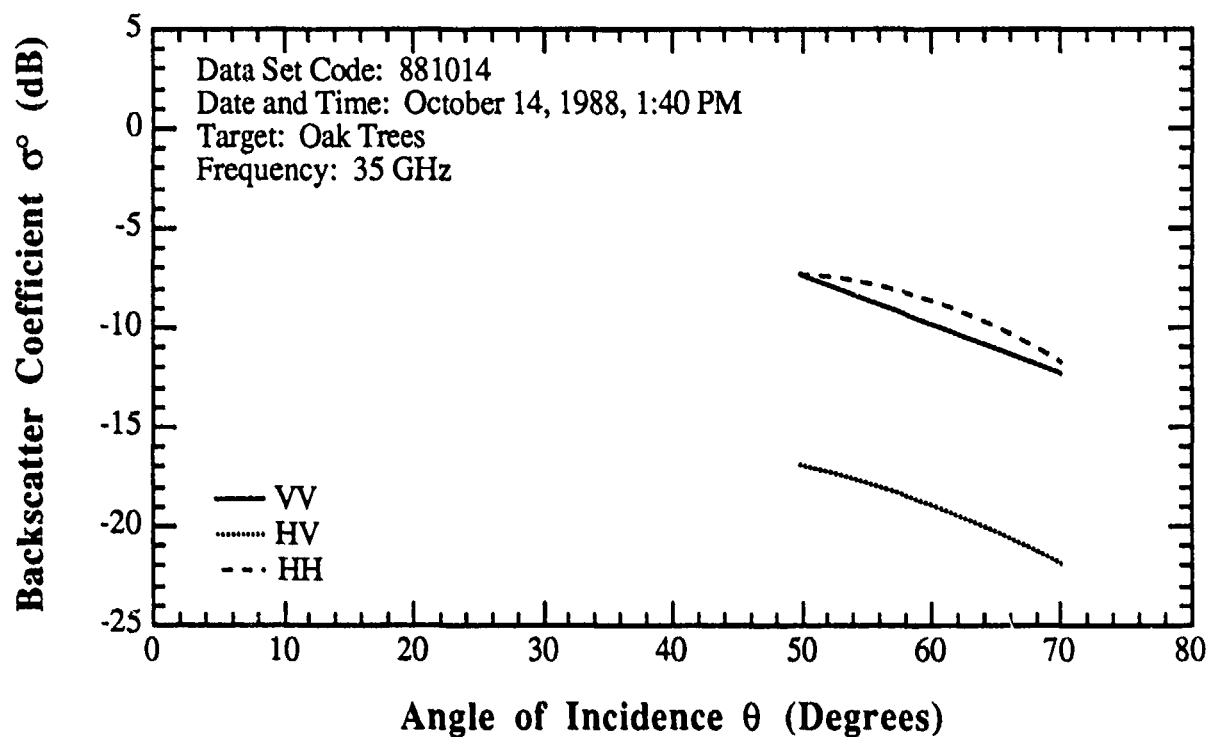
# MMW DATA FOR TREE CANOPIES

881013



Bur Oaks (*Quercus Macrocarpa*) Leaf Moisture Content = 63.4%

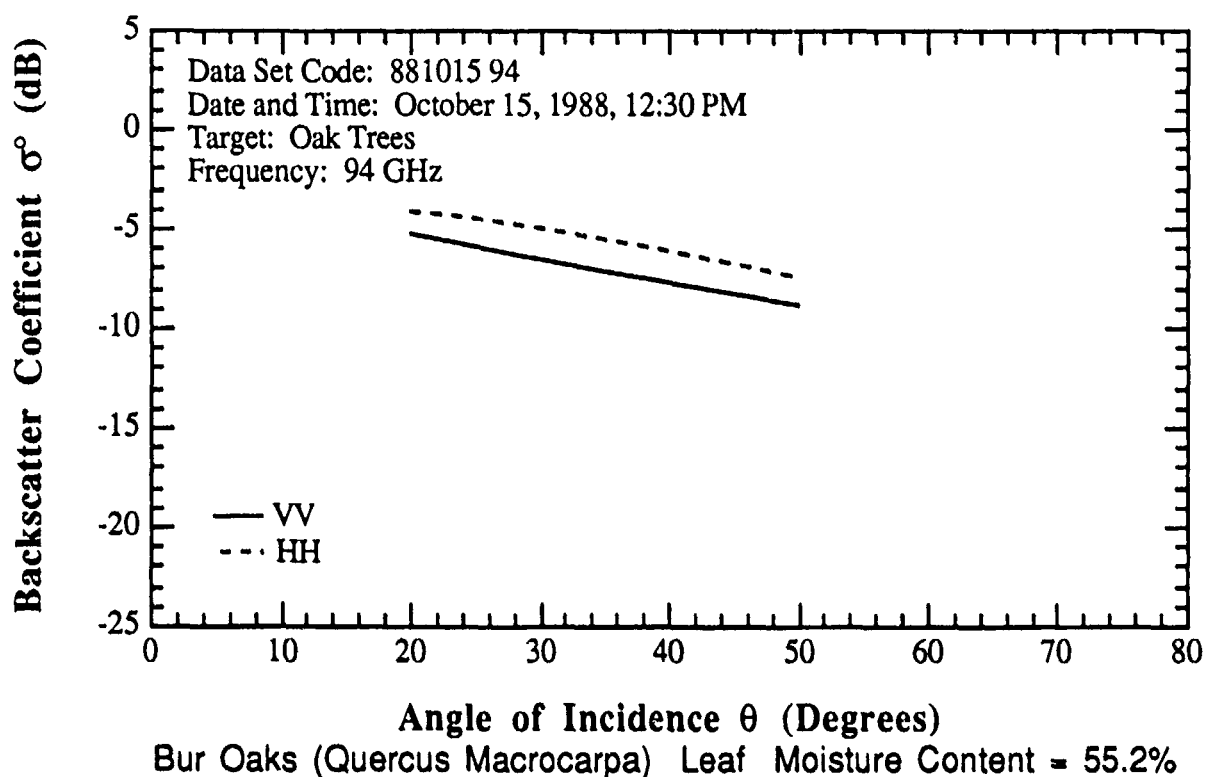
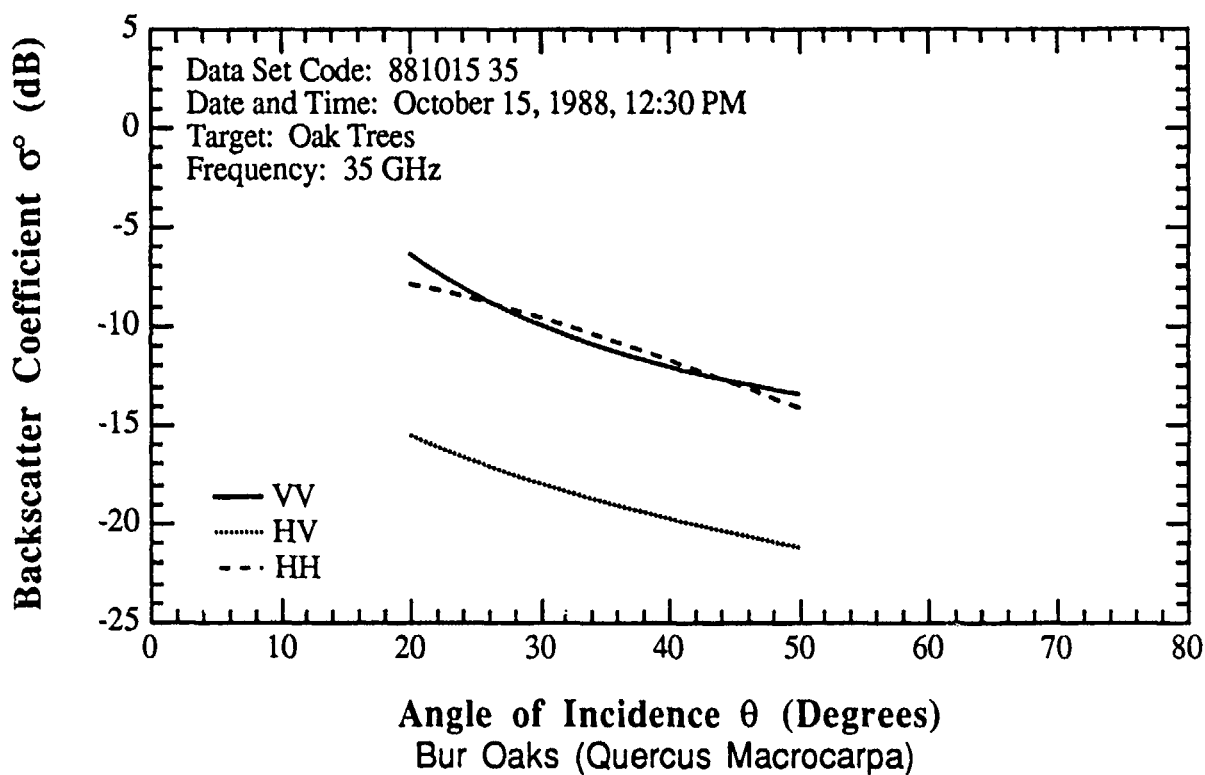
881014



Bur Oaks (*Quercus Macrocarpa*) Leaf Moisture Content = 50.1%

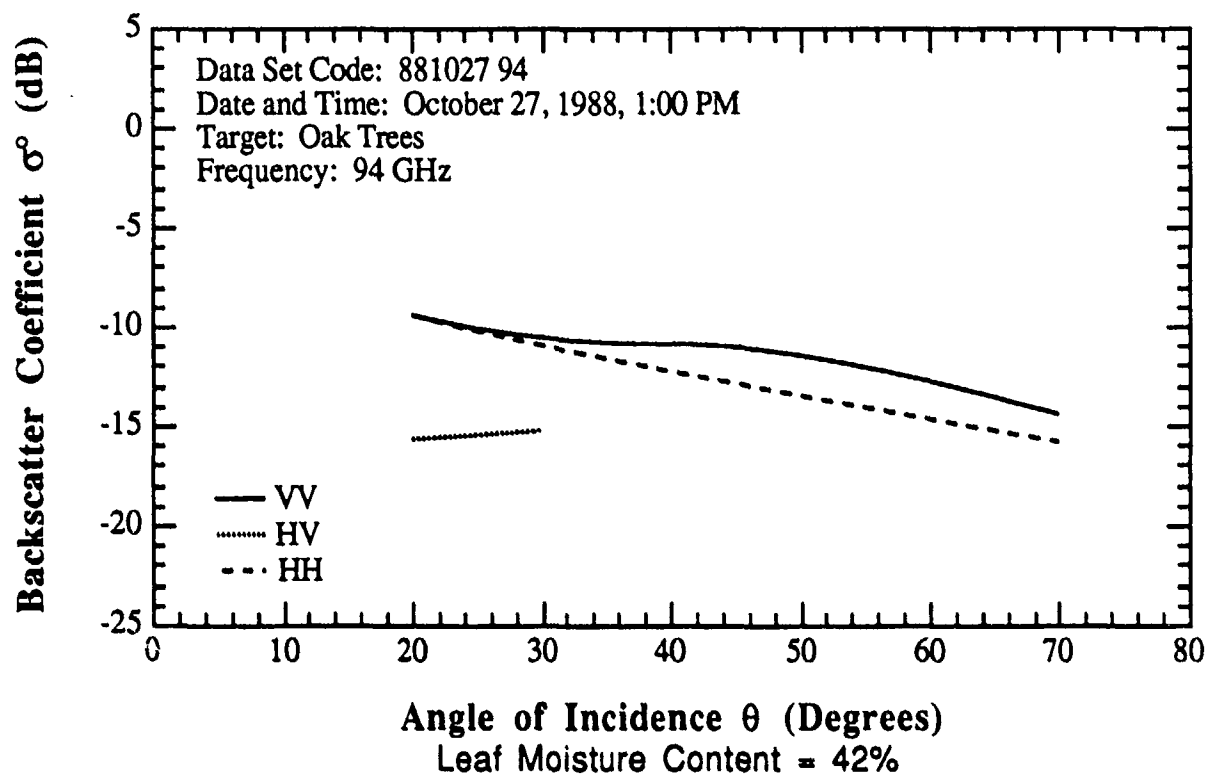
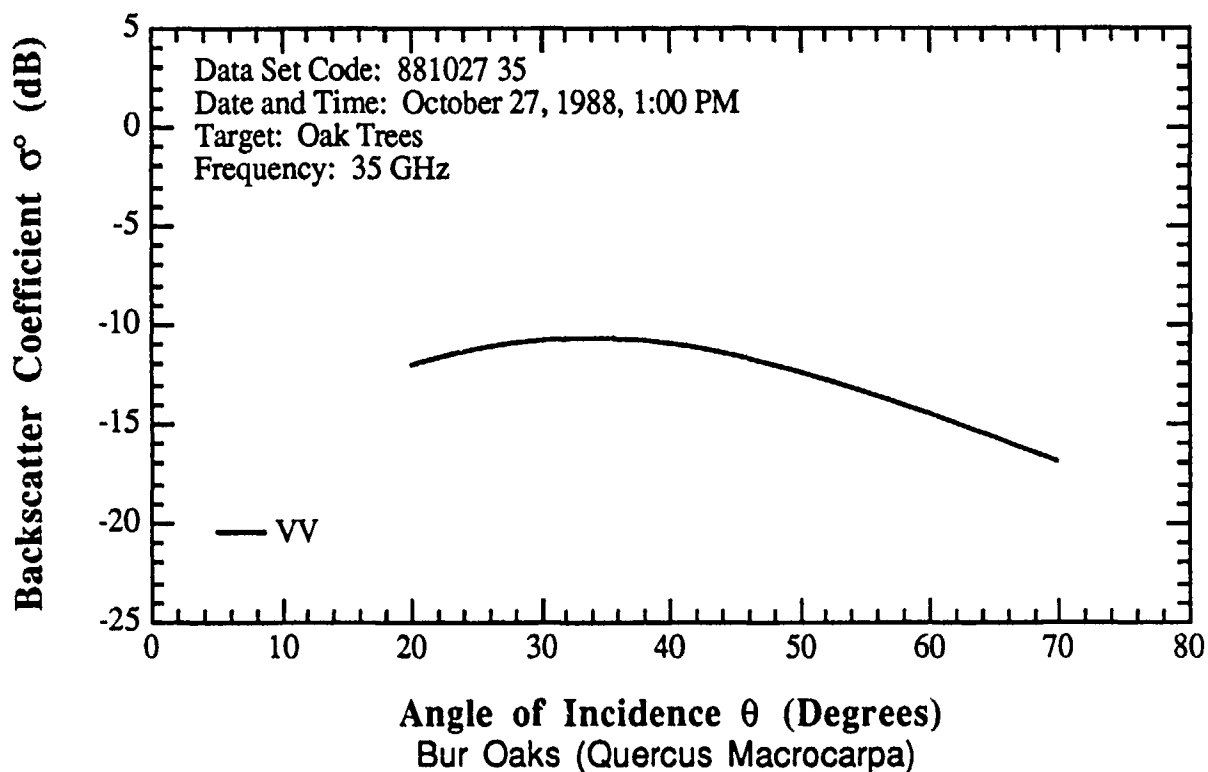
# MMW DATA FOR TREE CANOPIES

881015



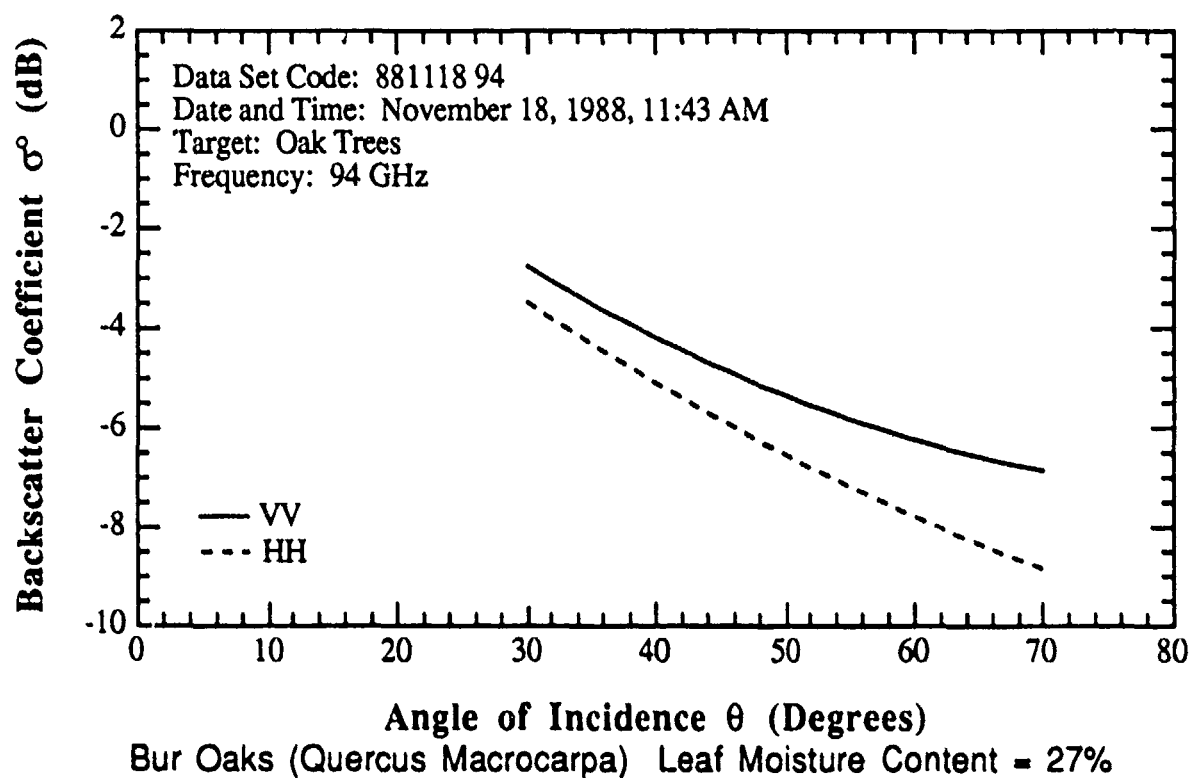
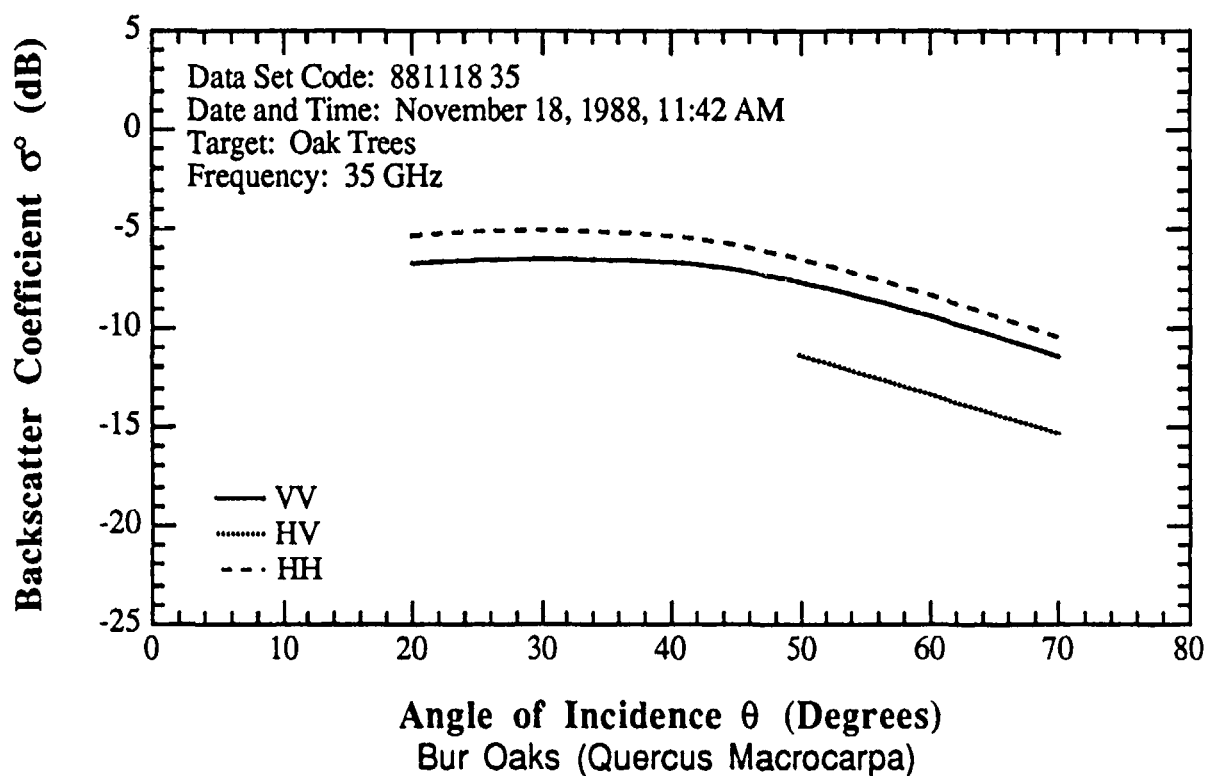
# MMW WAVE DATA FOR TREE CANOPIES

881027



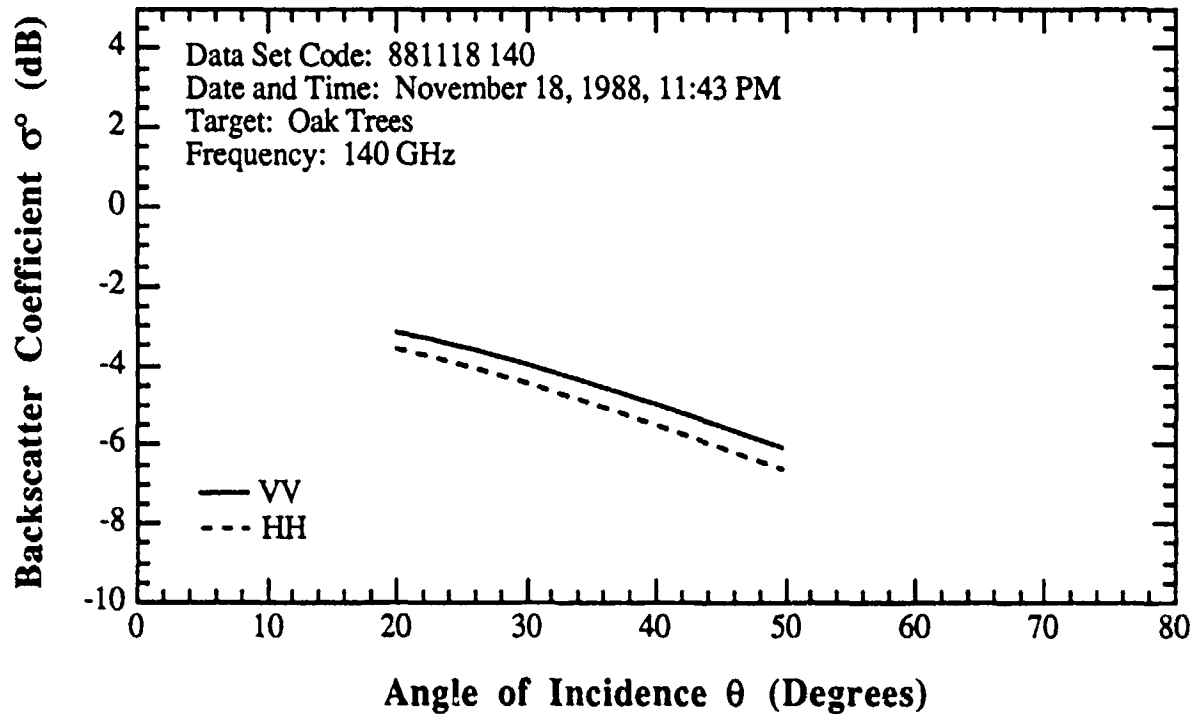
# MMW WAVE DATA FOR TREE CANOPIES

881118



# MMW DATA FOR TREE CANOPIES

881118



Bur Oaks (*Quercus Macrocarpa*) Leaf Moisture Content = 27%

## E. Spruce Trees

Spruce (*Picea abies*)

Data set code: 881031/881122

Tree density: 0.03 trees/m<sup>2</sup>

Average needle dimensions: 2 cm

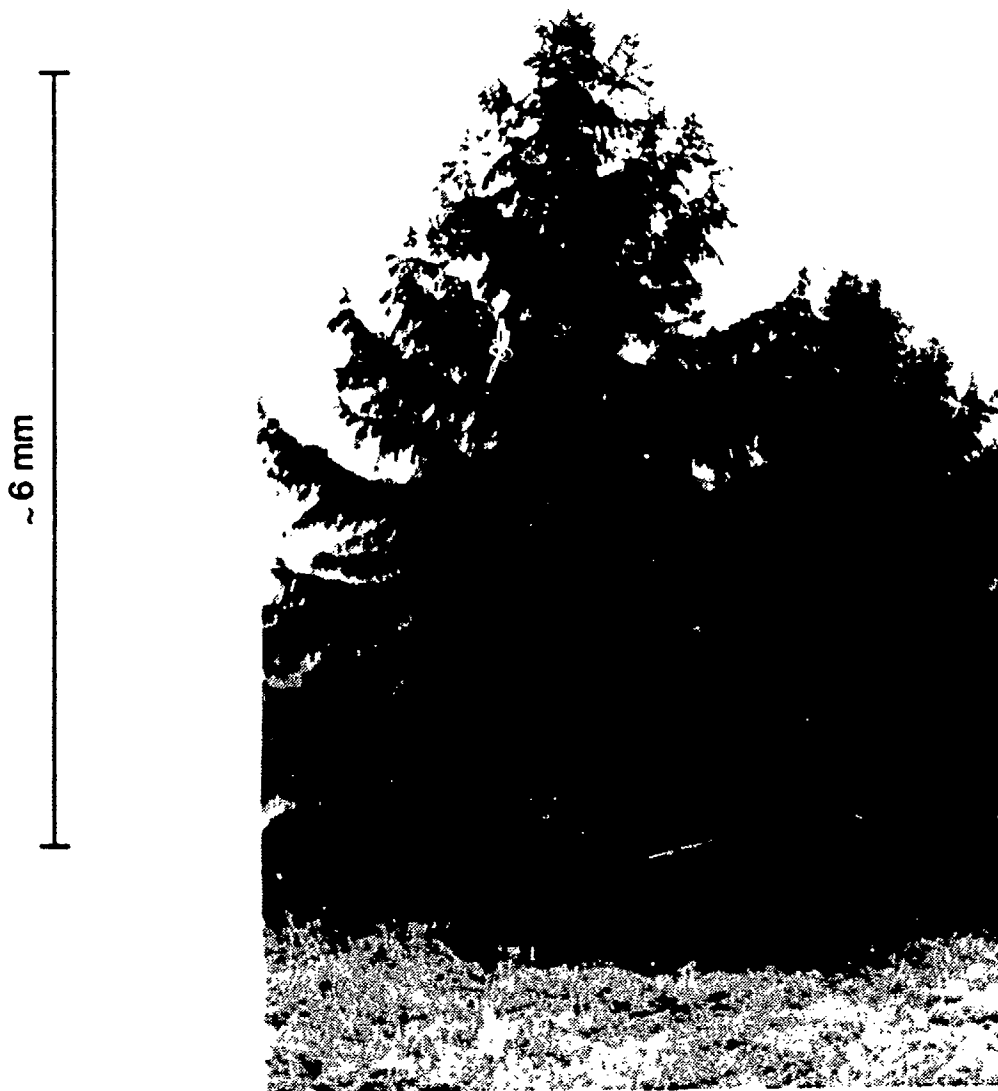
Leaf moisture content: 53.1%(881031); 56%  
(881122)

Percent vegetation cover (est.): 80 %

Percent cover of undergrowth: 100%

Moisture content of undergrowth: 35%

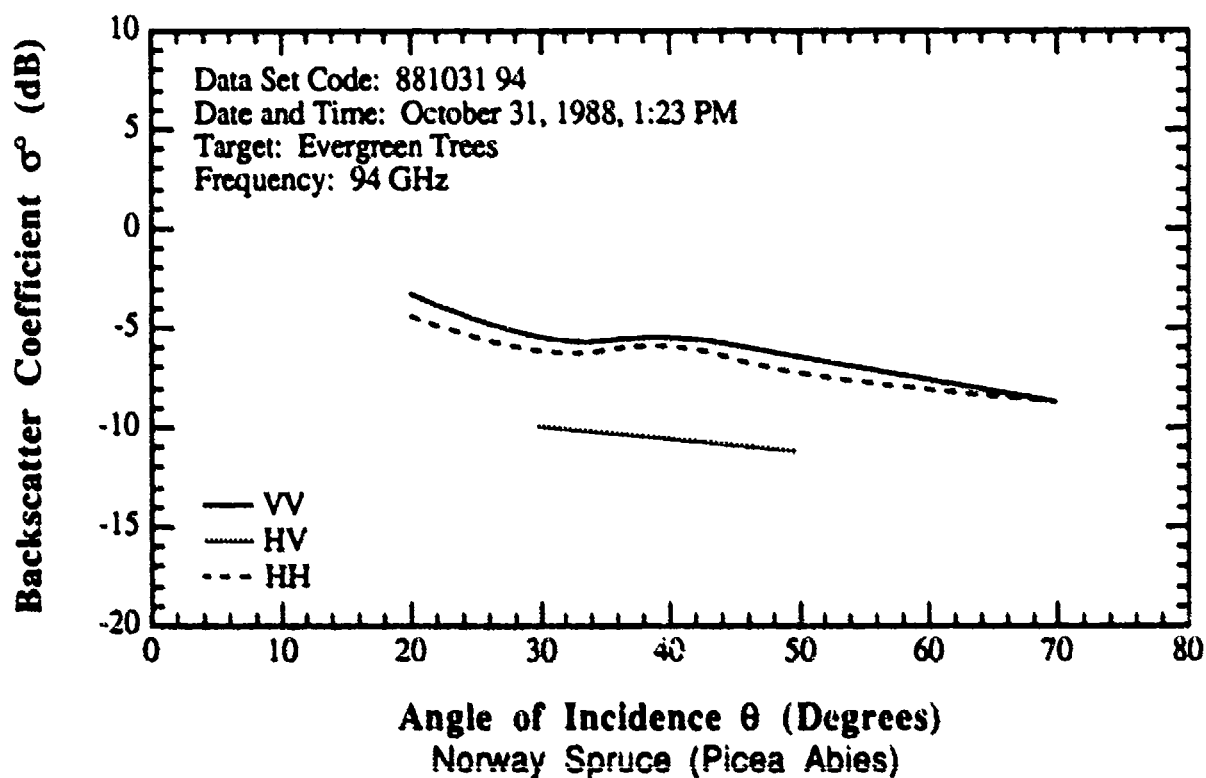
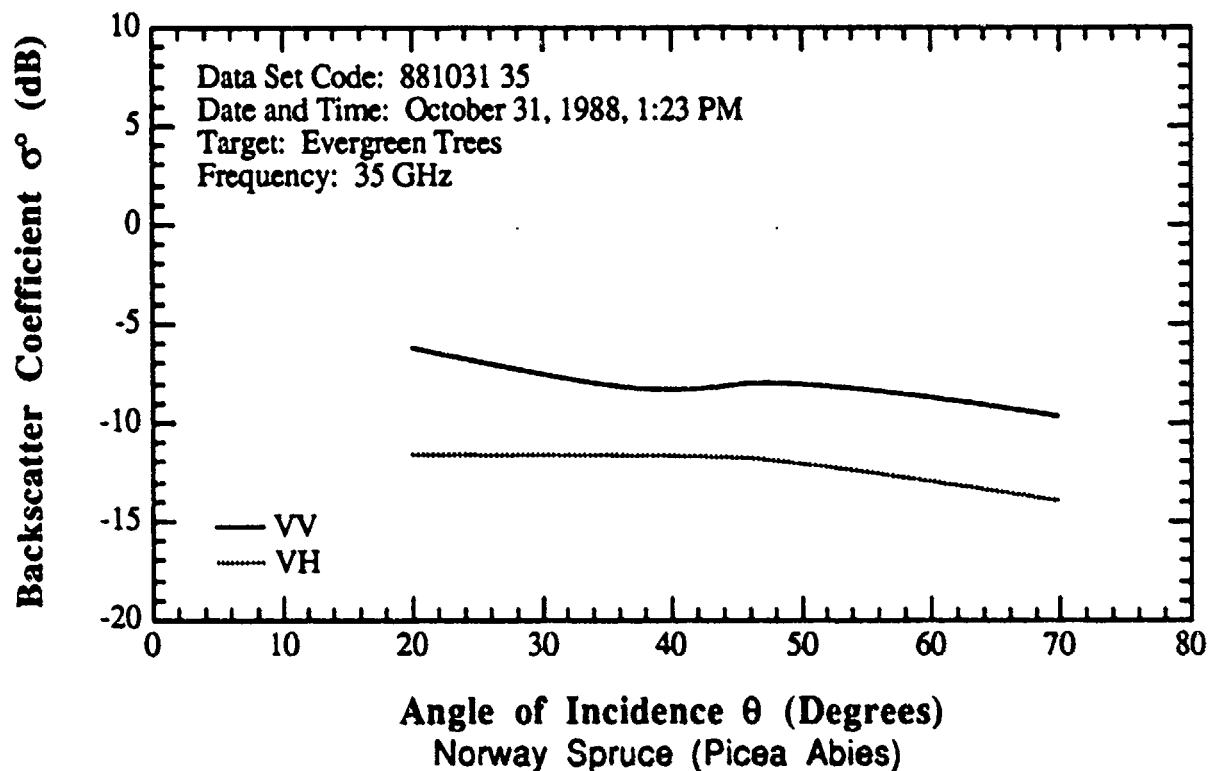
Description: stand of mature spruce trees with weedy  
ground cover



Spruce trees

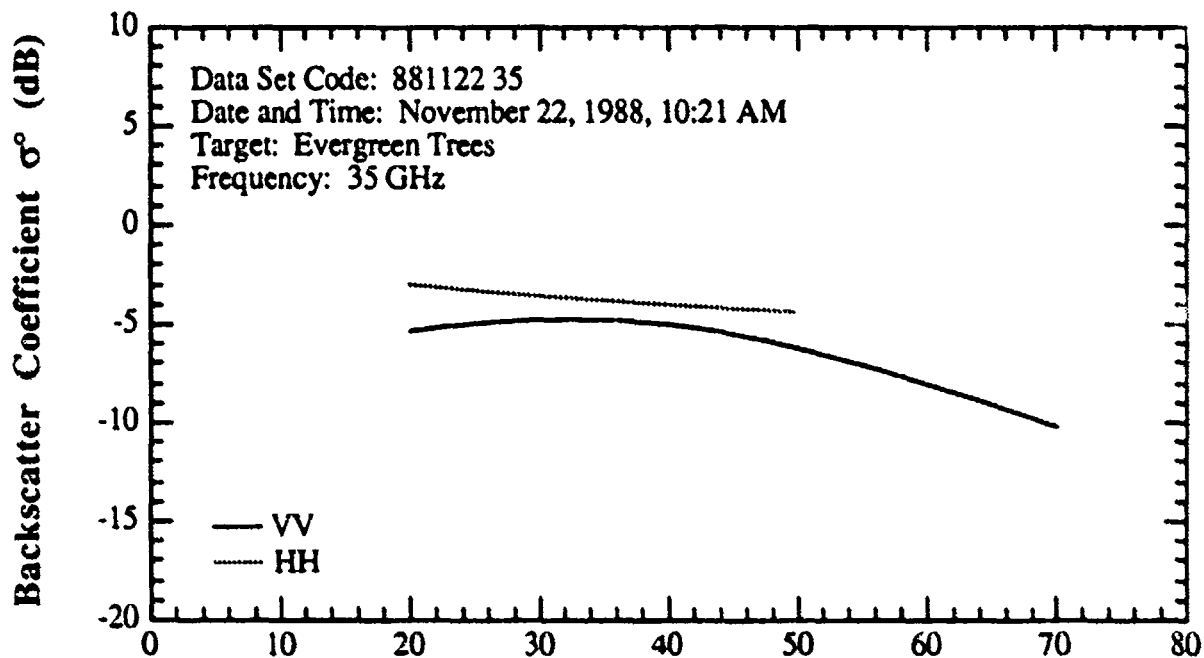
# MMW DATA FOR TREE CANOPIES

881031

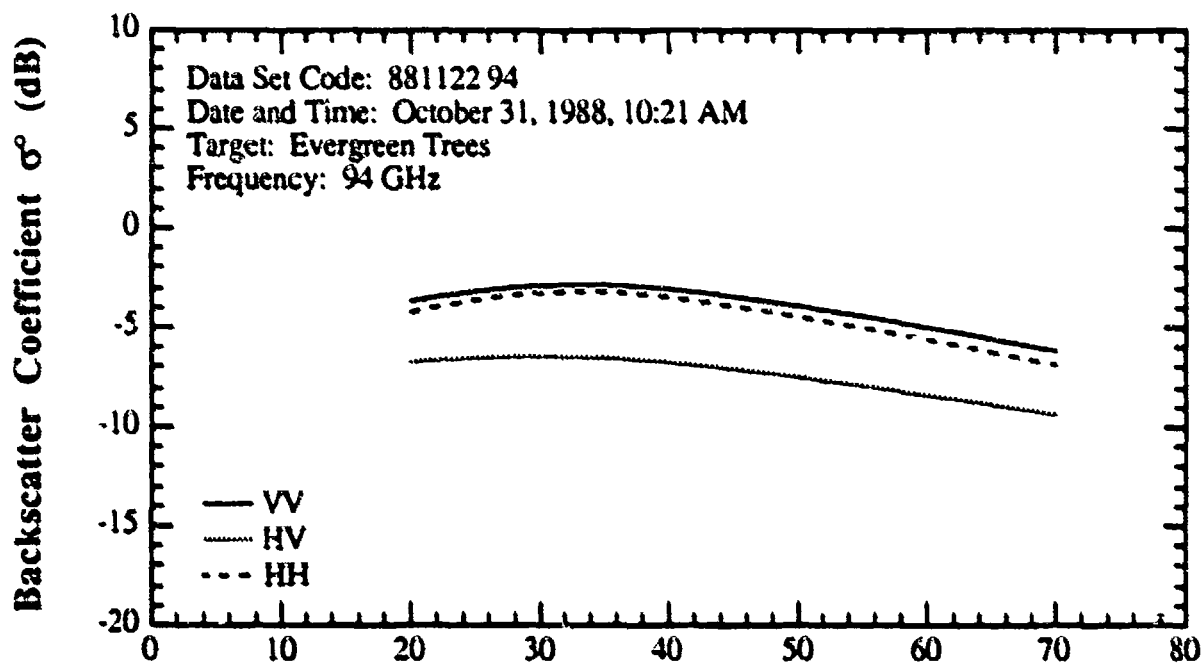


# MMW DATA FOR TREE CANOPIES

881122



Blue Spruce & Norway Spruce (*Picea Purpurea* & *Picea Abies*)



Blue Spruce & Norway Spruce (*Picea Purpurea* & *Picea Abies*)

## **F. White Cedar Bushes**

White Cedar bush (*Thuja occidentalis*)

Data set code: 881116

Height: 3 m

Density: 80 %

Average leaf (or needle) dimension: 5 cm

Leaf moisture content: 56 %

Percent vegetation cover: 80 %

Percent cover of undergrowth: 50%

Description: dense stand of White cedar bushes



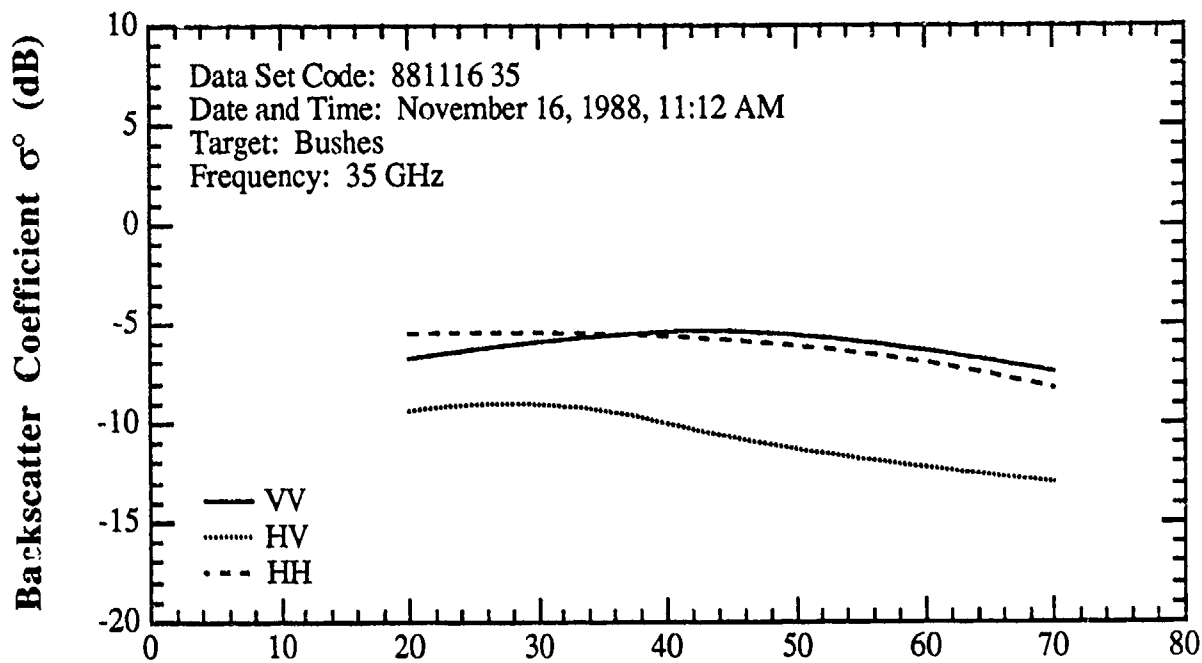
**White Cedar bush**

## MMW DATA FOR TREE CANOPIES



Close-up view of branches of White Cedar Bush

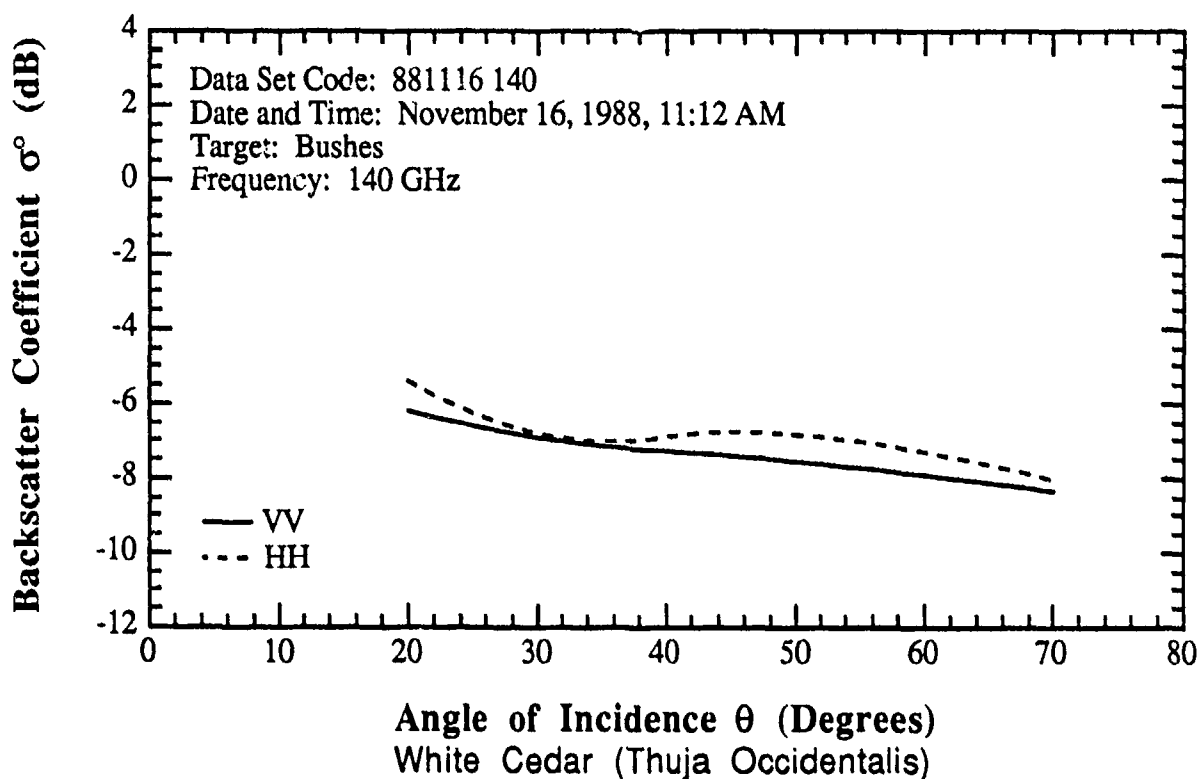
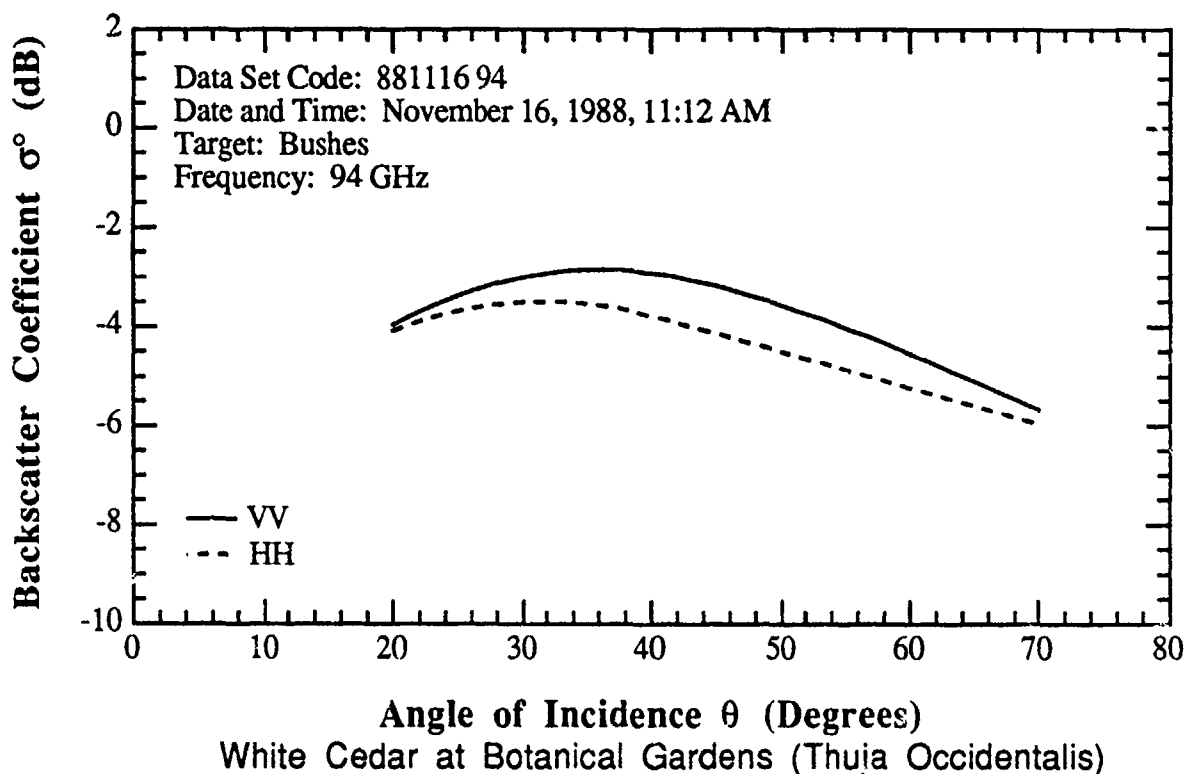
881116



Angle of Incidence  $\theta$  (Degrees)  
White Cedar at Botanical Gardens (*Thuja Occidentalis*)

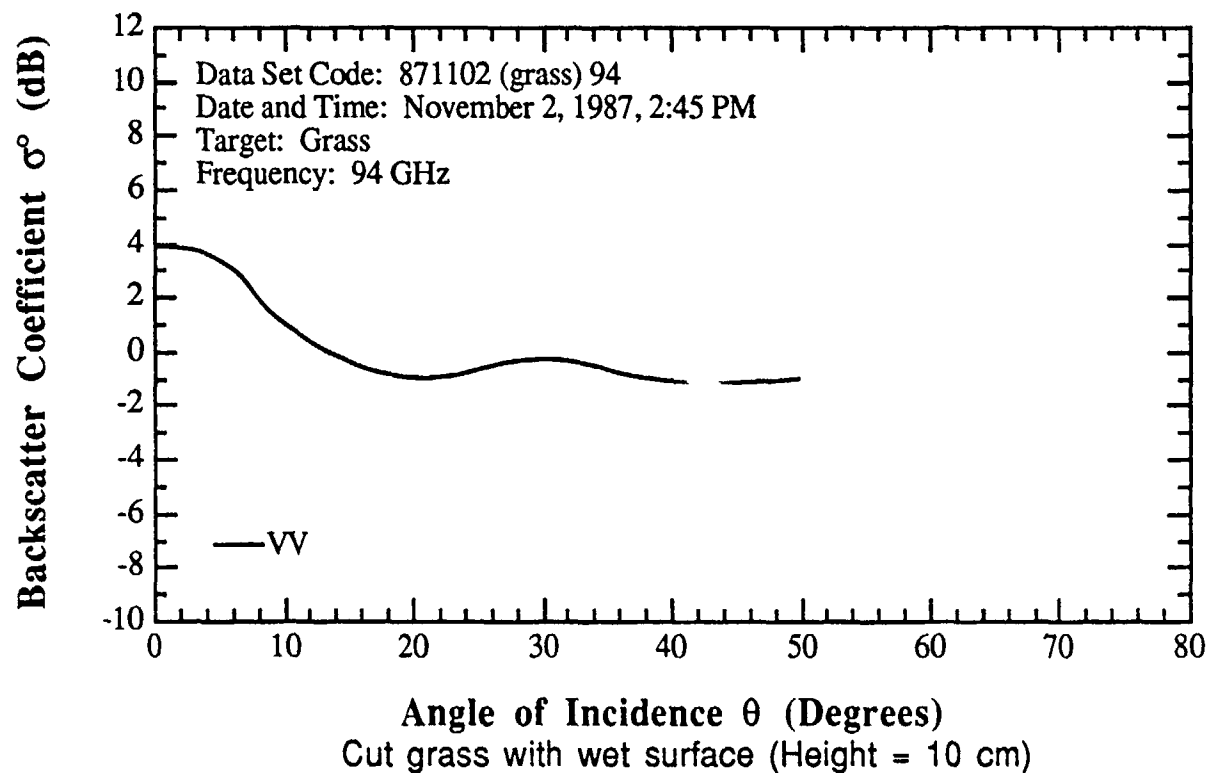
# MMW WAVE DATA FOR TREE CANOPIES

881116

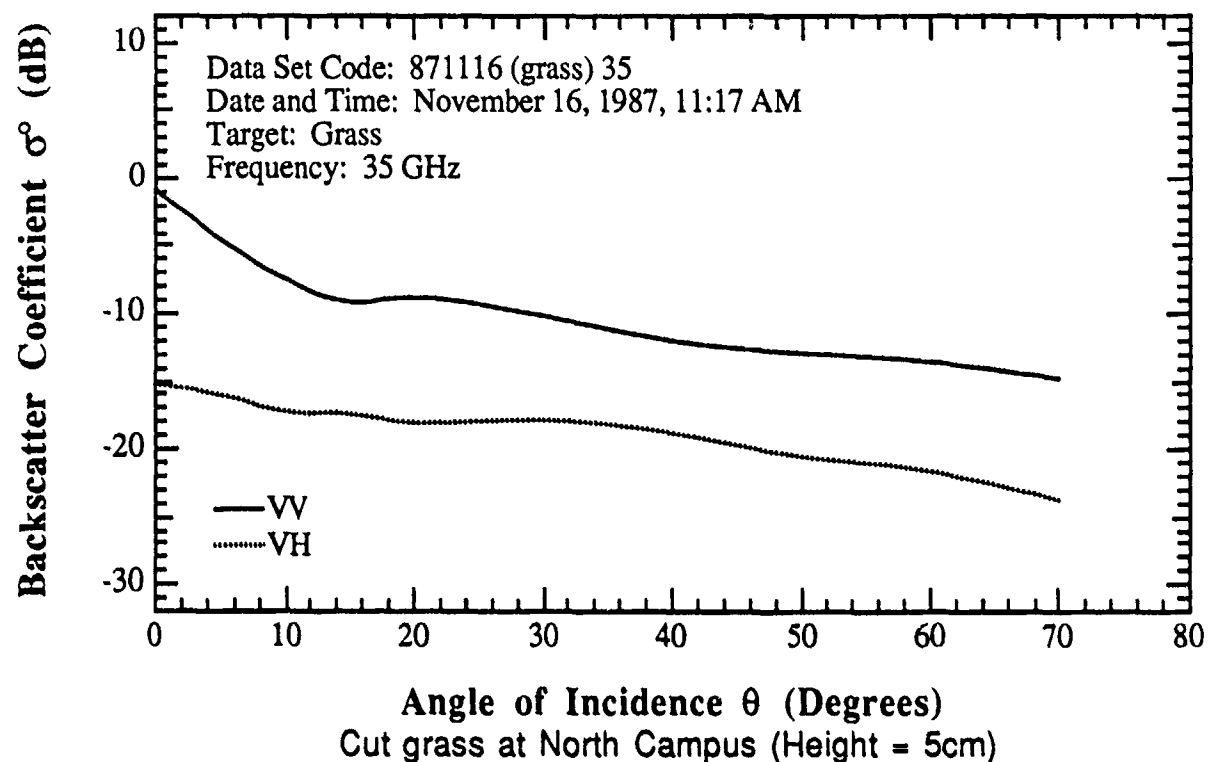


## VII. MMW DATA FOR GRASSES

871102

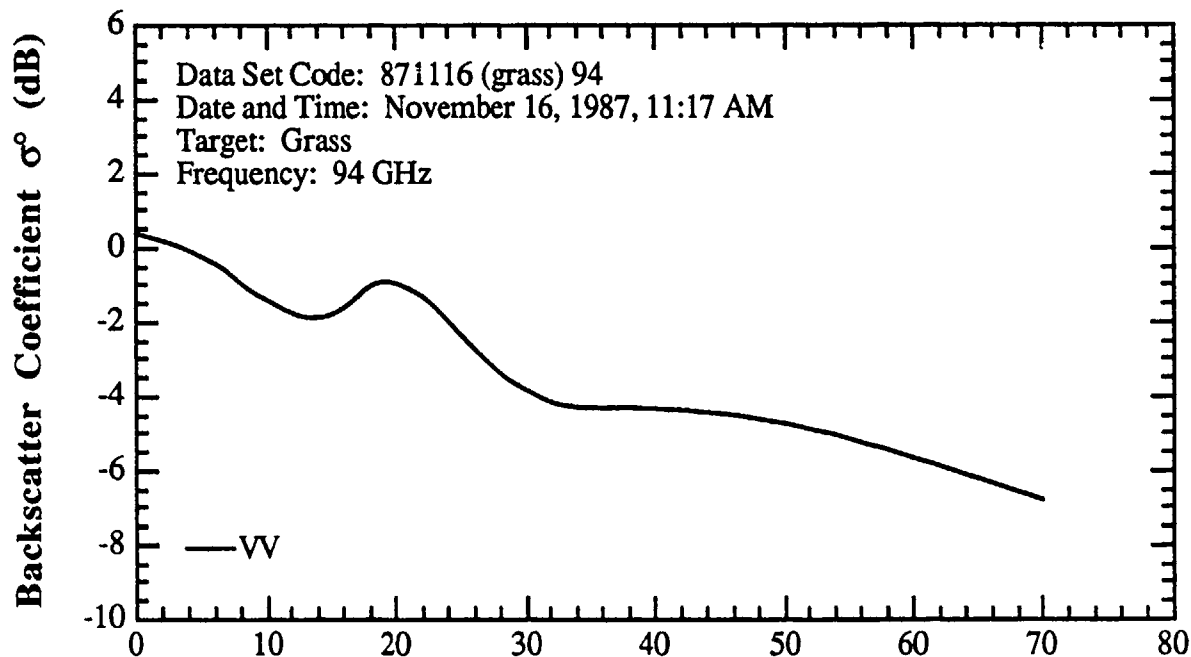


871116



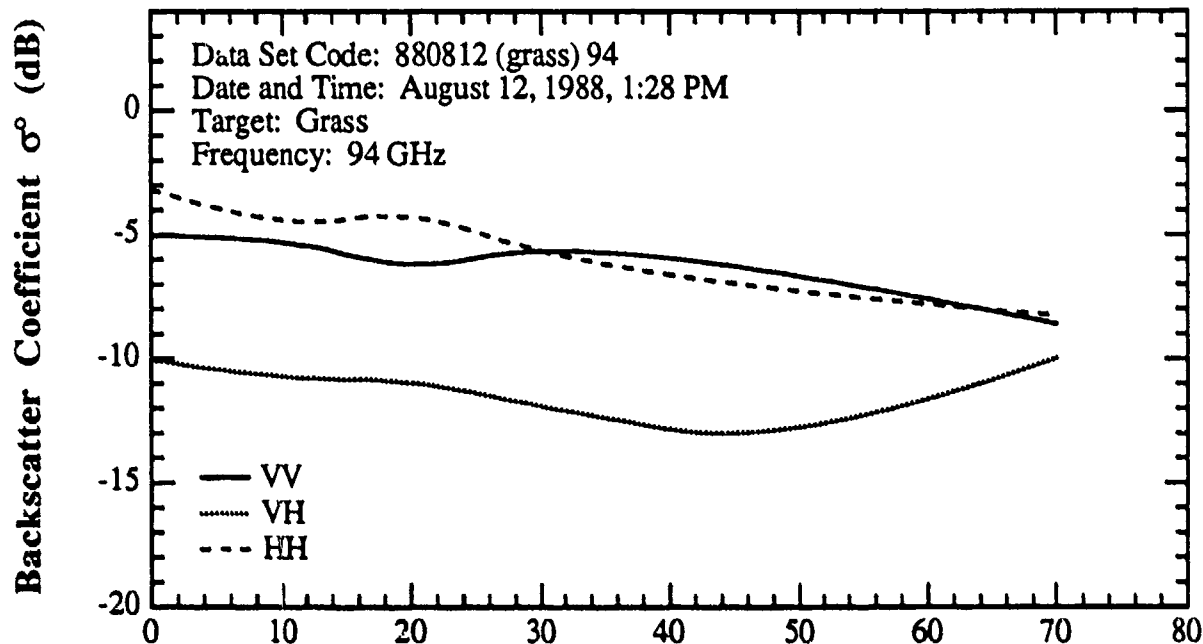
# MMW WAVE DATA FOR GRASSES

871116



Angle of Incidence  $\theta$  (Degrees)  
Cut Grass at North Campus (Height = 5 cm)

880812



Angle of Incidence  $\theta$  (Degrees)  
Cut Grass (Height = 6 cm)

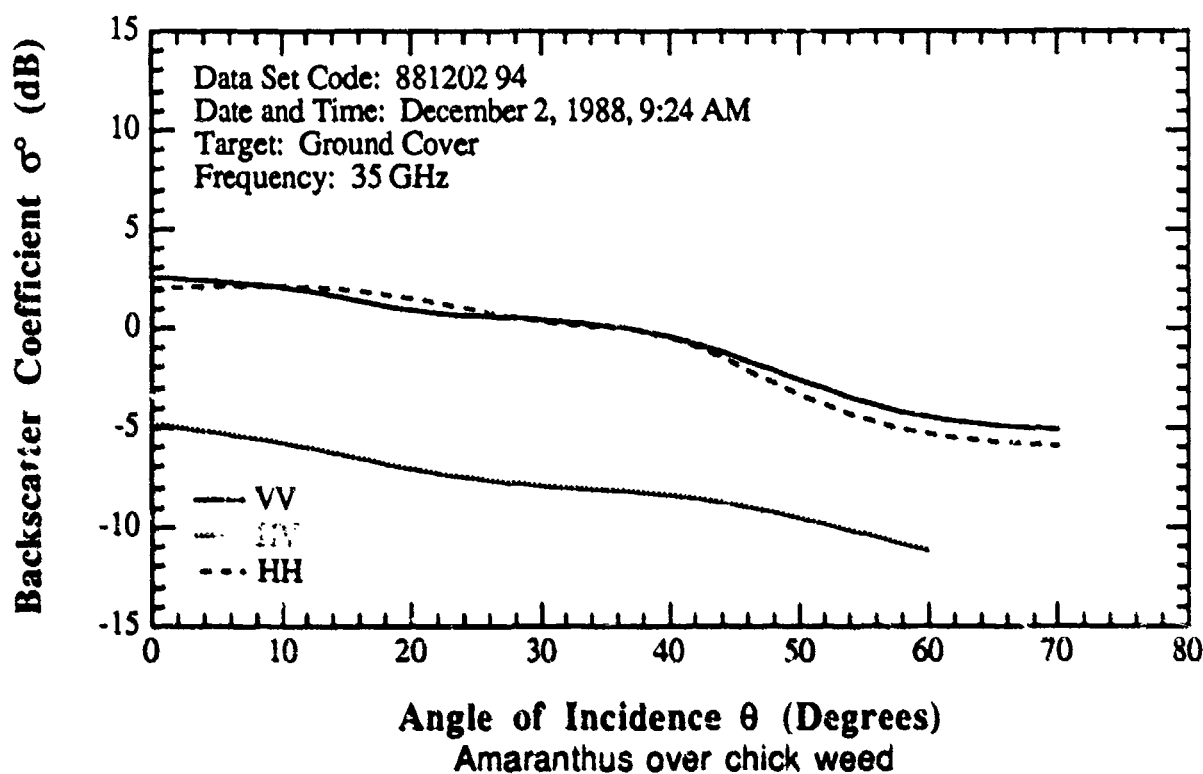
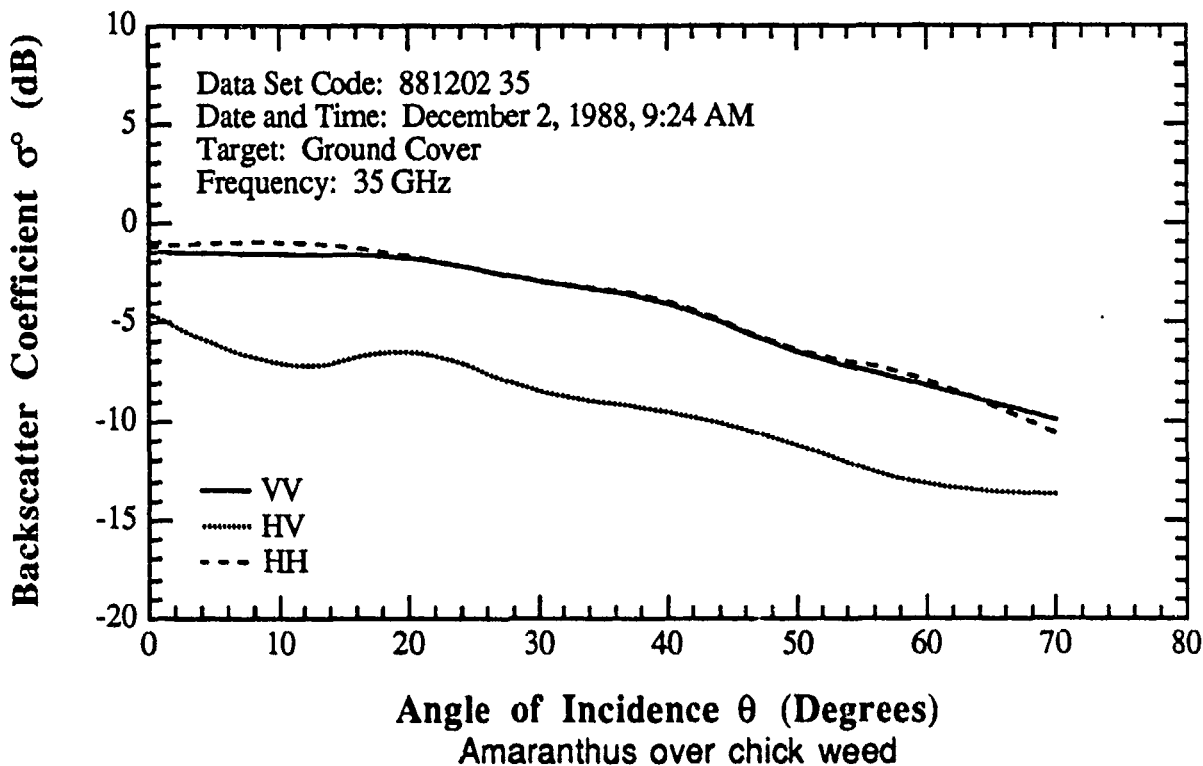
Tall Grass (Amaranthus)  
Data set code: 881202  
Grass Moisture Content: 37.6%  
Height: 50 cm  
Description: uncut



Amaranthus over chickweed

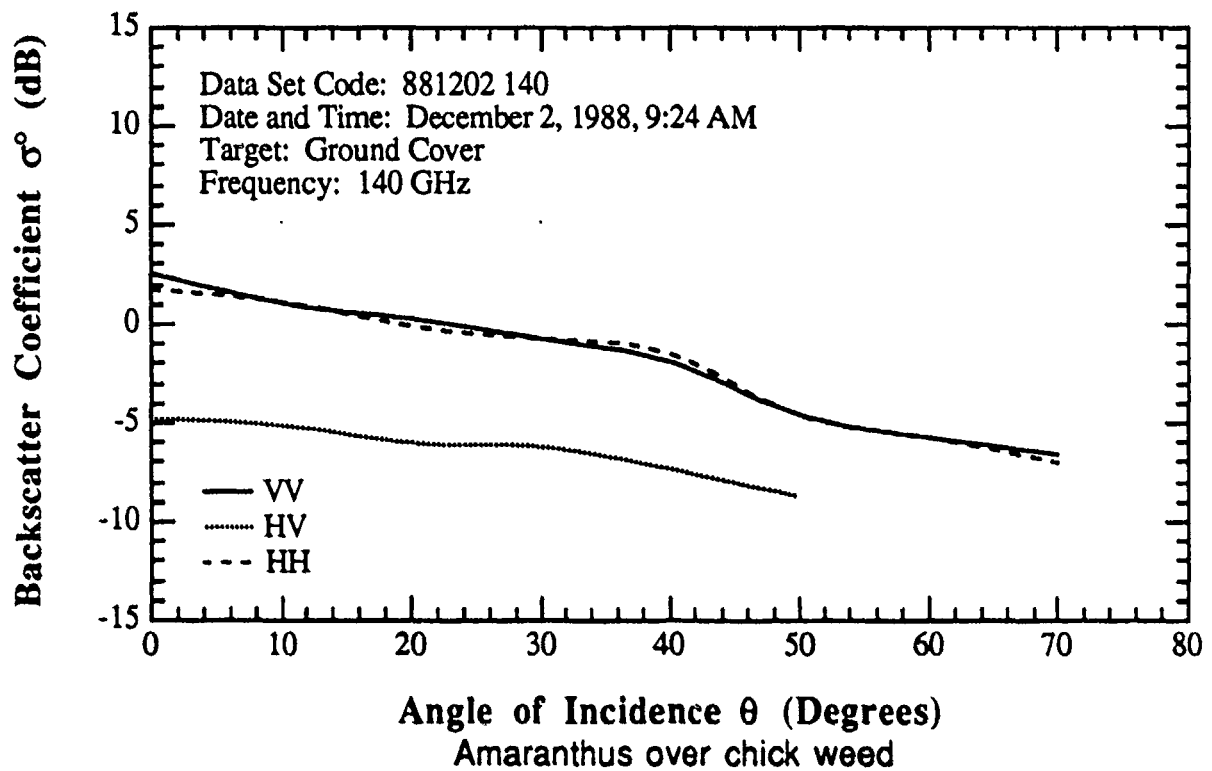
# MMW DATA FOR GRASSES

881202



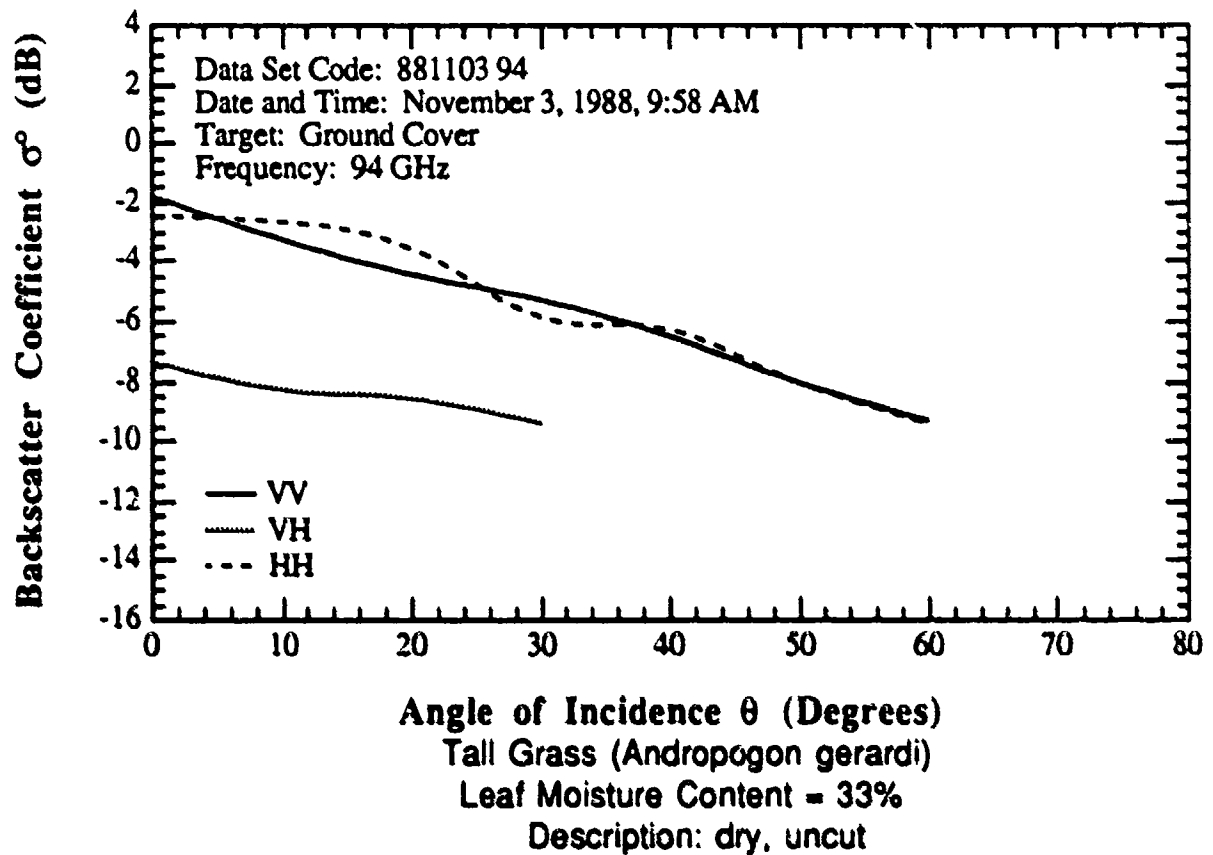
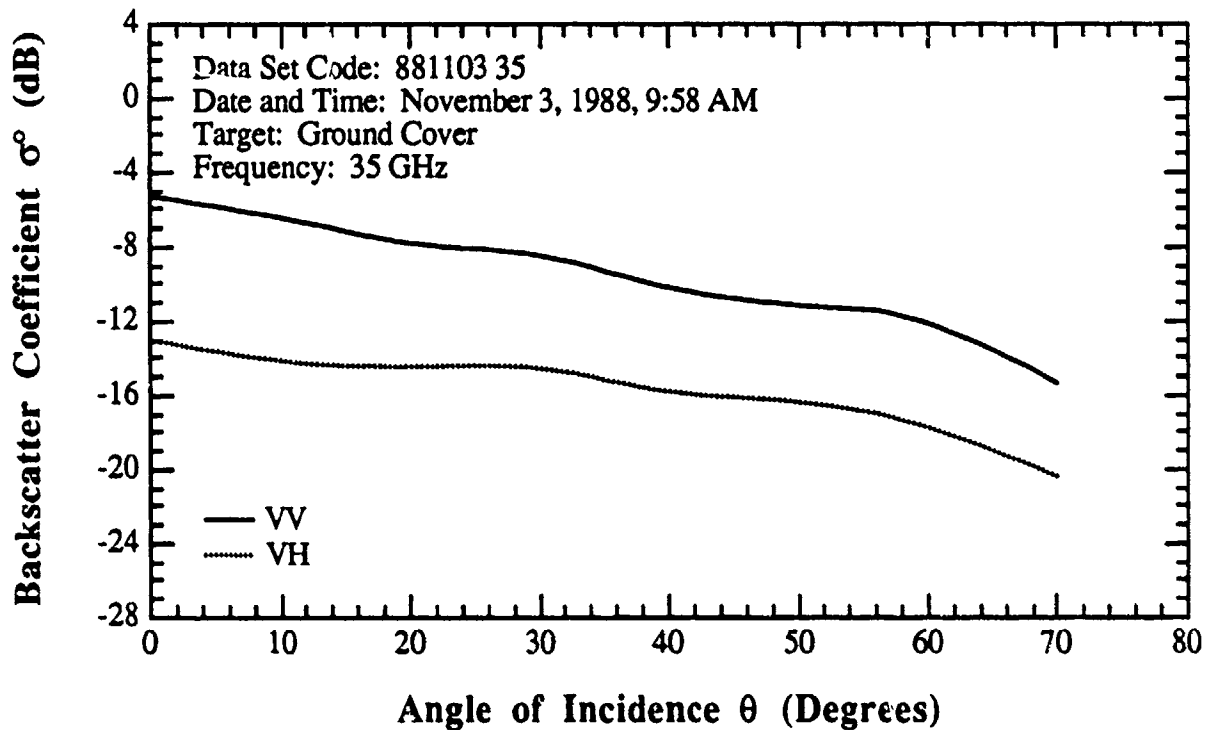
# MMW WAVE DATA FOR GRASSES

881202



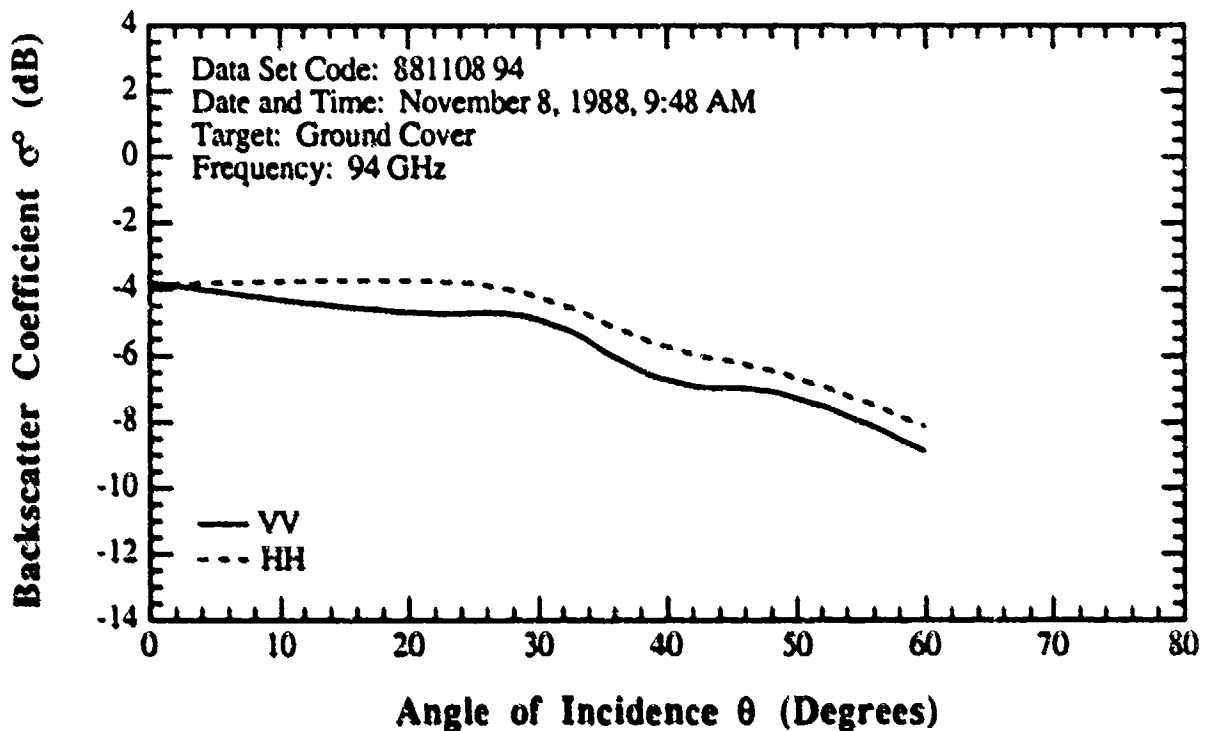
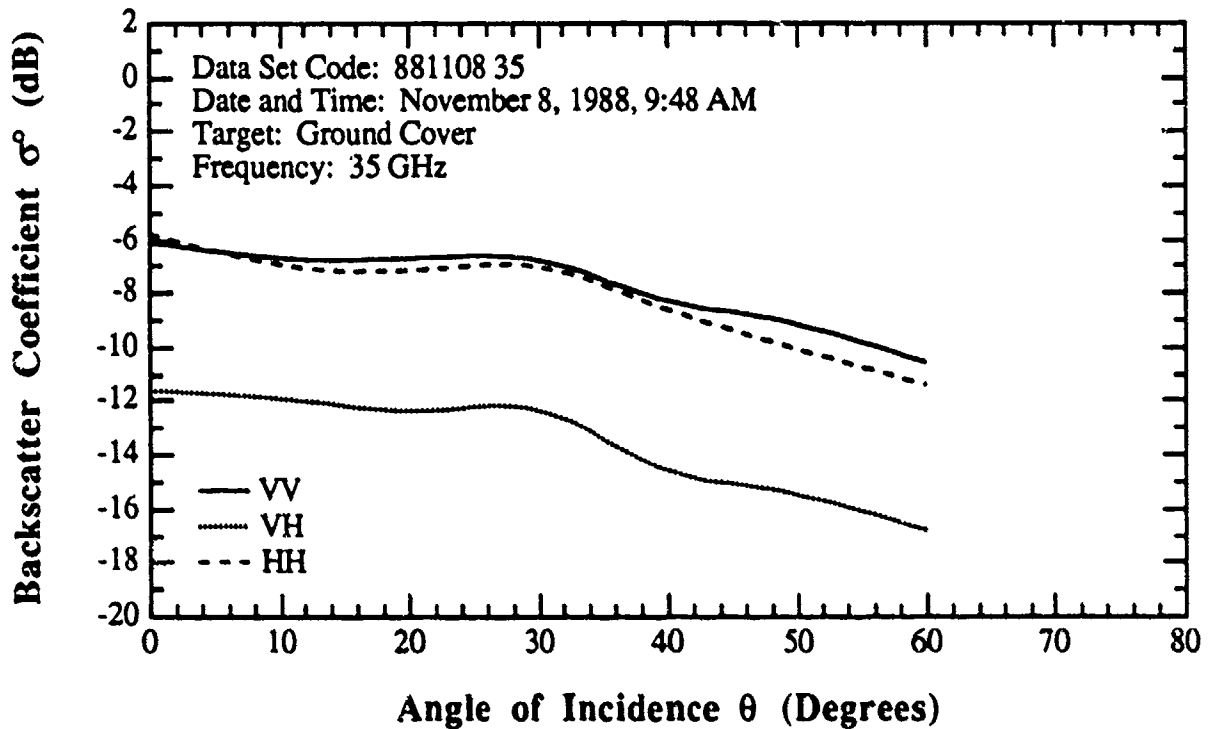
# MMW WAVE DATA FOR GRASSES

881103



# MMW WAVE DATA FOR GRASSES

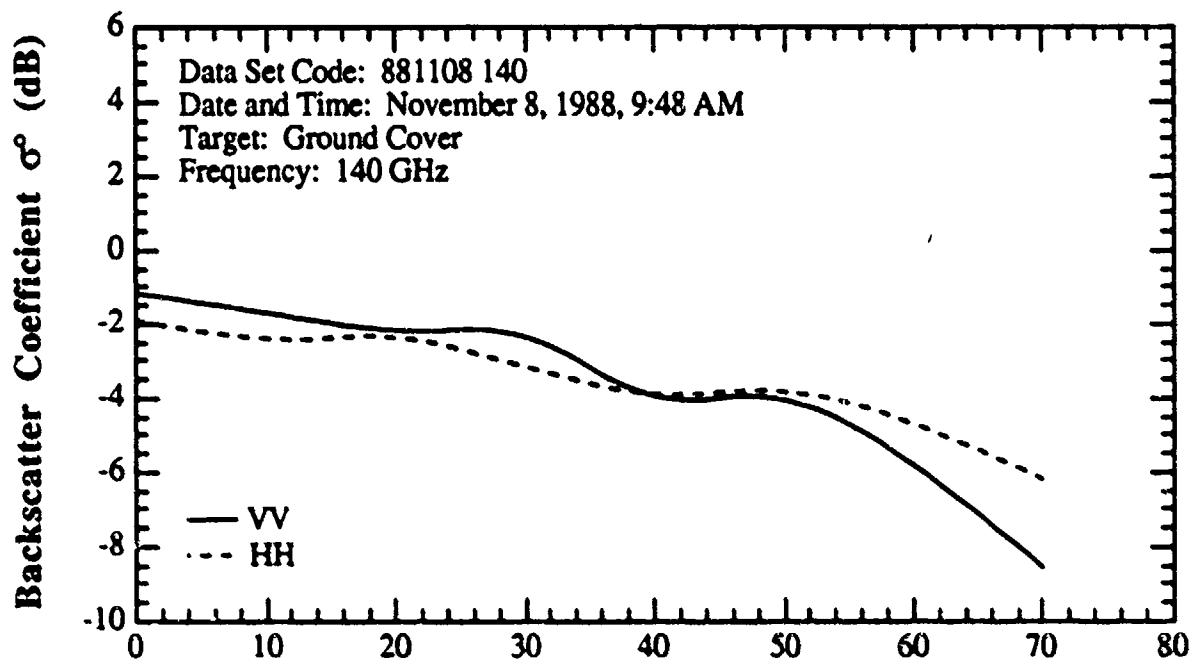
.881108



Turkey Foot or Big Bluestem (Andropogon gerardi)  
Grass (Andropogon gerardi)  
Leaf Moisture Content = 44.5%  
Description: moist, uncut

# MMW WAVE DATA FOR GRASSES

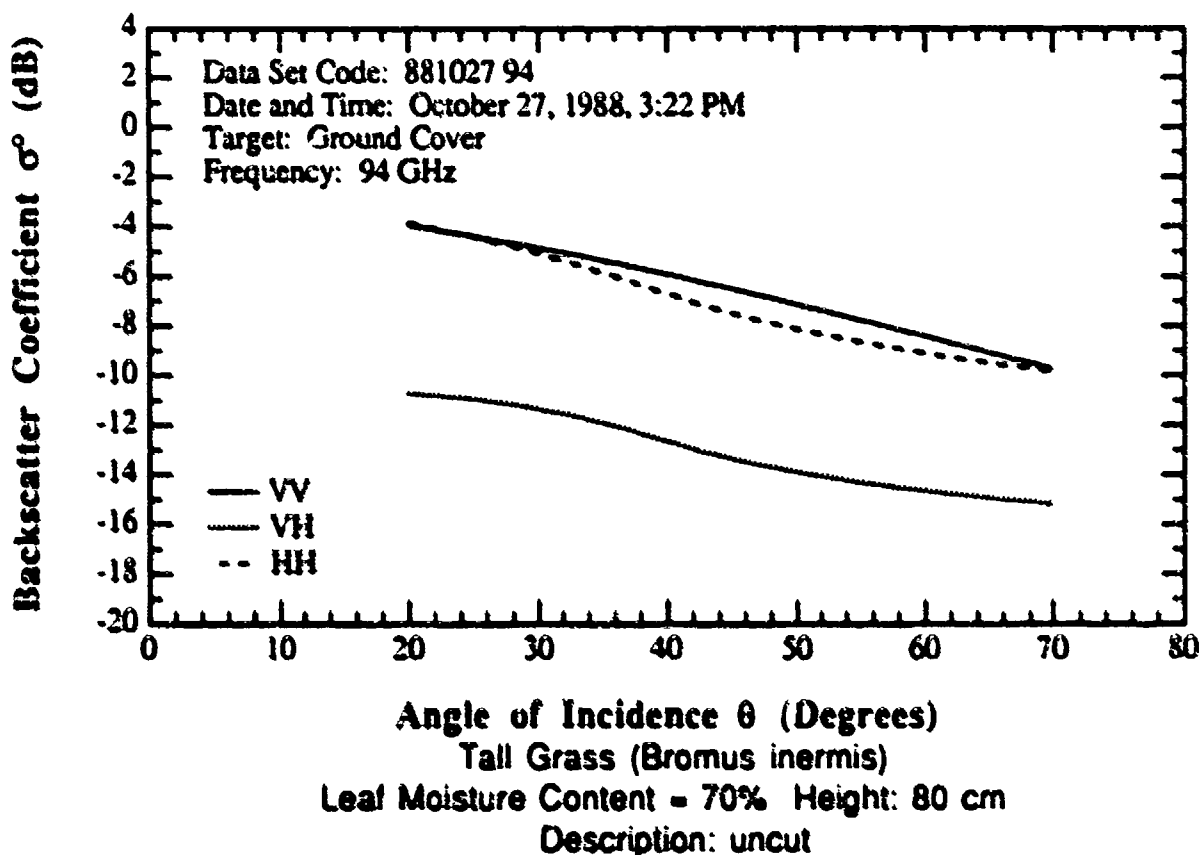
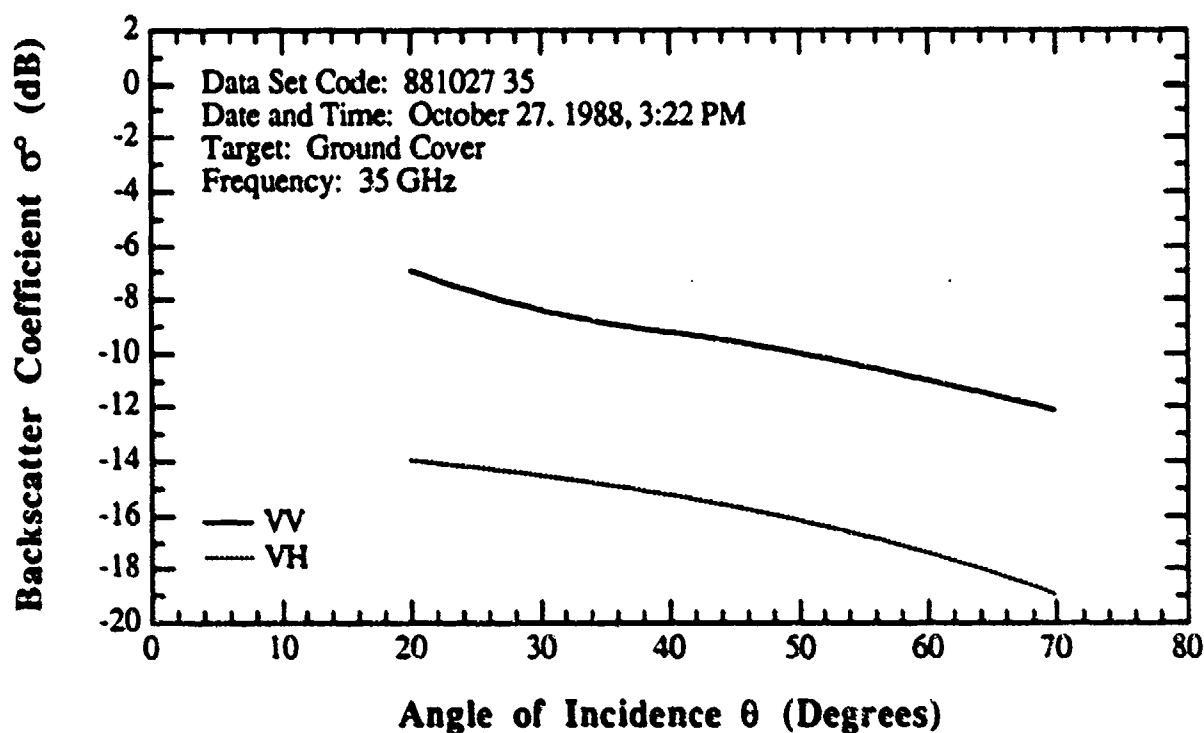
881108



Angle of Incidence  $\theta$  (Degrees)  
Turkey Foot or Big Bluestem (*Andropogon gerardi*)  
Grass (*Andropogon gerardi*)

# MMW WAVE DATA FOR GRASSES

881027



881114

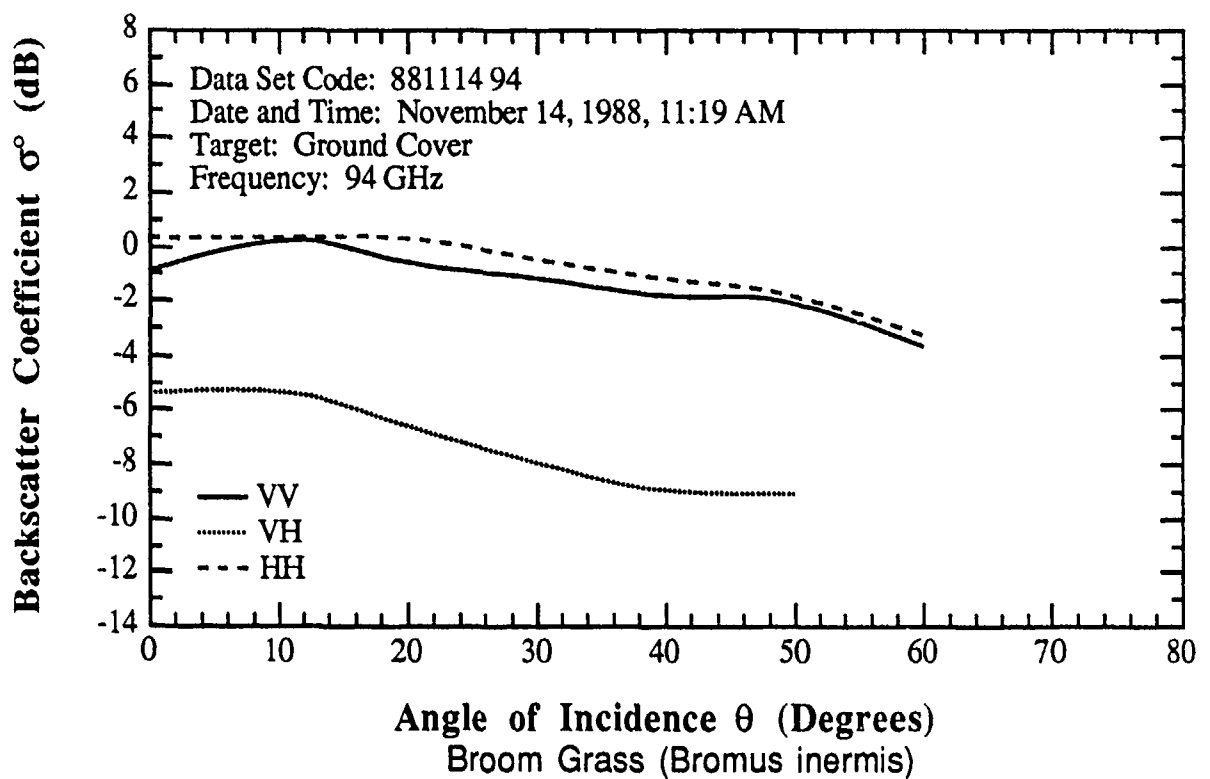
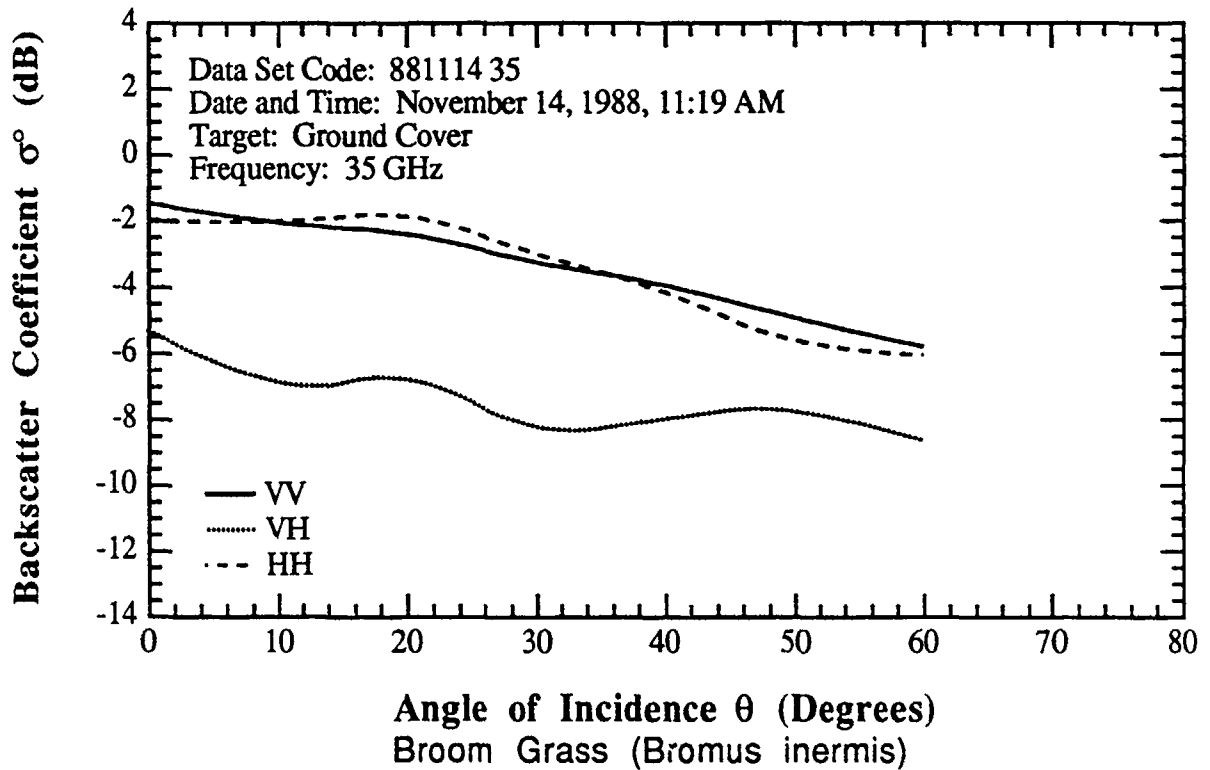
- Grass (*Bromus inermis*)  
Data set code: 881114  
Leaf Water Content = 43.1%  
Height: 10 cm  
Description: cut



Broom grass (*Bromus inermis*)

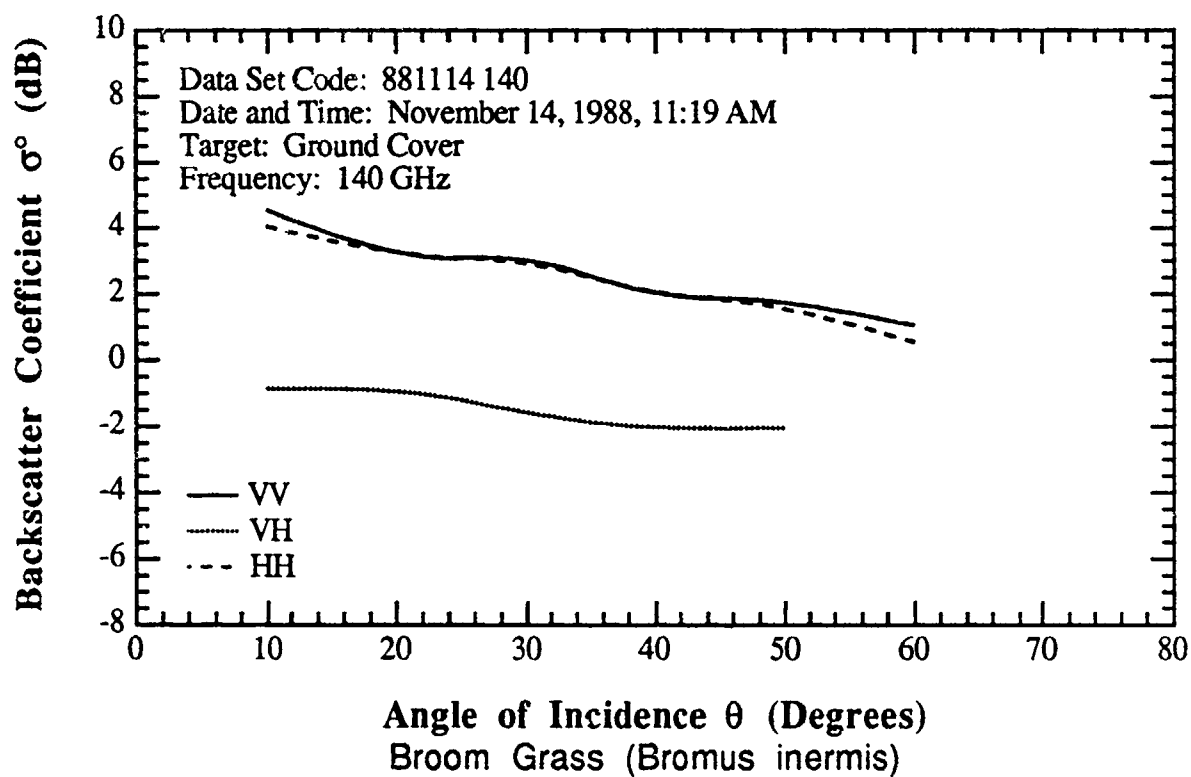
# MMW WAVE DATA FOR GRASSES

881114



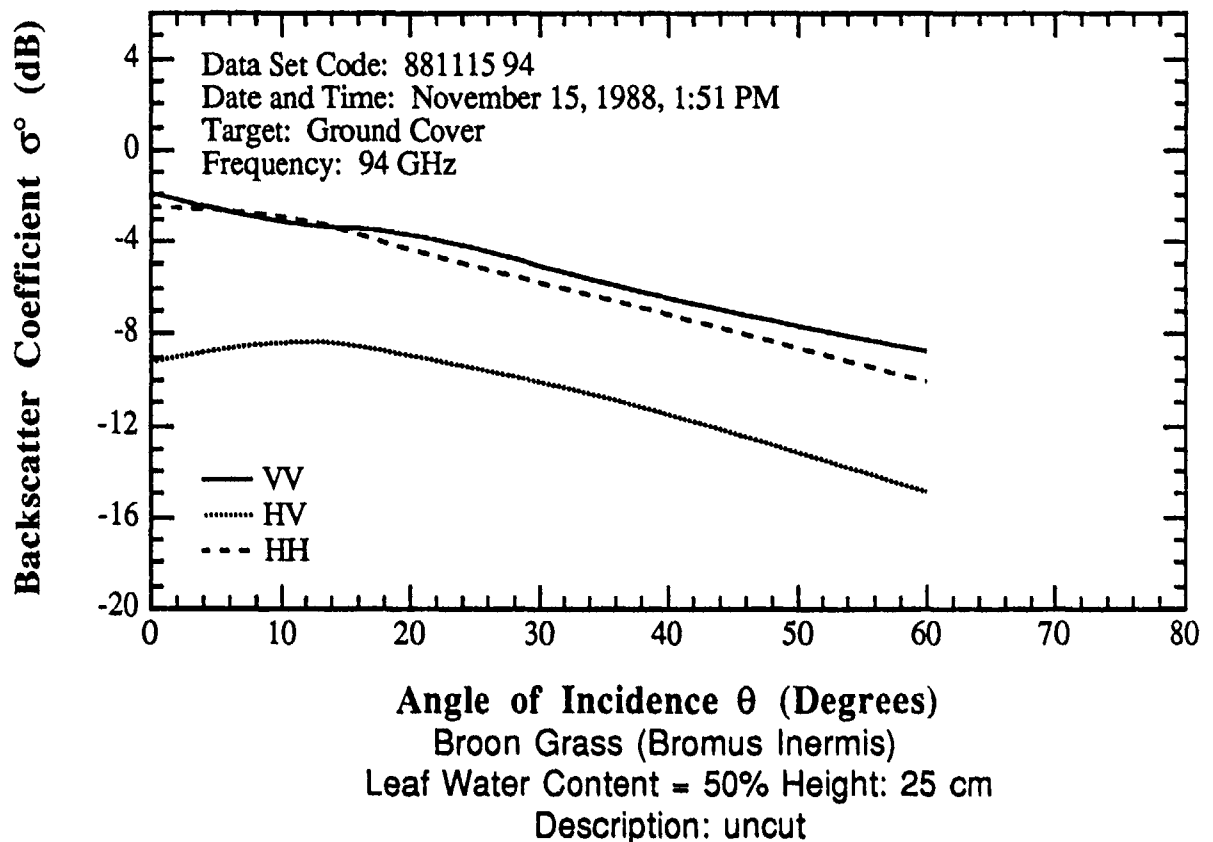
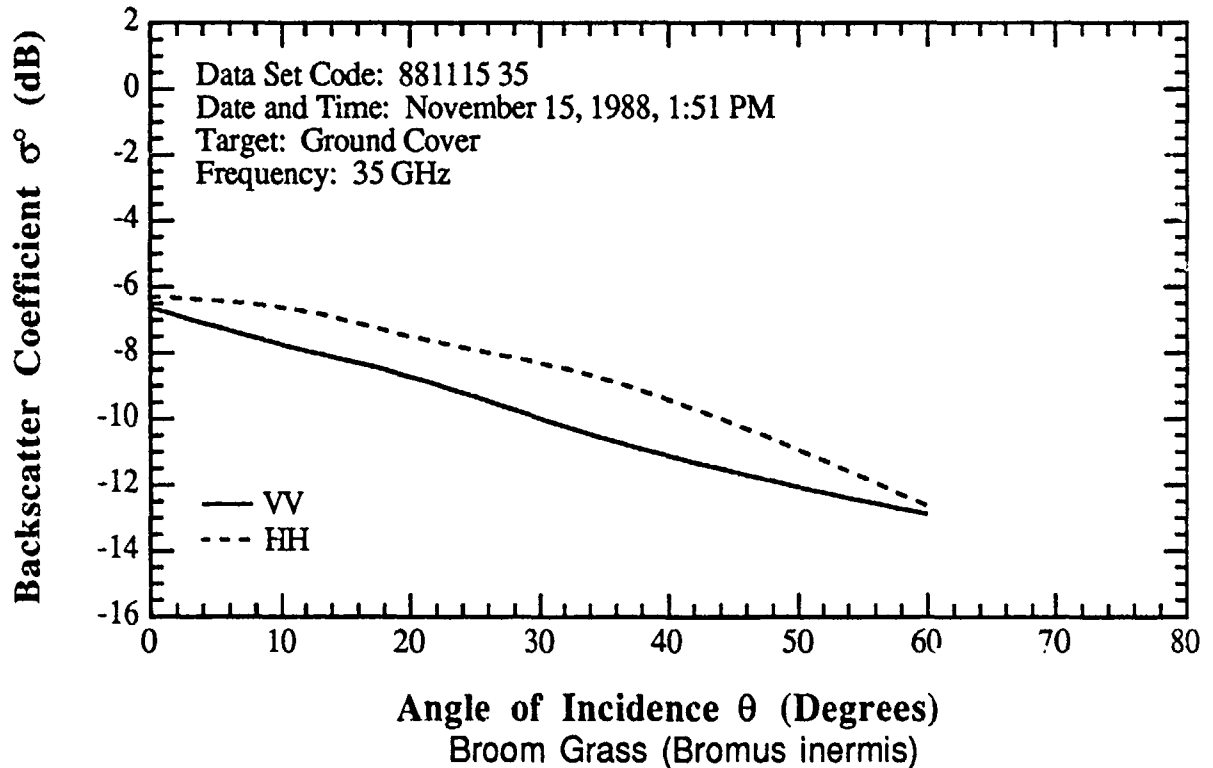
# MMW WAVE DATA FOR GRASSES

881114



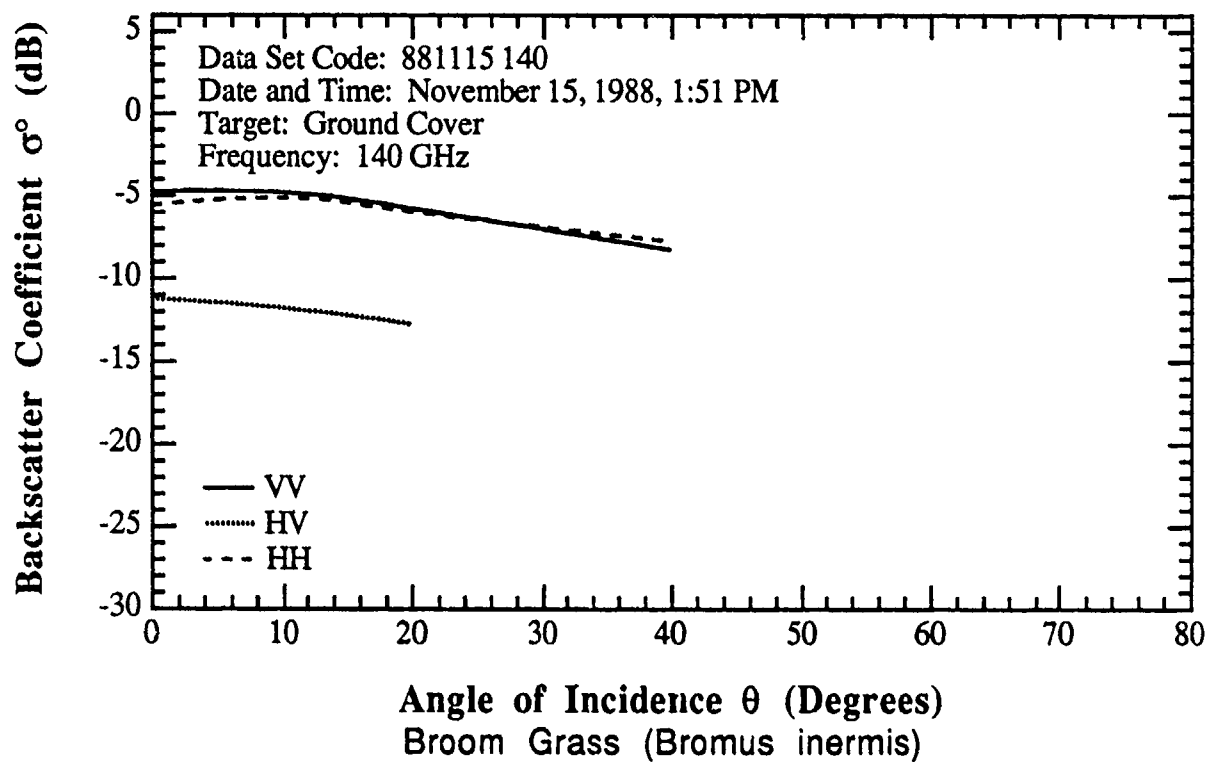
# MMW WAVE DATA FOR GRASSES

881115



# MMW WAVE DATA FOR GRASSES

881115



881117

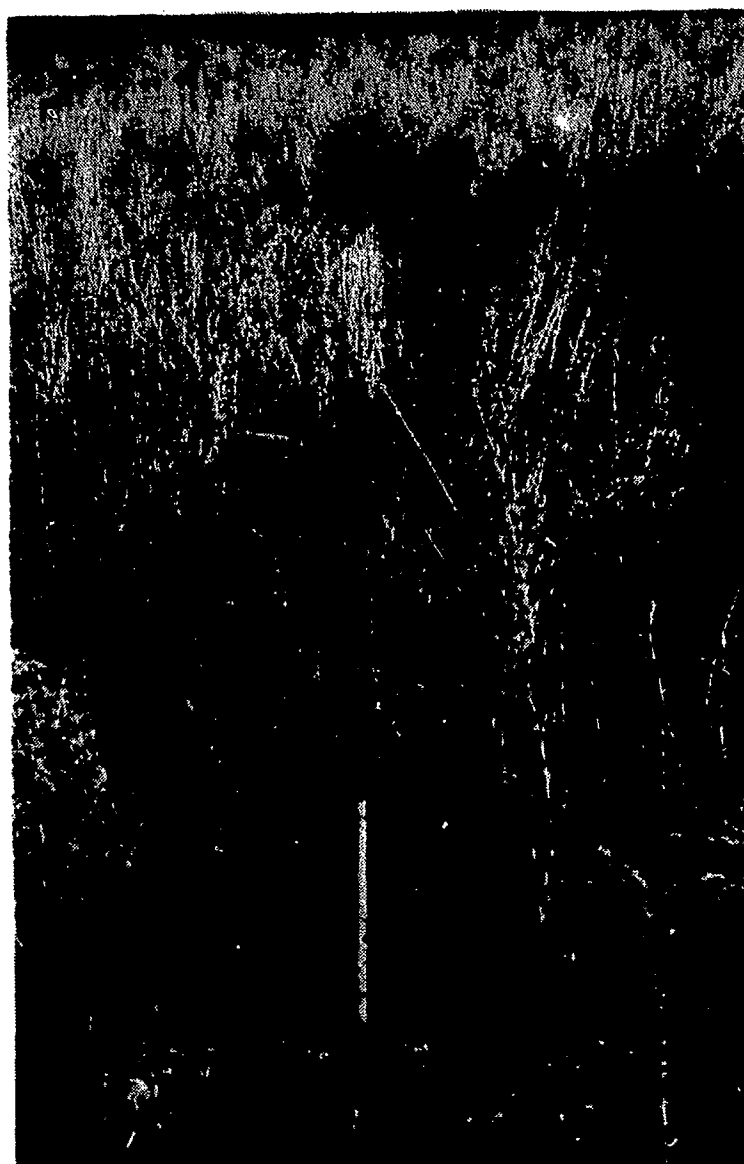
Grass (*Lythrum salicaria*)

Data set code: 881117

Leaf Moisture Content = 24.8%

Height: 1 m

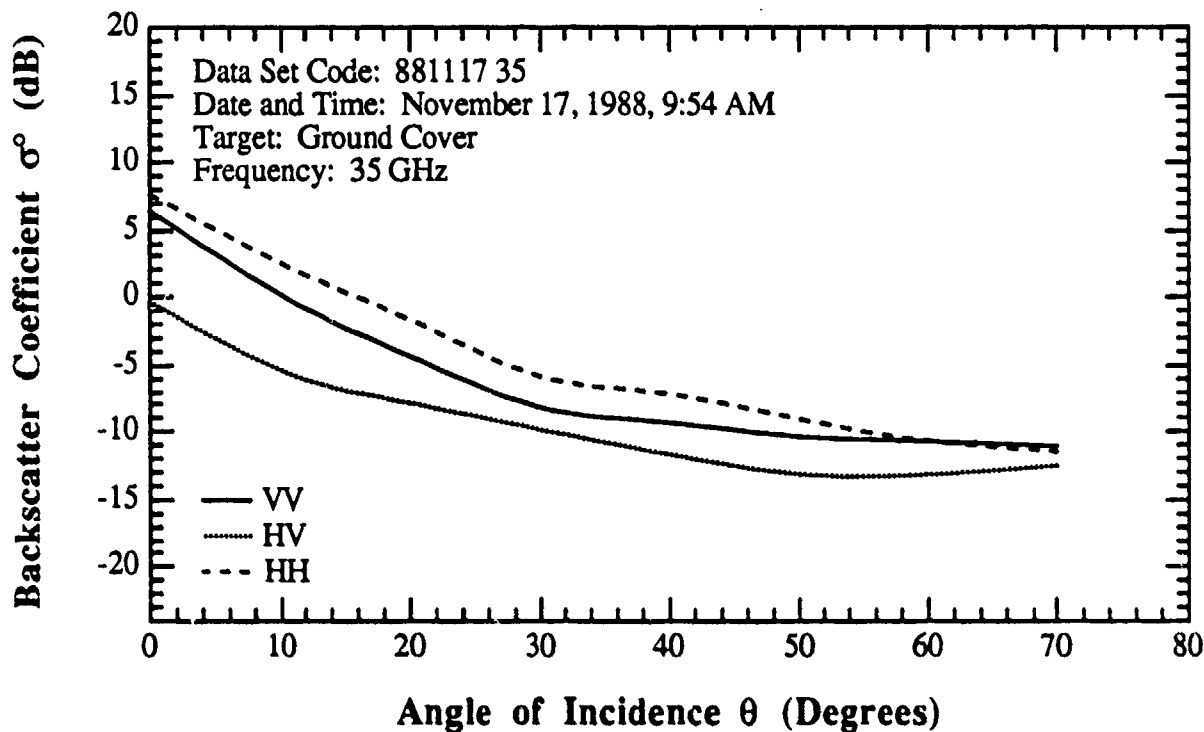
Description: uncut



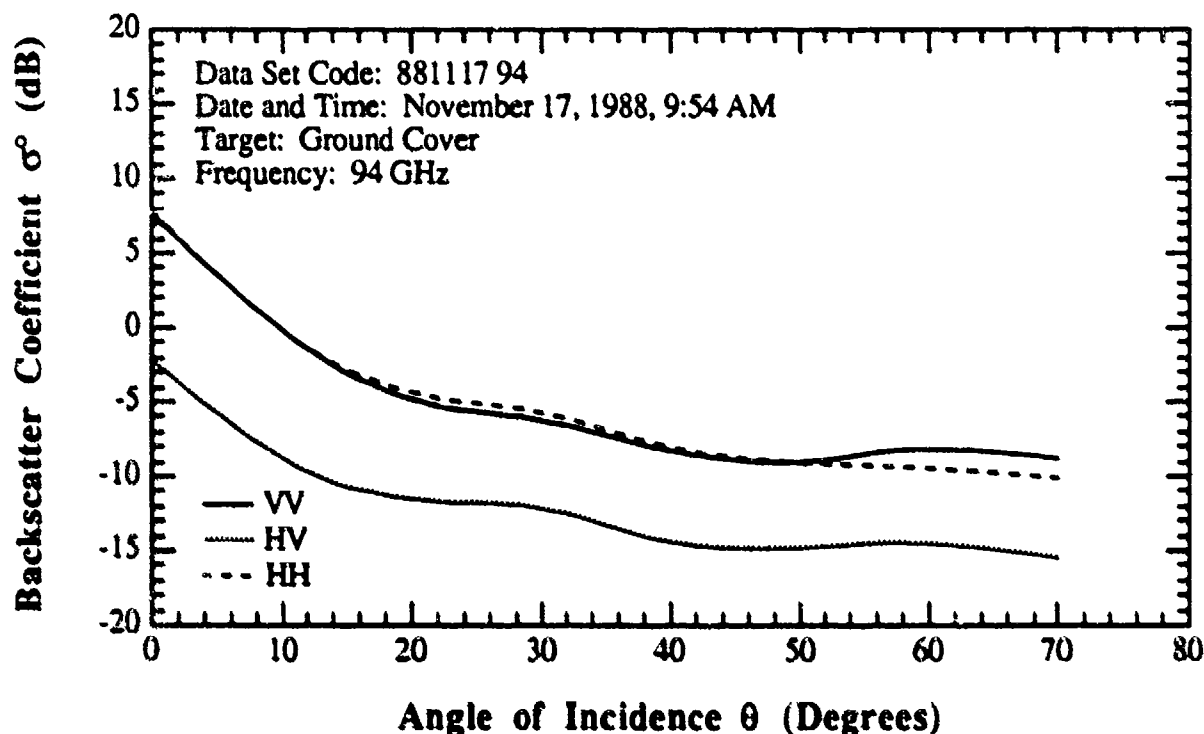
Purple loose strife (*Lythrum salicaria*)

# MMW WAVE DATA FOR GRASSES

881117



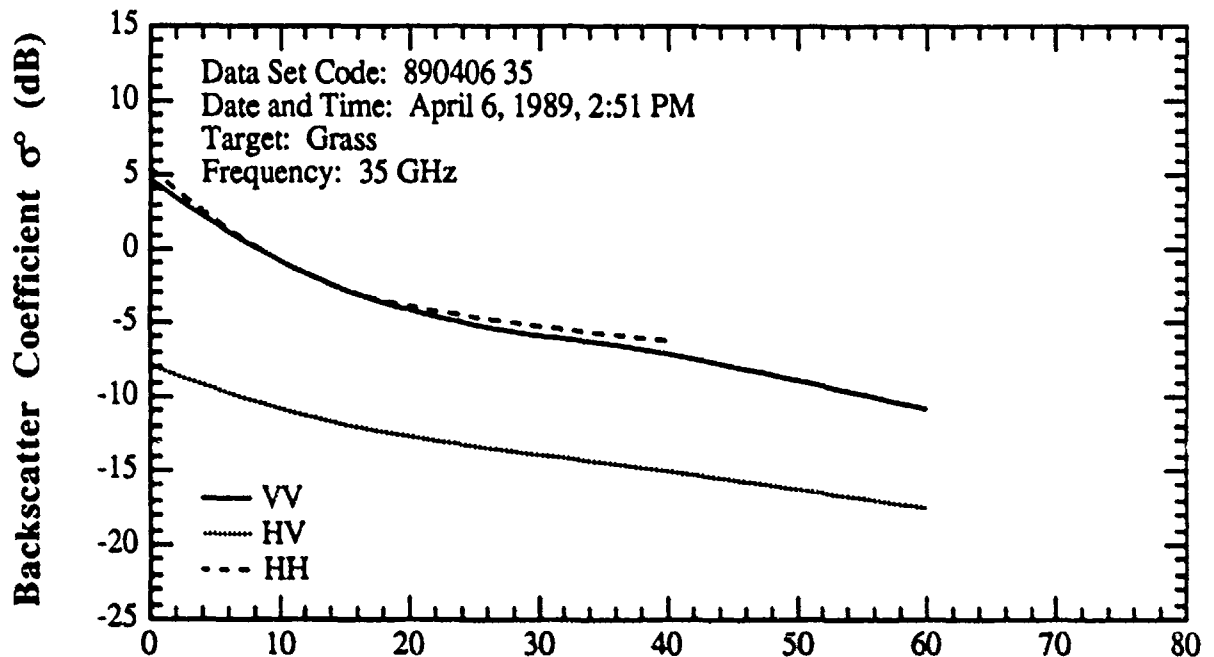
Purple Loose Strife over water (*Lythrum salicaria*)



Purple Loose Strife over water (*Lythrum salicaria*)

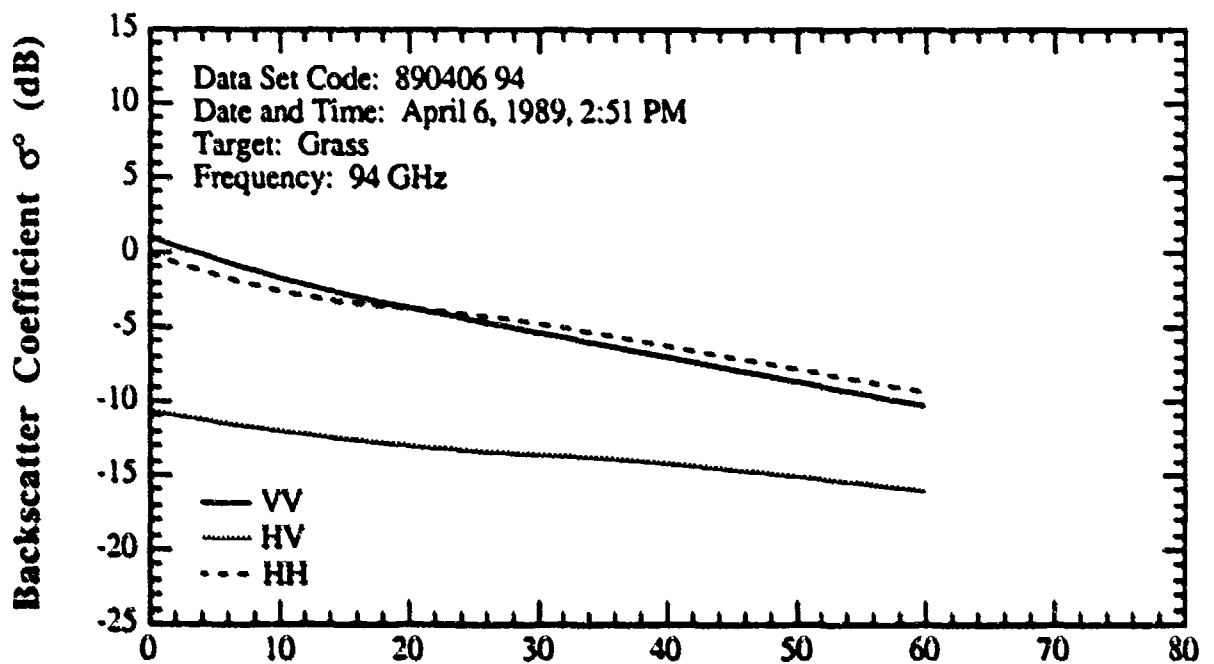
# MMW WAVE DATA FOR GRASSES

890406



Angle of Incidence  $\theta$  (Degrees)

Brighton grass substrate



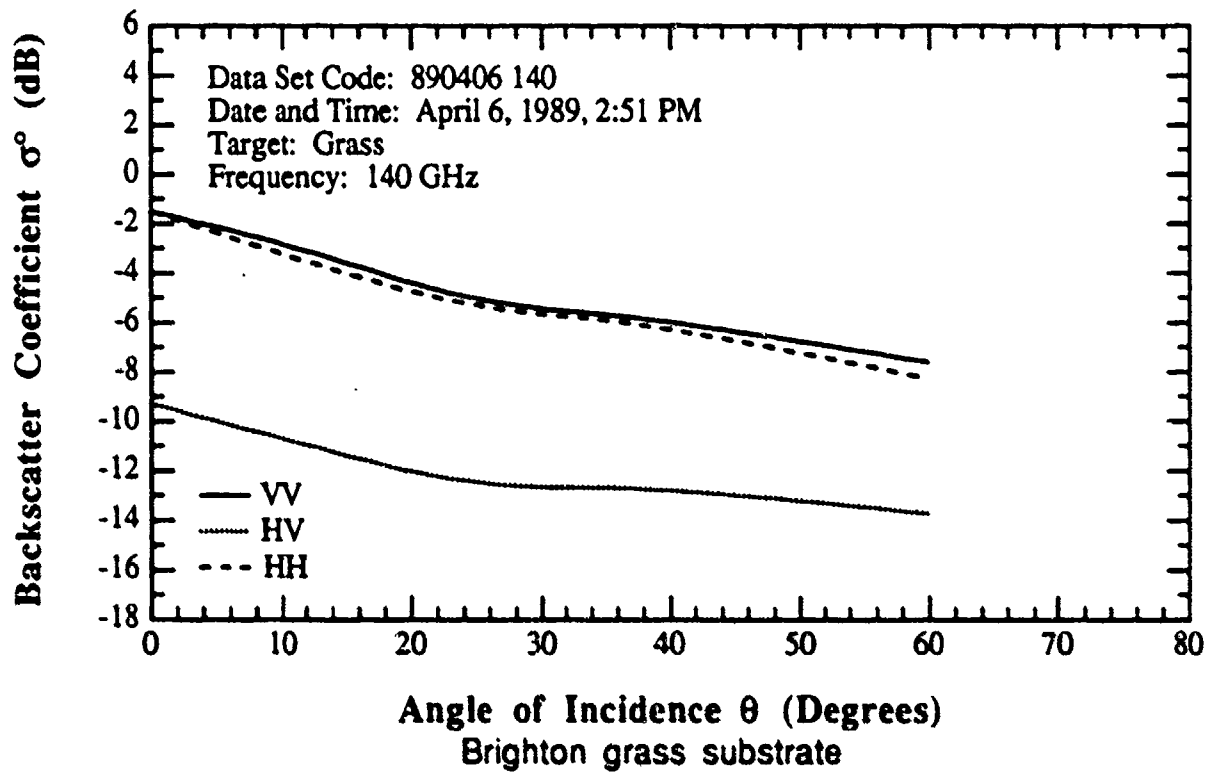
Angle of Incidence  $\theta$  (Degrees)

Leaf Moisture Content = 70% Height: 4 cm

Description: cut, packed down by winter's snow. This is the grass from under the Brighton snow for which data was taken in early 1989.

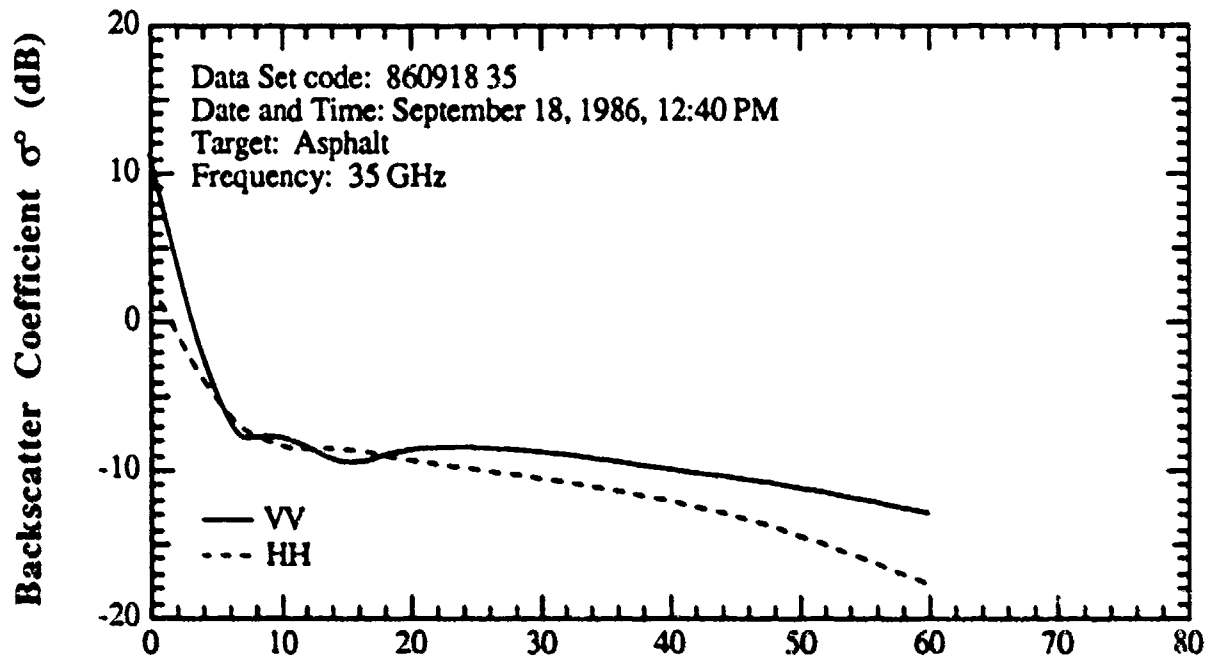
# MMW WAVE DATA FOR GRASSES

890406



# MMW WAVE DATA FOR ROAD SURFACES

860918



Angle of Incidence  $\theta$  (Degrees)

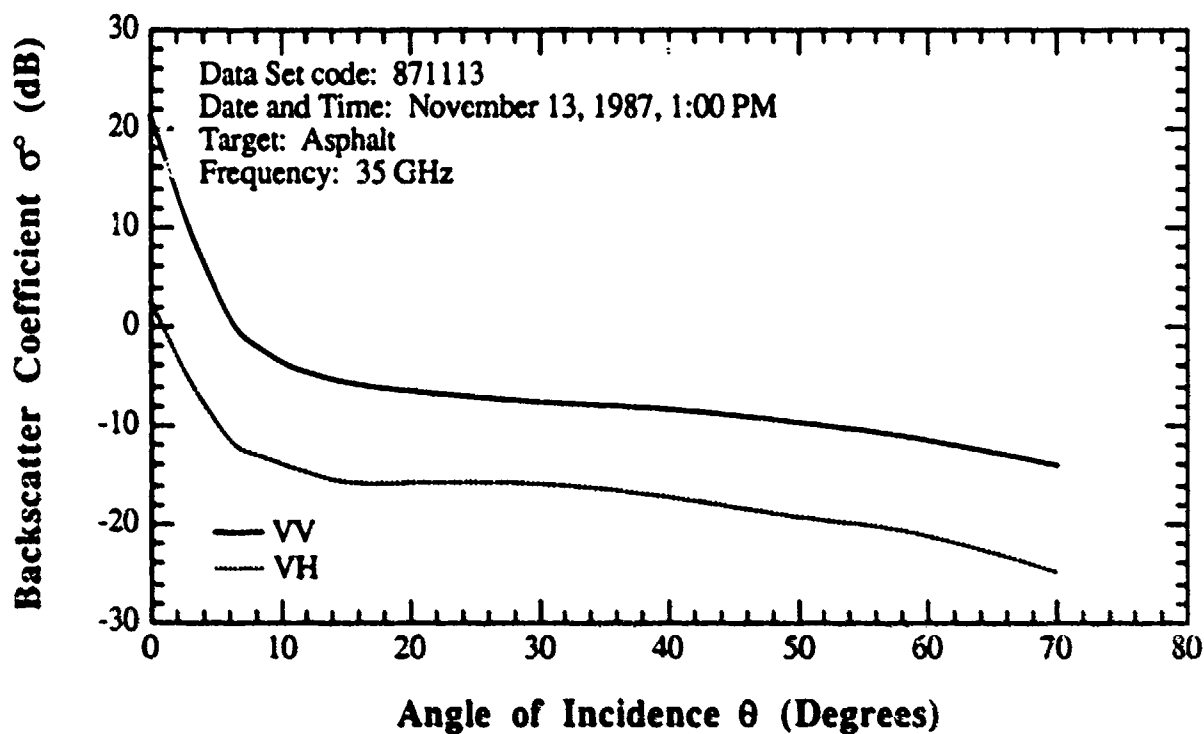
Dry Asphalt at Willow Run

Surface RMS height: 0.7 mm

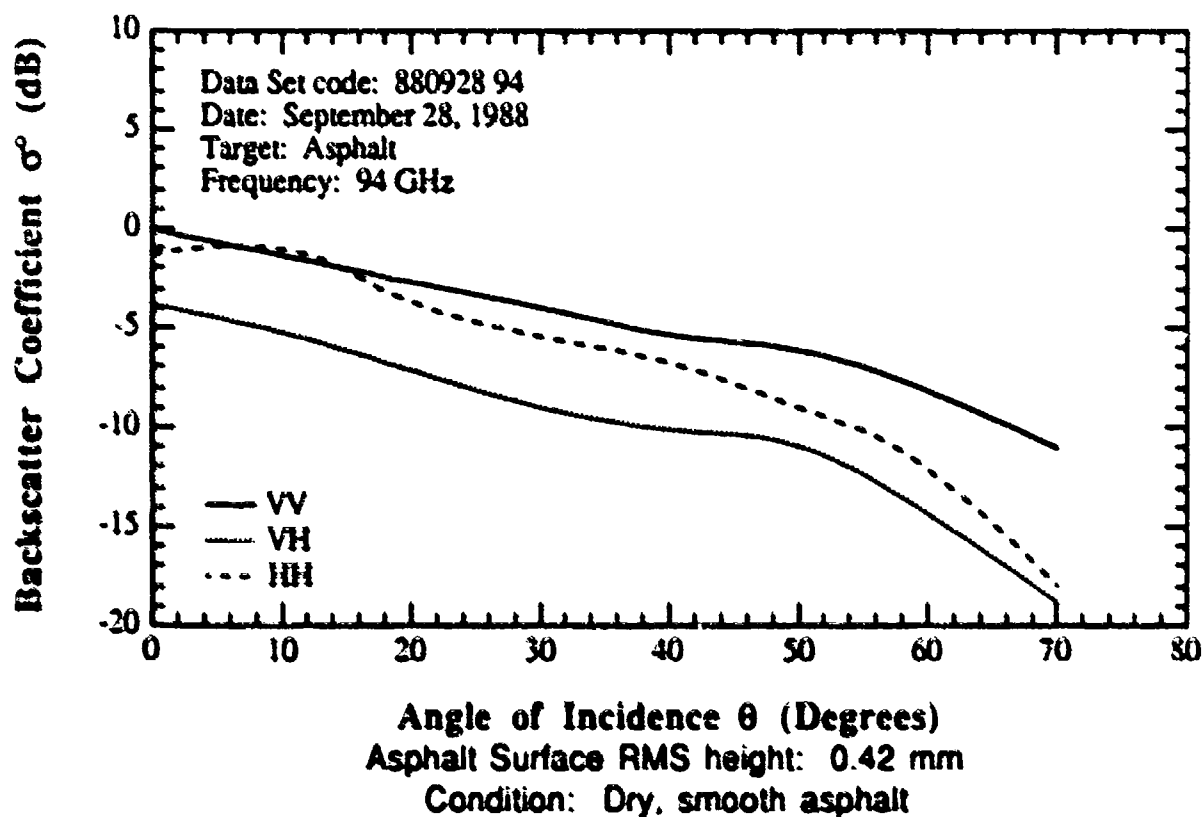
Description: smooth, dry asphalt

# MMW WAVE DATA FOR ROAD SURFACES

871113

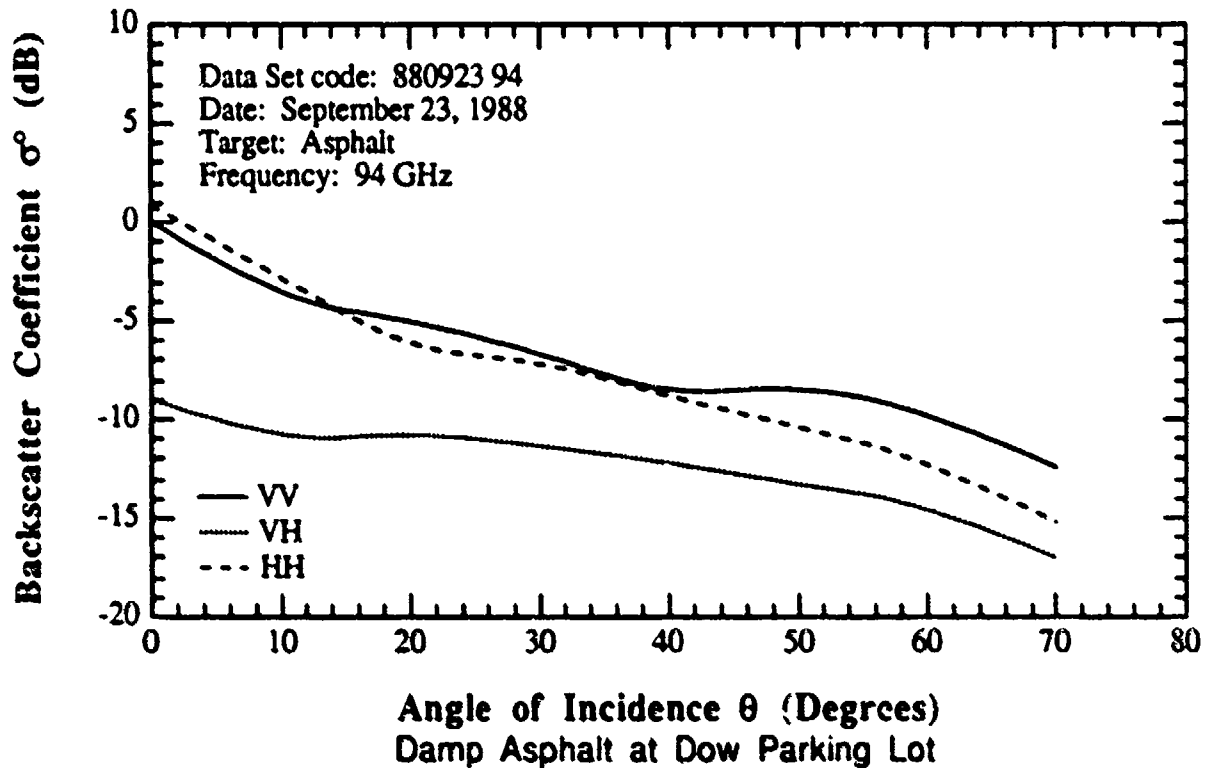


880928

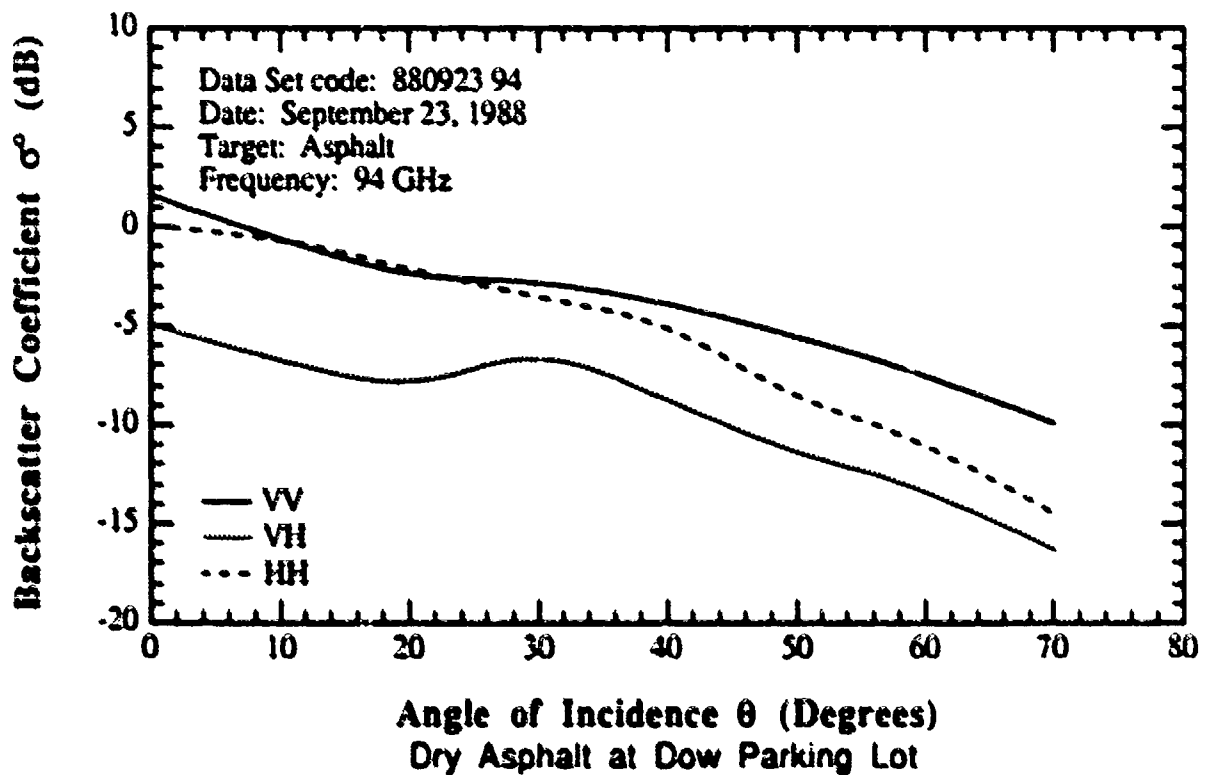


# MMW WAVE DATA FOR ROAD SURFACES

880923 (1)



880923 (2)



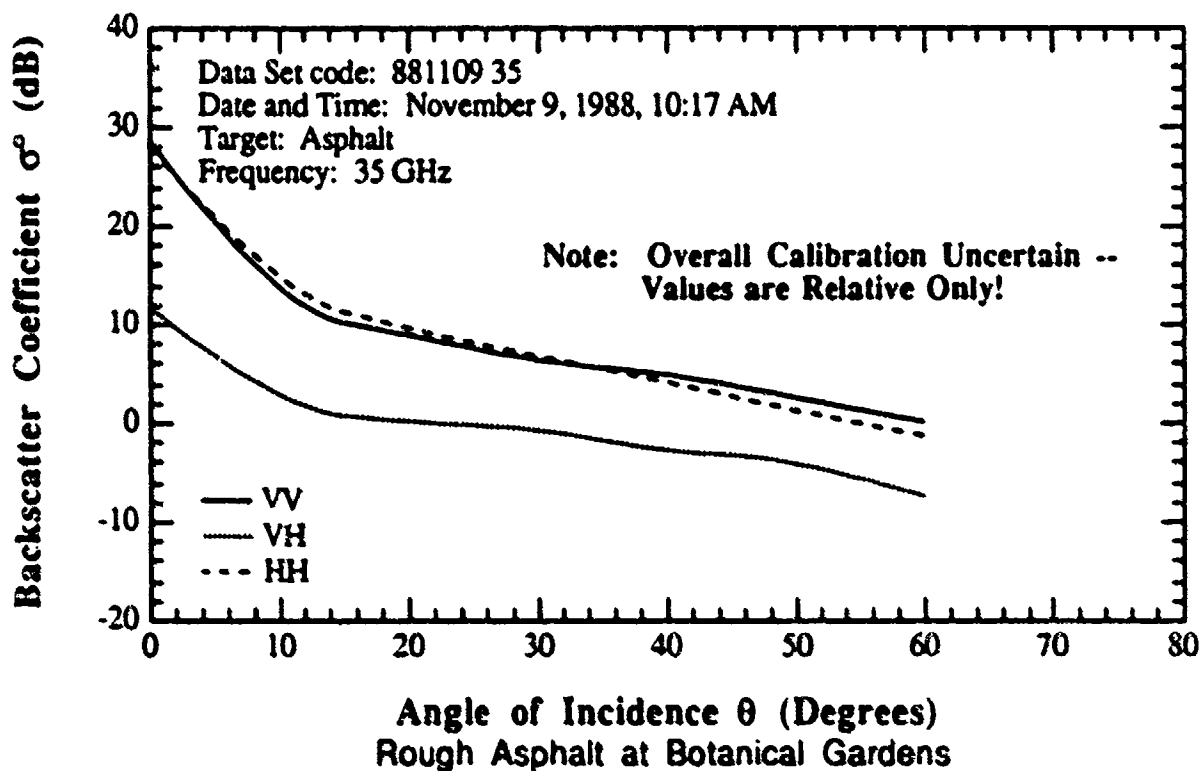
Rough Asphalt  
Data set code: 881109  
Surface RMS height: ~ 2 mm  
Condition: rough, dry asphalt



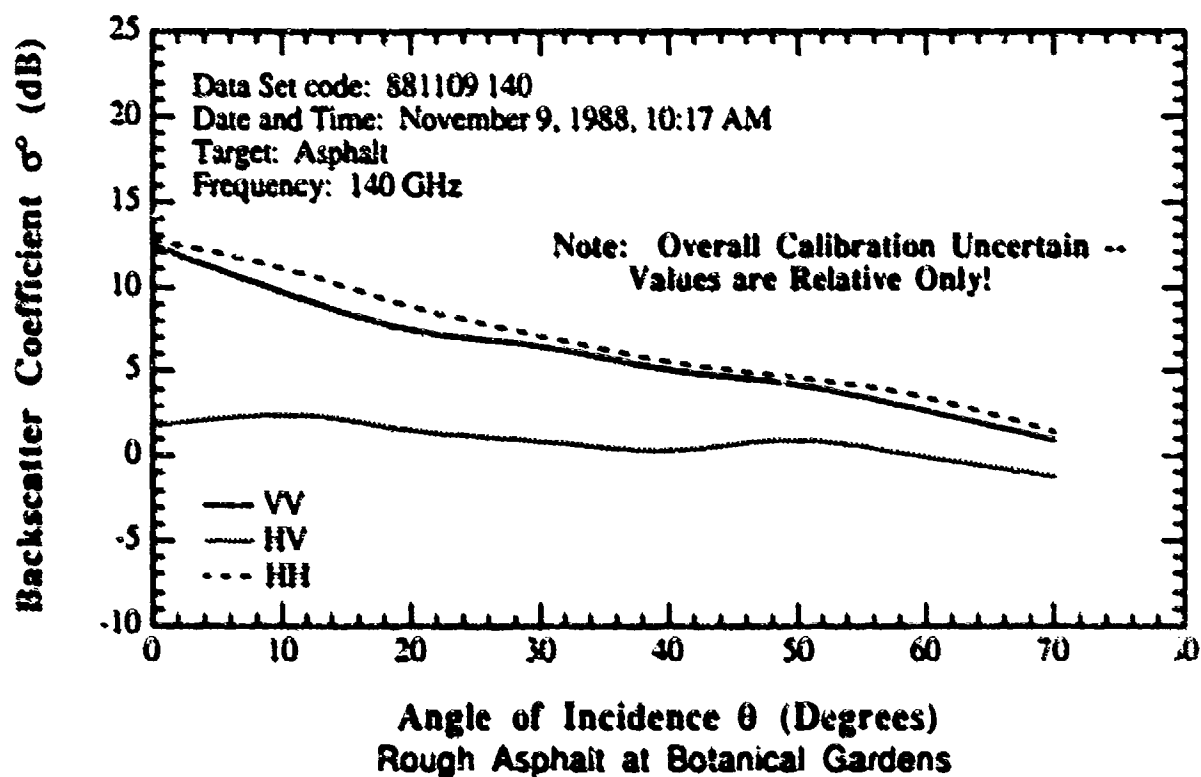
Asphalt at Botanical Gardens

## MMW WAVE DATA FOR ROAD SURFACES

881109



881109



871113/880815

**B. Gravel**

Gravel

Data set code: 871113 and 880815

Surface RMS height: ~ 2 mm

Typical stone size: ~ 6 mm

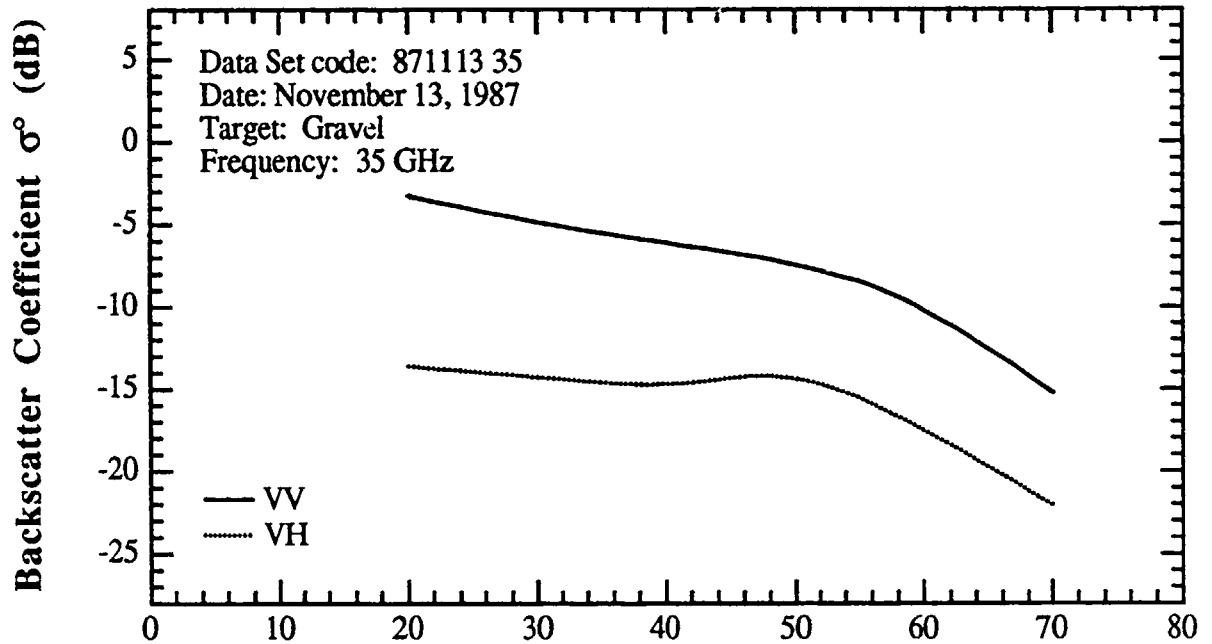
Description: dry gravel



Gravel in North Campus parking lot

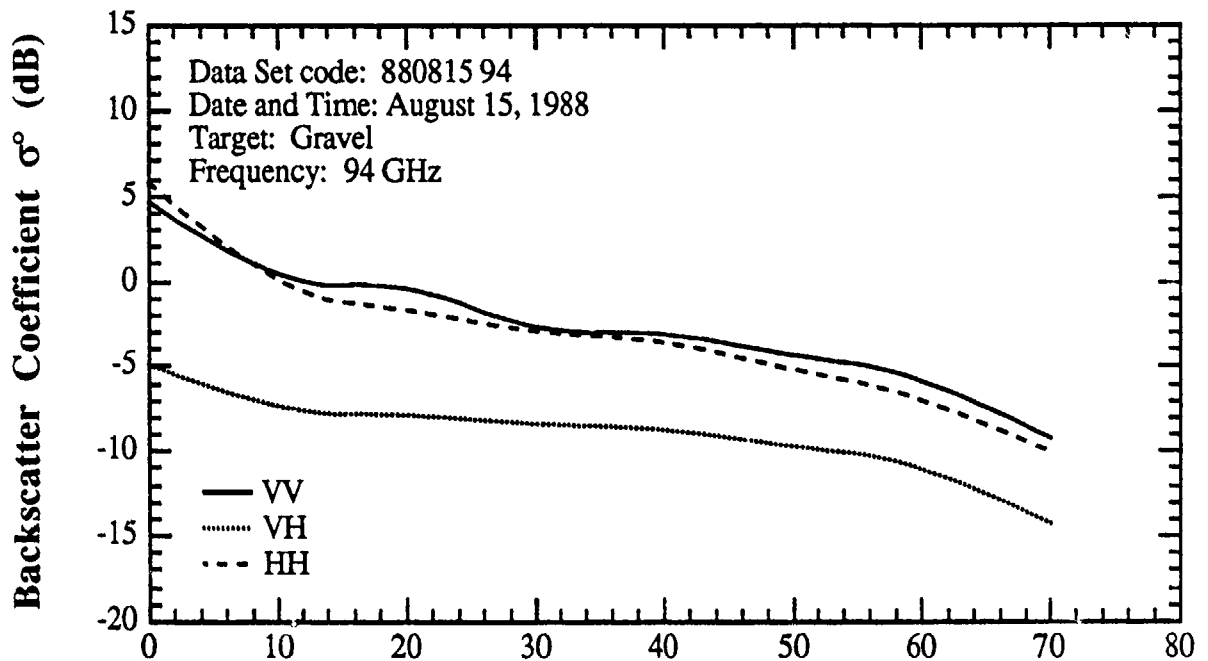
# MMW WAVE DATA FOR ROAD SURFACES

871113



Gravel in North Campus Parking Lot

880815 (2)



Gravel in North Campus Parking Lot

## PART II. UNIVERSITY OF MASSACHUSETTS DATA

Using a 215-GHz radar system, multipolarization backscatter measurements were made by the University of Massachusetts [15, 16] for various types of trees and for snow covered terrain in 1987 and 1988. The measurements were made from a 80-m high tower at the University of Massachusetts. The radar system used an extended interaction oscillator (EIO) capable of producing 100-ns pulses with 60 W of peak power. The transmit antenna consisted of a 15-cm lens fed by a corrugated scalar horn, with a beam width of  $0.64^\circ$ , and the receiver antenna was a horn with a wide beam width of  $23^\circ$ .

## 9. 215-GHZ DATA FOR TREES

Table II-1 provides a summary of the parameters of the trees for which the backscattering coefficient  $\sigma^0$  was measured. The radar observations were made as a function of time over an approximately six-month period, and were augmented with ground-truth measurements including:

**GLWC:** gravimetric liquid water content of leaves

**Cover:** percentage of the sky covered by leaves and branches as seen looking up from the base of the tree

**Normalized Leaf Area:** Average leaf area of between 10 and 50 leaf samples, normalized to the maximum value during the season.

TABLE II-1

CHARACTERISTICS OF TREES SELECTED FOR STUDY

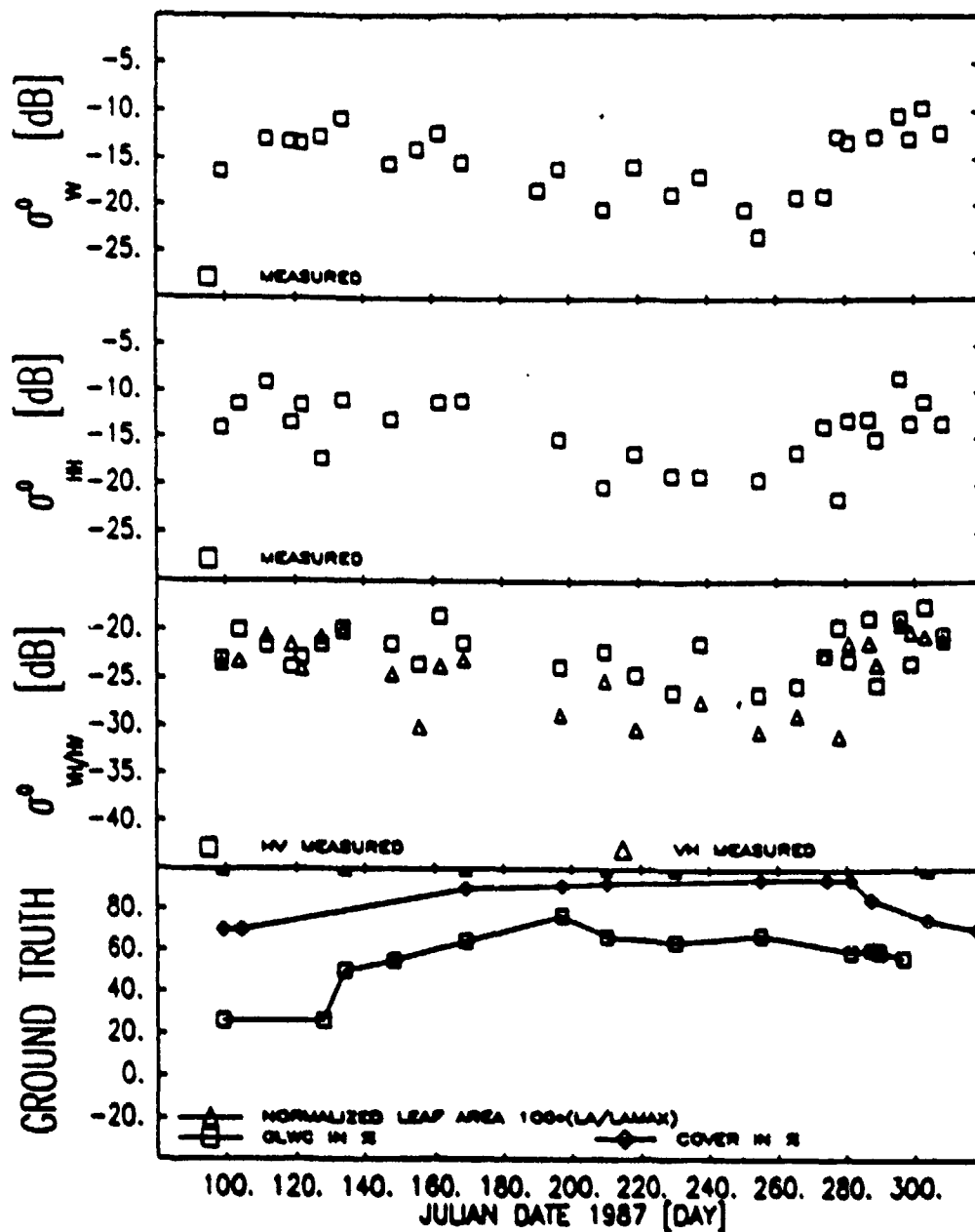
| Tree Code | Tree Name<br>(Latin Name)                             | Basal Diameter<br>[m] | Canopy Height<br>[m] | Crown Diameter<br>[m] | Canopy Cover<br>Day 99<br>[%] | Canopy Cover<br>210<br>[%] | Tree Type | Position<br>Depression<br>[deg] | Position<br>Azimuth<br>[deg] |
|-----------|-------------------------------------------------------|-----------------------|----------------------|-----------------------|-------------------------------|----------------------------|-----------|---------------------------------|------------------------------|
| A         | Northern White Cedar<br>( <i>Thuja occidentalis</i> ) | 0.15-0.3              | 13.                  | 5.                    | 90                            | 90                         | C         | 28.8                            | 56.5                         |
| B         | White Pine<br>( <i>Pinus strobus</i> )                | 0.73                  | 30.                  | 16.                   | 85                            | 90                         | E         | 20.8                            | 41.                          |
| C         | Fir<br>( <i>Abies spp.</i> )                          | 0.48                  | 21.                  | 8.                    | 80                            | 85                         | D         | 21.9                            | 38.5                         |
| D         | Sugar Maple<br>( <i>Acer saccharum</i> )              | 0.32                  | 19.                  | 14.                   | 40                            | 95                         | A         | 19.2                            | 31.5                         |
| E         | Eastern Cottonwood<br>( <i>Populus deltoides</i> )    | 0.43                  | 25.                  | 3.                    | 35                            | 65                         | B         | 24.3                            | 30.5                         |
| F         | Pin Oak<br>( <i>Quercus palustris</i> )               | 1.05                  | 38.                  | 24.                   | 45                            | 90                         | E         | 14.2                            | 37.                          |
| G         | Black Oak<br>( <i>Quercus velutina</i> )              | 1.02                  | 20.                  | 24.                   | 30                            | 90                         | A         | 11.6                            | 43.                          |
| H         | Silver Maple<br>( <i>Acer saccharinum</i> )           | 0.78                  | 21.                  | 20.                   | 30                            | 75                         | A         | 11.8                            | 46.                          |
| I         | Weeping Willow<br>( <i>Salix babylonica</i> )         | 0.82                  | 22.                  | 15.                   | 50                            | 90                         | B         | 10.4                            | 49.5                         |
| J         | White Pine<br>( <i>Pinus strobus</i> )                | 1.05                  | 27.                  | 13.                   | 85                            | 95                         | E         | 10.4                            | 51.                          |
| L         | White Pine<br>( <i>Pinus strobus</i> )                | 0.6                   | 27.                  | 14.                   | 85                            | 90                         | E         | 8.3                             | 56.5                         |
| M         | Pin Oak<br>( <i>Quercus Palustris</i> )               | 0.92                  | 20.                  | 14.                   | 35                            | 90                         | B         | 9.1                             | 58.                          |
| N         | Red Maple<br>( <i>Acer rubrum</i> )                   | 1.01                  | 14.                  | 15.                   | 35                            | 80                         | A         | 9.7                             | 59.                          |
| O         | Group of White Pines                                  | 0.5-0.8               | 20.-30.              | 5.-10.                | 85                            | 90                         | E         | 9.4                             | 63.5                         |
| X         | Mixed Forest*                                         | 0.2-0.6               | 15.-25.              | 3.-8.                 | 35                            | 85                         | AB        | 8.3                             | 53.                          |
| Y         | Mixed Forest**                                        | 0.2-0.6               | 15.-25.              | 3.-8.                 | 35                            | 85                         | AB        | 6.6                             | 53.                          |
| Z         | Mixed Forest***                                       | 0.2-0.6               | 15.-25.              | 3.-8.                 | 35                            | 85                         | ABE       | 7.0                             | 60.5                         |

\* Eastern Cottonwood (*Populus deltoides*), Grapes (*Vitis spp.*), Glossy Buckthorn (*Rhamnus frangula*) and Red Maple (*Acer rubrum*)

\*\* Eastern Cottonwood (*Populus deltoides*) and Red Maple (*Acer rubrum*)

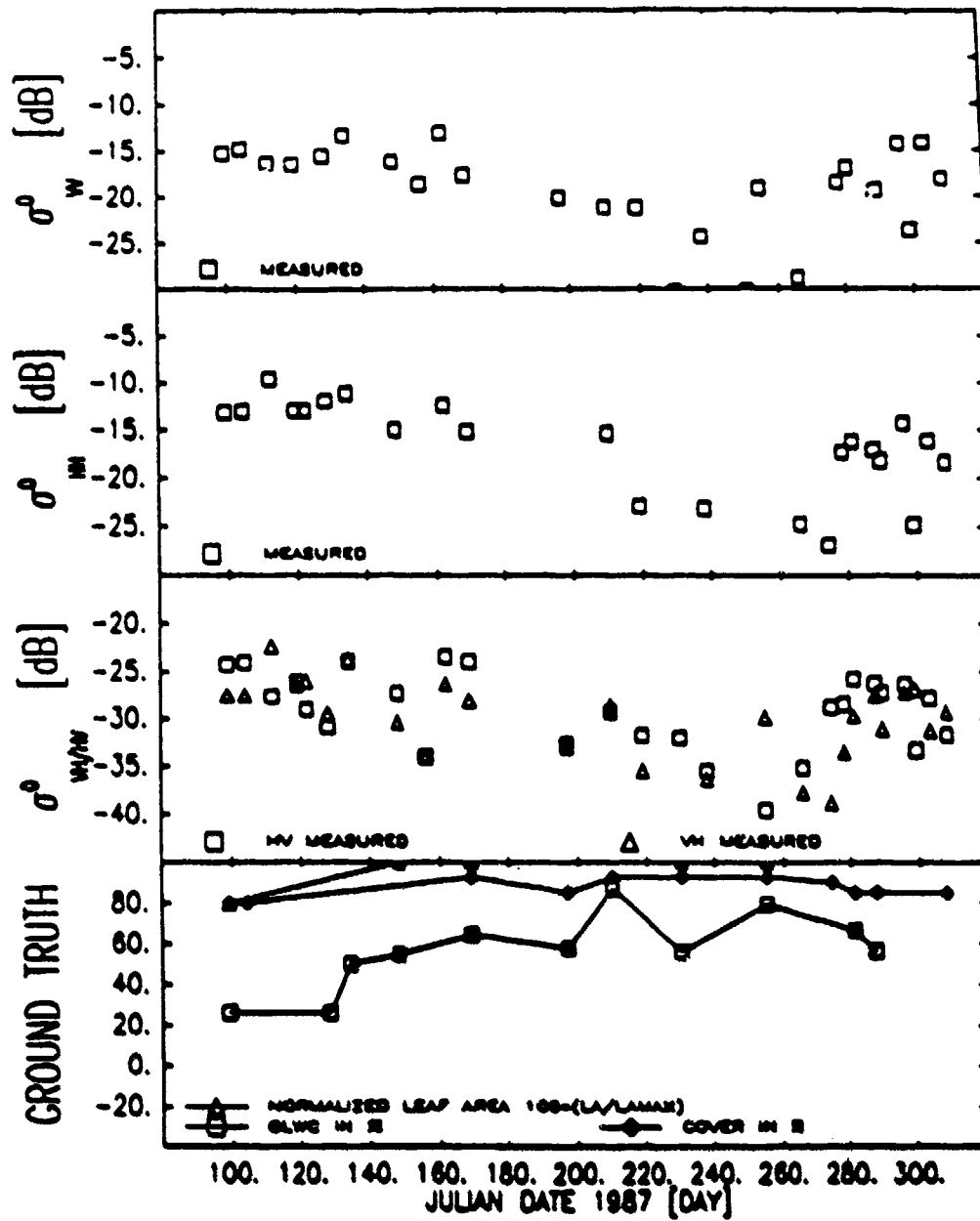
\*\*\* Red Maple (*Acer rubrum*), Pin Oak (*Quercus Palustris*) and White Pine (*Pinus strobus*)

# WHITE PINE (B)

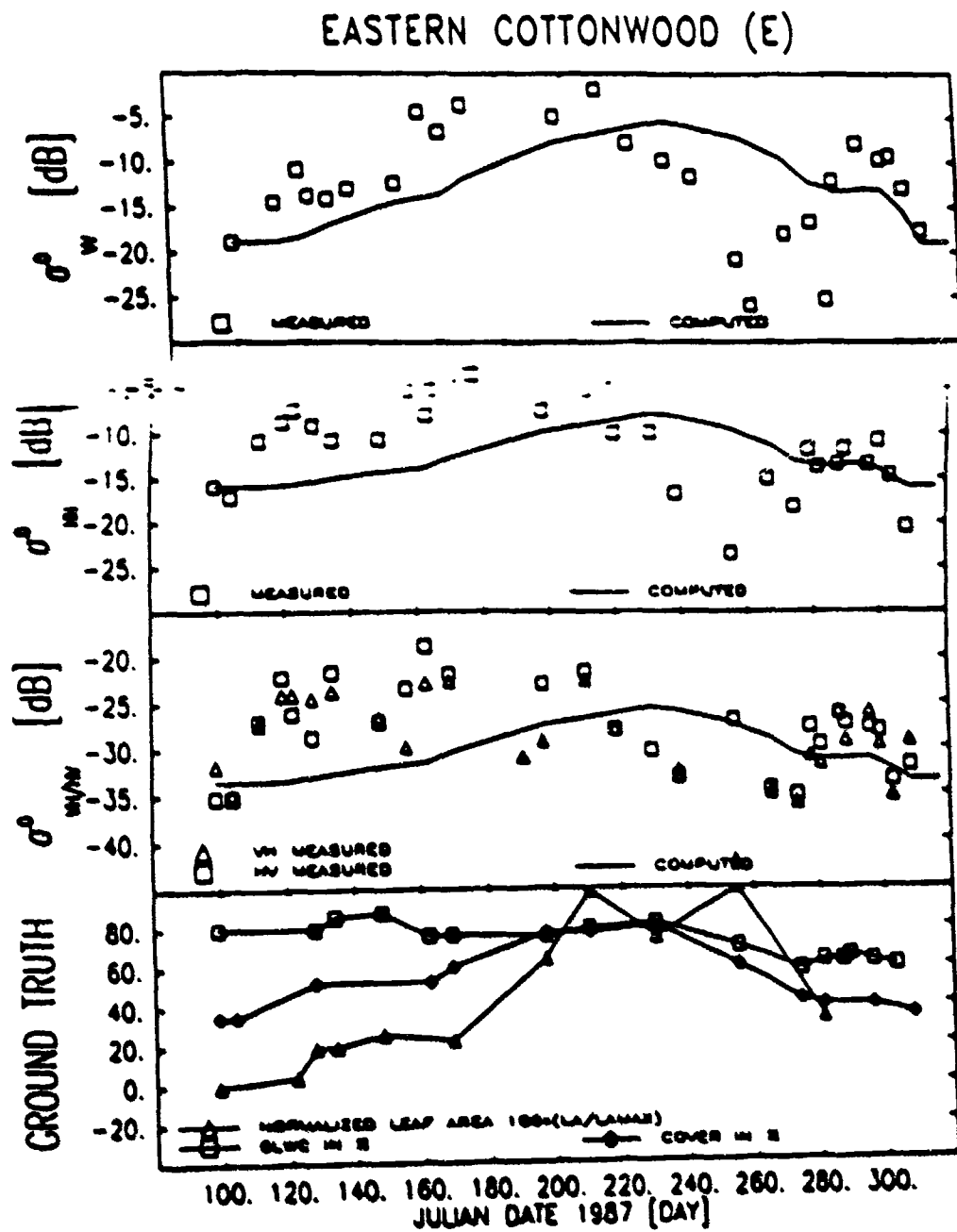


Curves showing measured  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for White Pine (B). Also shown is the corresponding measured ground truth data.

# FIR (C)

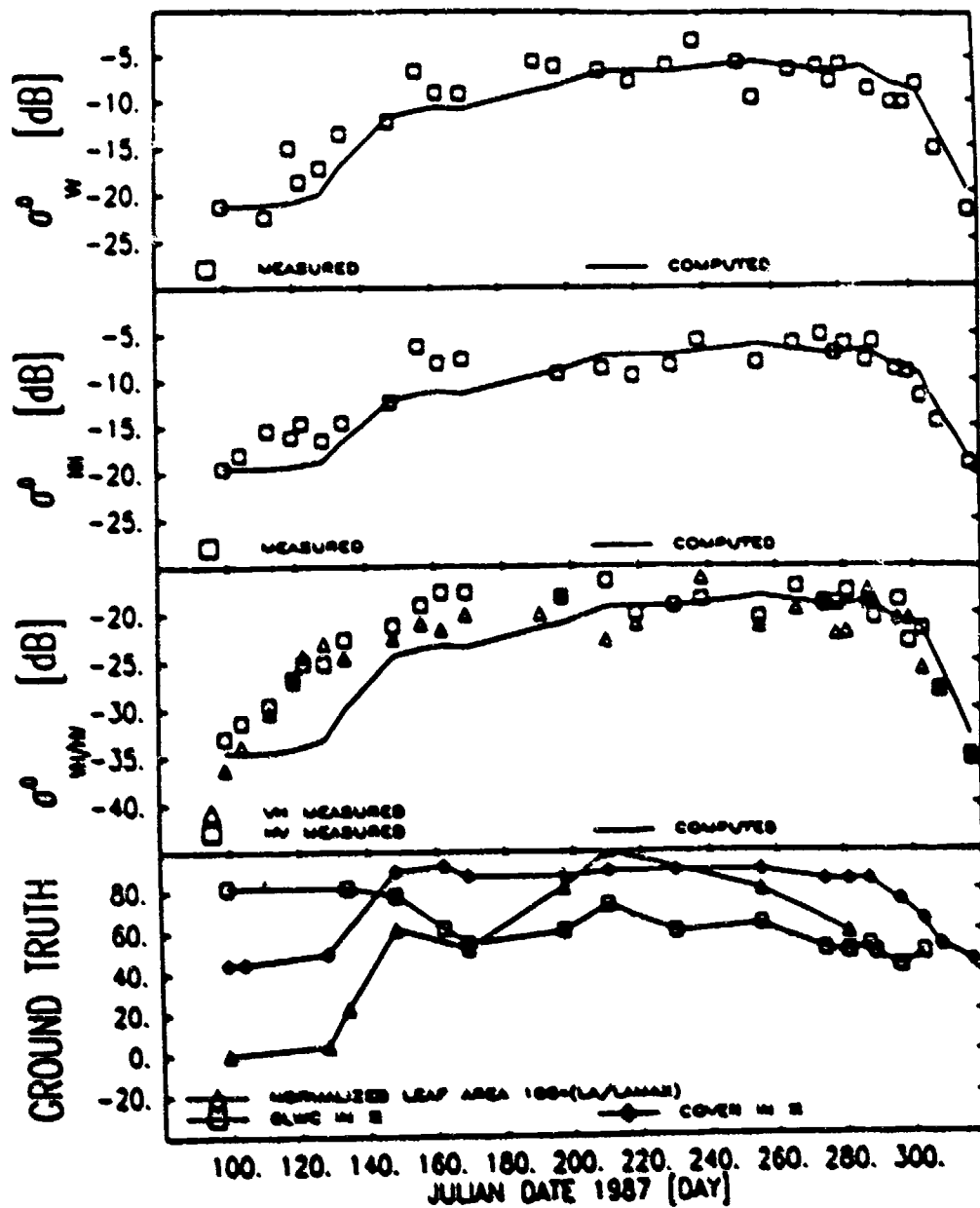


Curves showing measured  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for Fir (C). Also shown is the corresponding measured ground truth data.



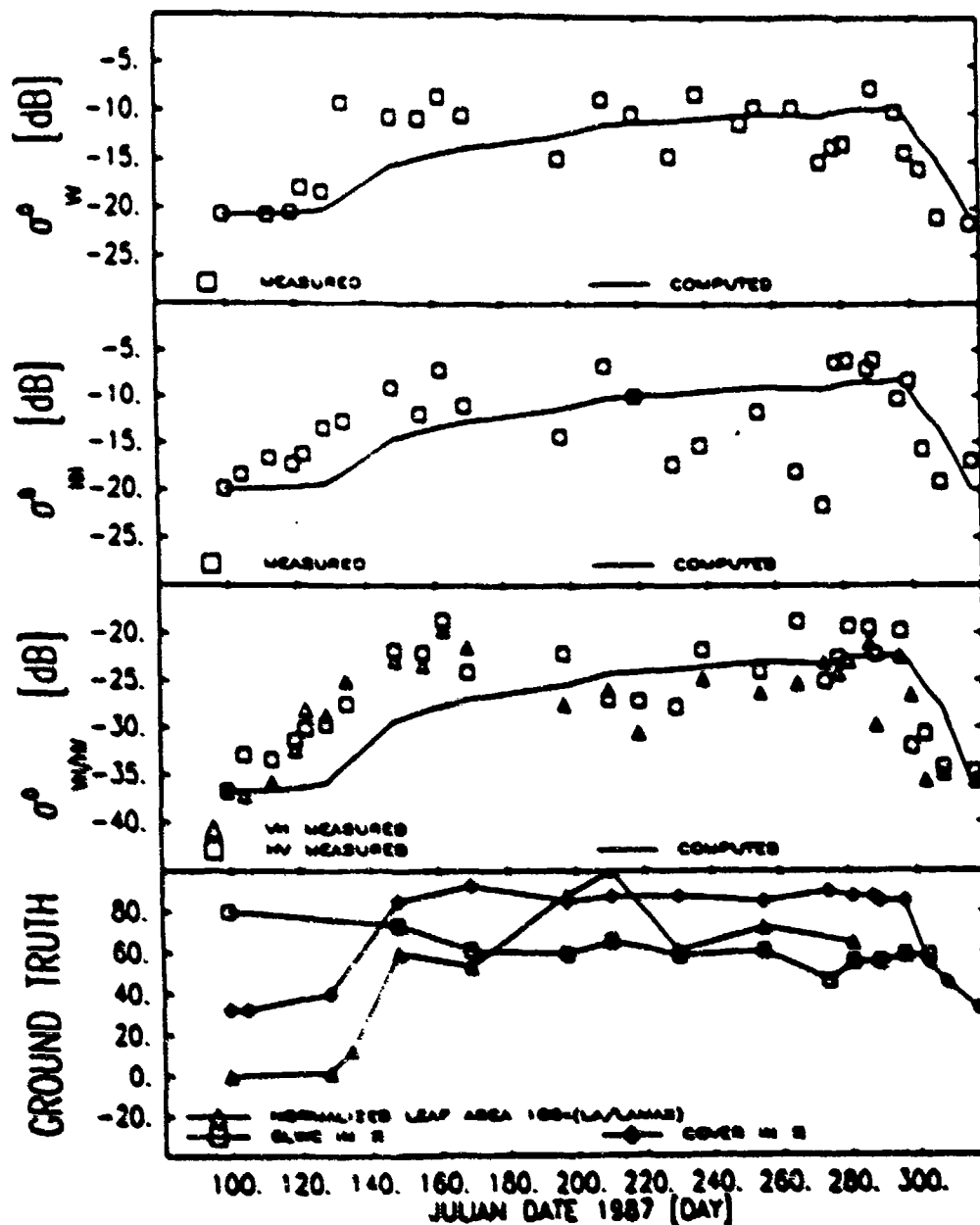
Curves showing measured and computed  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for Eastern Cottonwood (E). Also shown is the corresponding measured ground truth data.

# PIN OAK (F)



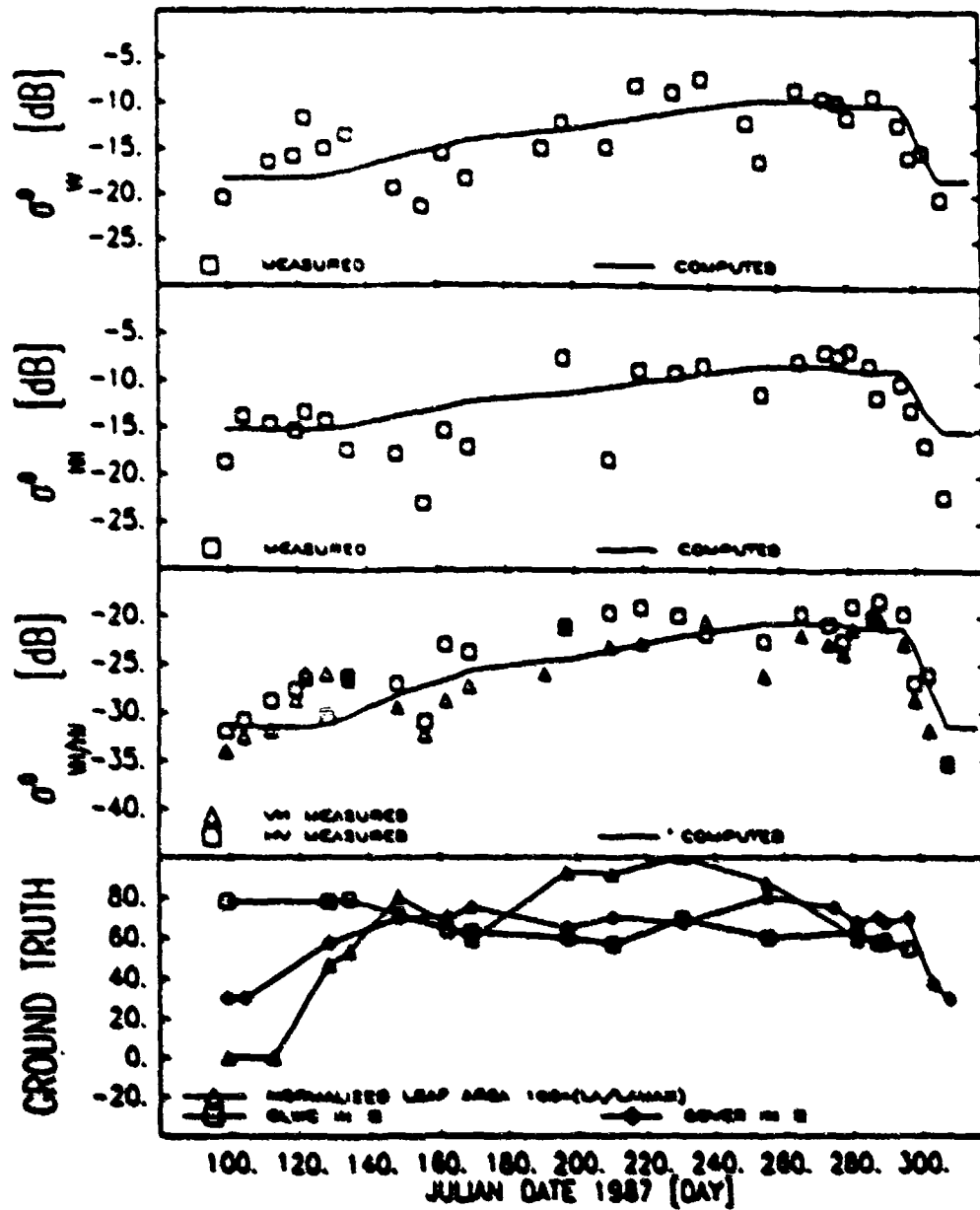
Curves showing measured and computed  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for Pine Oak (F). Also shown is the corresponding measured ground truth data.

# BLACK OAK (G)



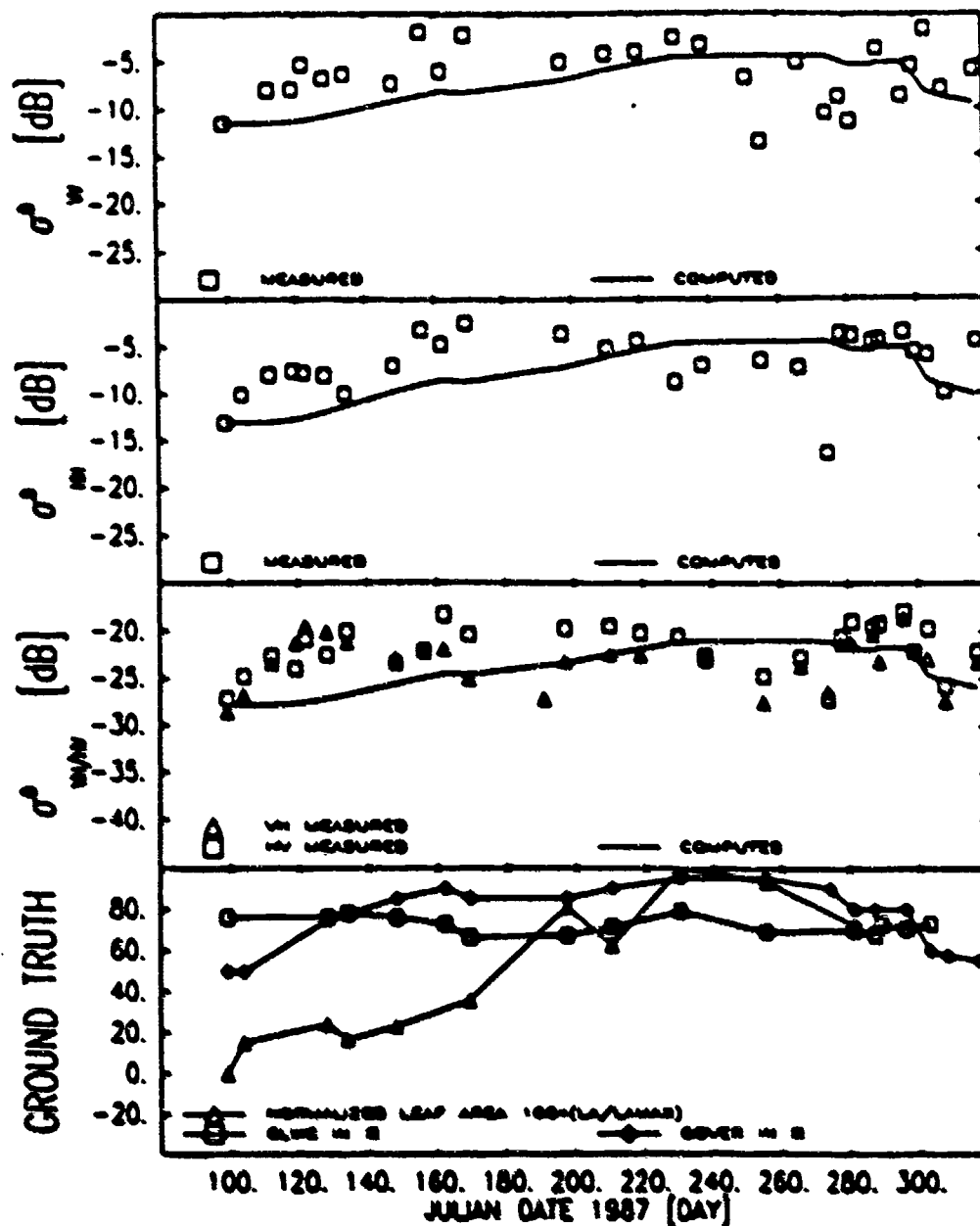
Curves showing measured and computed  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for Black Oak (G). Also shown is the corresponding measured ground truth data.

# SILVER MAPLE (H)



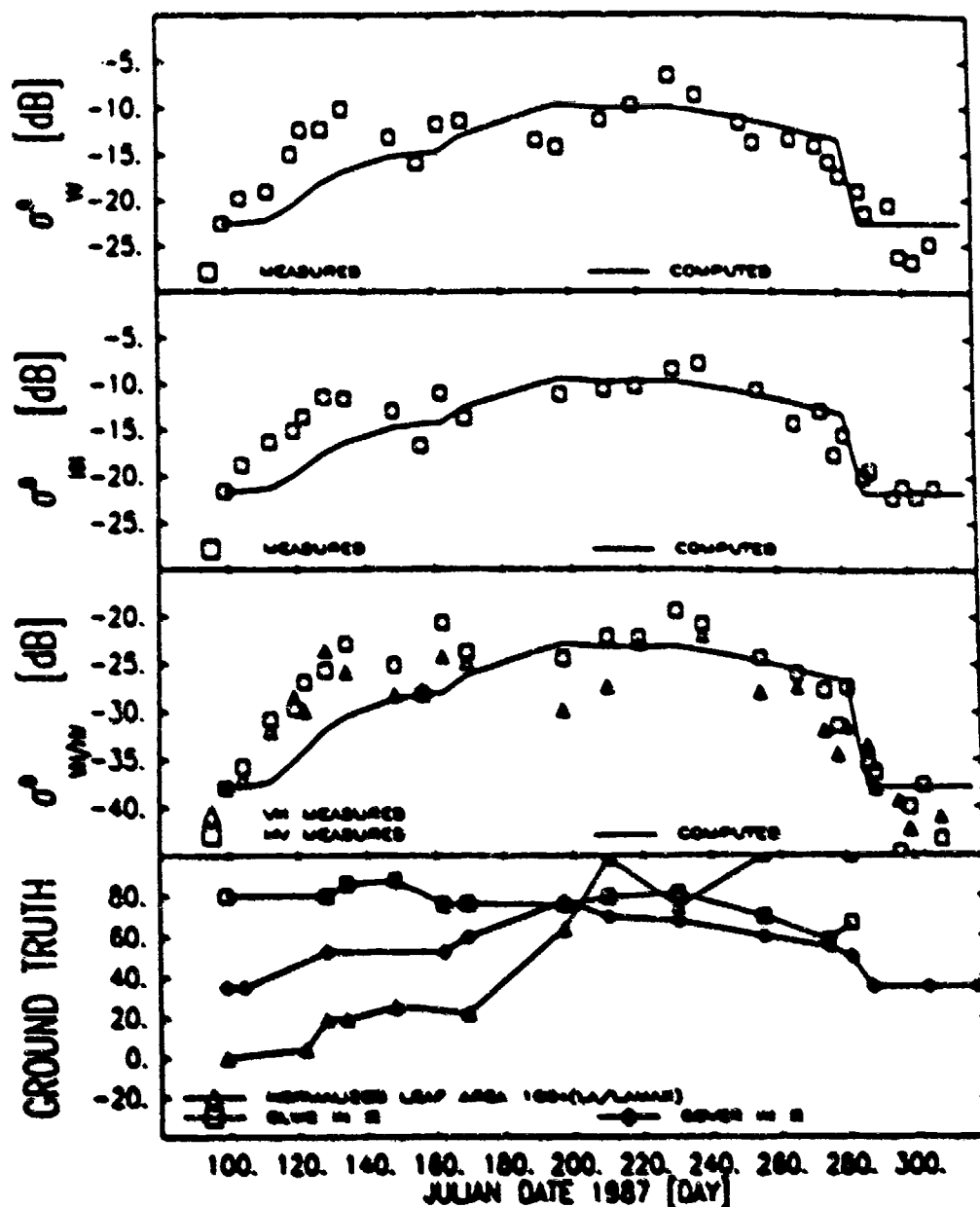
Curves showing measured and computed  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for Silver Maple (H). Also shown is the corresponding measured ground truth data.

# WEeping WILLOW (I)



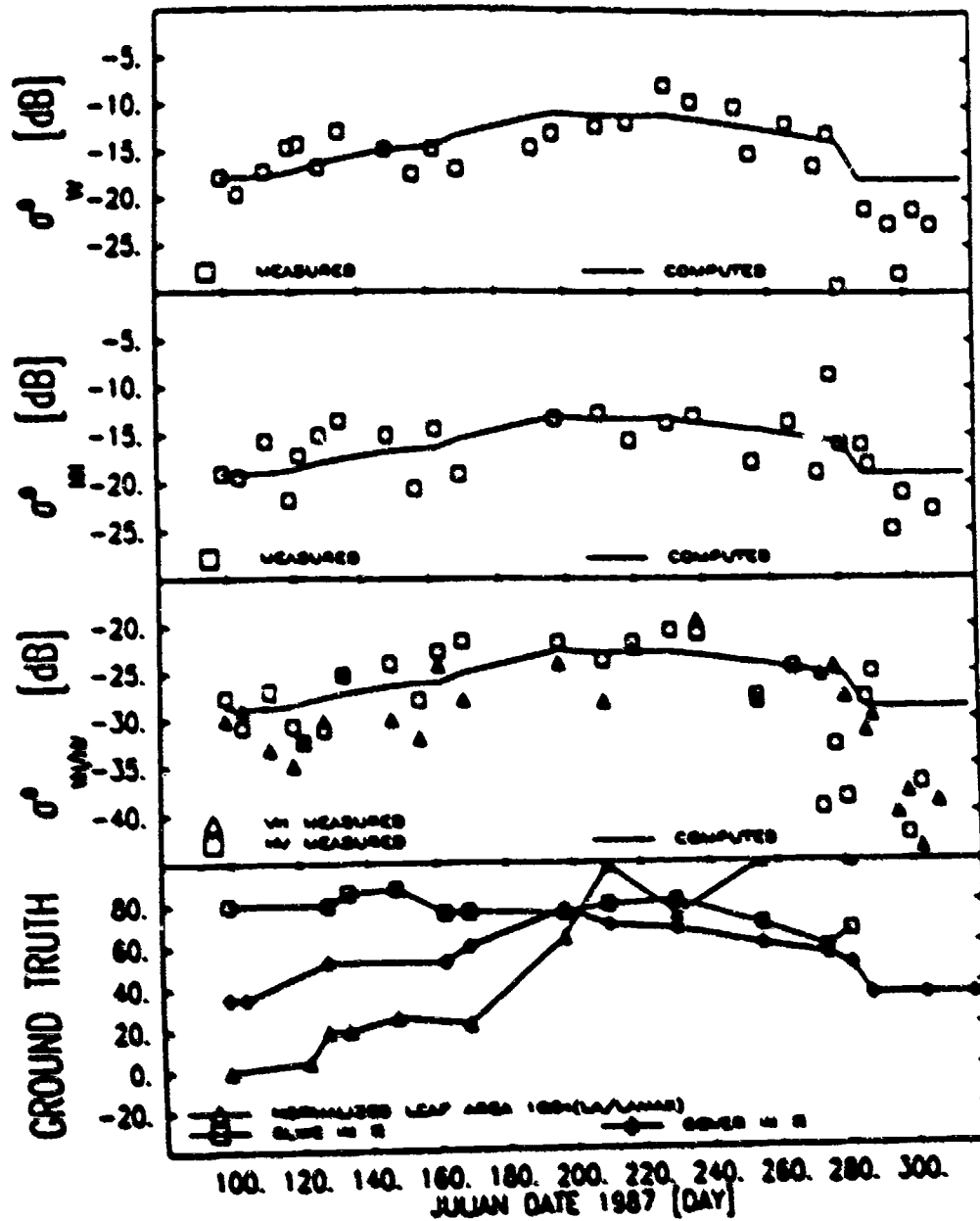
Curves showing measured and computed  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for Weeping Willow (I). Also shown is the corresponding measured ground truth data.

# MIXED FOREST (X)



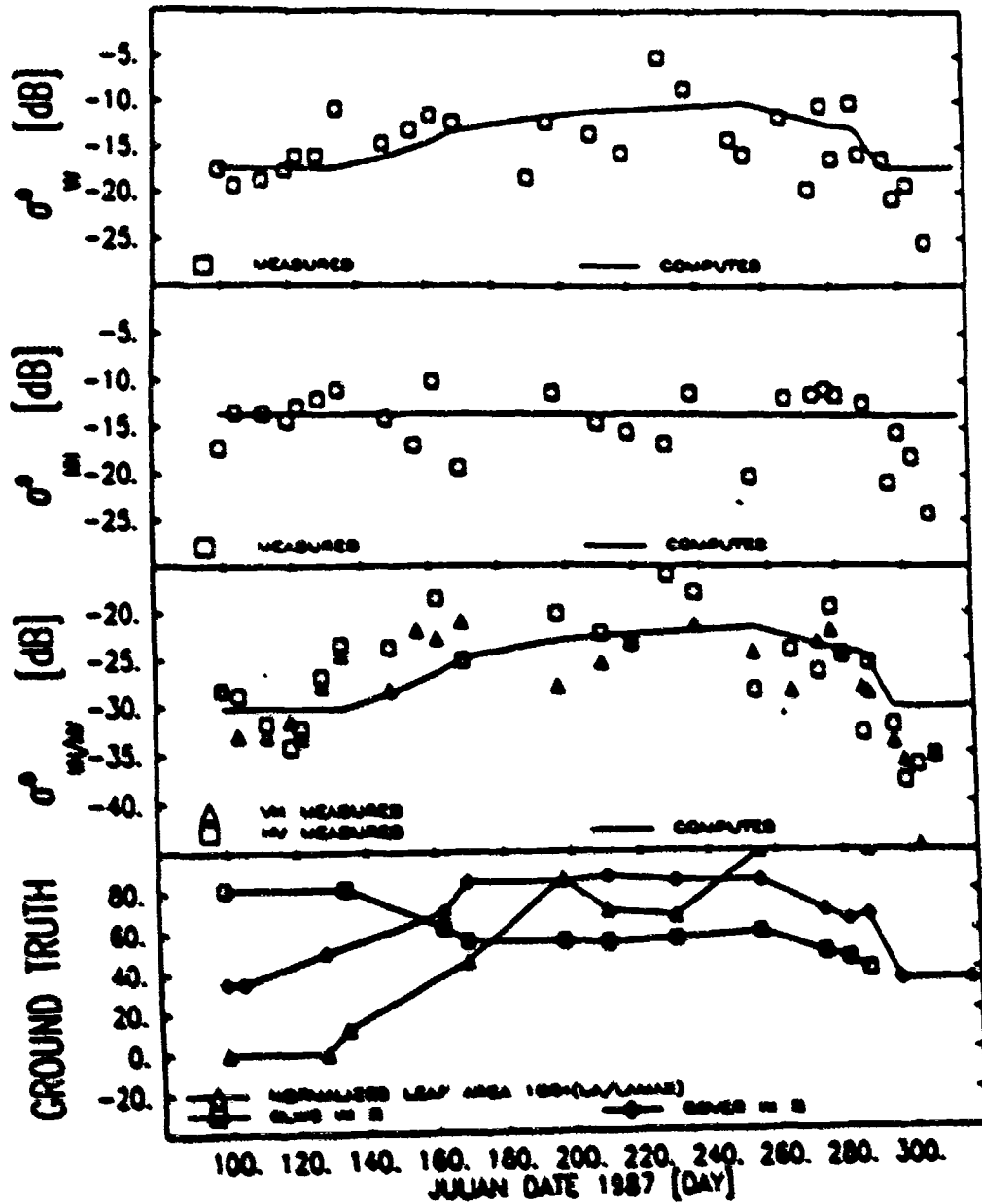
Curves showing measured and computed  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for Mixed Forest (X). Also shown is the corresponding measured ground truth data.

# MIXED FOREST (Y)



Curves showing measured and computed  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for Mixed Forest (Y). Also shown is the corresponding measured ground truth data.

# MIXED FOREST (Z)



Curves showing measured and computed  $\sigma^0$  versus Julian date for VV, HH, and VH/HV polarizations for Mixed Forest (Z). Also shown is the corresponding measured ground truth data.

## 10. 215-GHZ DATA FOR SNOW

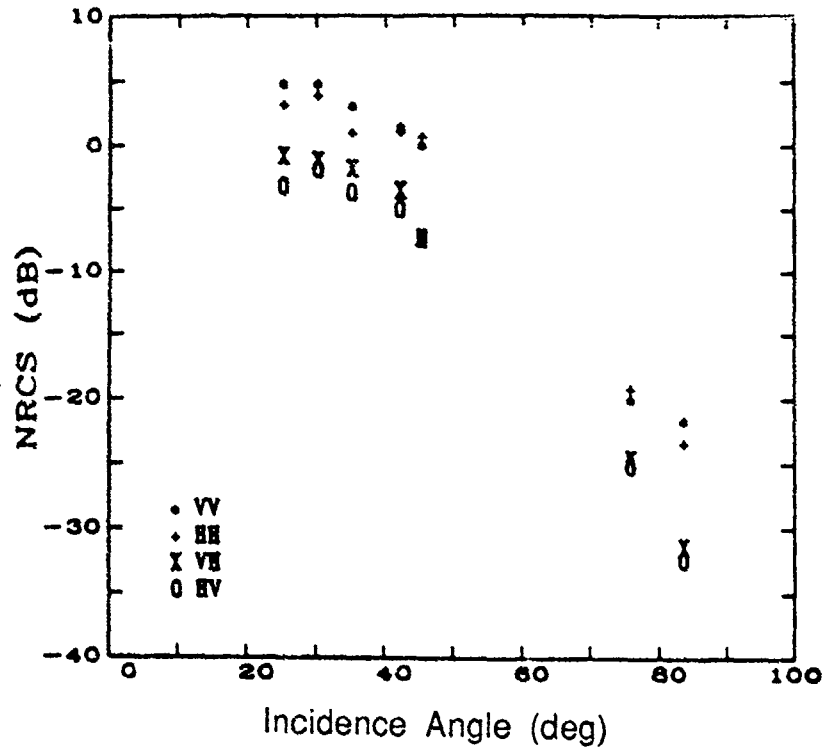
The snow observations, which were made from the same tower platform, included measurements at various incidence angles extending from 25° to 83.2°, corresponding to ground areas for which the radar had an unobstructed view. Table II-2 provides a summary of the ground truth observations that were recorded in support of the radar measurements.

TABLE II-2

GROUND TRUTH FOR SNOW DATA SHOWN IN FIG. 3

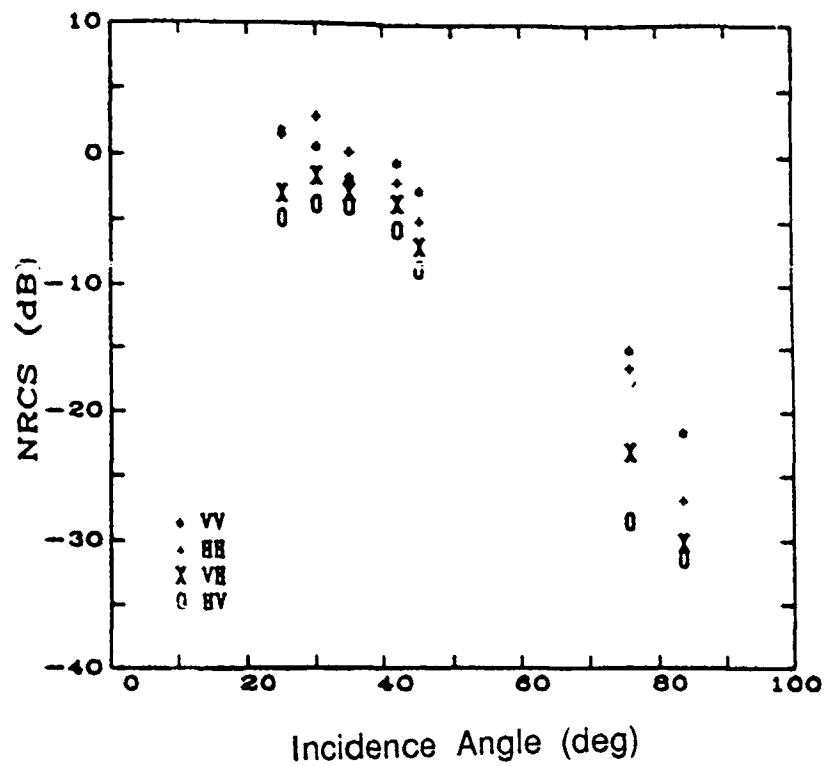
| Day #<br>(Fig. Ref.)  | RMS Surface<br>Roughness (mm) | No. of<br>Layers | Layer #                             | Particle Size (mm) |               | Temperature<br>(°C) | Density<br>(gm/cc)      | Volumetric<br>Moisture (%) | Layer<br>Thickness (mm) |
|-----------------------|-------------------------------|------------------|-------------------------------------|--------------------|---------------|---------------------|-------------------------|----------------------------|-------------------------|
| 7<br>(no figure)      | 0.88                          | 2                | 1 (Bottom)<br>2 (Top)               | 3<br>3             | 6<br>6        | -3.0<br>-6.5        | 0.190<br>0.260          | 0.00<br>0.00               | 30.0<br>42.5            |
| 8<br>(Fig. 3a)        | 1.32                          | 3                | 1 (Bottom)<br>2 (Middle)<br>3 (Top) | 3<br>2<br>2        | 10<br>10<br>5 | 0.0<br>1.0<br>1.0   | 0.200<br>0.210<br>0.080 | 0.00<br>1.08<br>0.68       | 15.0<br>60.0<br>45.0    |
| 9<br>(Fig. 3a)        | 1.03                          | 2                | 1 (Bottom)<br>2 (Top)               | 3<br>3             | 16<br>10      | -1.0<br>-4.5        | 0.245<br>0.225          | 0.60<br>0.00               | 60.0<br>55.0            |
| 10<br>(Fig. 3a)       | 1.35                          | 2                | 1 (Bottom)<br>2 (Top)               | 3<br>3             | 15<br>9       | 0.0<br>-3.5         | 0.255<br>0.180          | 0.93<br>0.00               | 42.5<br>47.5            |
| 11<br>(Figs. 3a & 3b) | 1.16                          | 2                | 1 (Bottom)<br>2 (Top)               | 1<br>1             | 10<br>10      | 0.0<br>0.0          | 0.240<br>0.296          | 1.77<br>0.15               | 42.5<br>65.0            |
| 12<br>(Fig. 7b)       | 1.17                          | 1                | 1                                   | 2                  | 6             | 1.5                 | 0.280                   | 1.30                       | 65.5                    |
| 13<br>(Fig. 3a)       | 1.22                          | 1                | 1                                   | 1                  | 4             | -1.5                | 0.150                   | 0.65                       | 50.0                    |
| 14<br>(Fig. 3d)       | 1.58                          | 2                | 1 (Bottom)<br>2 (Top)               | 1<br>1             | 3<br>3        | -1.0<br>-2.0        | 0.180<br>0.180          | 1.90<br>0.00               | 60.0<br>50.0            |

# SNOW AT 215 GHz: DAY 09

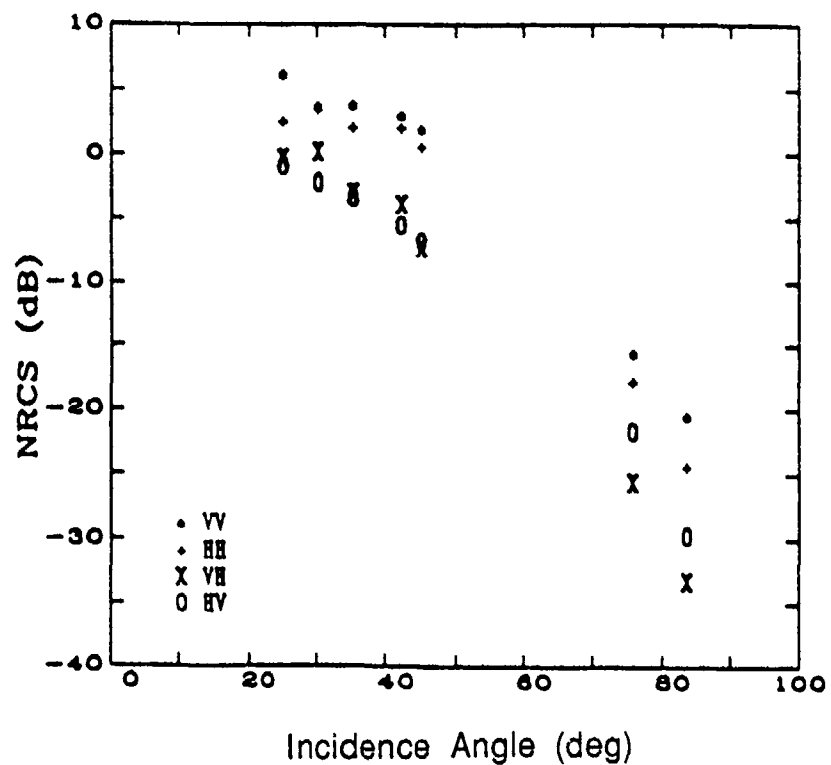


Measured value of  $\sigma_W^0$  (\*),  $\sigma_{HH}^0$  (+),  $\sigma_{VH}^0$  (x), and  $\sigma_{HV}^0$  (o) of snow at 215 GHz

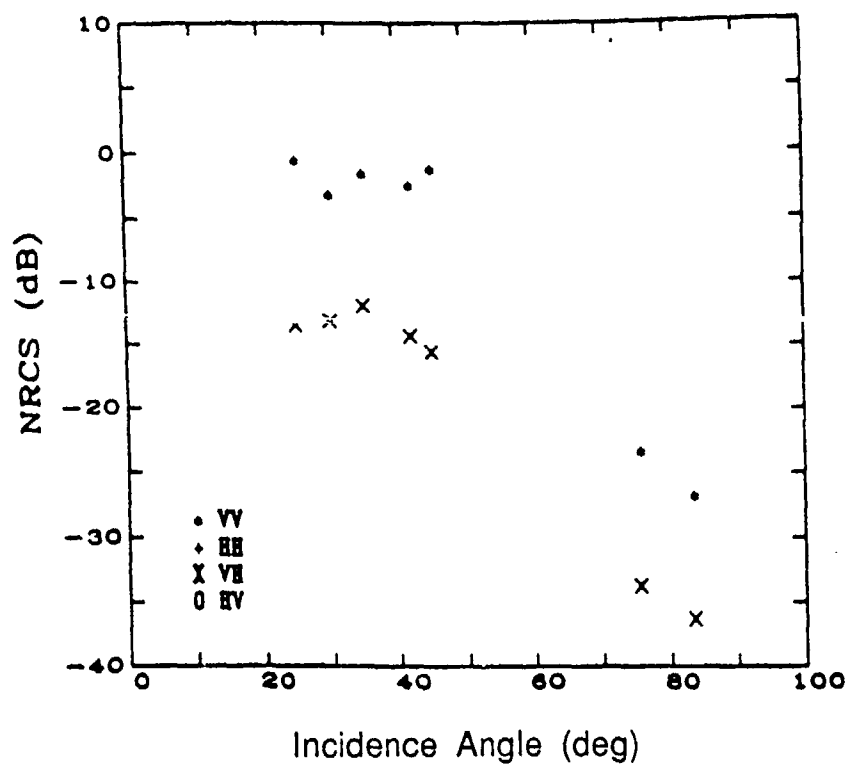
# SNOW AT 215 GHz: DAY 11



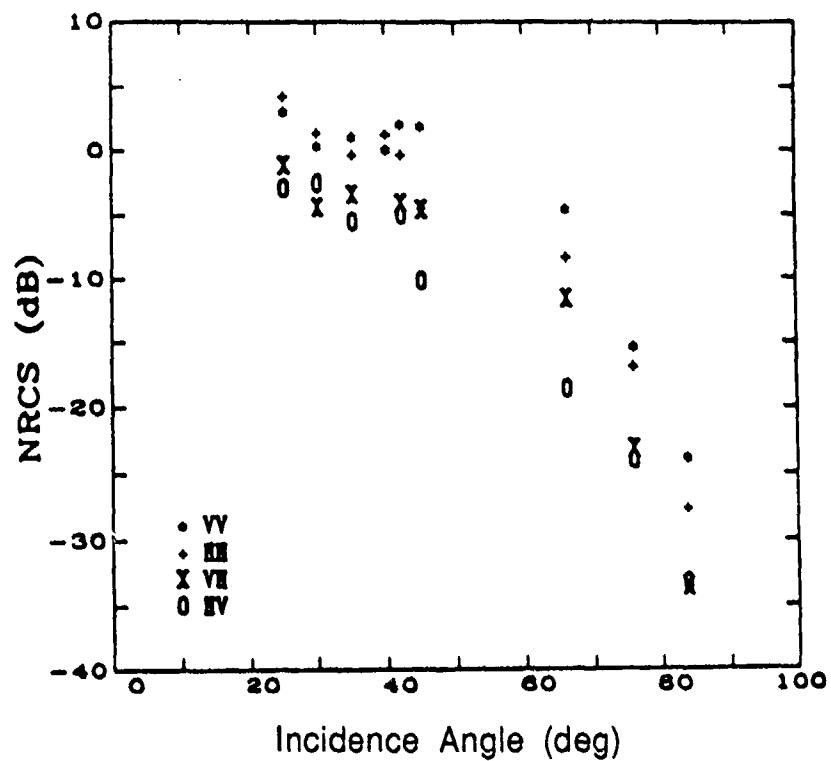
# SNOW AT 215 GHz: DAY 10

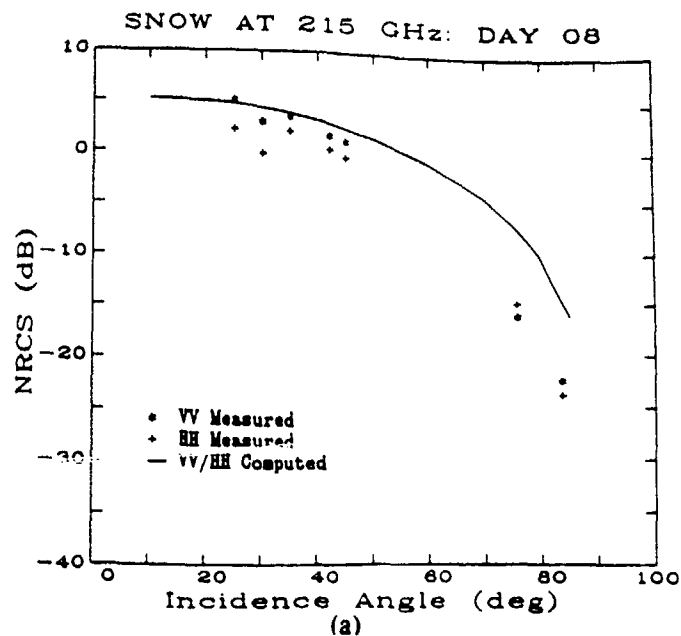


# SNOW AT 215 GHz: DAY 12

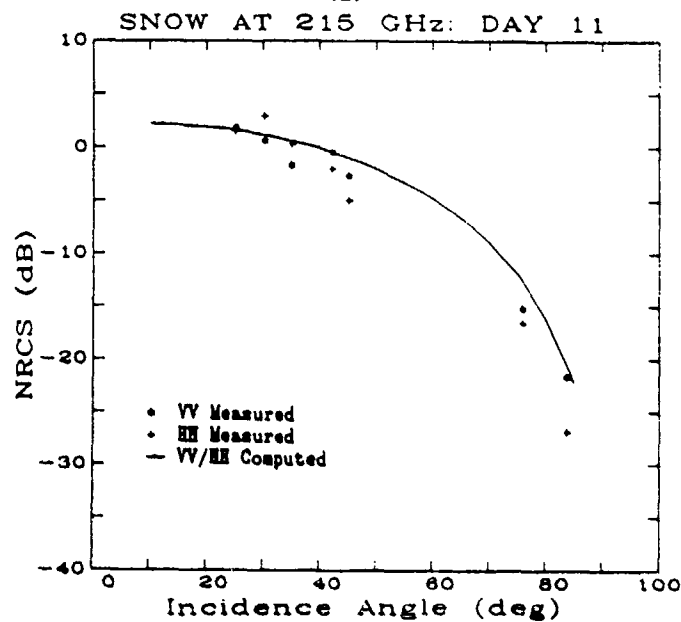


# SNOW AT 215 GHz: DAY 14

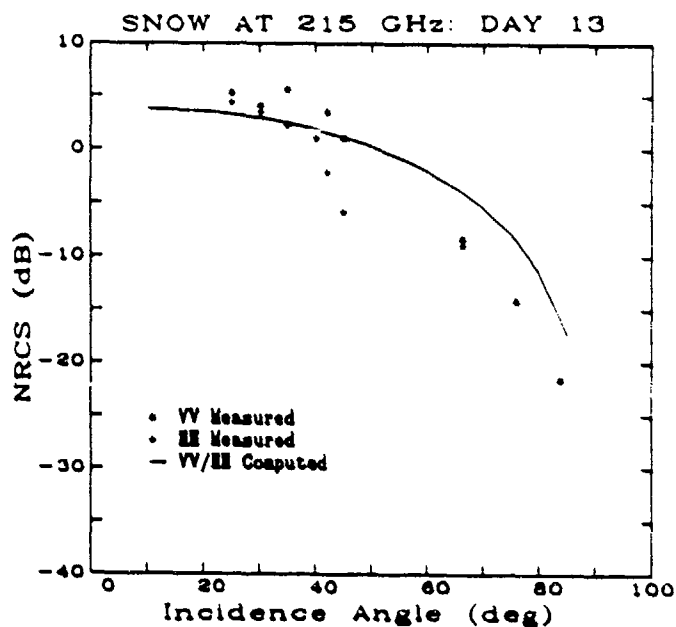




(a)



(b)



(c)

Measured (\*:  $\sigma_{VV}^0$ , +:  $\sigma_{HH}^0$ ) and computed (—) values of co-polarized backscatter for (a) Day 8, (b) Day 11, (c) Day 13.

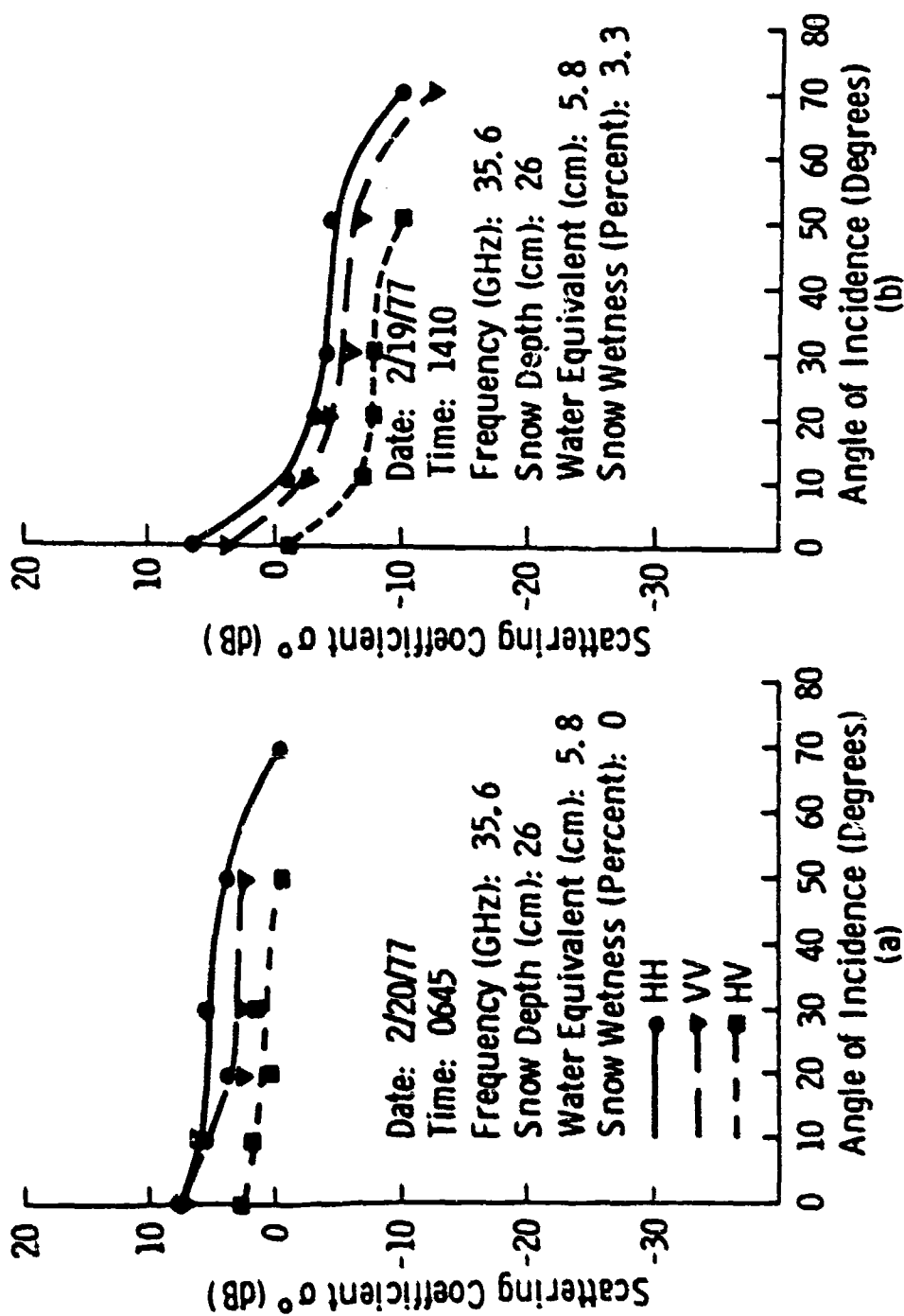
### PART III. UNIVERSITY OF KANSAS DATA

The University of Kansas program used a 20-m high truck-mounted platform, similar to that used by the University of Michigan, to make multipolarization radar backscatter measurements at 35 GHz for various types of terrain surfaces. The majority of the data were recorded for HH, HV, VH, and VV linear polarization combinations, although a few were made for circular polarization configurations (RL, LL, LR, RR) also.

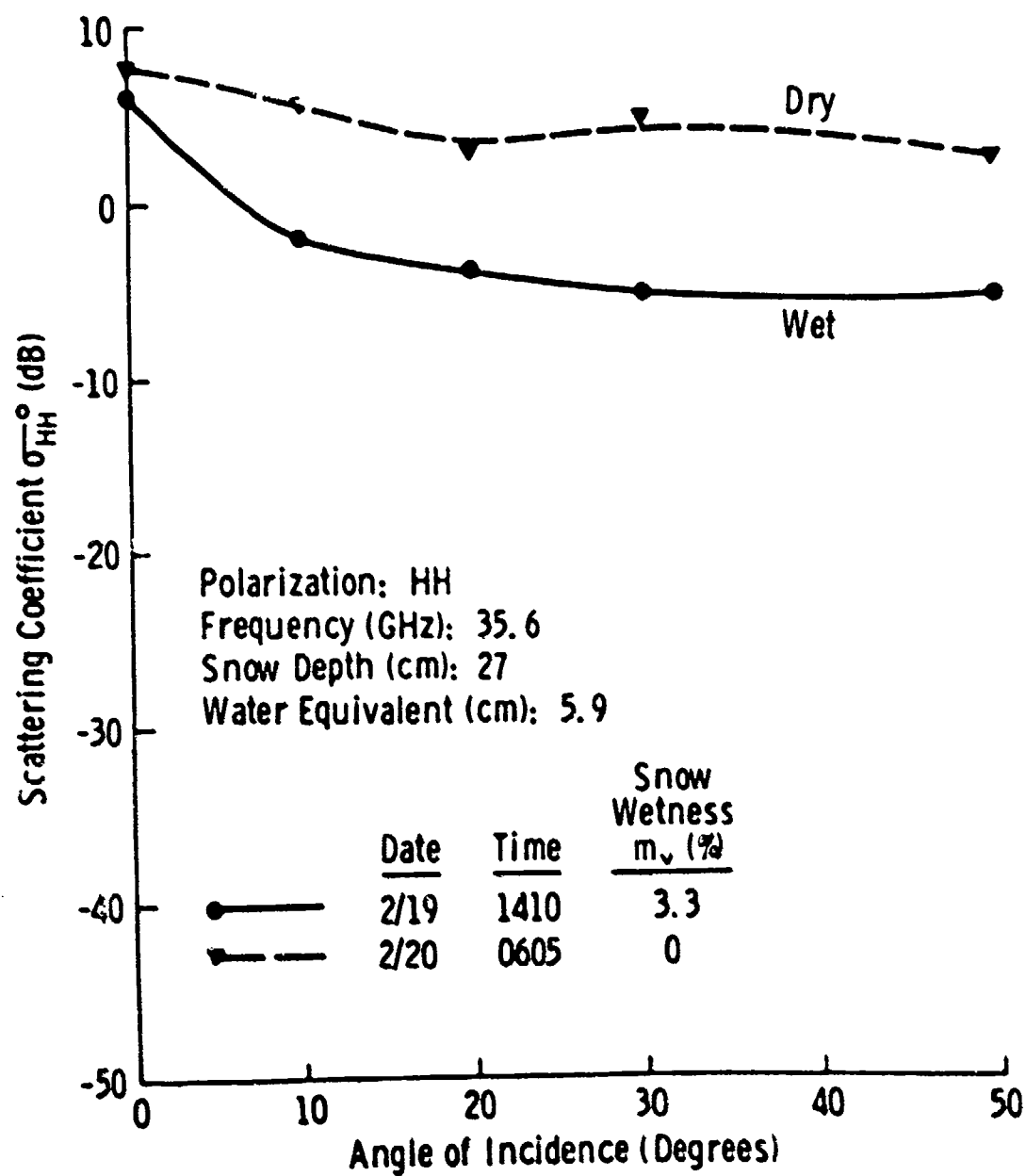
The radar used was an FM-CW system with separate transmit and receiver antennas. The antennas were equipped with polarizers and had a beam width of  $3^\circ$  each, resulting in a product beam width of about  $2^\circ$ .

The data reported in this part of the Handbook, which was extracted from reference [17]-[20], is divided into three categories: (1) angular plots of  $\sigma^\circ$  for snow-covered ground under both dry and wet conditions, (2) diurnal plots of  $\sigma^\circ$  as a function of time for snow, and (3) angular plots for various types of road surfaces with and without snow cover.

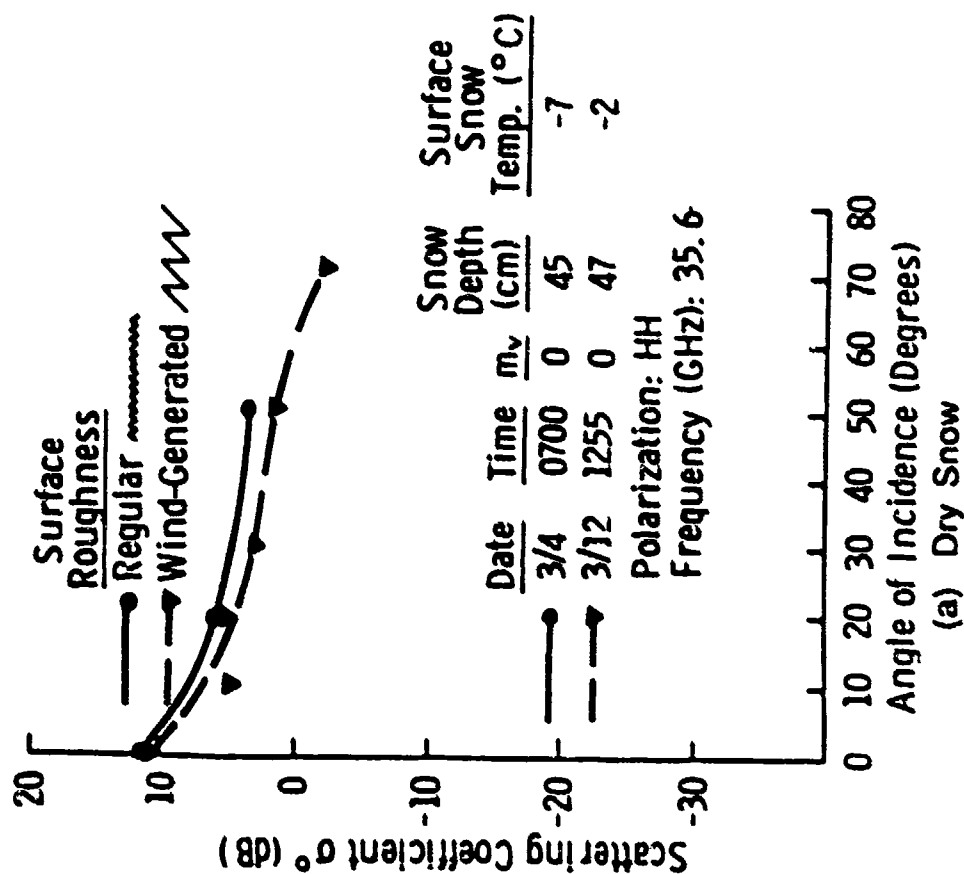
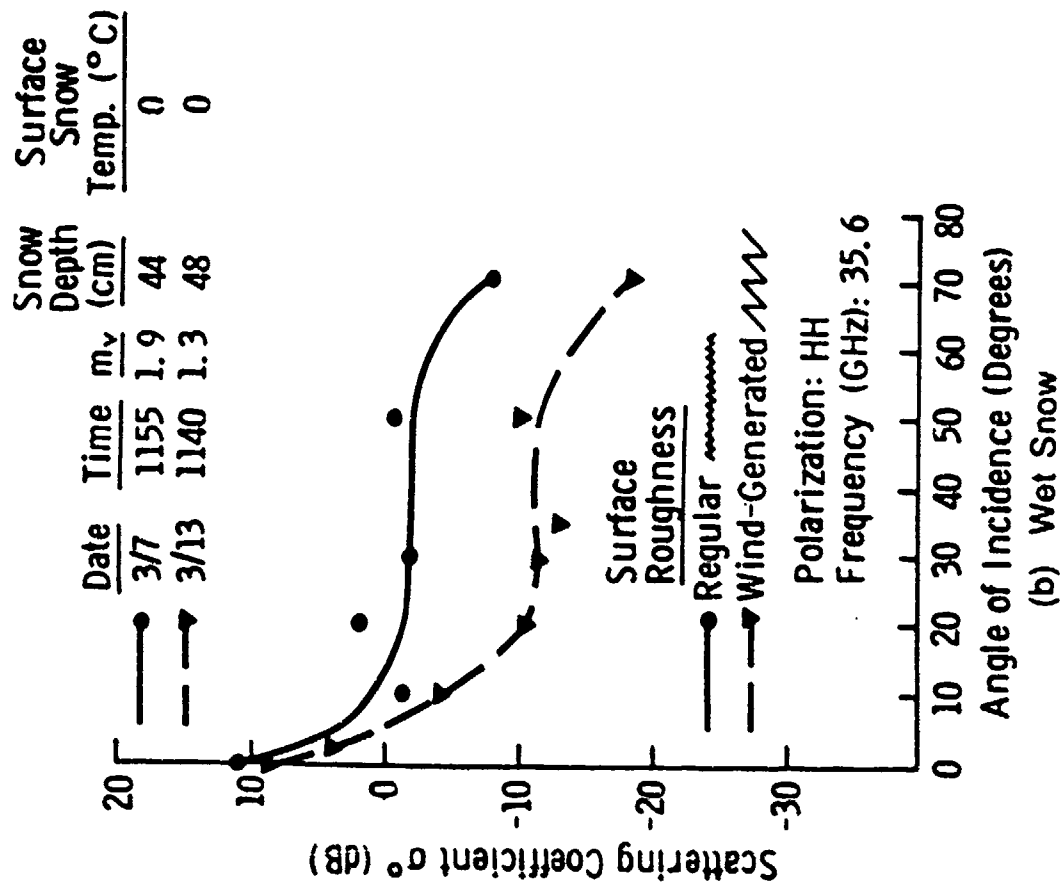
# 11. 35 GHz DATA FOR SNOW



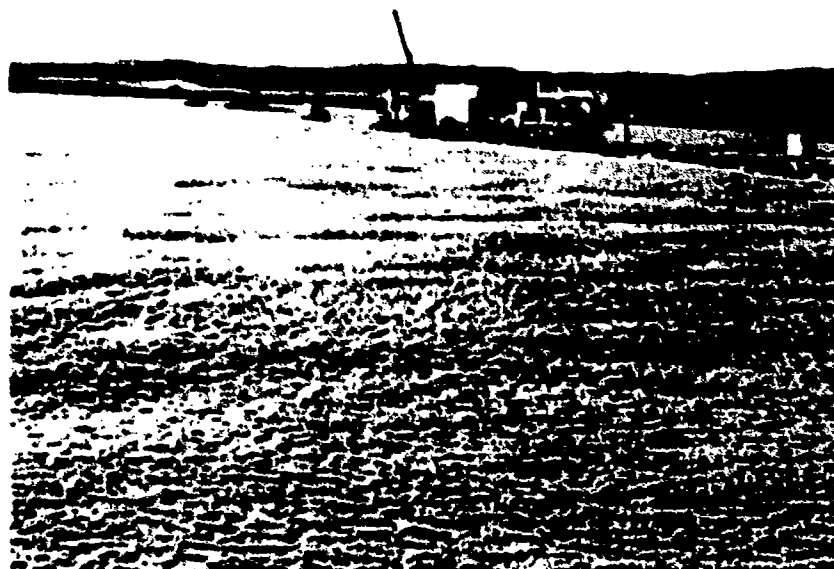
Polarization and angular response of  $\sigma^0$  for (a) dry snow condition and (b) wet snow condition.



Angular Response of  $\sigma^0$  at 35.6 GHz to Wet and Dry Snow

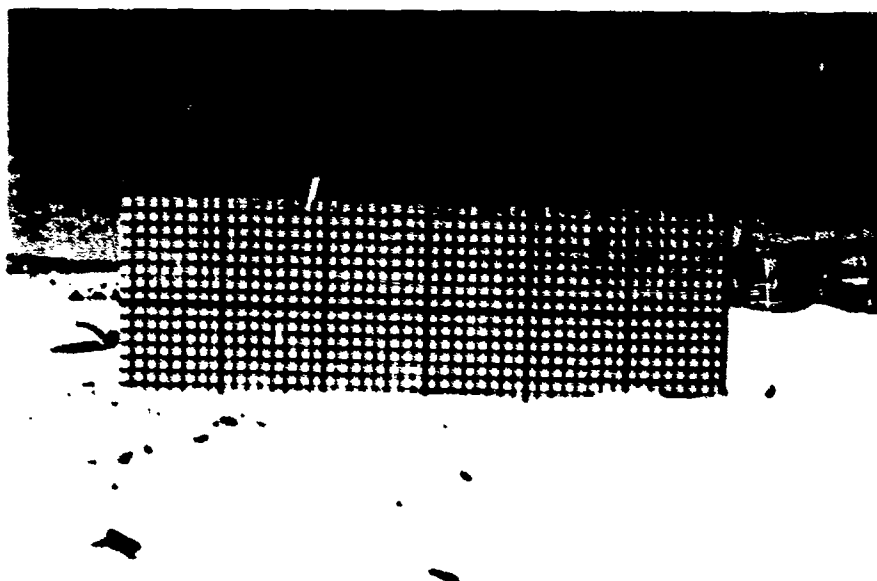


Effect of surface roughness for (a) dry snow and (b) wet snow. ( $m_v$  is volumetric liquid water content of 5-cm surface layer). Photographs of surfaces are shown on the following page.



(a)  $\frac{\lambda}{T} \approx 0.5 \text{ cm}$

(b)  $\approx 30 \text{ cm}$   
 $\approx 2 \text{ cm}$



Snow surface structure: (a) regular snow surface, (b) wind-generated snow surface

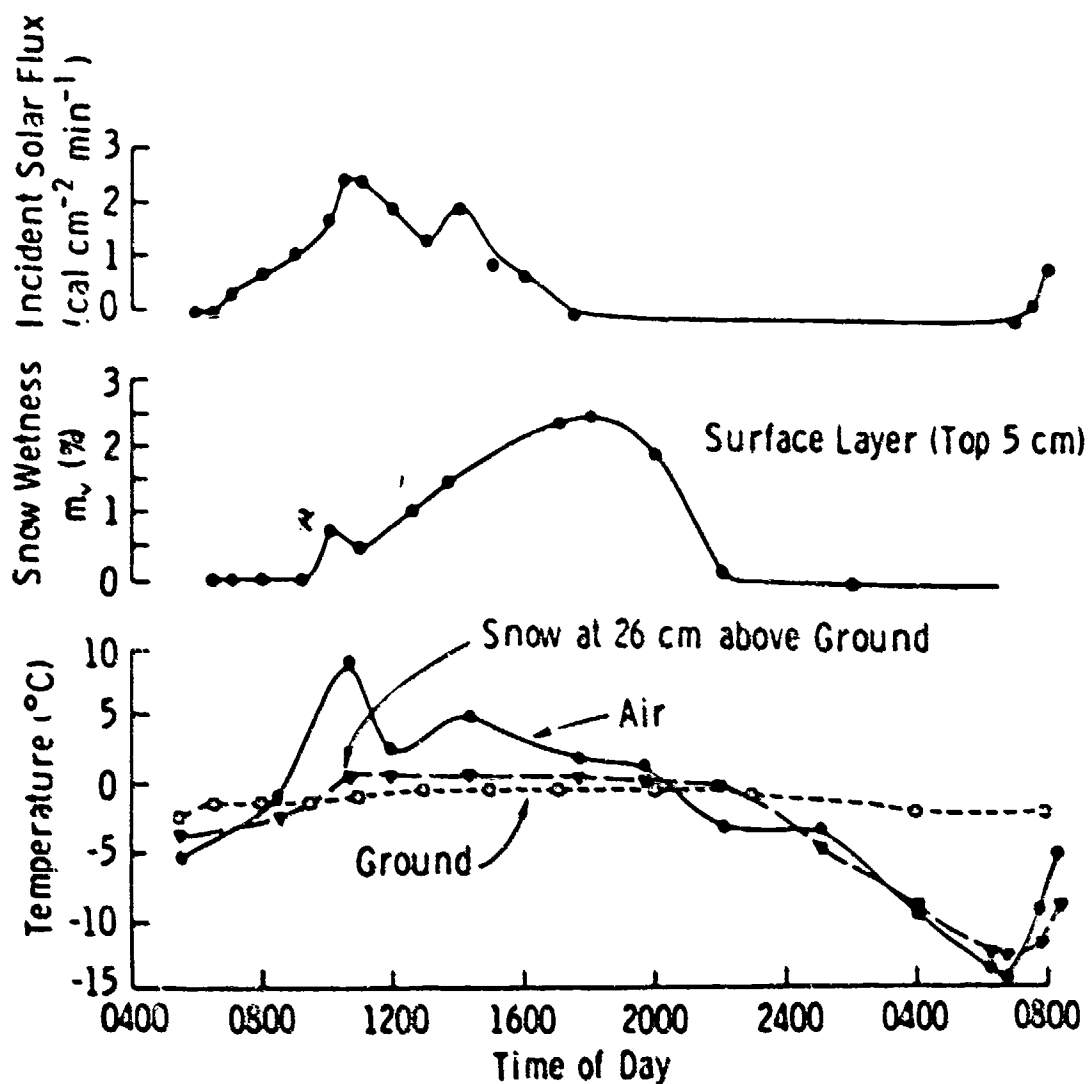
## 12. 35 GHz DIURNAL DATA FOR SNOW

### A. February 17-18, 1977 Diurnal

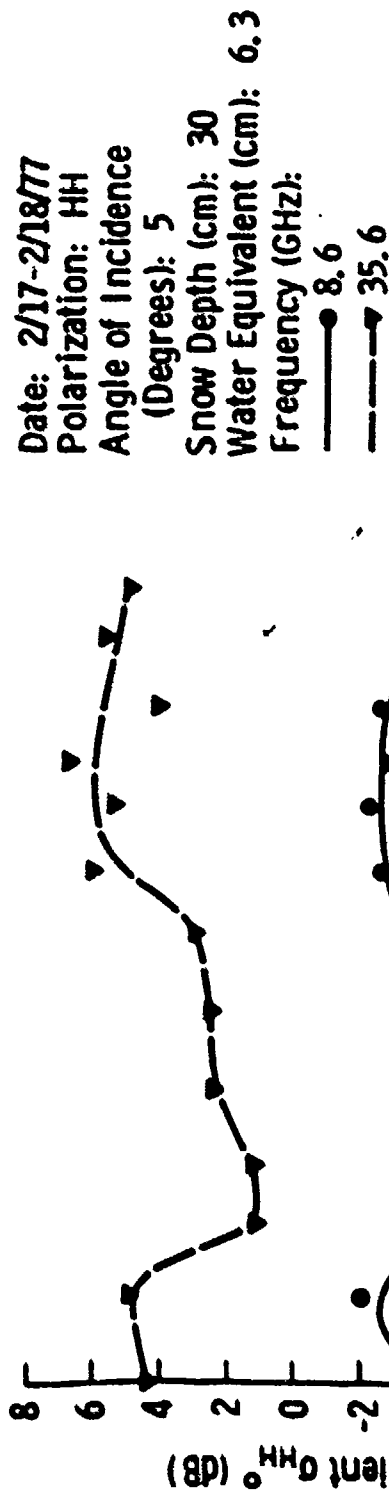
Date: 2/17 - 2/18/77

Snow Depth (cm): 30

Water Equivalent (cm): 6.3

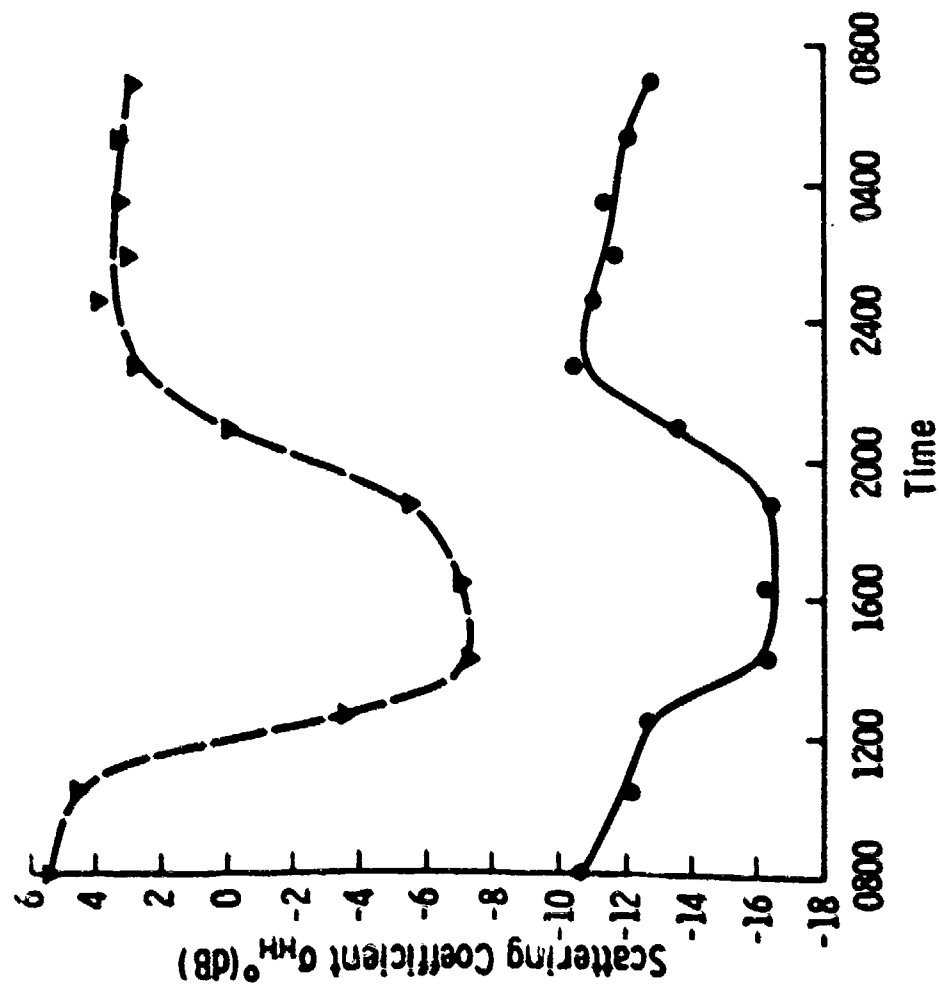


Diurnal variation of the supportive ground truth data on 2/17 - 2/18/77.  $m_v$  is the volumetric snow wetness of the top 5-cm layer.



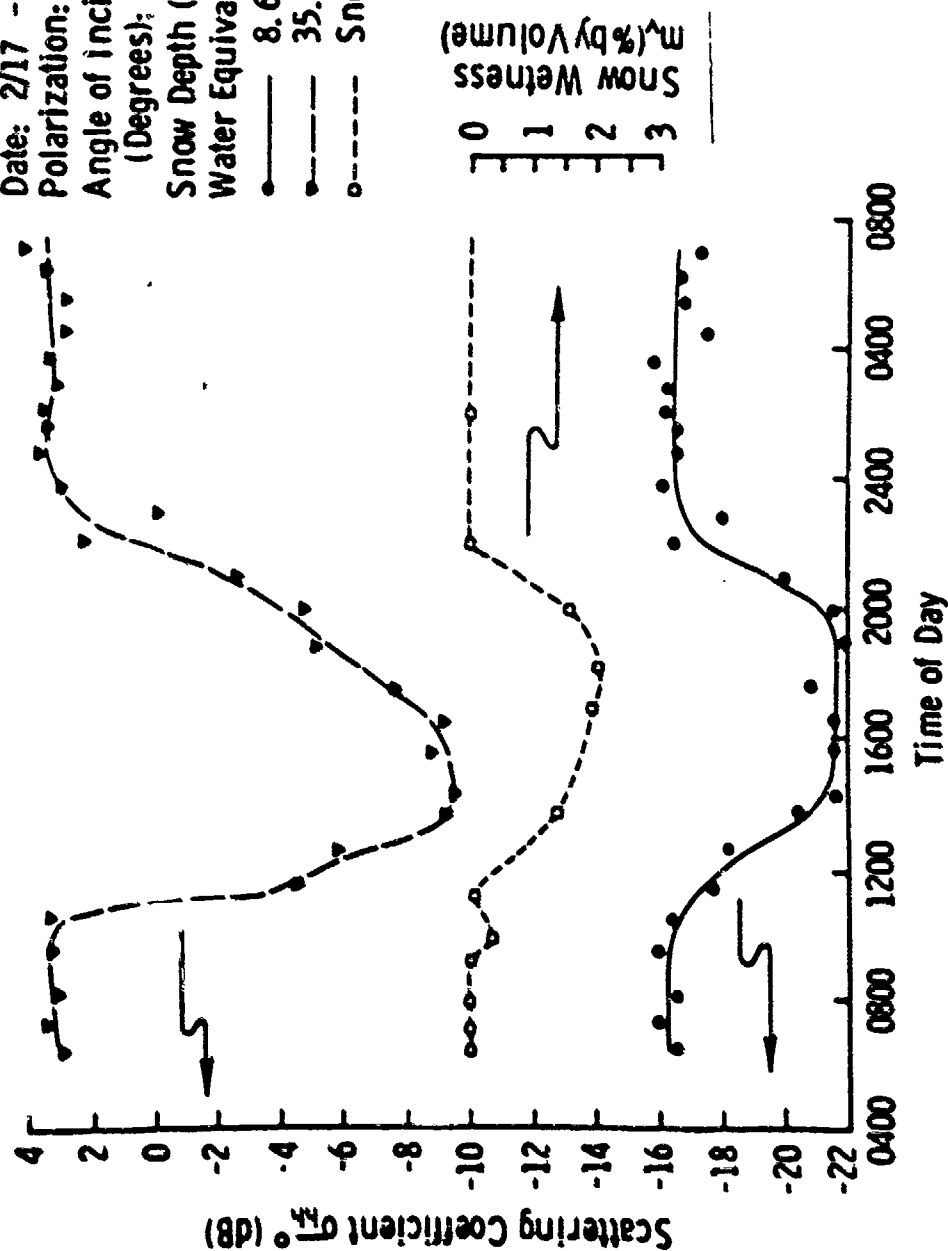
Diurnal variation of  $\sigma^0$  at 8.6 and 35.6 GHz at 5° angle of incidence.

Date: 2/17-2/19/77  
 Polarization: HH  
 Angle of Incidence  
 (Degrees): 25  
 Snow Depth (cm): 30  
 Water Equivalent (cm): 6.3  
 Frequency (GHz):  
 —●— 8.6  
 - - - ▴ 35.6



Diurnal variation of  $\sigma^0$  at 8.6 and 35.6 GHz at 25° angle of incidence.

Date: 2/17 - 2/18/77  
Polarization: HH  
Angle of incidence (Degrees): 55  
Snow Depth (cm): 30  
Water Equivalent (cm): 6.3  
— 8.6 GHz  
--- 35.6 GHz  
o--- Snow Wetness



Diurnal variation snow wetness and  $\sigma^\circ$  at 8.6 and 35.6 GHz. (Note that snow wetness scale has been reversed for ease of comparison with  $\sigma^\circ$ .)

B. March 3-4, 1977 Diurnal

Date: 3/3-3/4/77

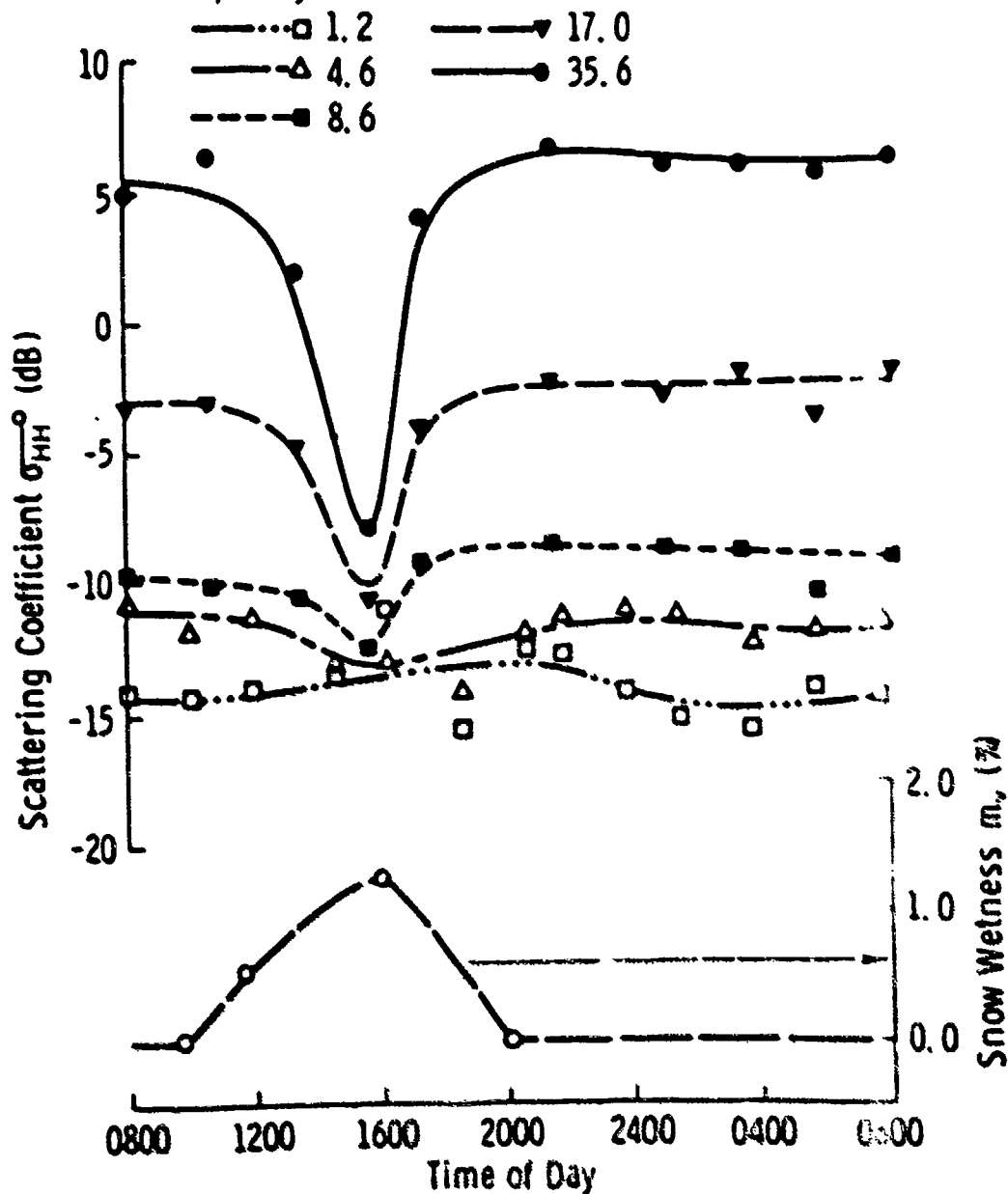
Polarization: HH

Angle of Incidence: (Degrees): 20

Snow Depth (cm): 48

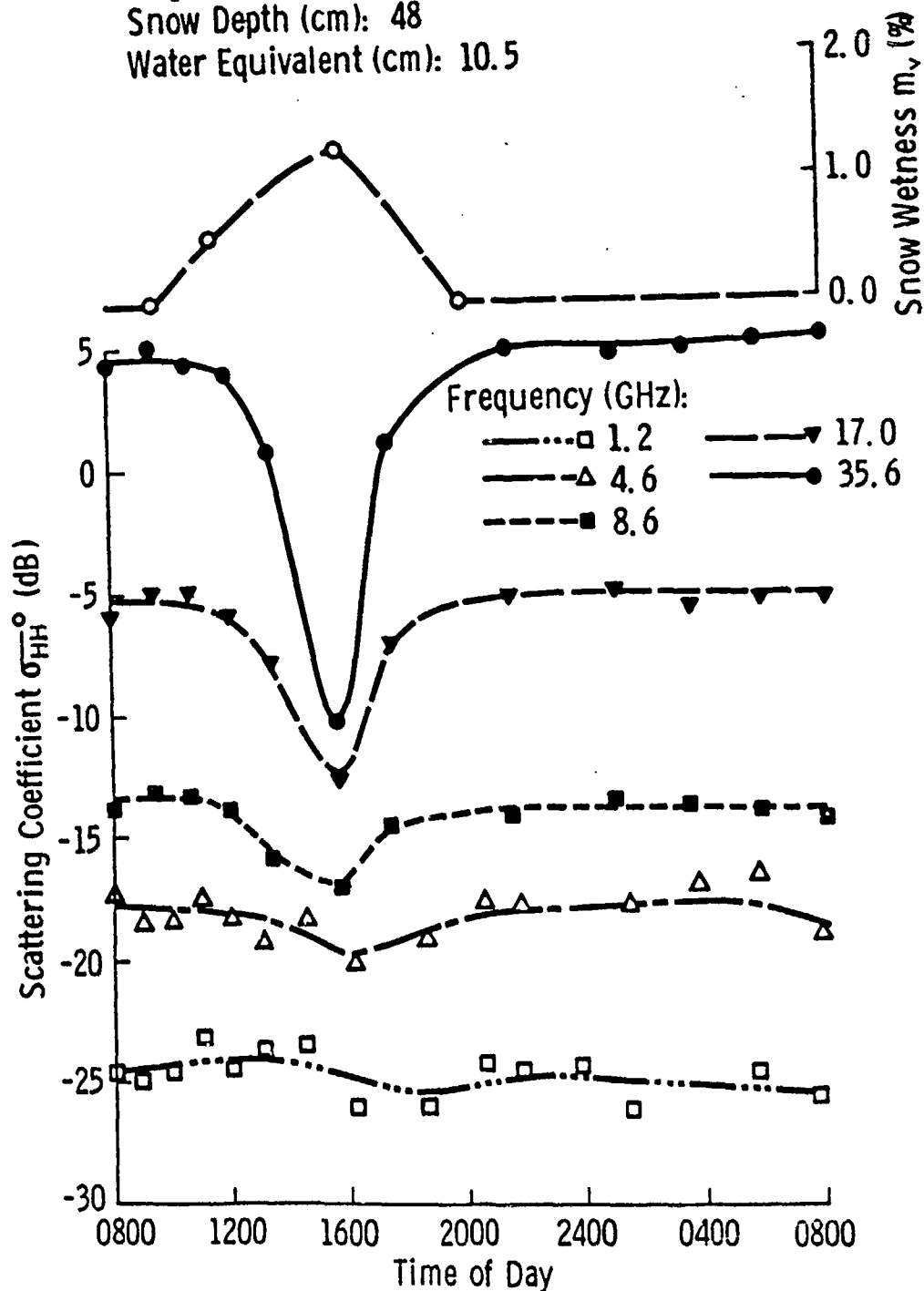
Water Equivalent (cm): 10.5

Frequency (GHz):



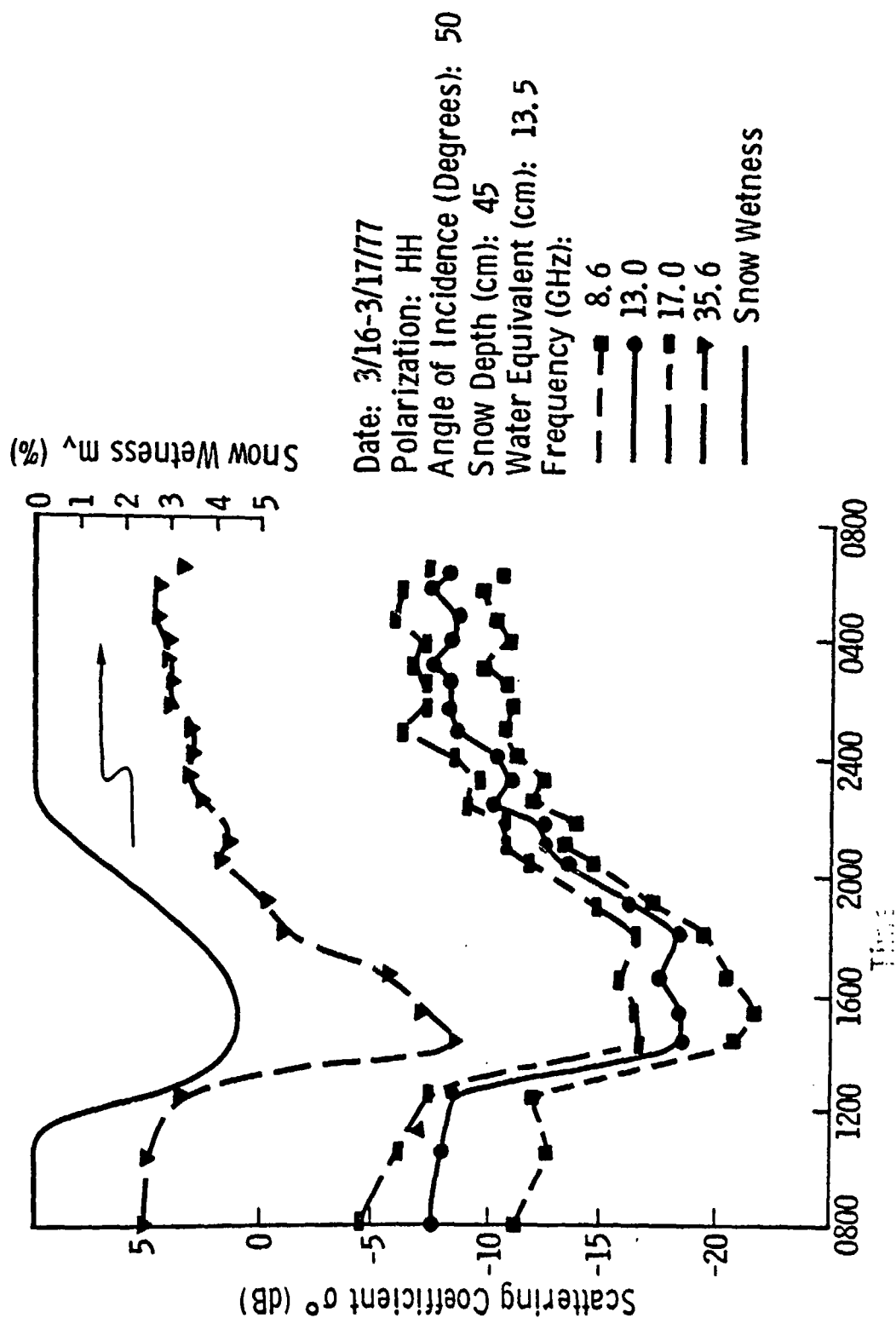
Diurnal Variation of Snow Wetness and  $\sigma^0$  Between 1 and 35 GHz at 20° Angle of Incidence.

Date: 3/3-3/4/77  
 Polarization: HH  
 Angle of Incidence (Degrees): 50  
 Snow Depth (cm): 48  
 Water Equivalent (cm): 10.5

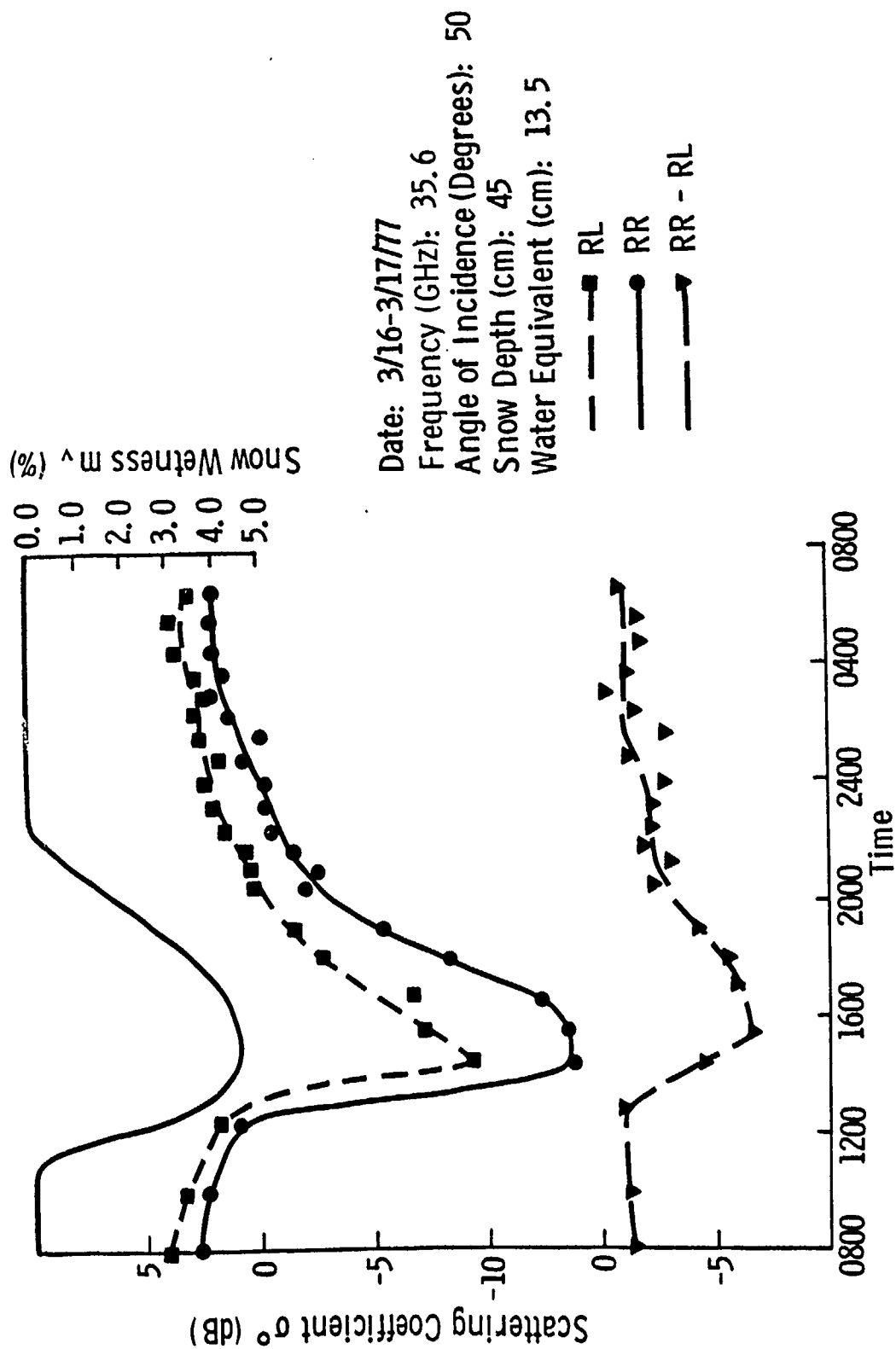


Diurnal Variation of Snow Wetness and  $\sigma^0$  Between 1 and 35 GHz at 20° Angle of Incidence.

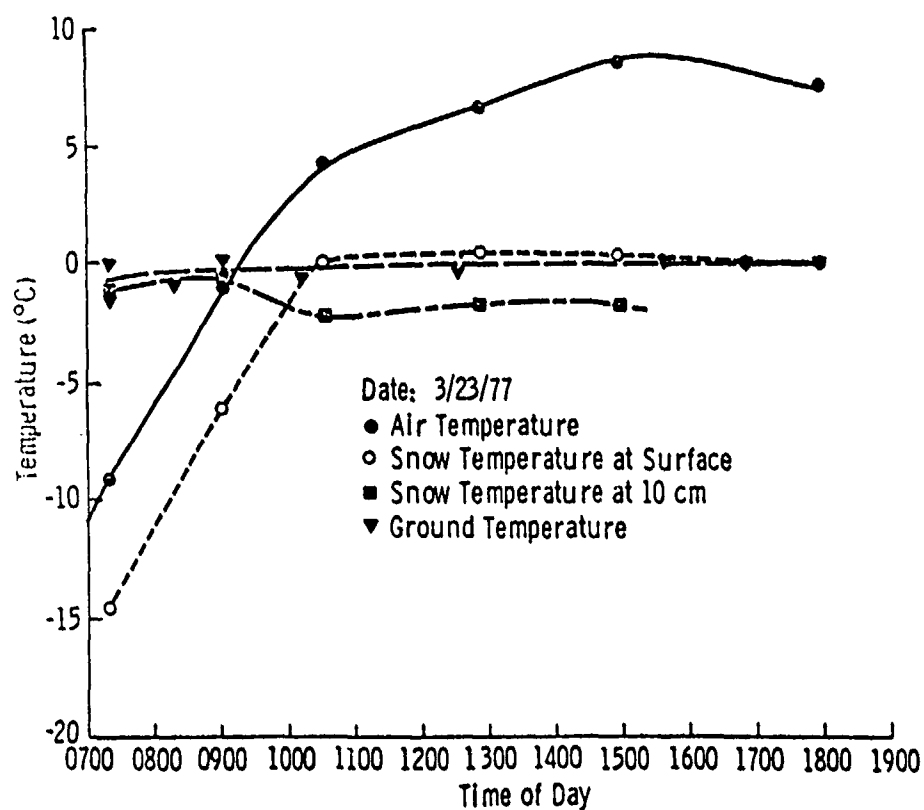
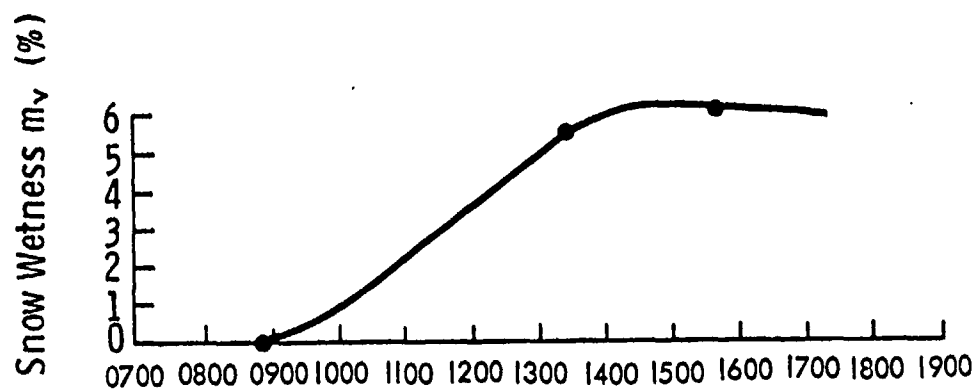
C. March 16-17, 1977 Diurnal



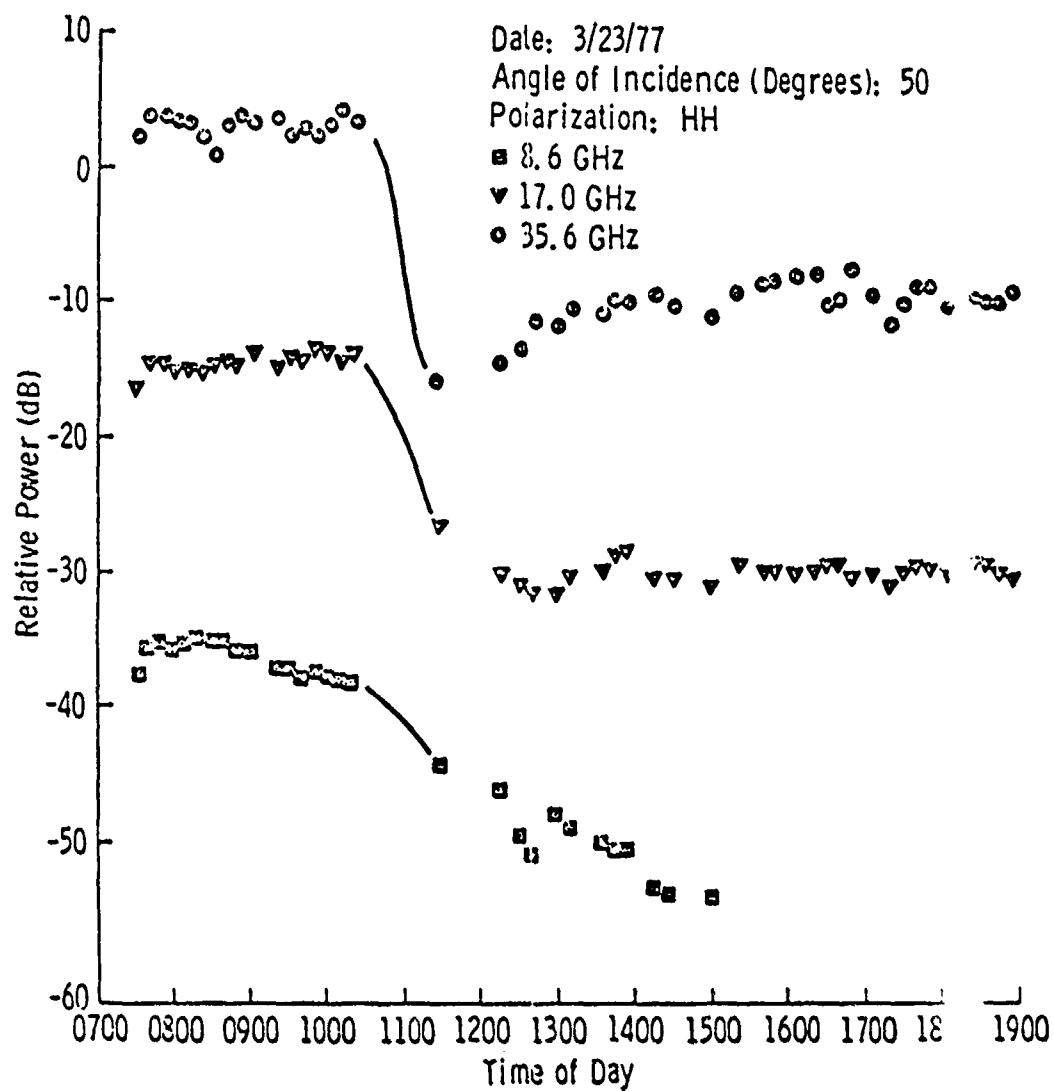
Diurnal variation of snow wetness and  $\sigma^0$  at 8.6, 13.0, 17.0 and 35.6 GHz at 50° angle of incidence.



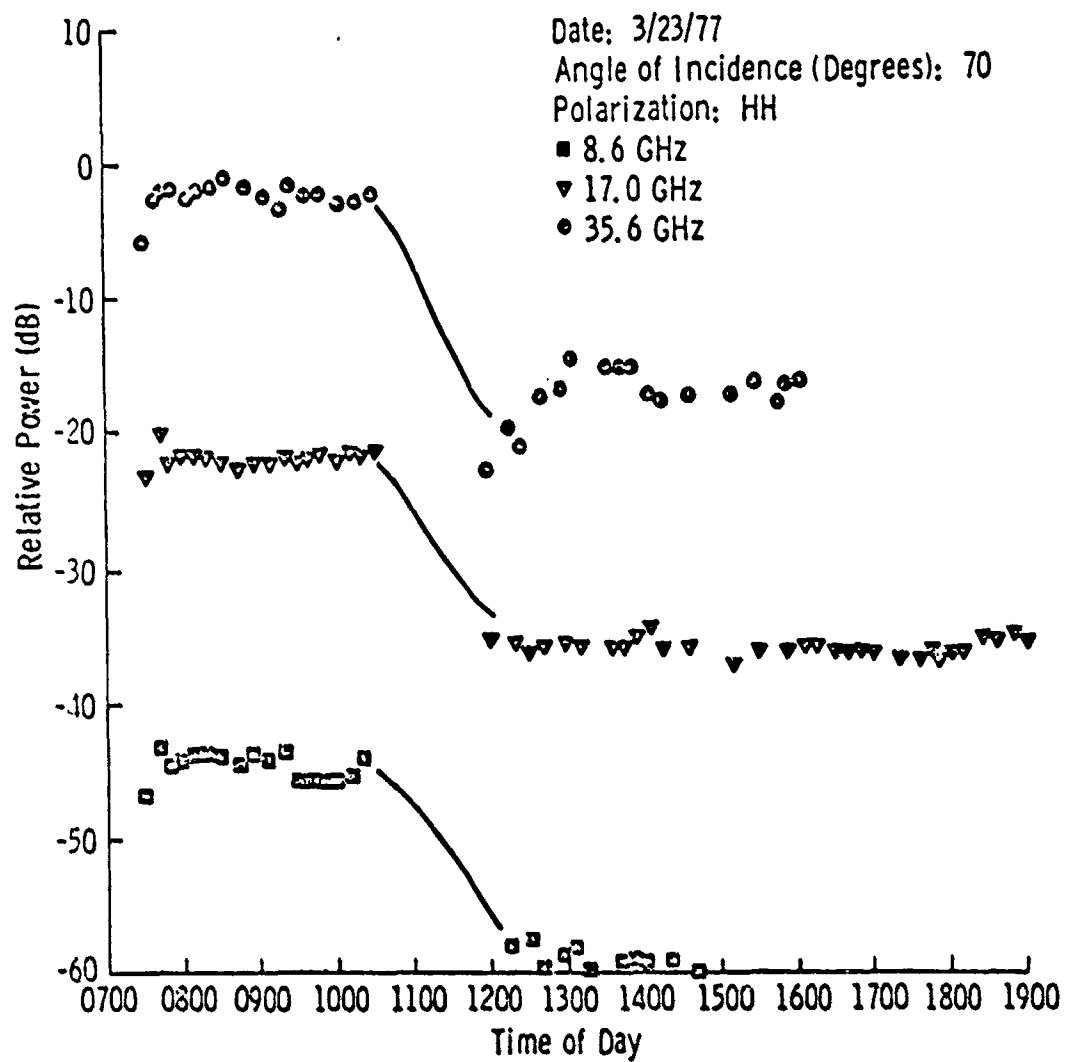
# D. March 23, 1977 Diurnal



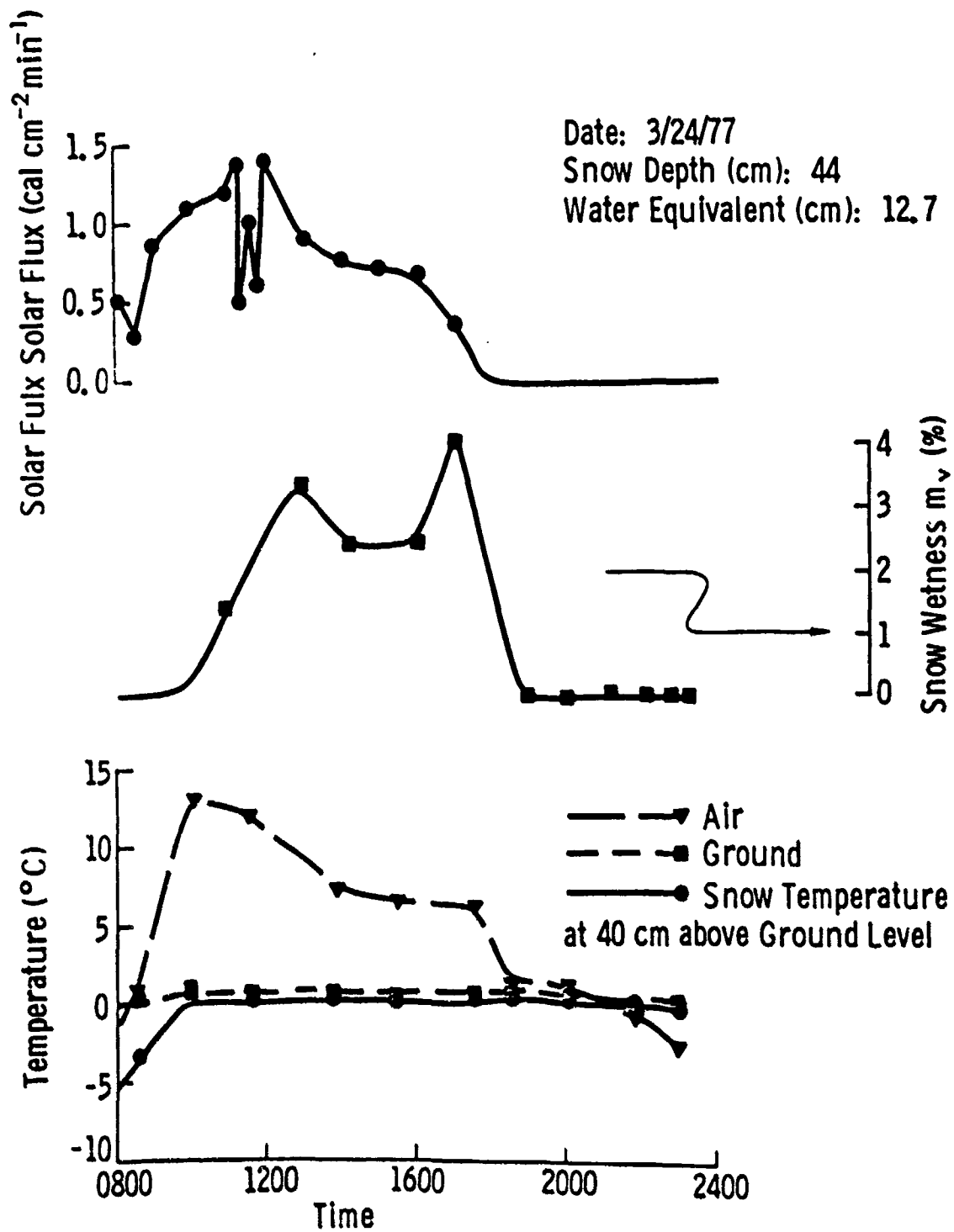
Snow wetness and temperature variation over the measurement period of the diurnal experiment on 3/23/77.



Time variation of 50° backscatter power at 8.6, 17.0, and 35.6 GHz.

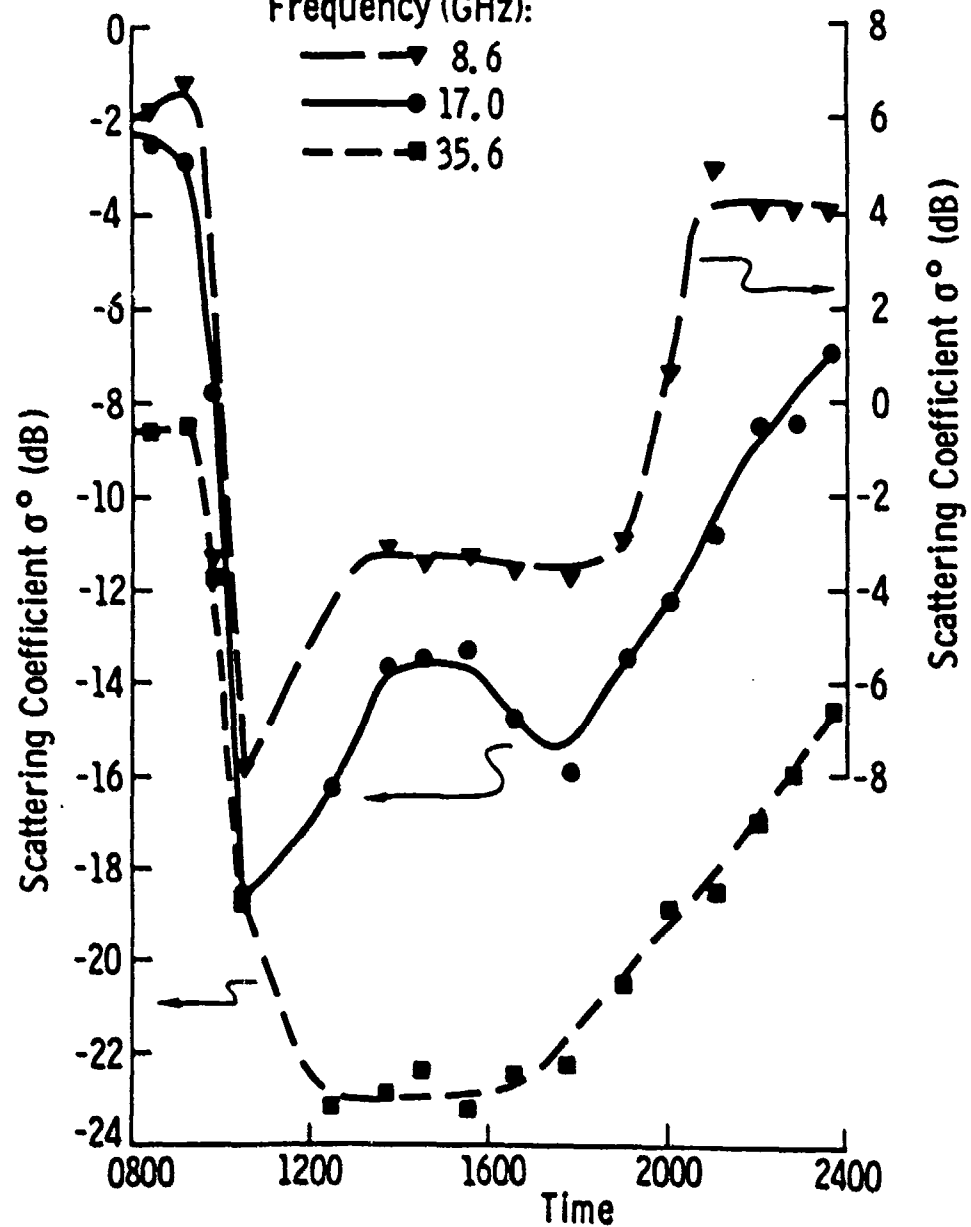


Time variation of 70° backscatter power at 8.6, 17.0, and 35.6 GHz.



Diurnal variation of ground truth data on 3/24/77.

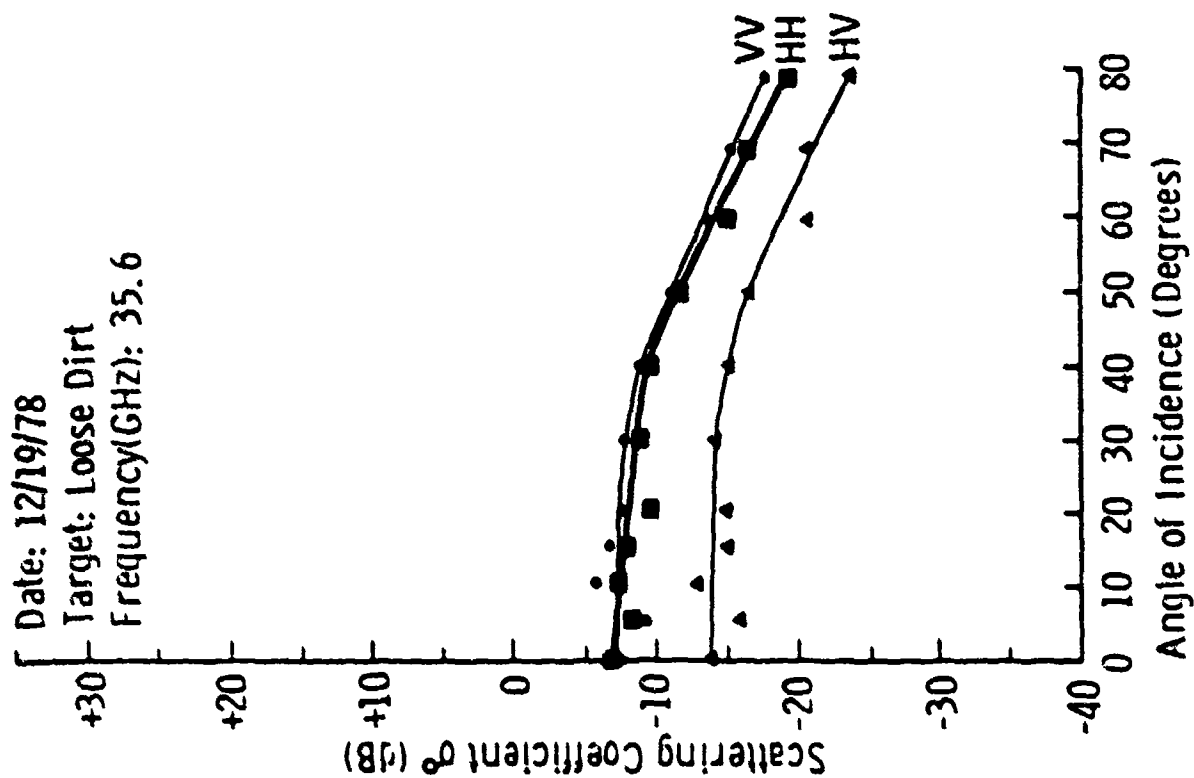
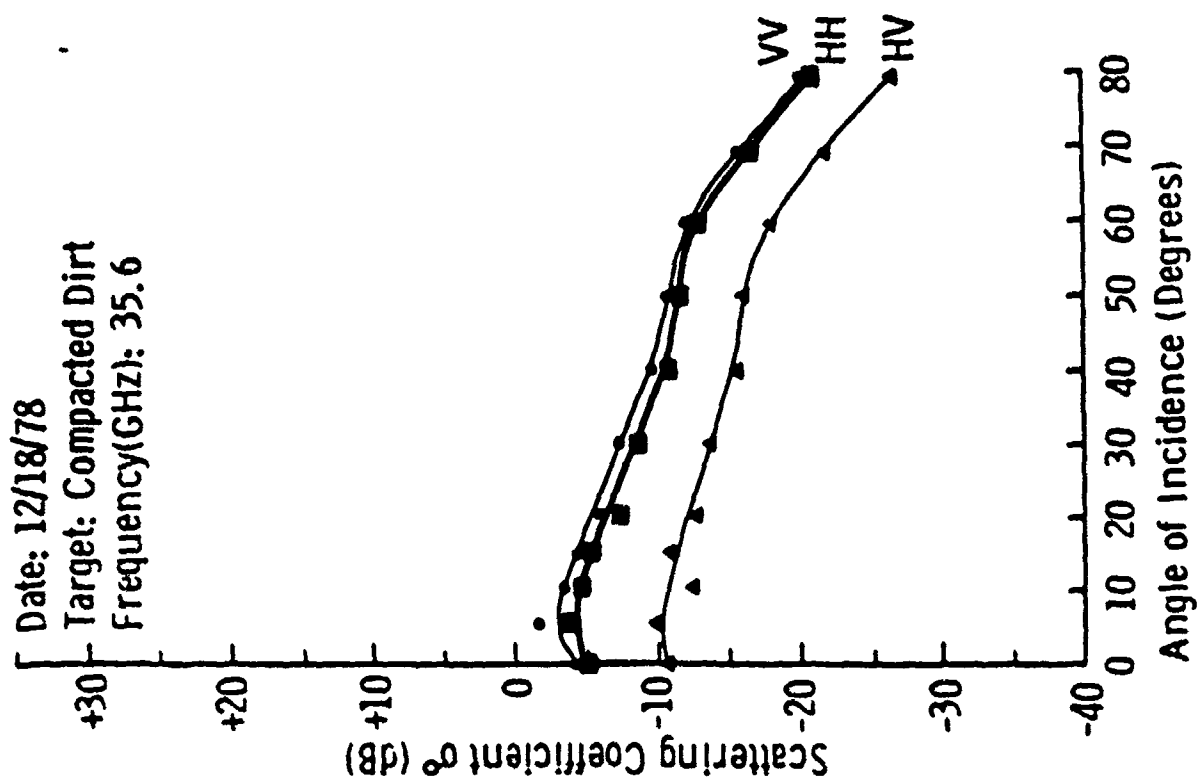
Date: 3/24/77  
 Polarization: HH  
 Angle of Incidence (Degrees): 50  
 Snow Depth (cm): 44  
 Water Equivalent (cm): 12.7  
 Frequency (GHz):



Diurnal variation of  $\sigma^0$  at 8.6, 17.0 and 35.6 GHz at 50° angle of incidence.

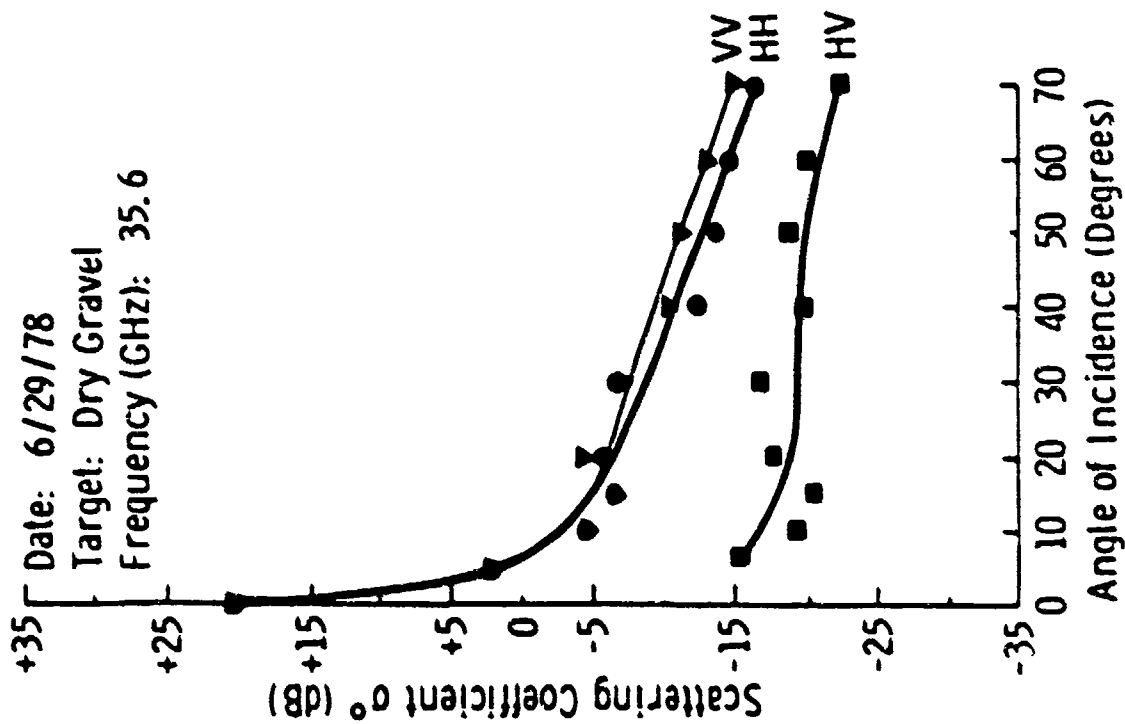
### 13. 35 GHz DATA FOR ROAD SURFACES

#### A. Various Surfaces

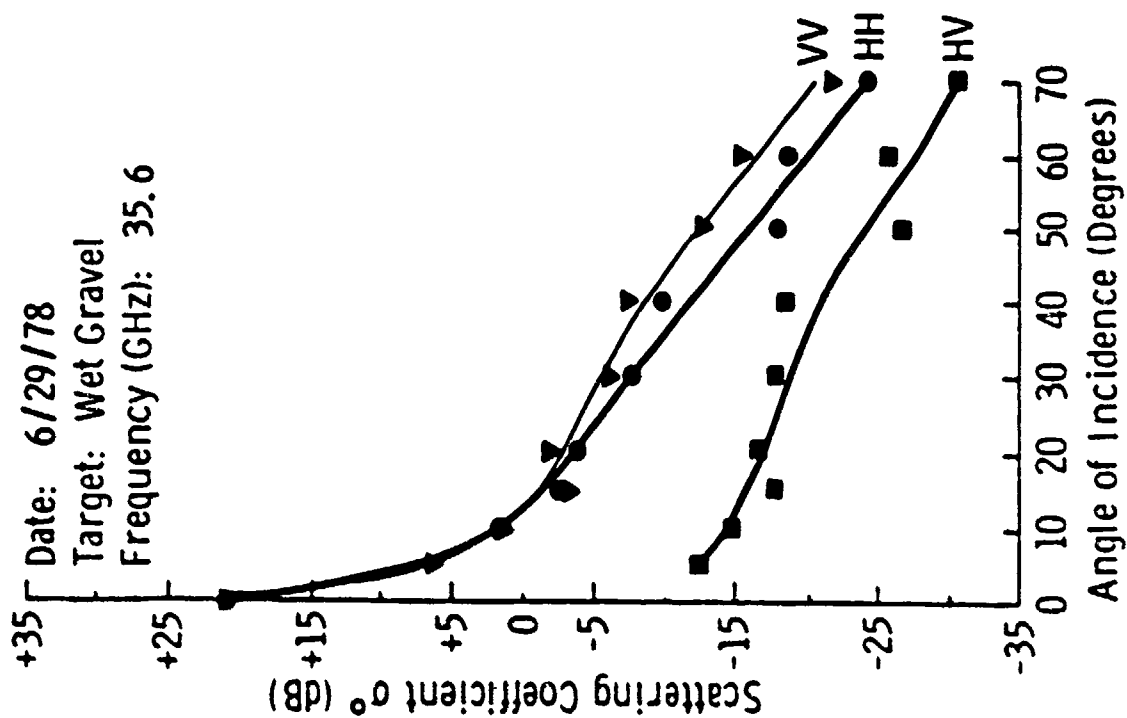


Compacted Dirt Surface

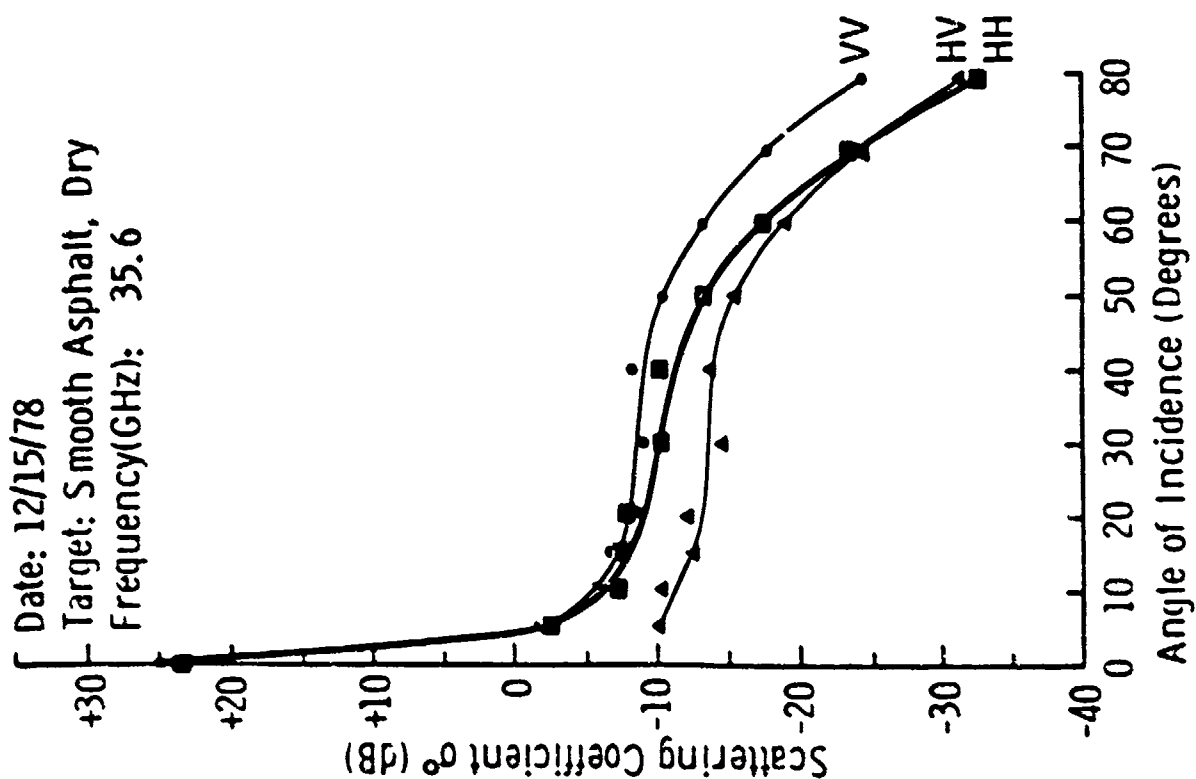
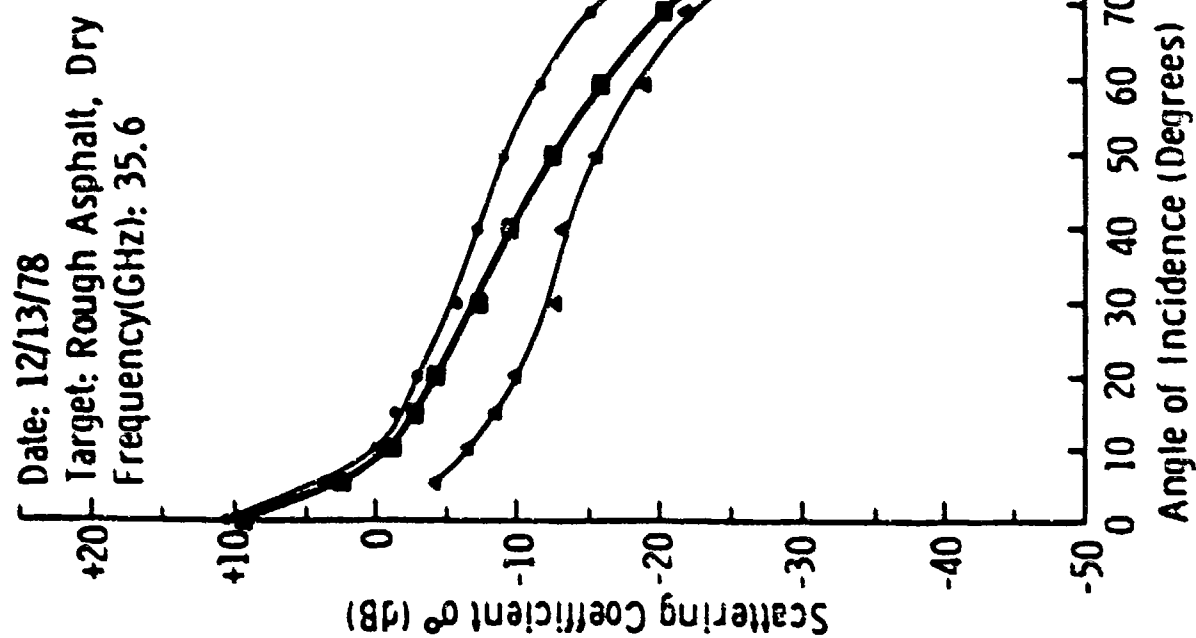
Loose Dirt Surface

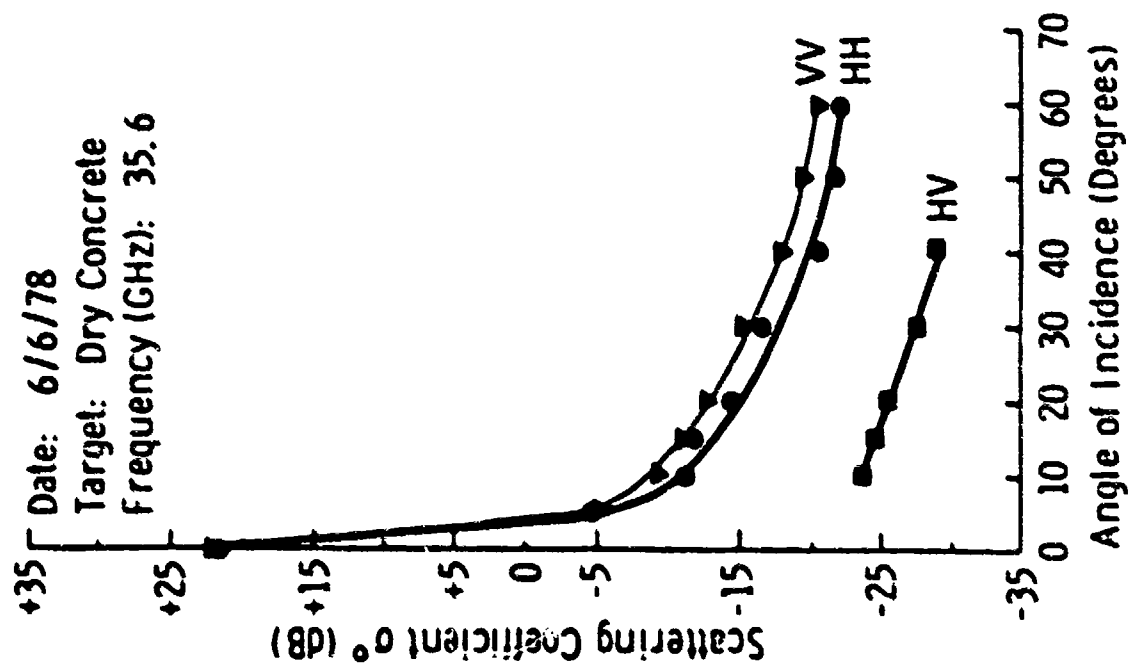


Dry Gravel Surface

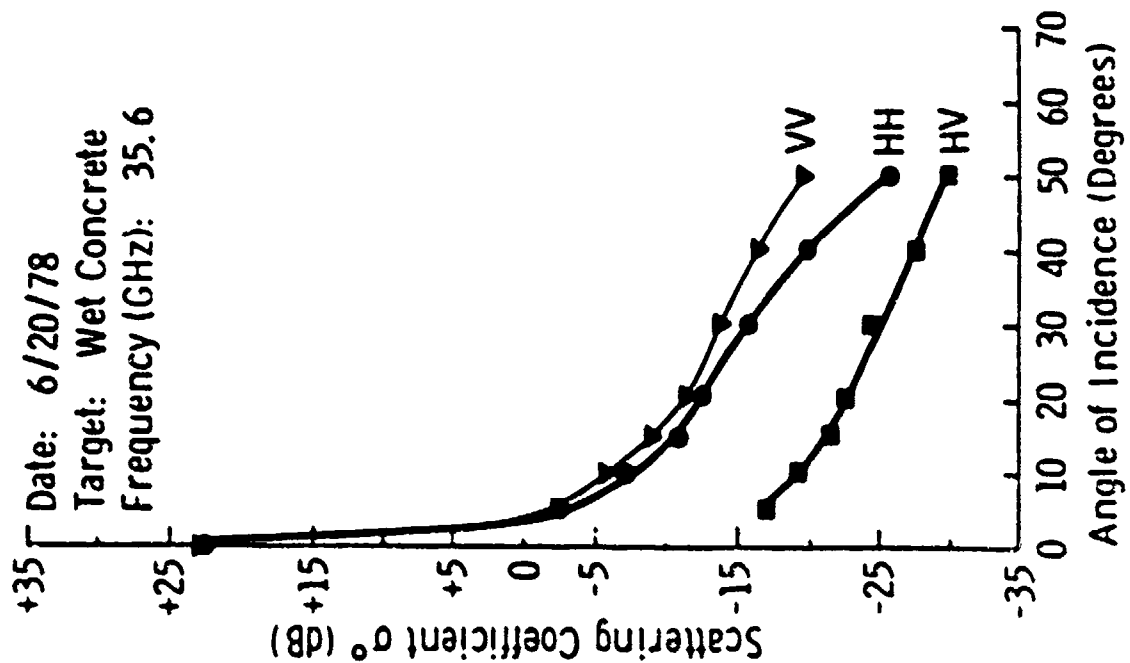


Wet Gravel Surface

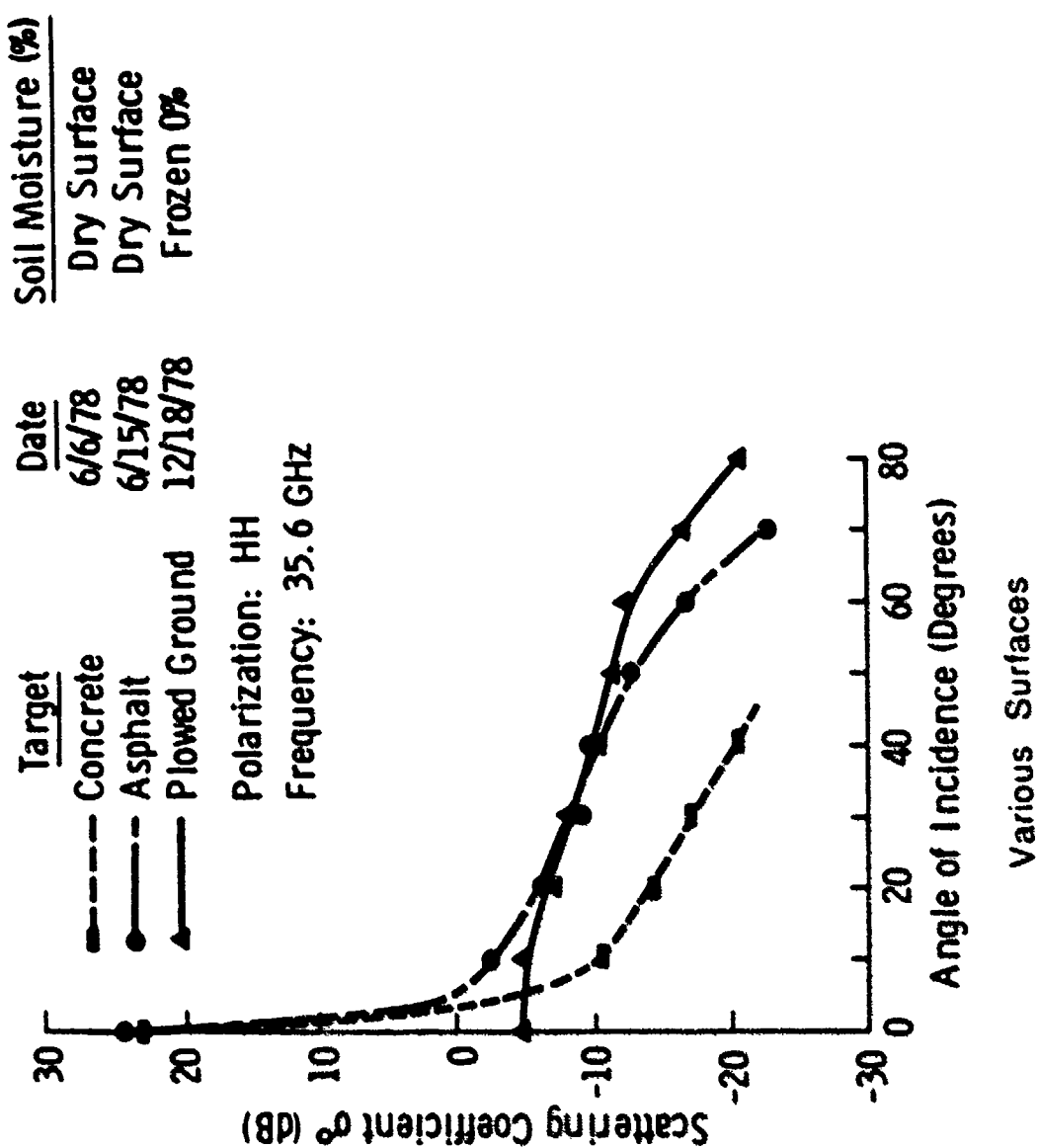
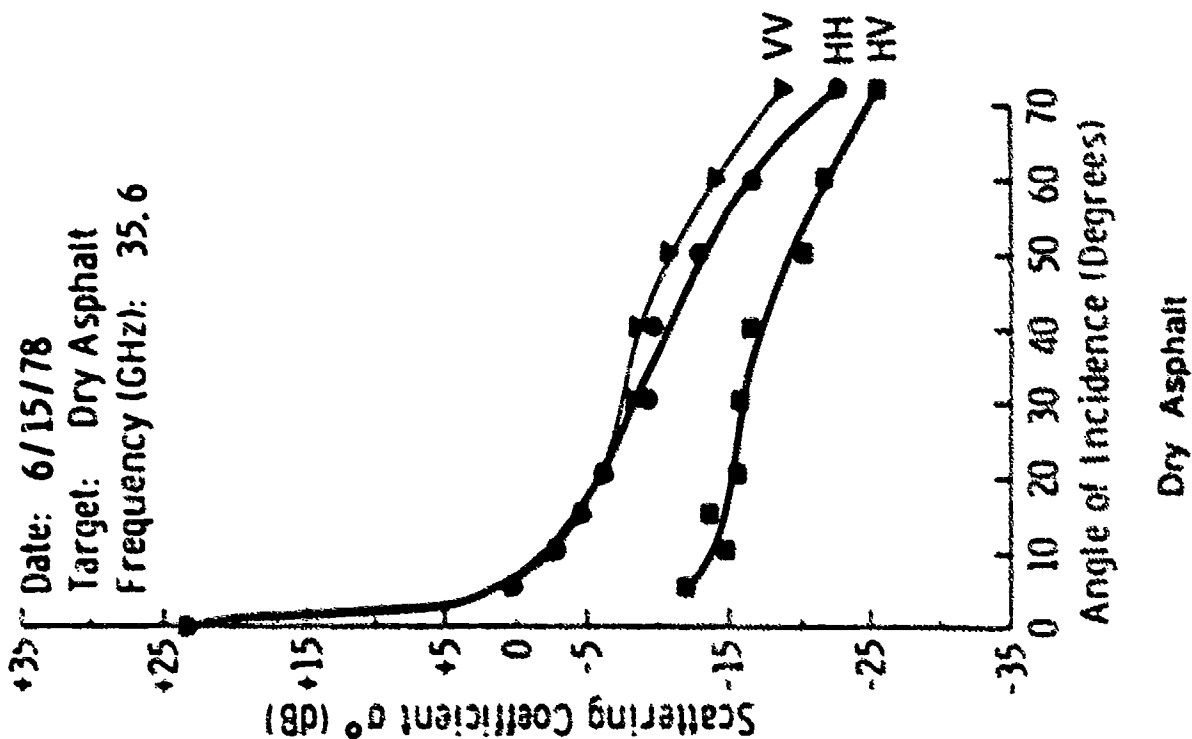




Dry Concrete



Wet Concrete



## B. Road Surfaces With Snow Cover

### Ground Truth Data

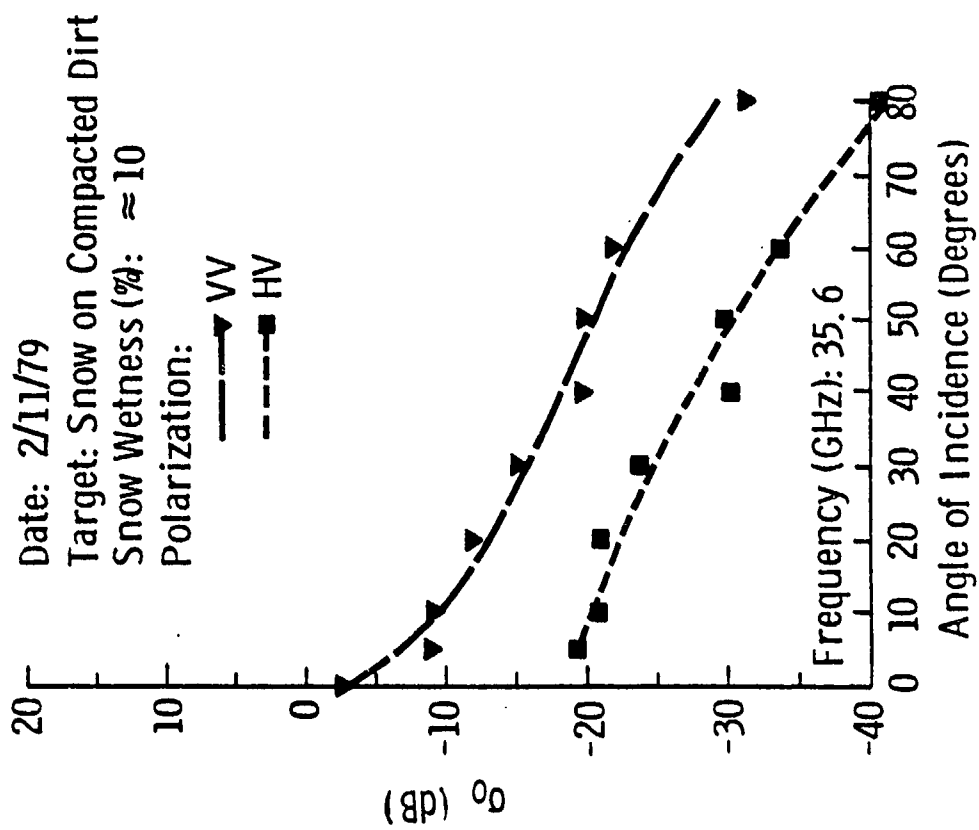
| Date | Time | Target<br>(Snow) | Soil<br>State       | Soil<br>Moisture<br>(% vol.) | Snow<br>Depth<br>(cm) | # of<br>Layers | Water<br>Equiv.<br>(cm) | Snow<br>Wetness<br>(% vol.) | Air<br>Temp.<br>(°C) | (1) Snow<br>Temp.<br>(°C) | Snow/<br>Ground<br>Temp.<br>(°C) |
|------|------|------------------|---------------------|------------------------------|-----------------------|----------------|-------------------------|-----------------------------|----------------------|---------------------------|----------------------------------|
| 2/10 | 1315 | Dirt             | Frozen              | ---                          | 6-14                  | 1-3            | 3.0                     | 0                           | -1.3                 | -3.3                      | -1.9                             |
| 2/11 | 1030 | Dirt             | Frozen              | ---                          | 6-14                  | 1-3            | 2.8                     | 10                          | 2.8                  | -4                        | -2.0                             |
| 2/13 | 1037 | Grass            | Partially<br>Frozen | N.M. (4)                     | 14-20                 | 2-3            | 5.2                     | 0                           | -3.0                 | -5                        | -5                               |
| 2/13 | 1350 | Asphalt (2)      | ---                 | ---                          | 5-13                  | 2              | 2.0                     | 7.7                         | -2                   | -5                        | -8                               |
| 2/14 | 1050 | Concrete (3)     | ---                 | ---                          | 3-4                   | 1              | 3.0                     | 10                          | .5                   | ---                       | -4                               |
| 2/16 | 1400 | Asphalt          | ---                 | ---                          | 2-6                   | 2-3            | 1.5                     | 0                           | -14.6                | -5.5                      | -5.1                             |
| 2/18 | 1420 | Concrete         | ---                 | ---                          | 6-13                  | 2-3            | 3.1                     | 0                           | -5.2                 | -2.8                      | -3.1                             |
| 2/19 | 1100 | Grass            | Partially<br>Frozen | N.M.                         | 9-14                  | 2              | 2.8                     | 10.9                        | 4.5                  | .8                        | -9                               |
| 2/19 | 1430 | Concrete         | ---                 | ---                          | 0-3                   | 1              | 1.5                     | 3.9                         | 2.5                  | .0                        | -1                               |
| 2/20 | 1015 | Asphalt          | ---                 | ---                          | 0-9                   | 0-2            | 1.1                     | 13.4                        | 2.0                  | .0                        | -7                               |
| 2/20 | 1352 | Grass            | Partially<br>Frozen | N.M.                         | 0-14                  | 0-2            | 2                       | 12.1                        | 1.9                  | .0                        | -4                               |

(1) At 2 cm below the surface.

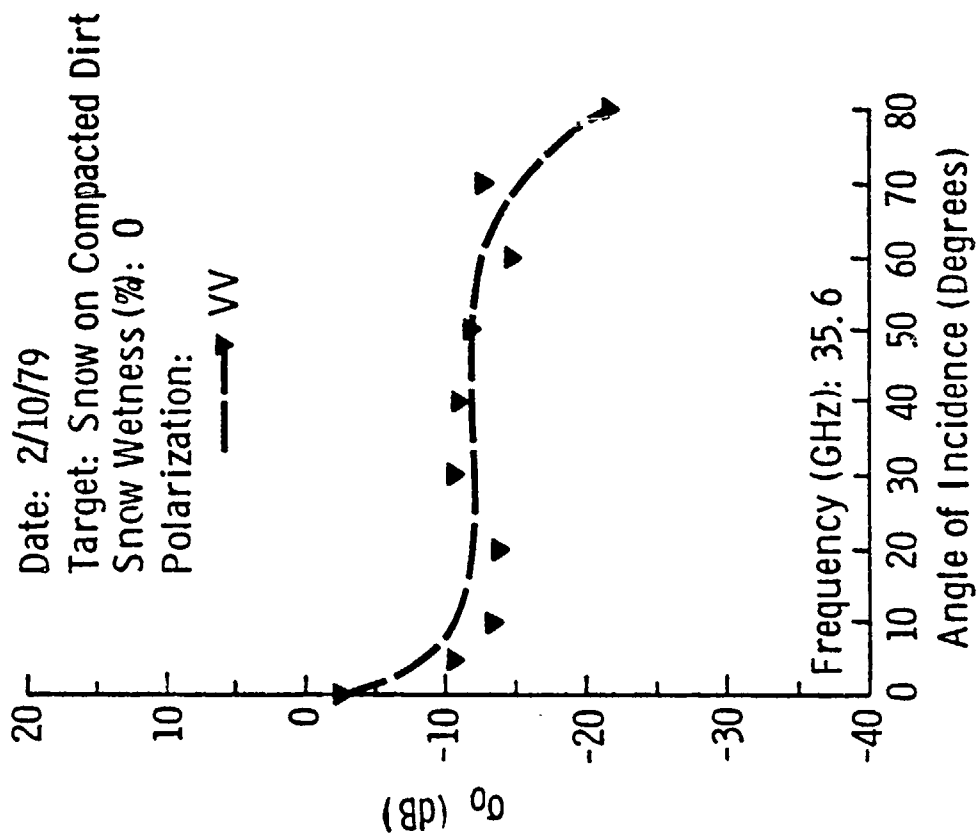
(2) Ice layer underneath snow 5 cm thick.

(3) Layer consisted of packed snow, slush, water and ice. Wetness was not measured; however, the snow was wet.

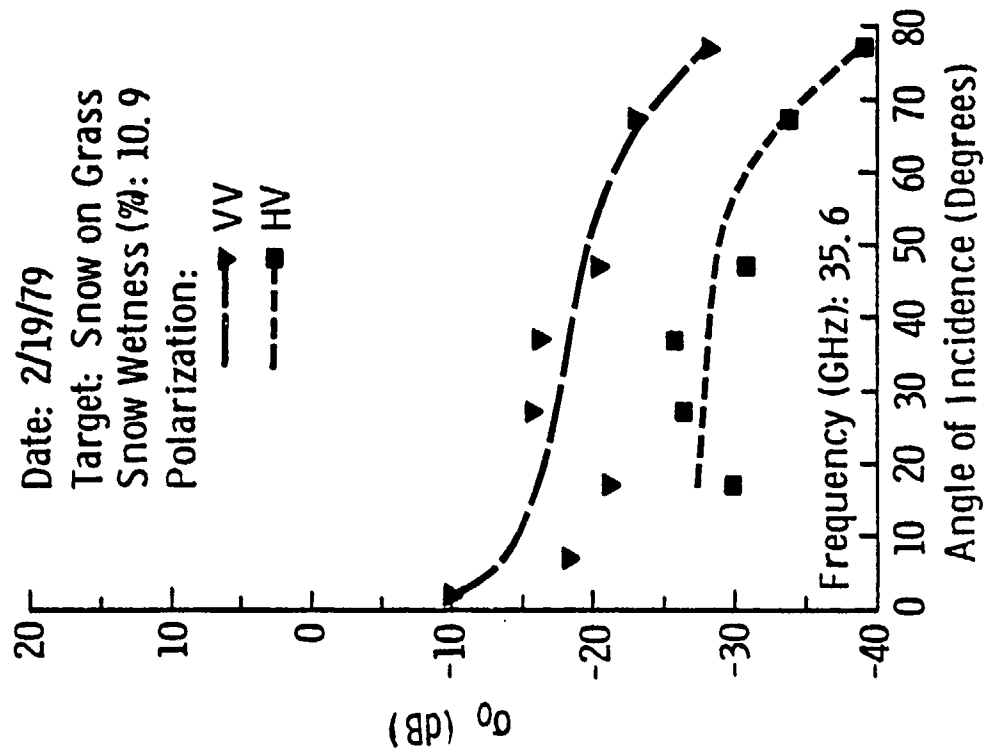
(4) N.M.--not measurable with present technique.



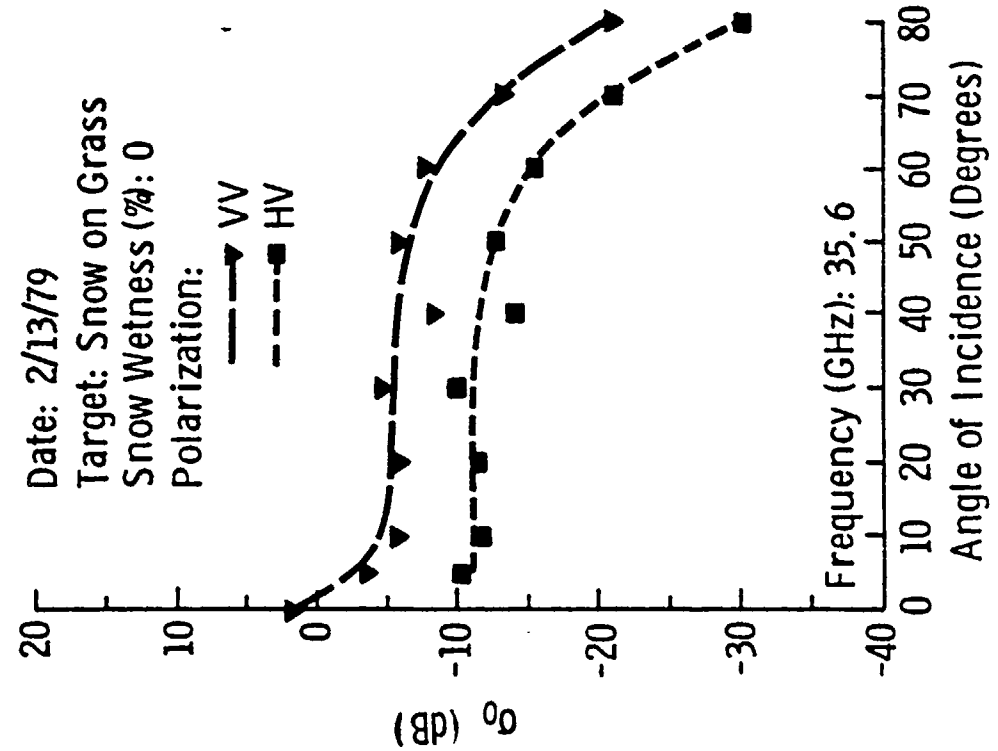
Wet Snow on Compacted Dirt Surface



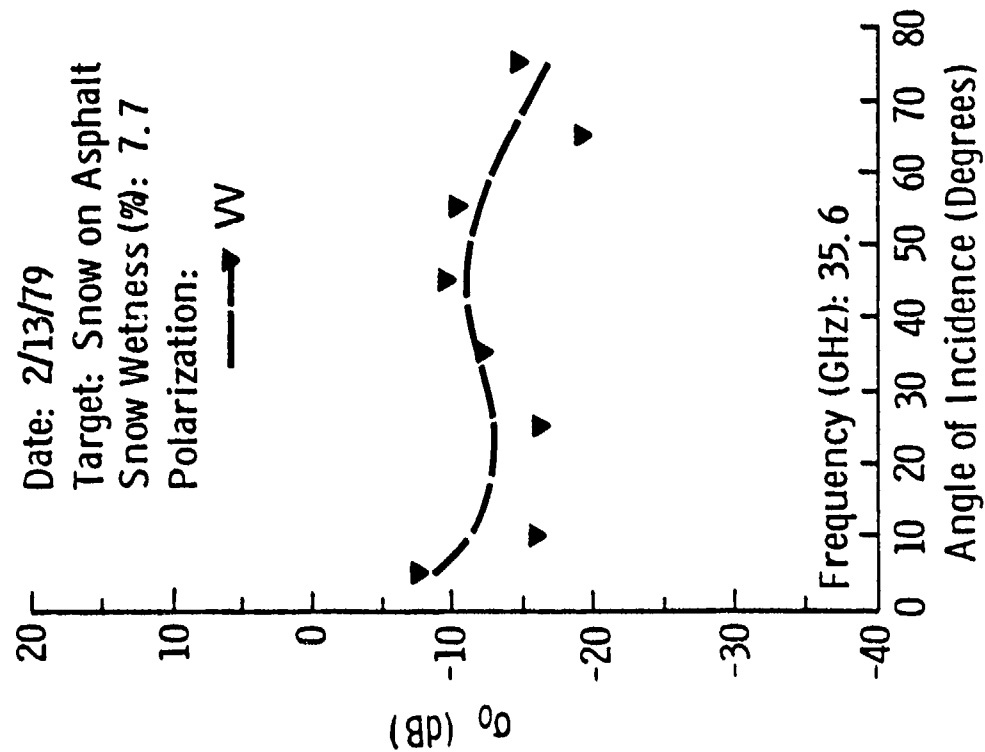
Dry Snow on Compacted Dirt Surface



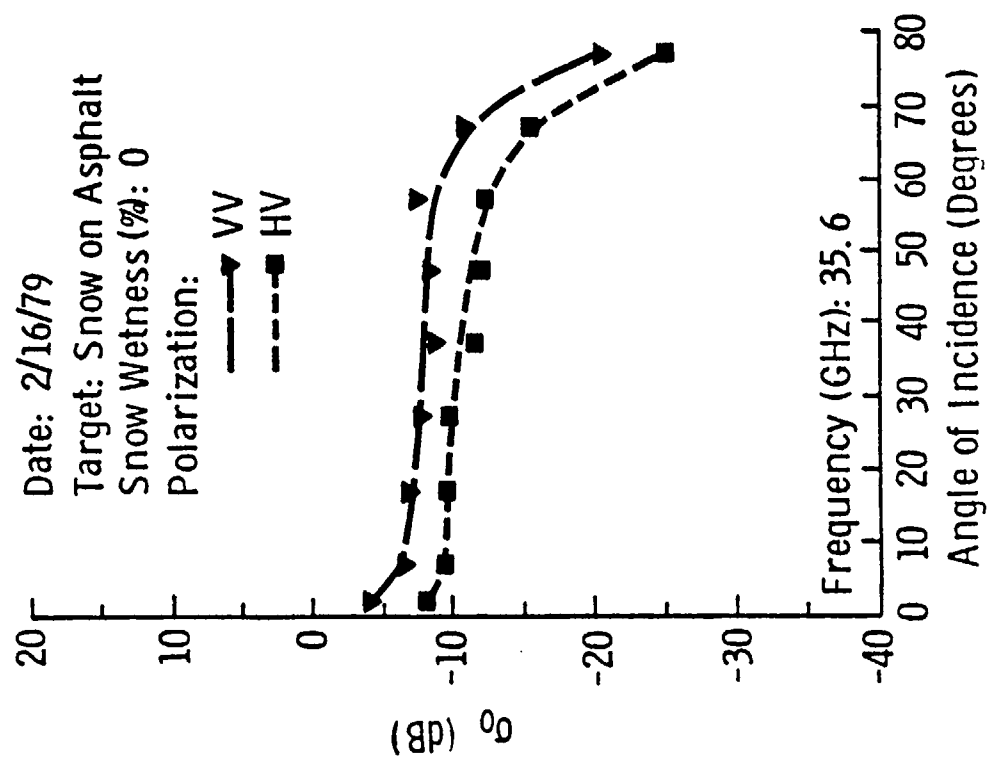
Wet Snow on Grass



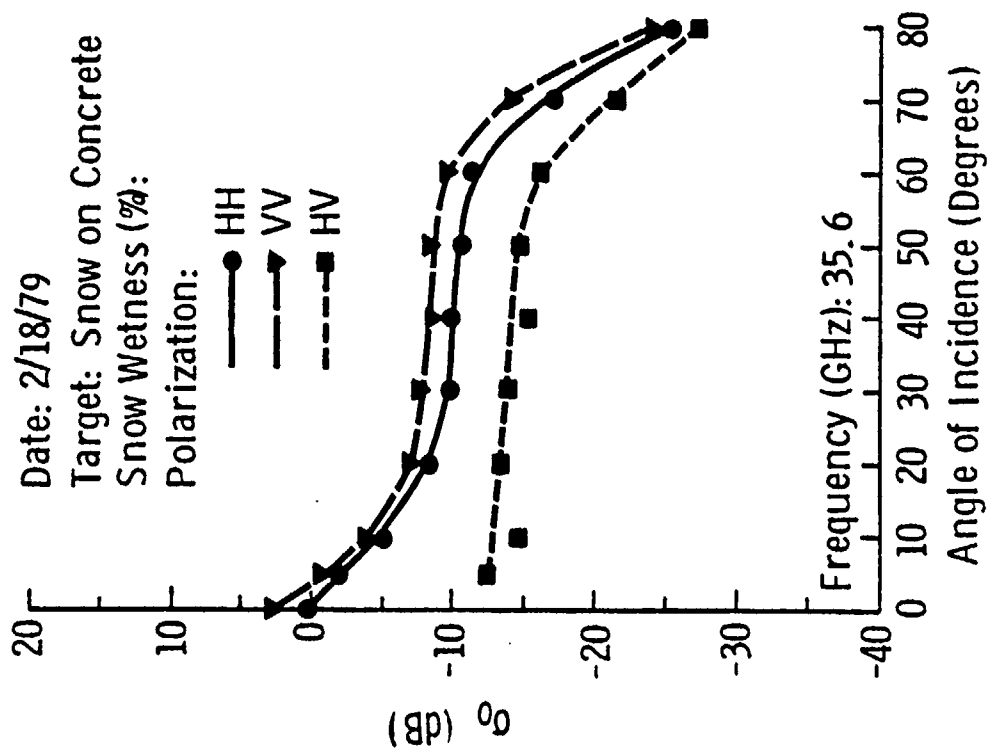
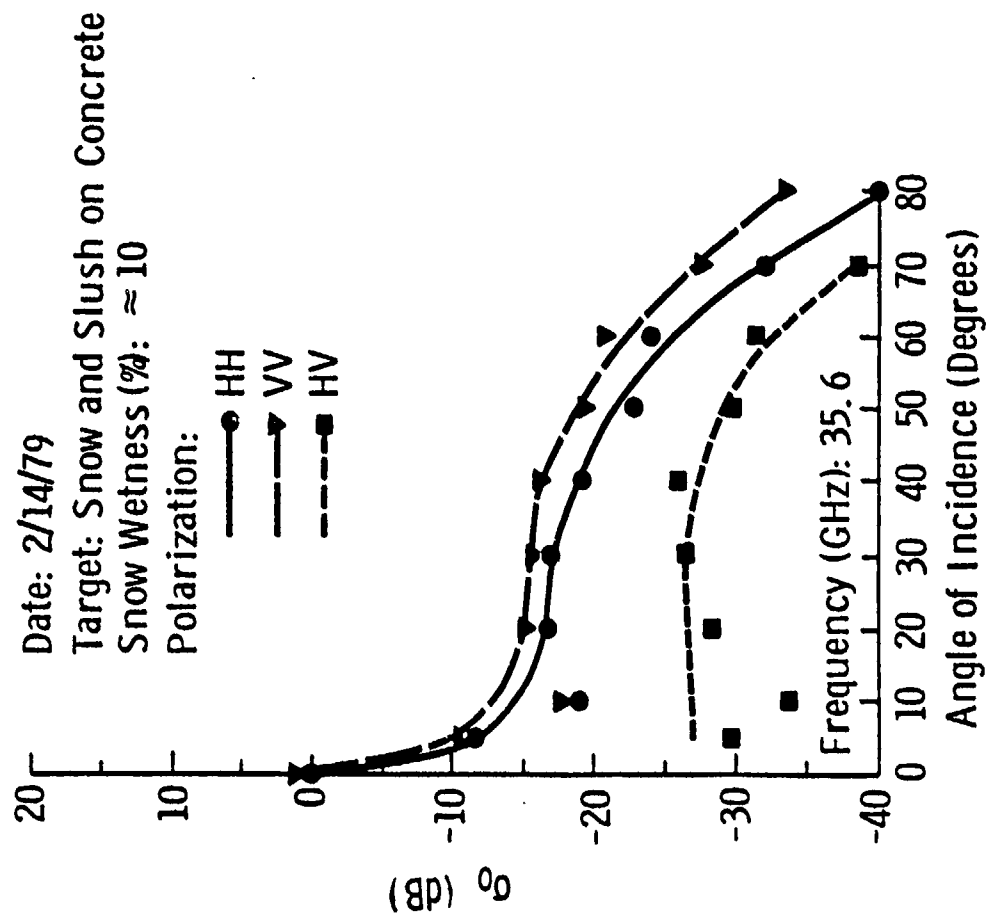
Dry Snow on Grass

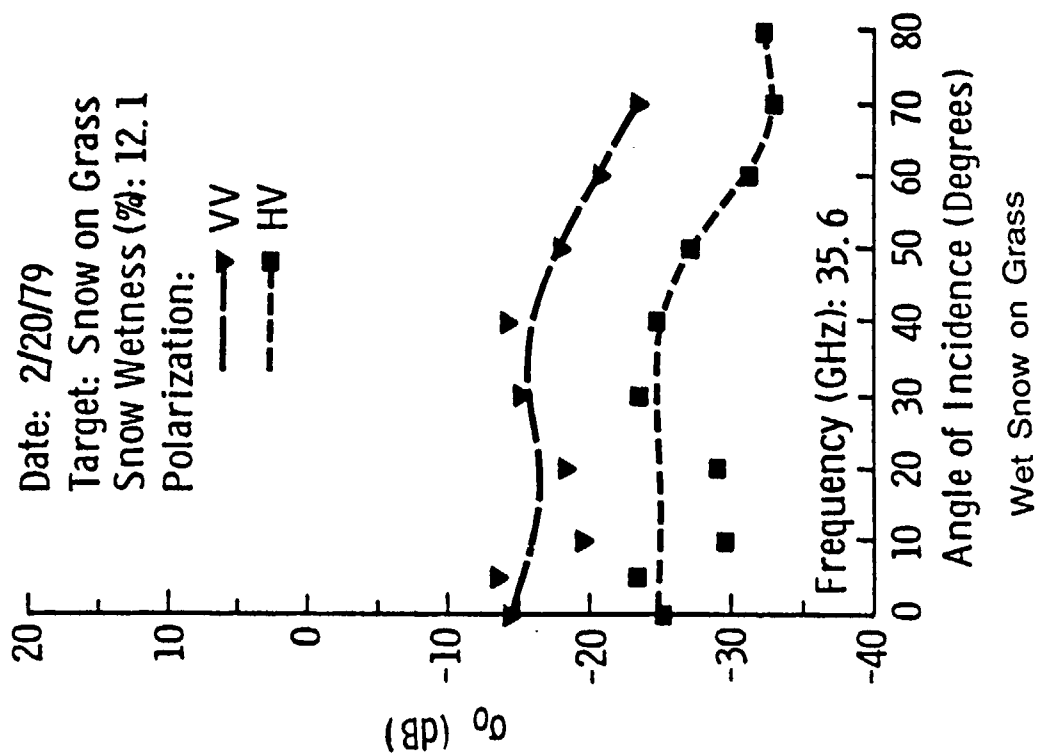
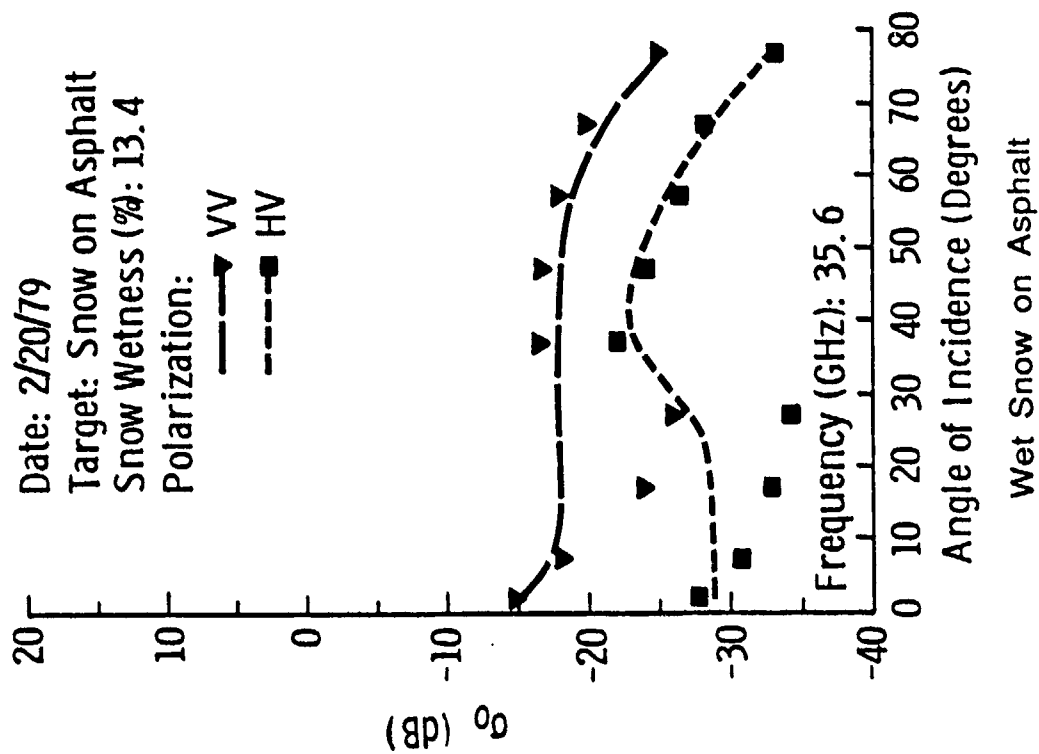


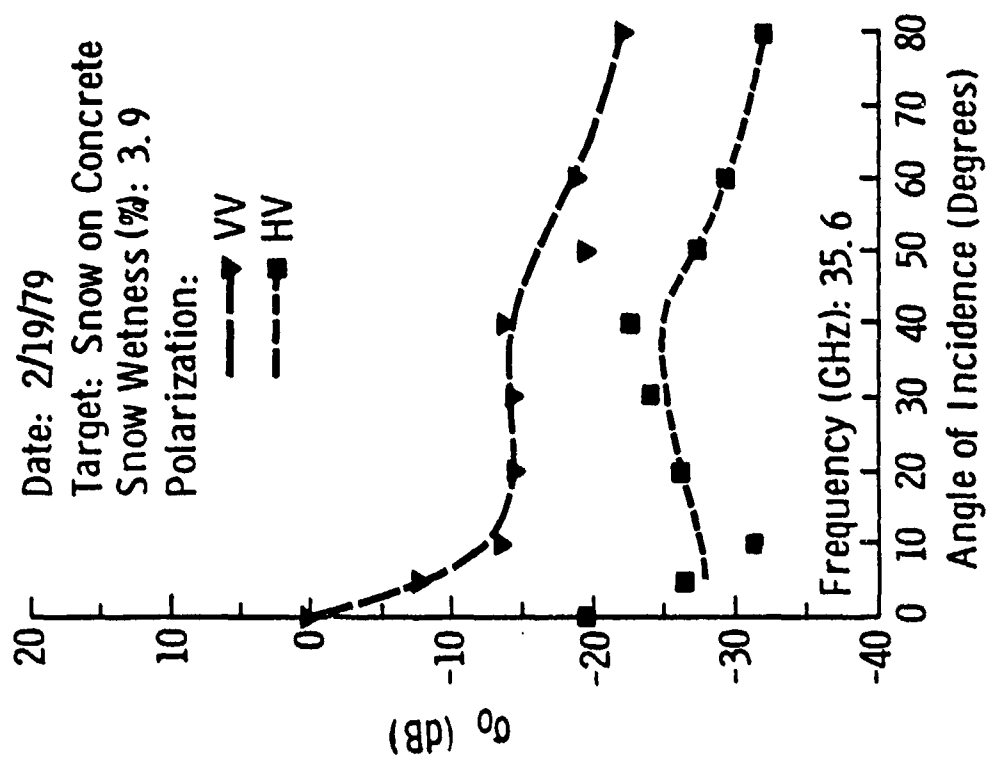
Wet Snow on Asphalt



Dry Snow on Asphalt







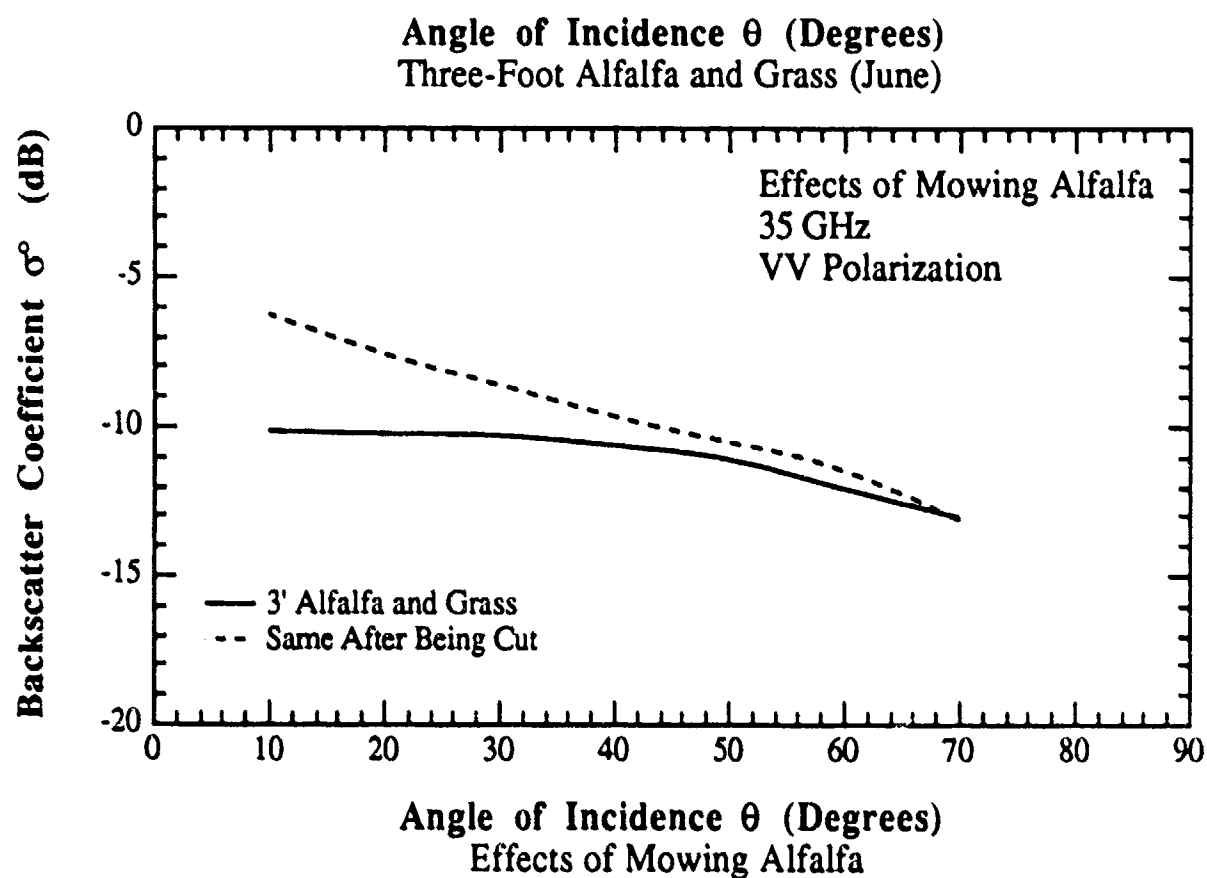
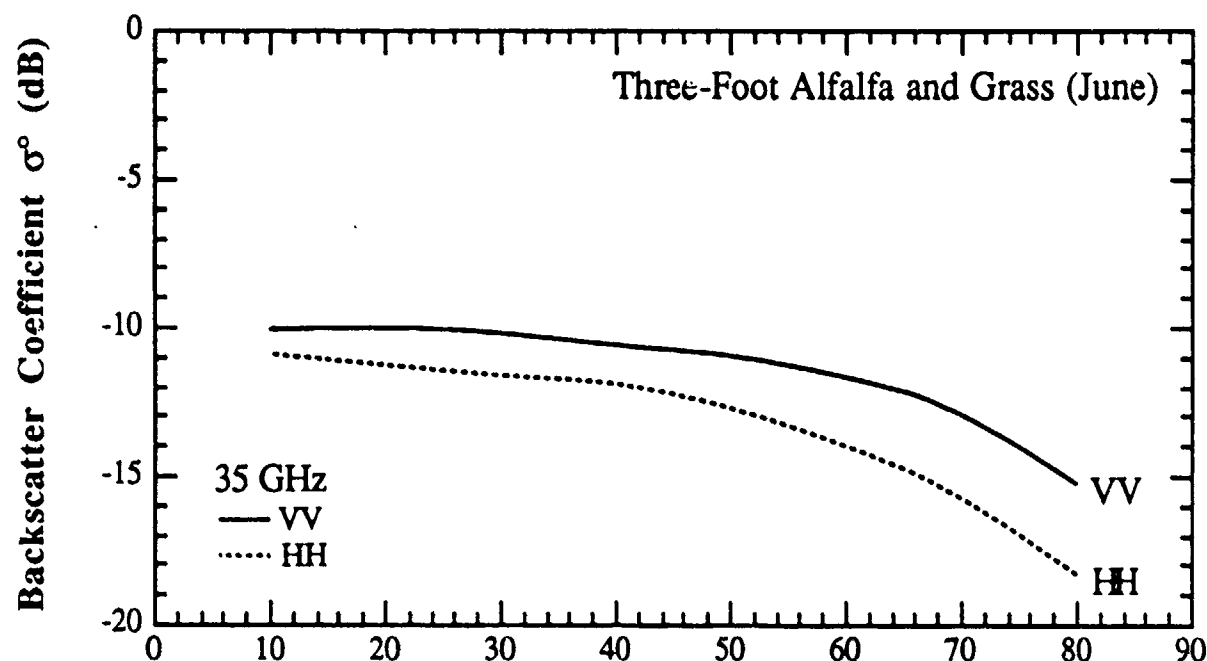
Wet Snow on Concrete

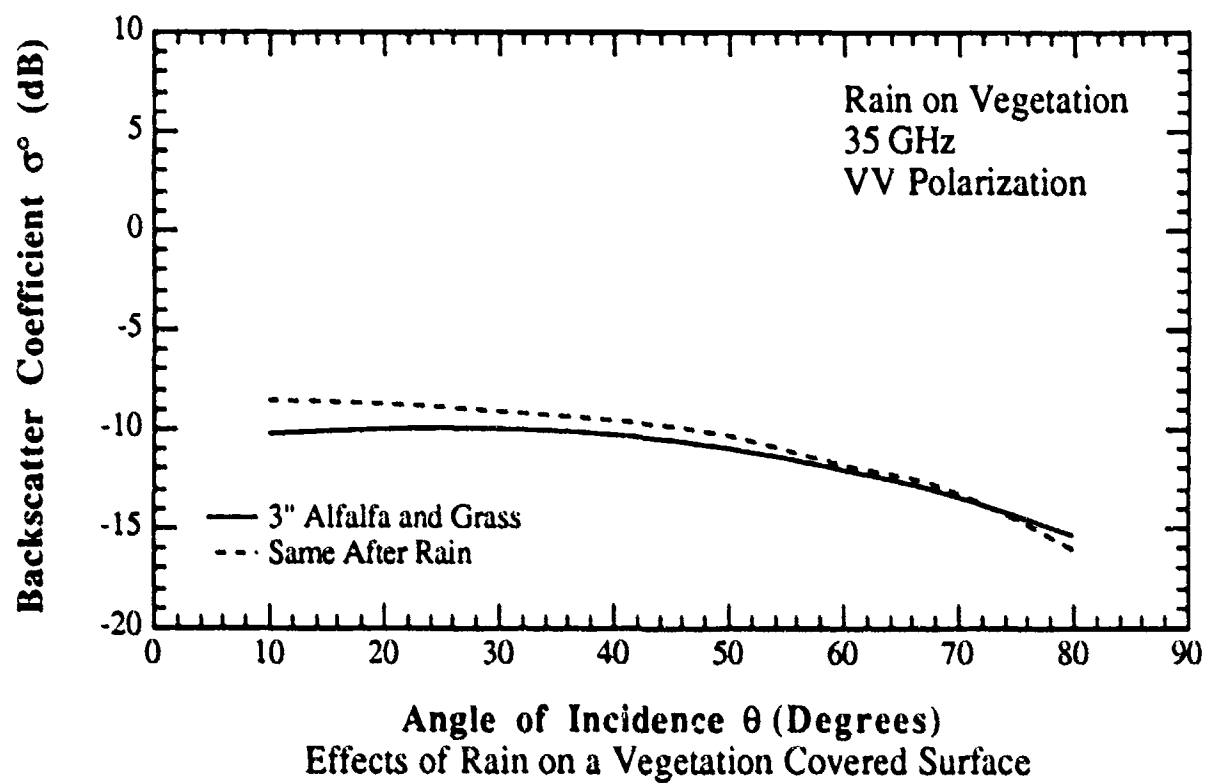
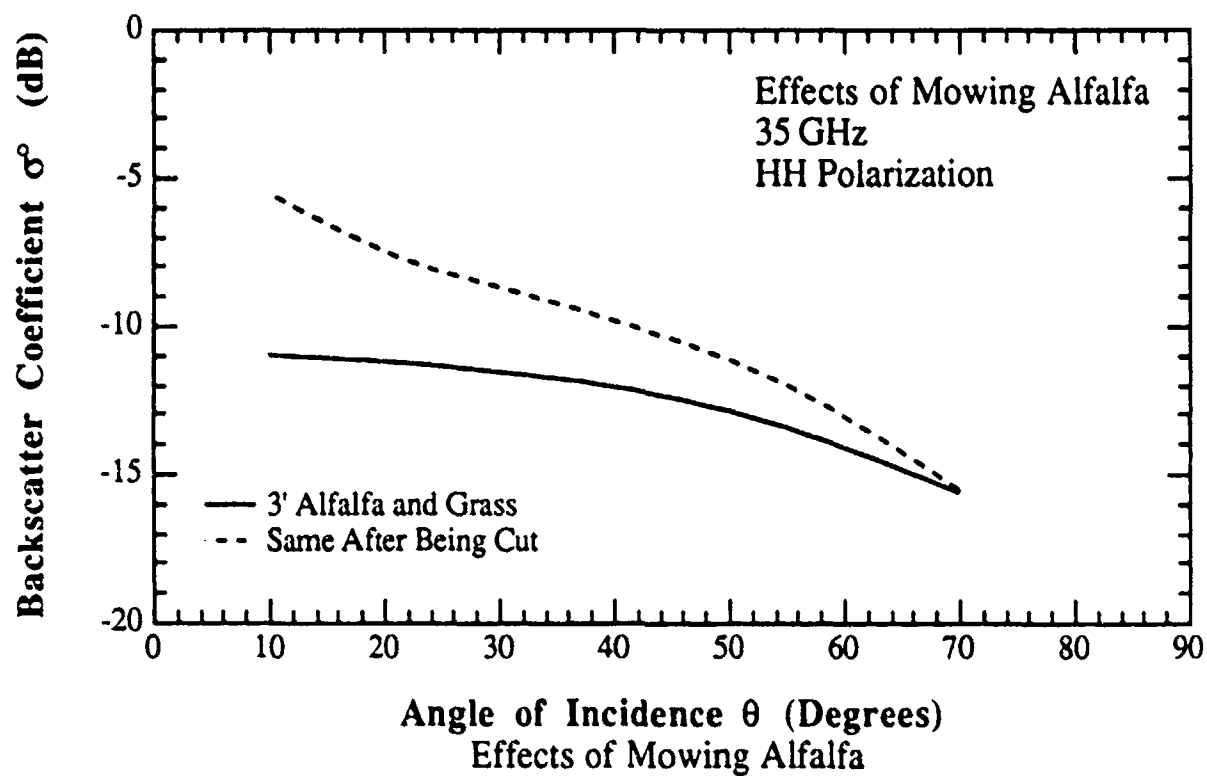
## PART IV. OHIO STATE UNIVERSITY DATA

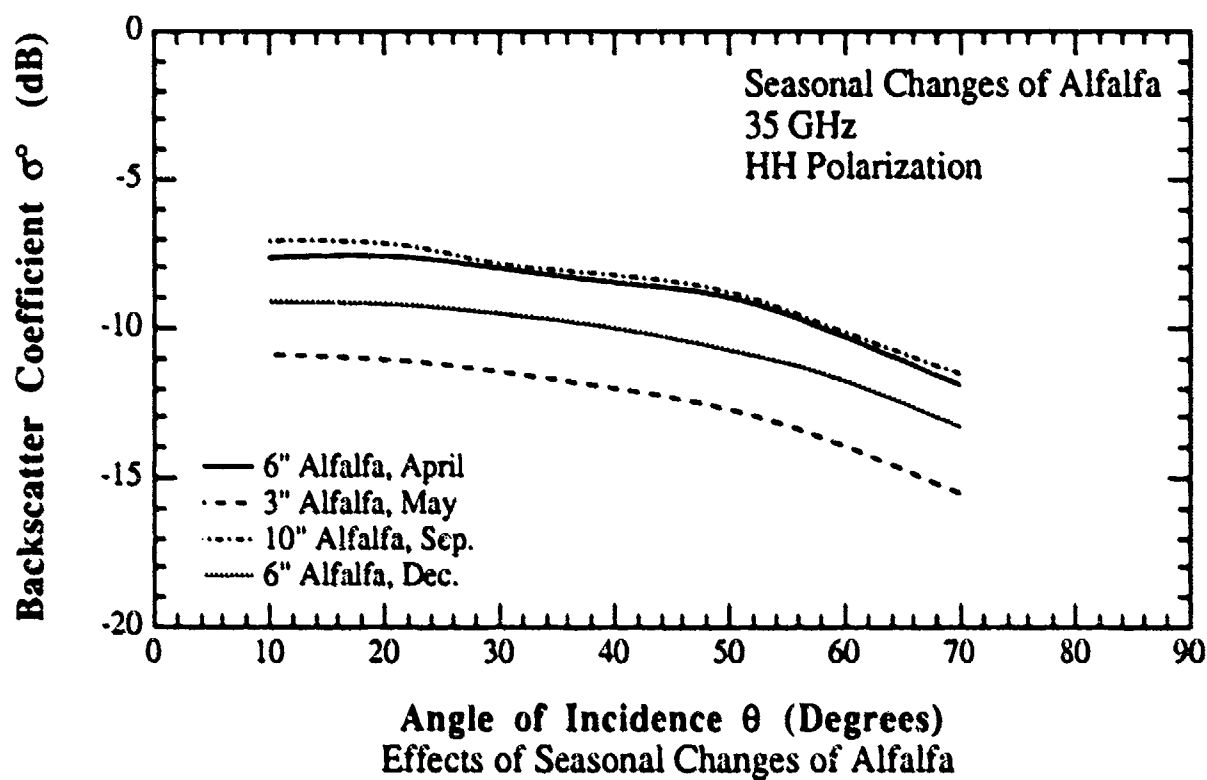
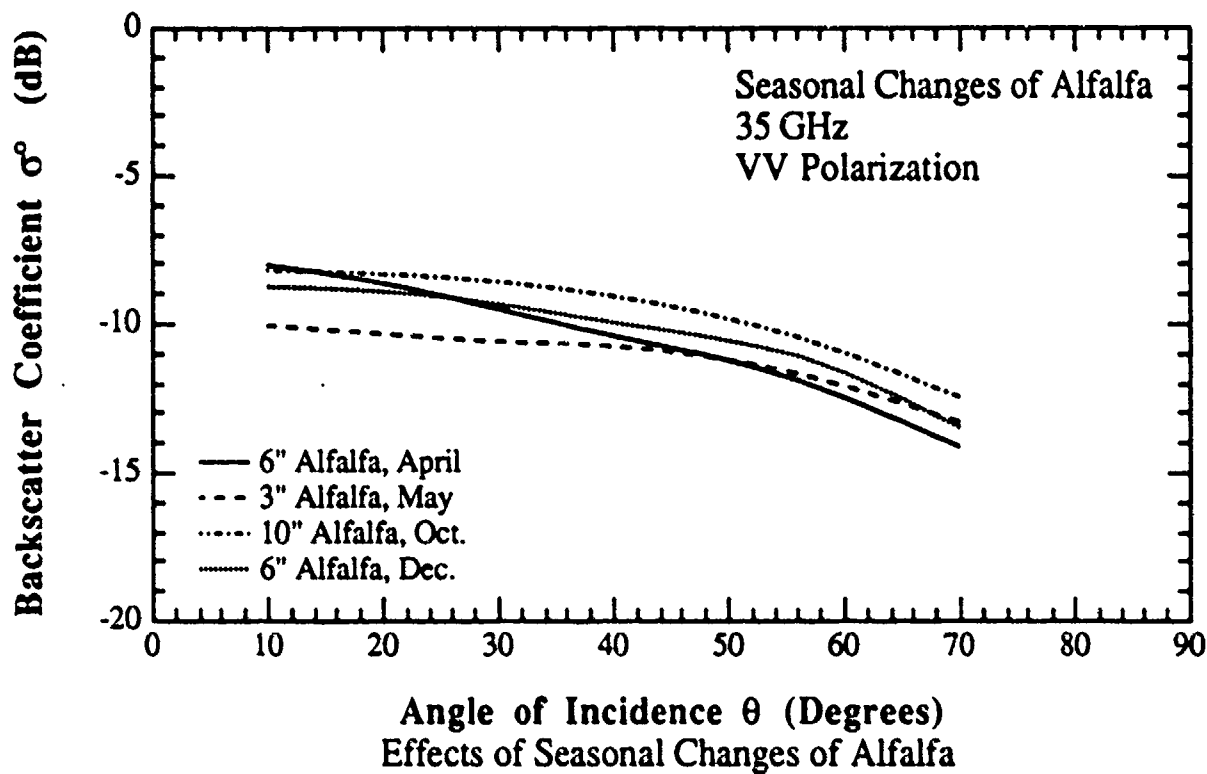
The Ohio State University data presented in this part of the Handbook were extracted from references [21] and [22]. In its original form, the data were presented in the form of plots of  $\gamma = \sigma^0 / \cos \theta$  versus the depression angle  $\theta' = 90^\circ - \theta$ . All data were converted to  $\sigma^0$  versus the incidence angle  $\theta$ . Moreover, for data measured prior to 1960, which includes all the data reported in the Terrain Handbook II [21] issued by OSU in May, 1960, the level of the data was off by about 6 dB due to a recorder calibration error. As noted in the article by Bush and Ulaby [27] and confirmed by Peake (one of the principal authors of the OSU reports) in the same article, the level of  $\sigma^0$  should be increased by 5-7 dB. Hence, all OSU data measured prior to 1960 has been increased in level by 6 dB in this Handbook.

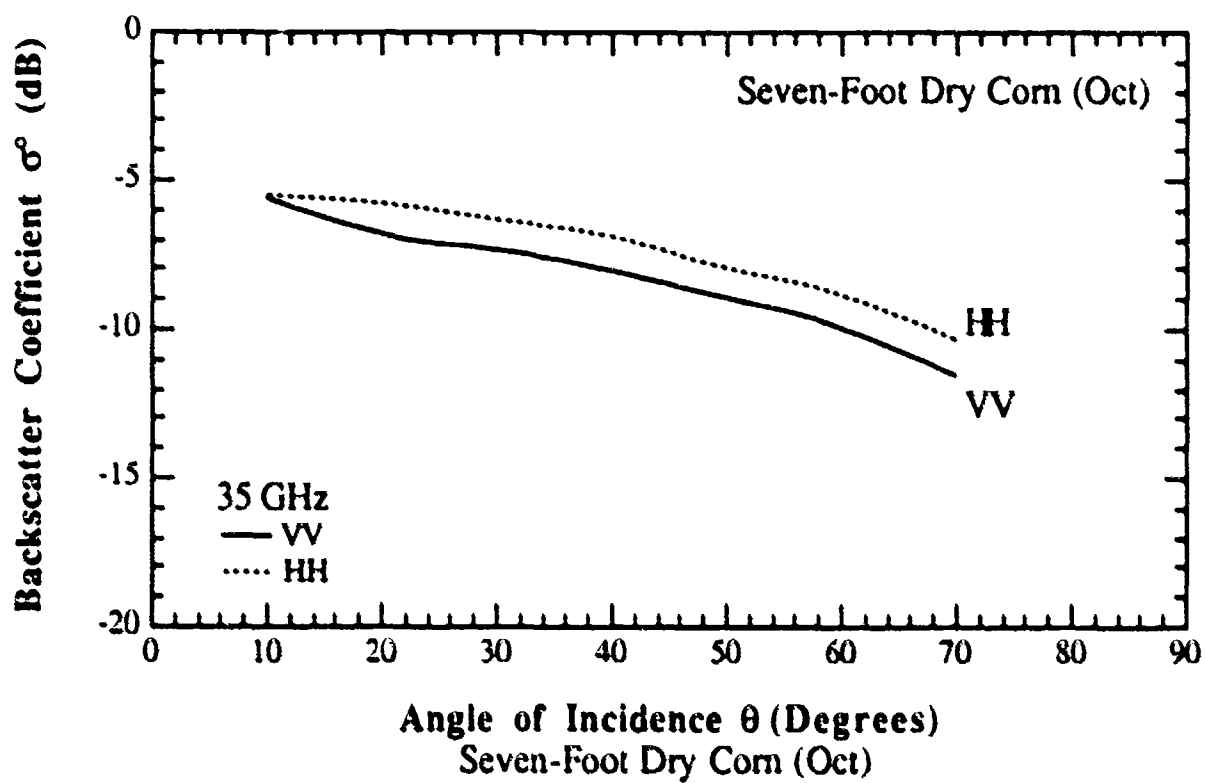
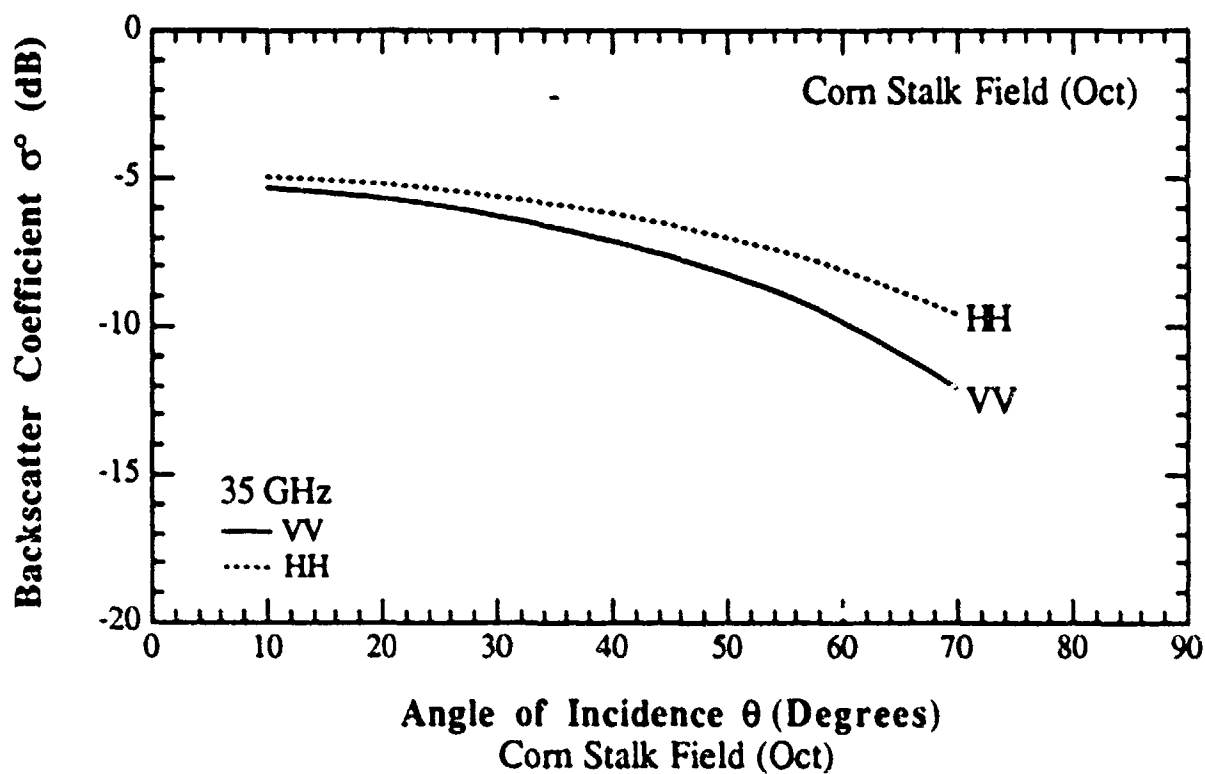
The OSU measurement program used a truck-mounted CW-Doppler radar to measure the backscatter as a function of incidence angle at 10, 15, and 35 GHz. Only the 35 GHz data is presented in this Handbook.

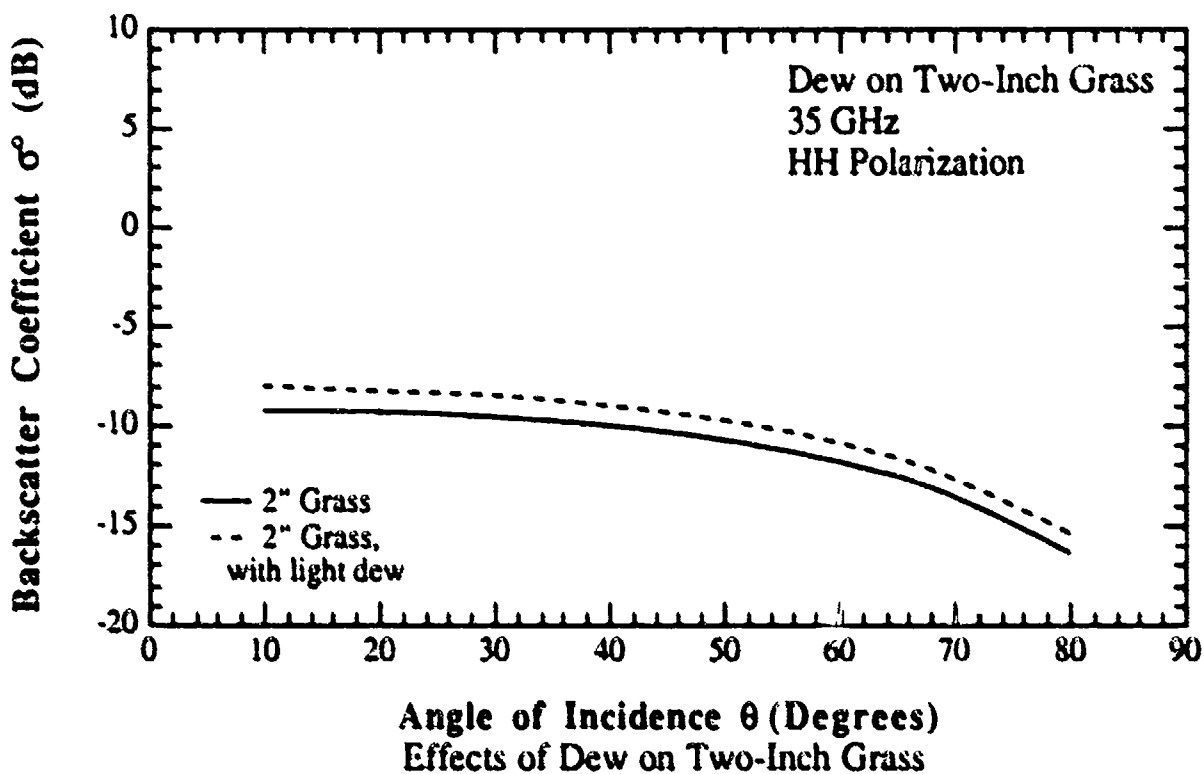
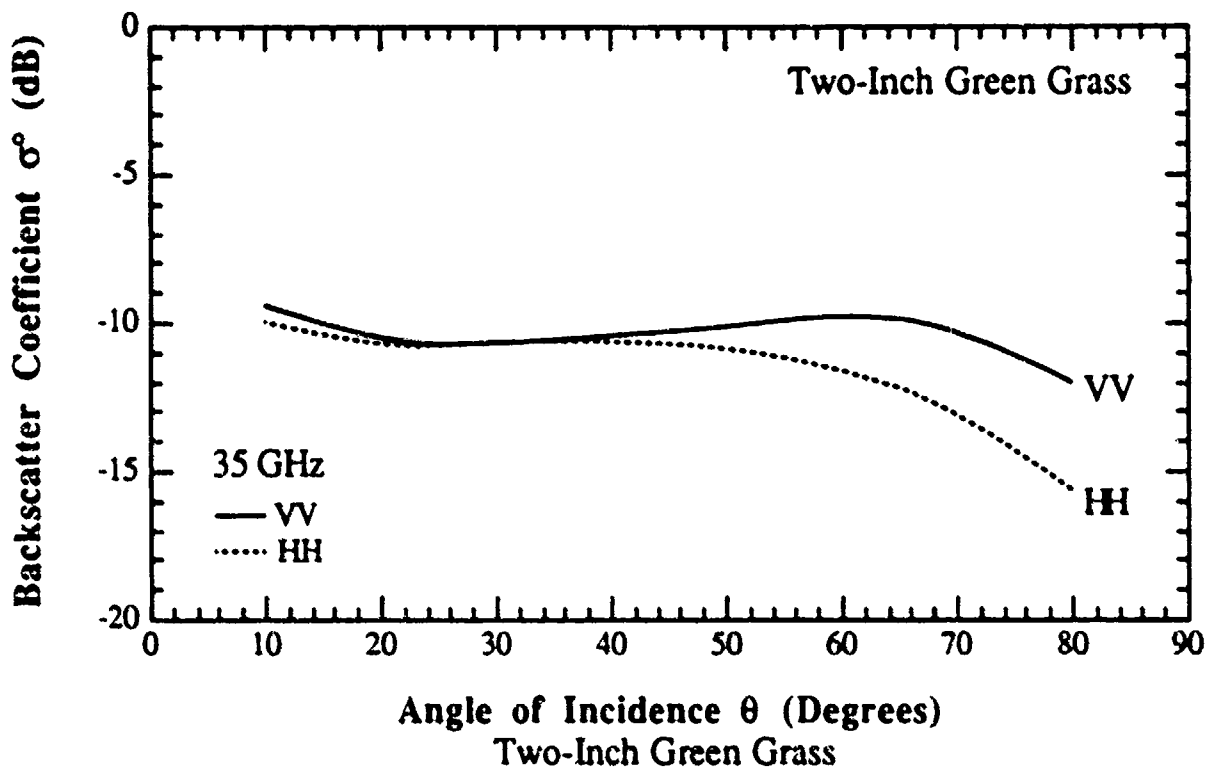
# 14. 35 GHz DATA FOR VEGETATION

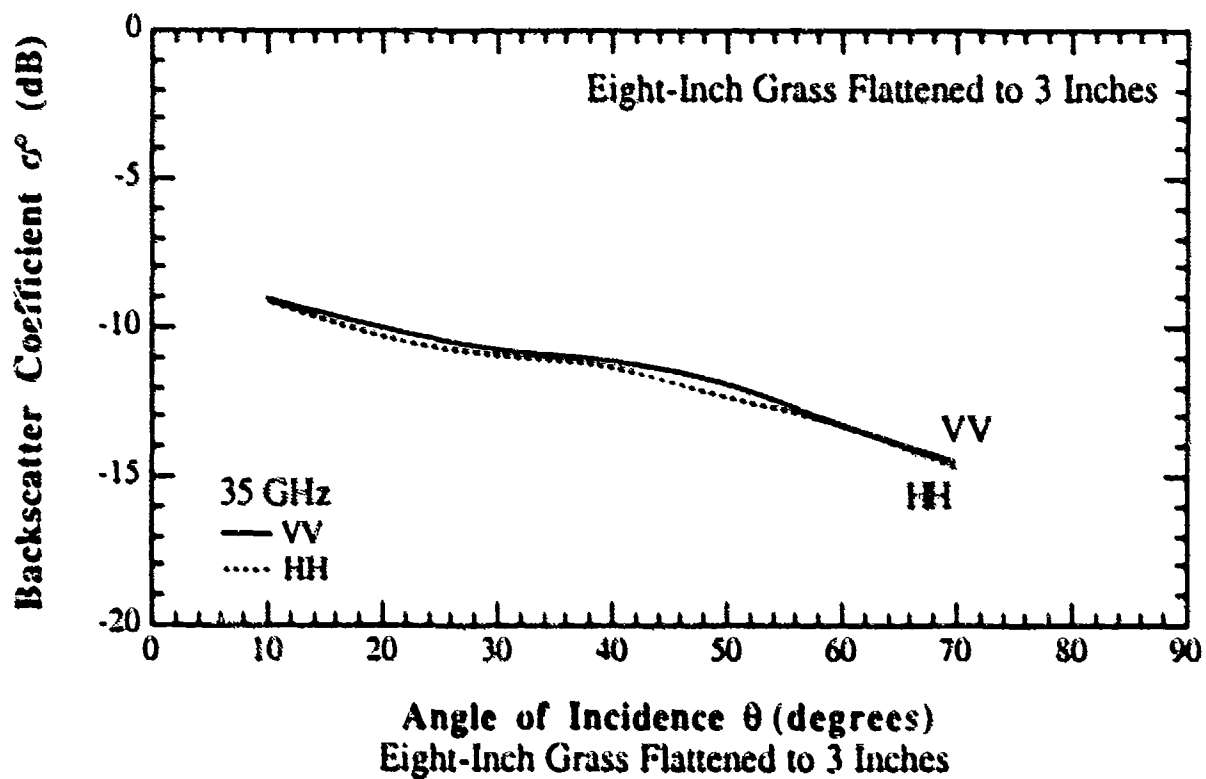
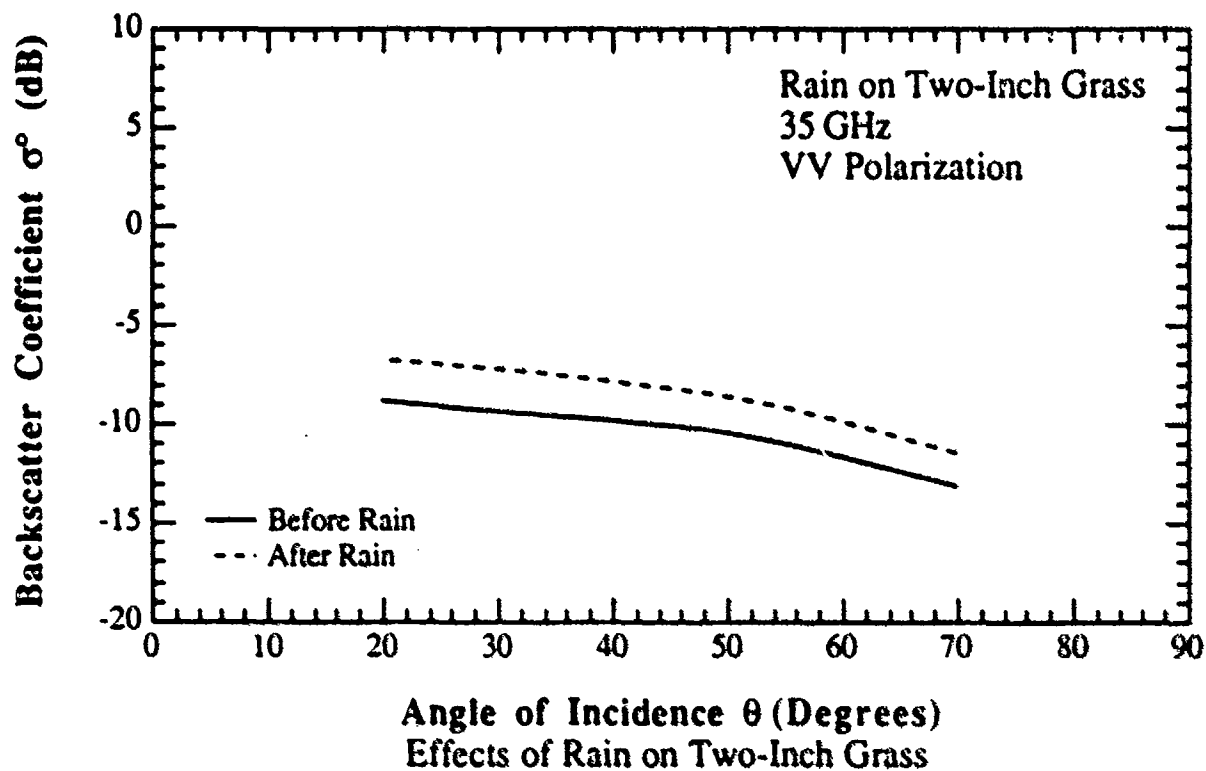


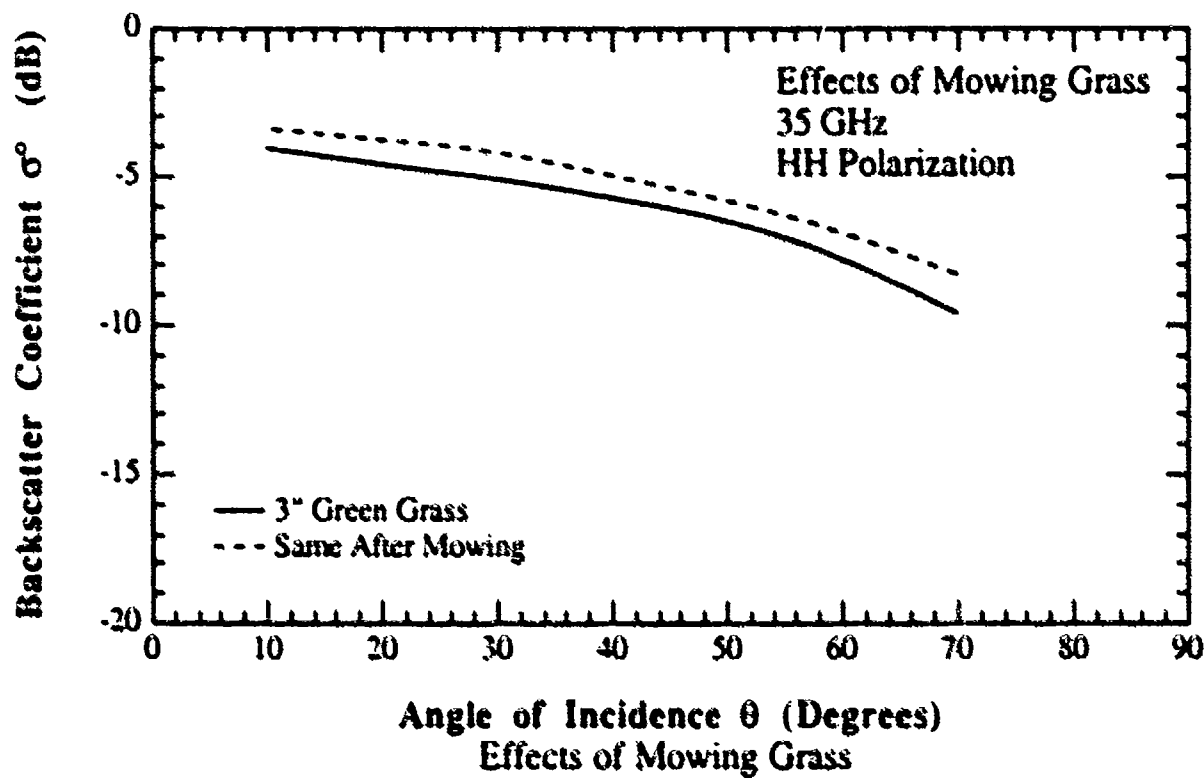
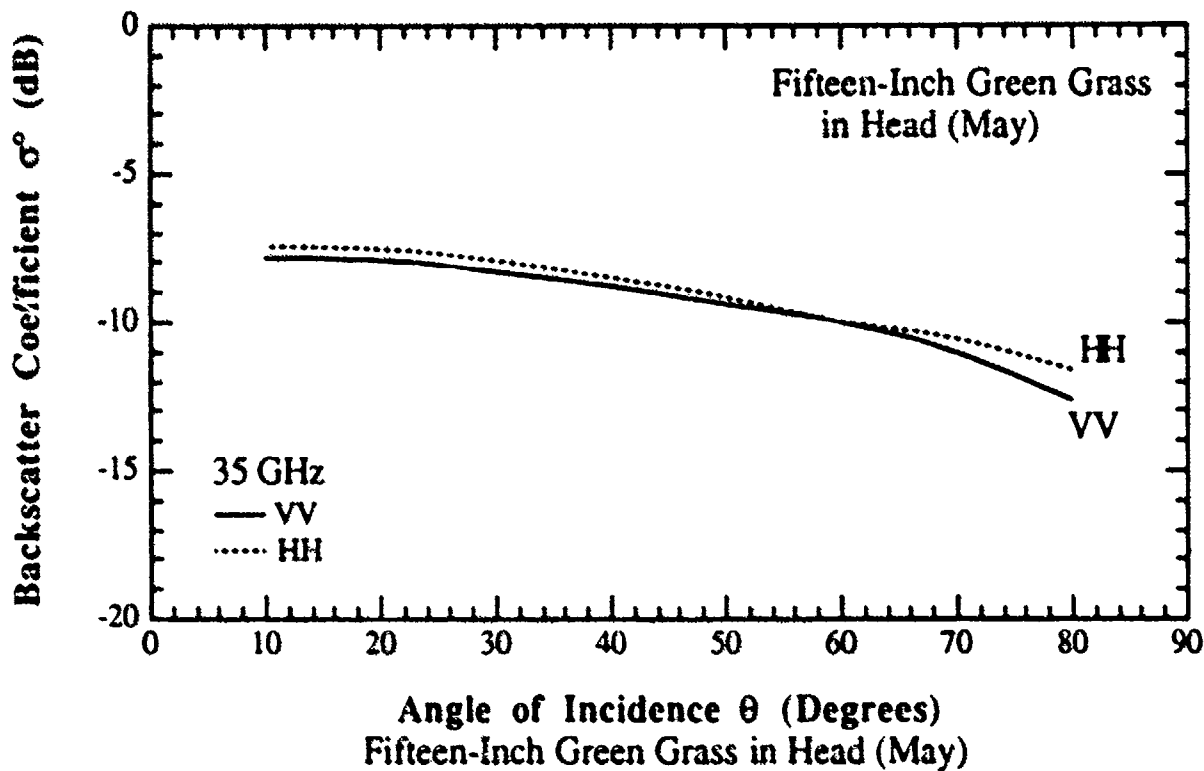


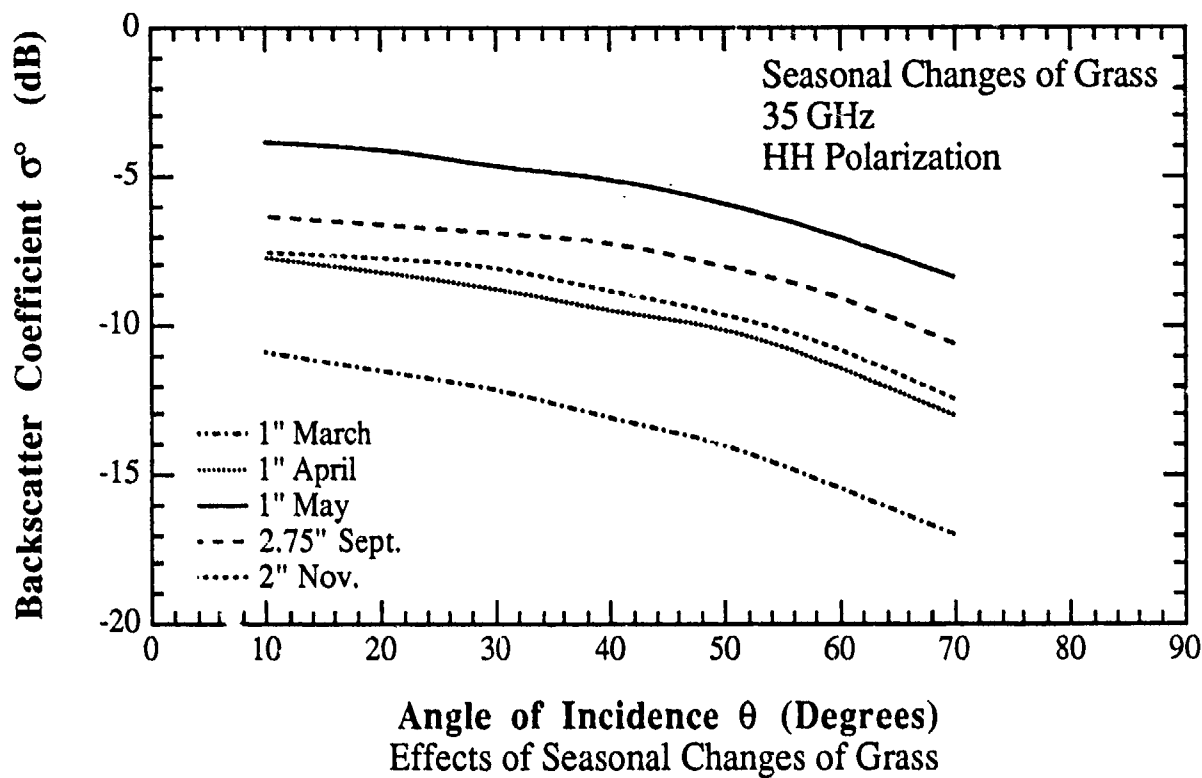
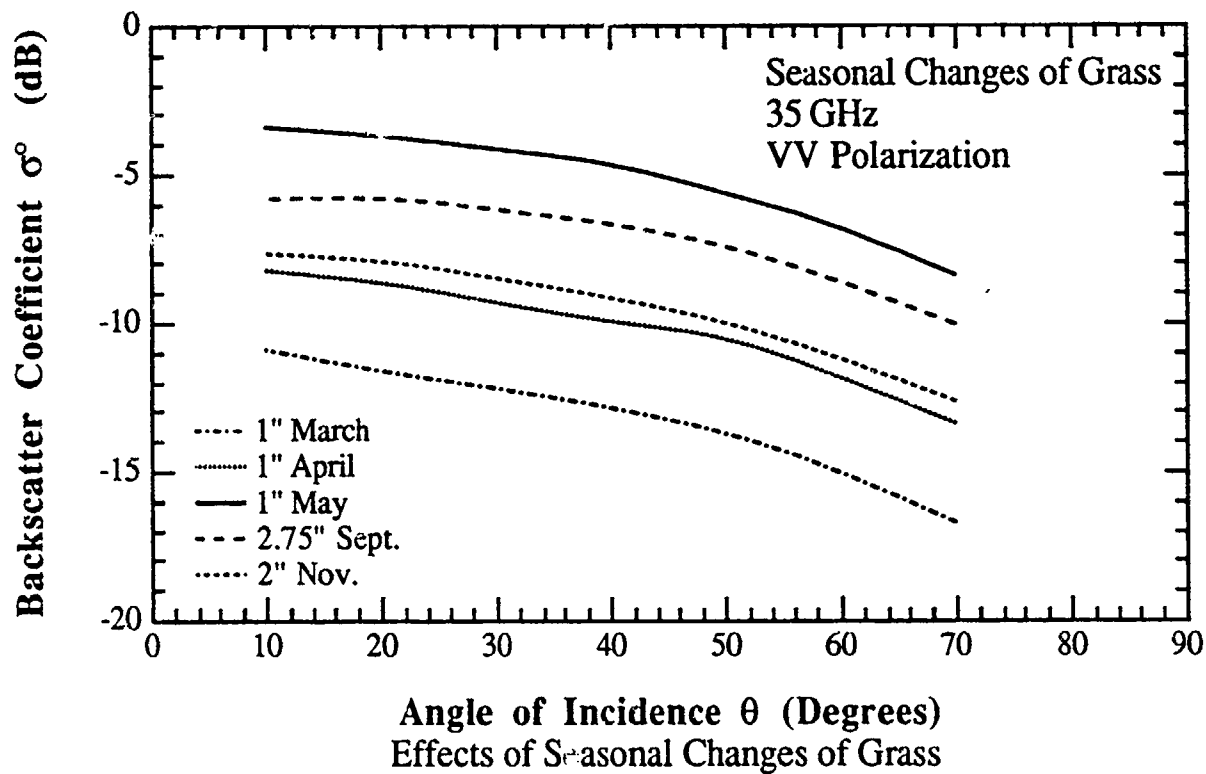


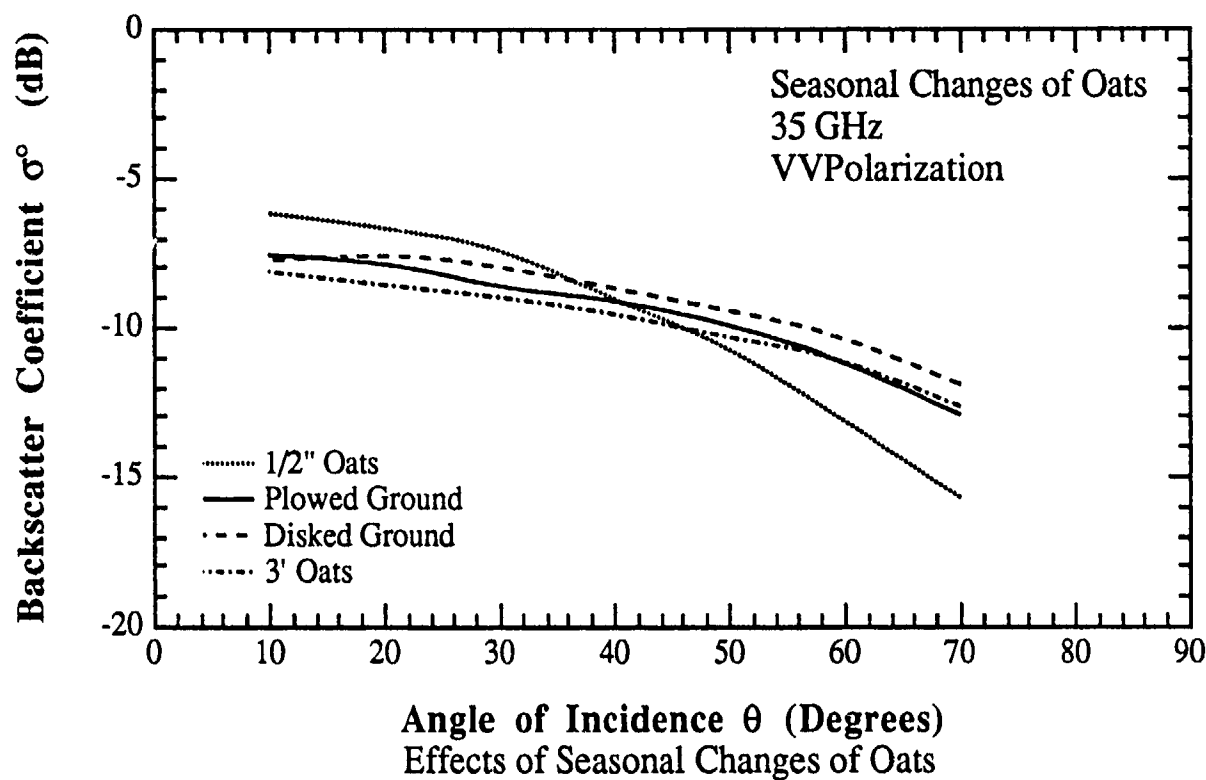
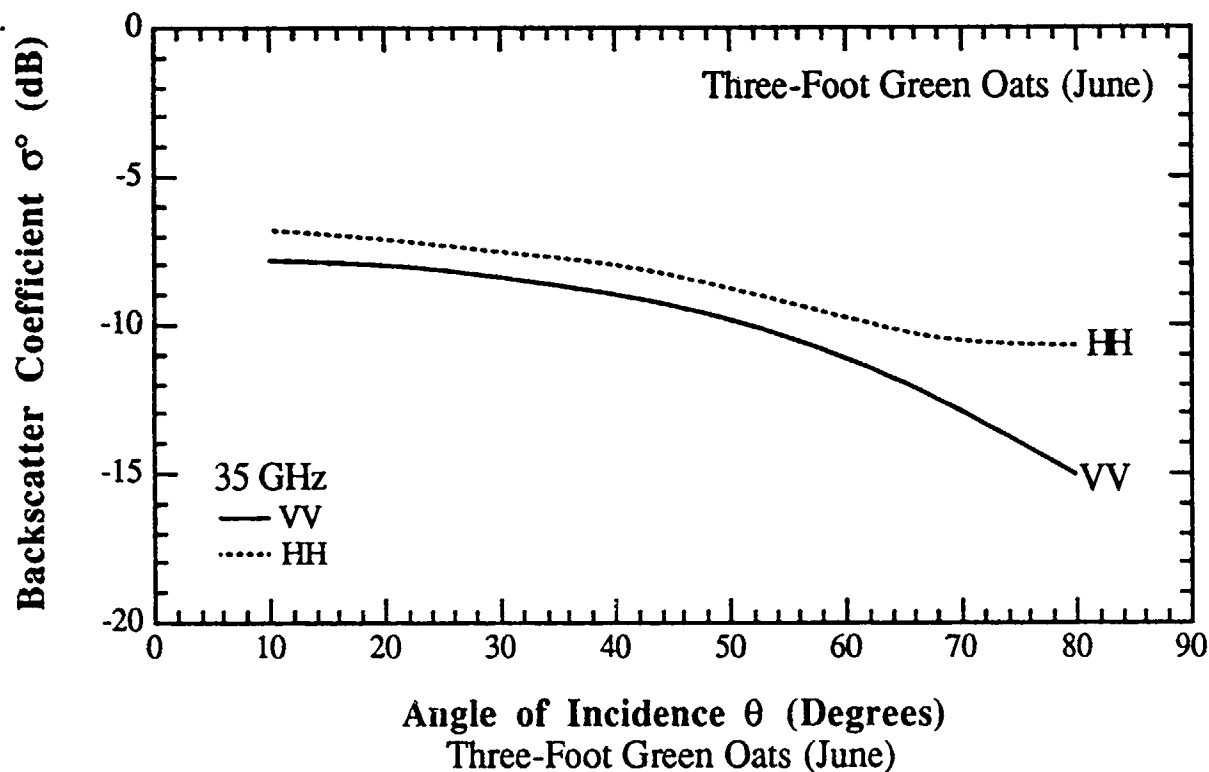


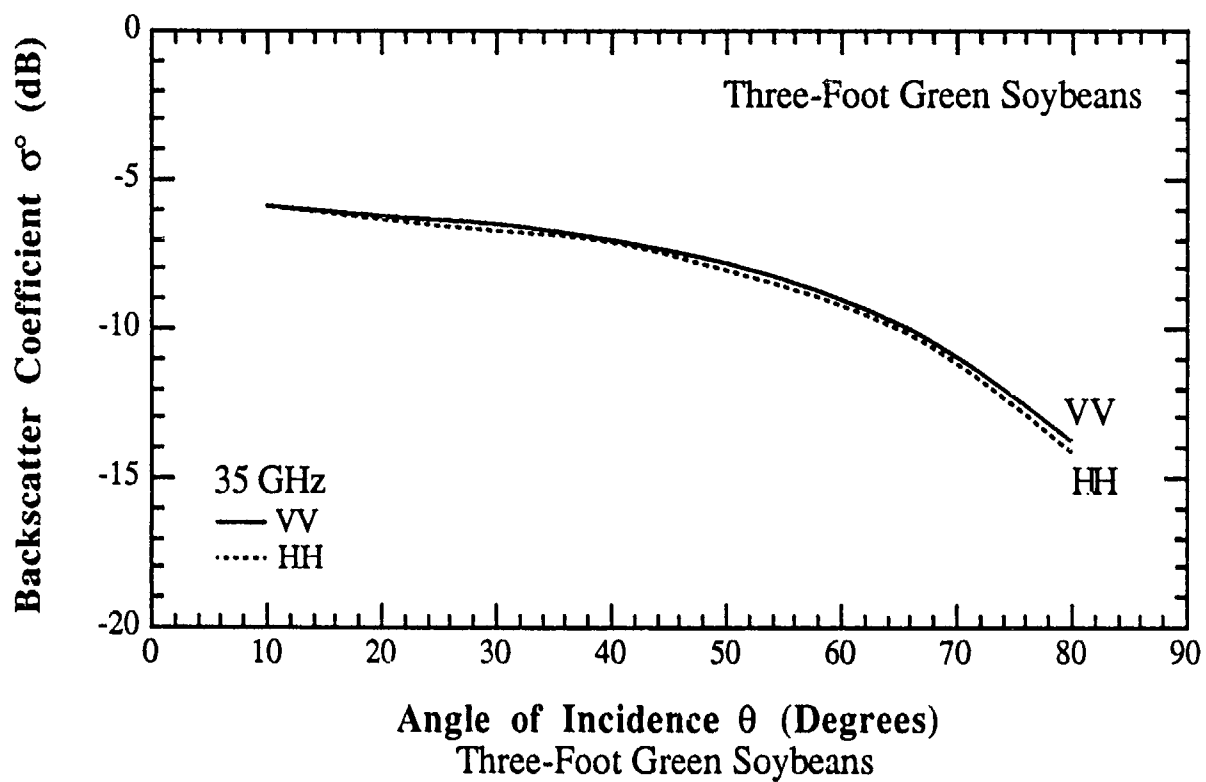
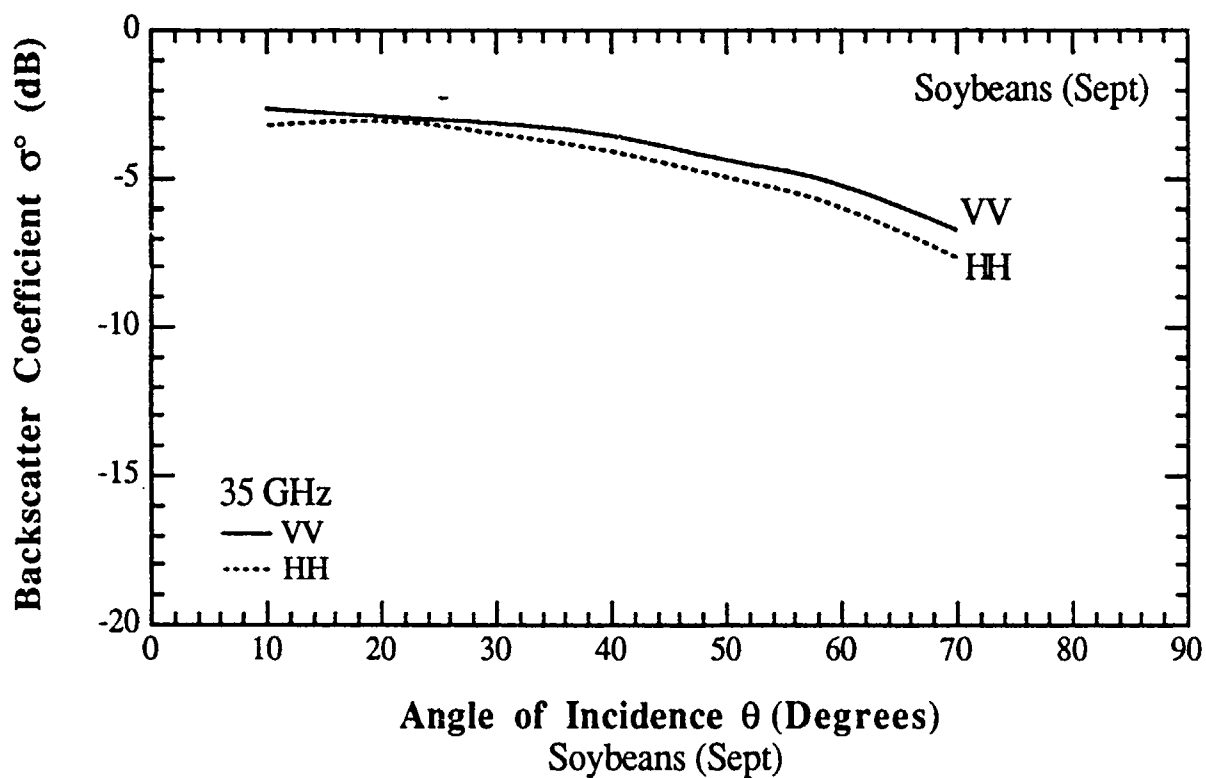


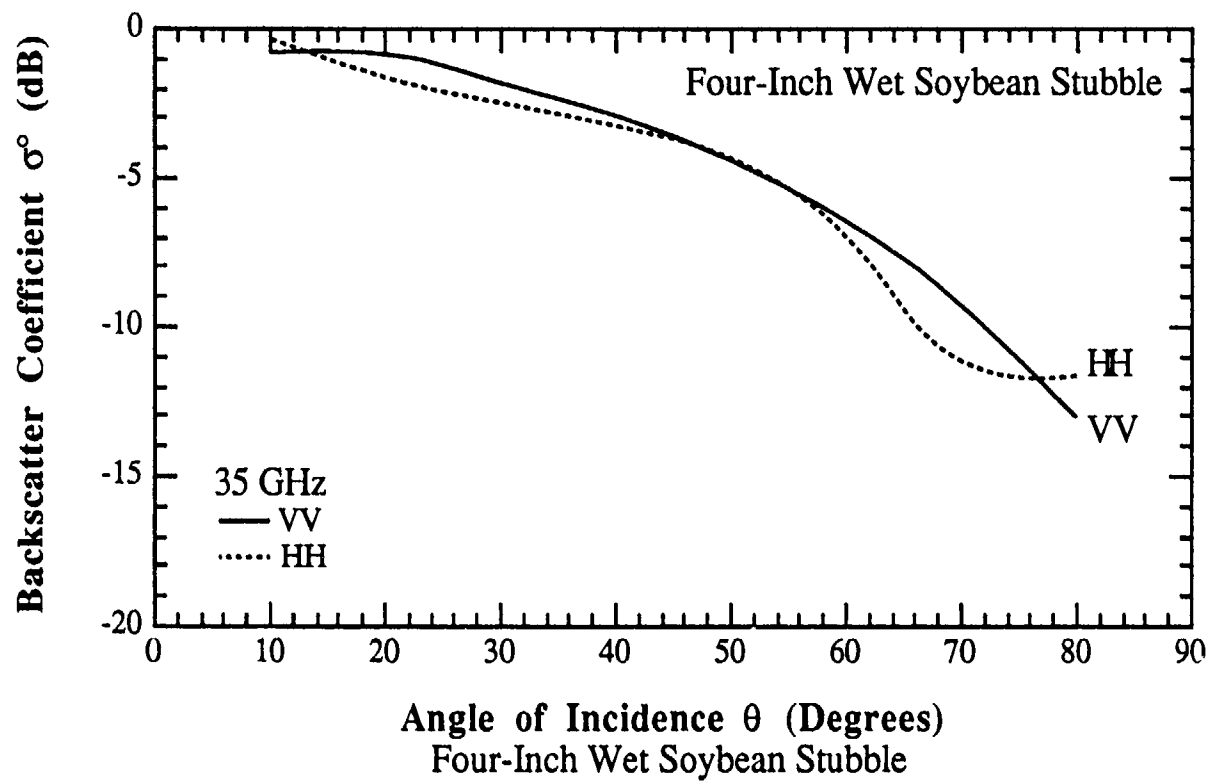
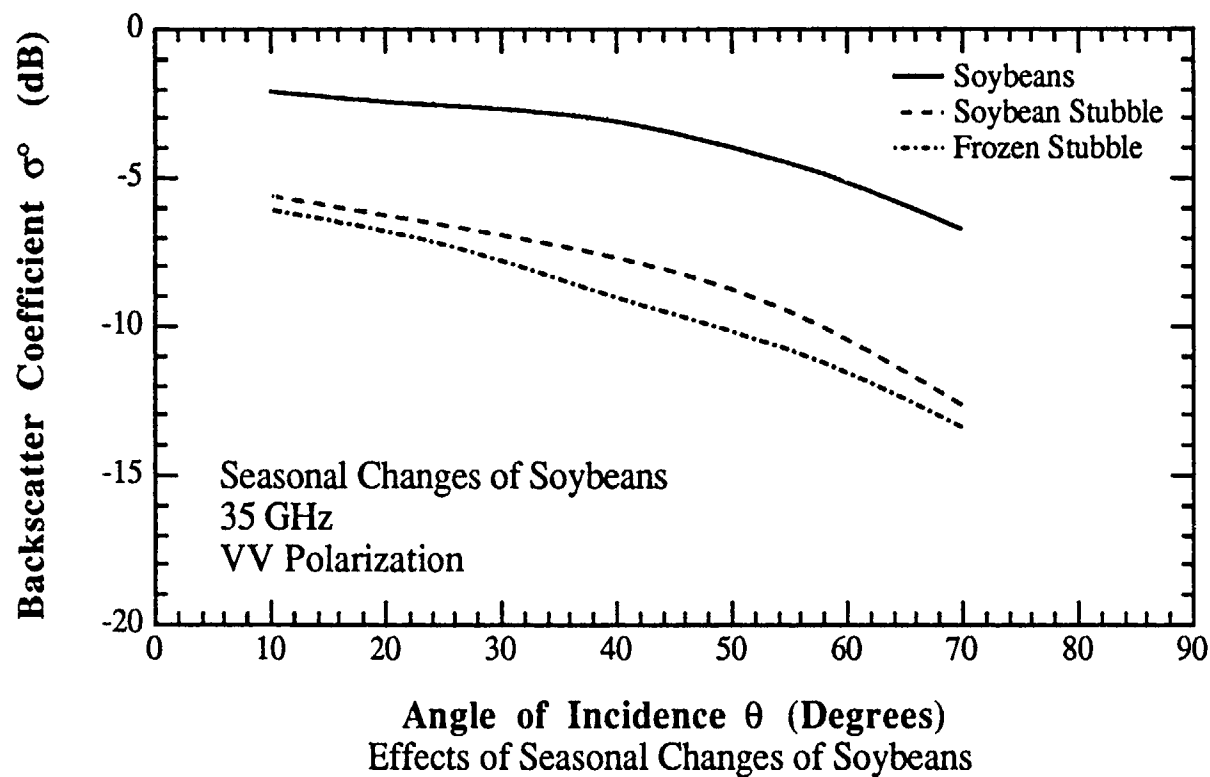


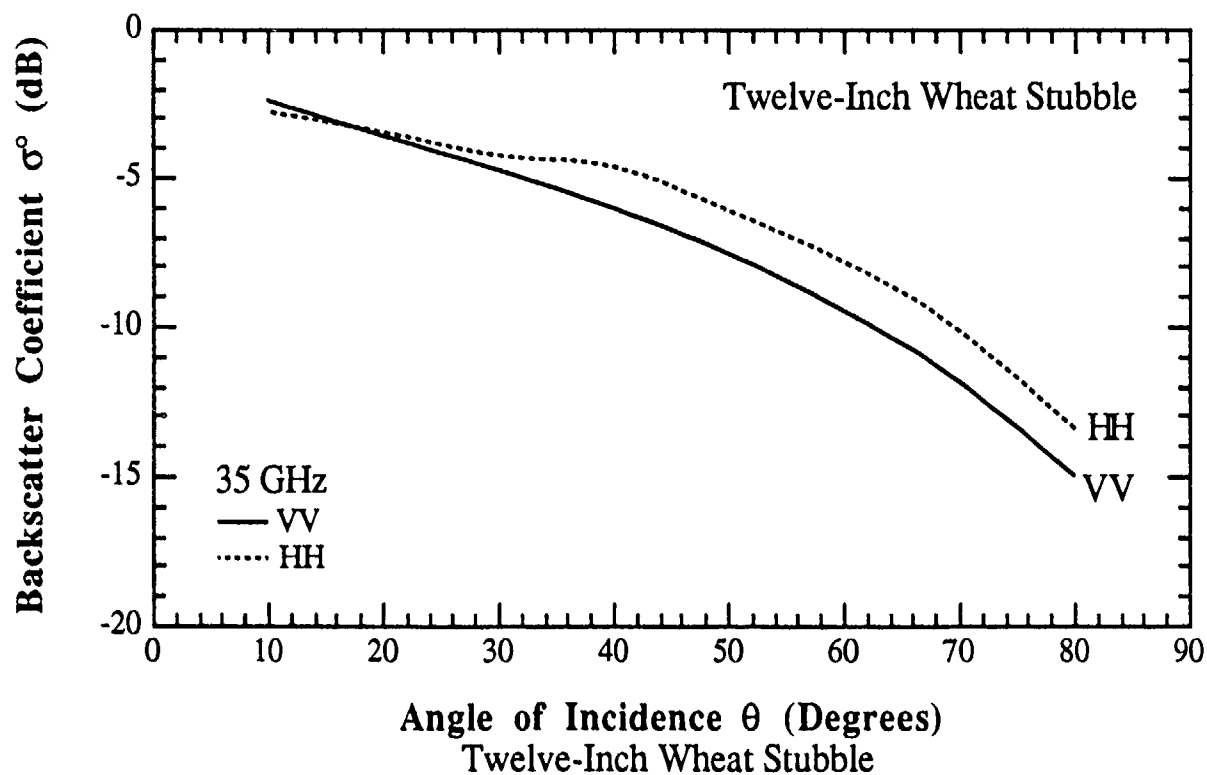
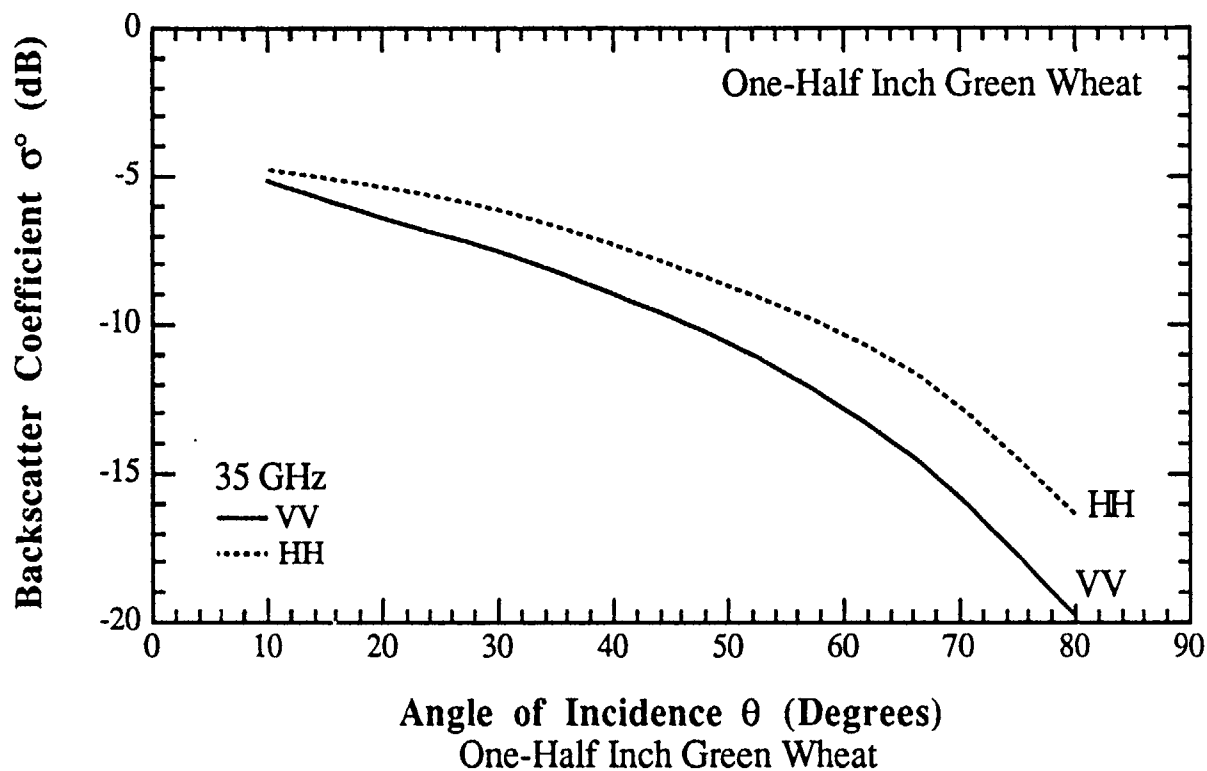


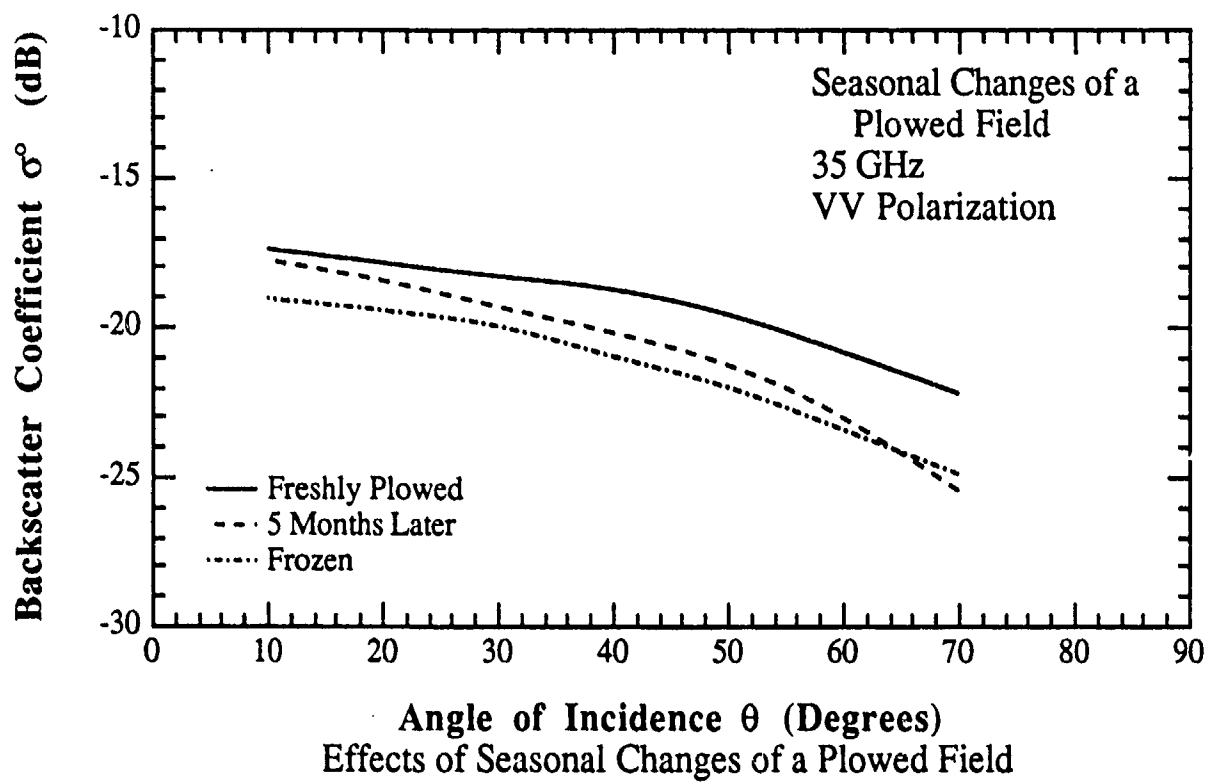
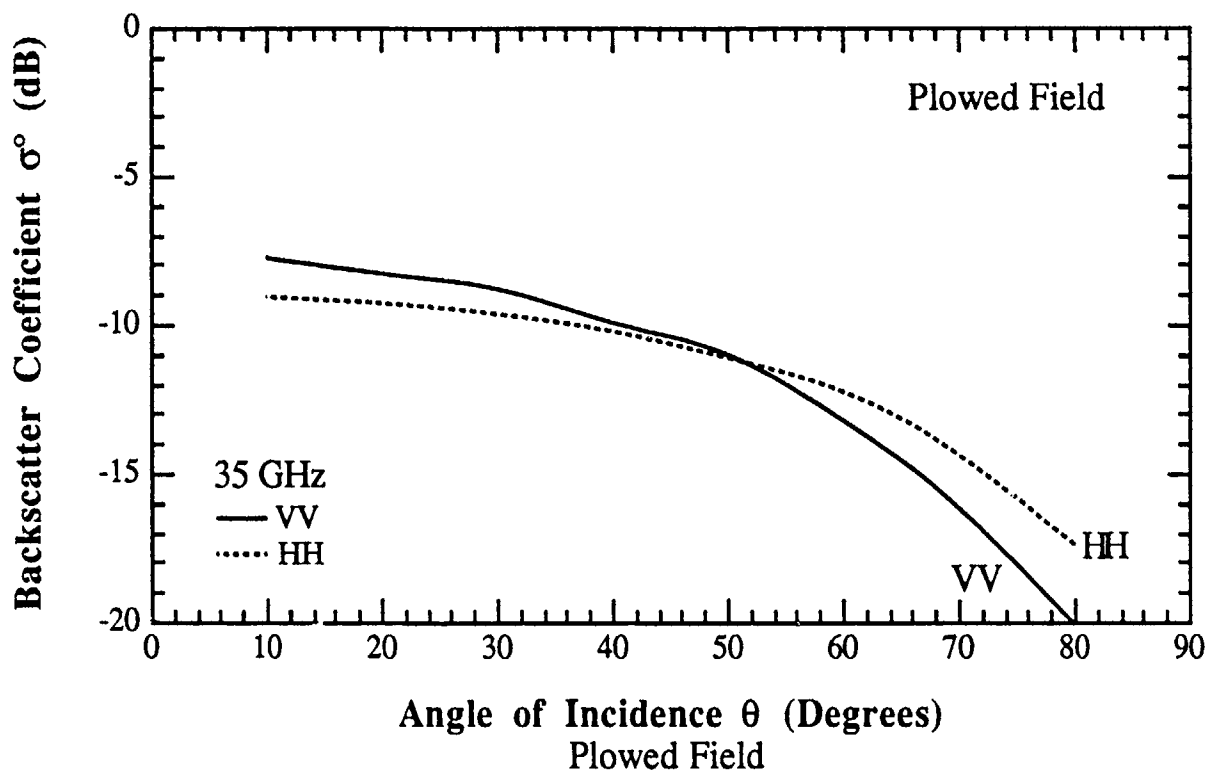






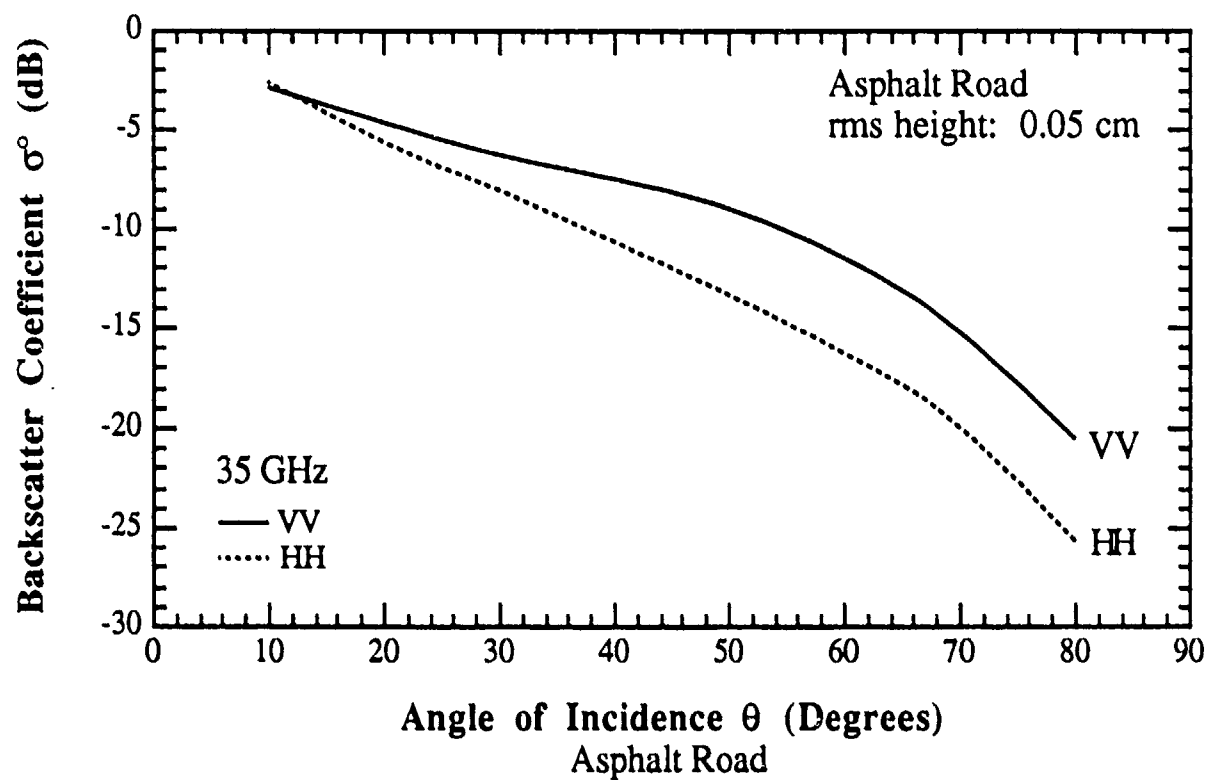
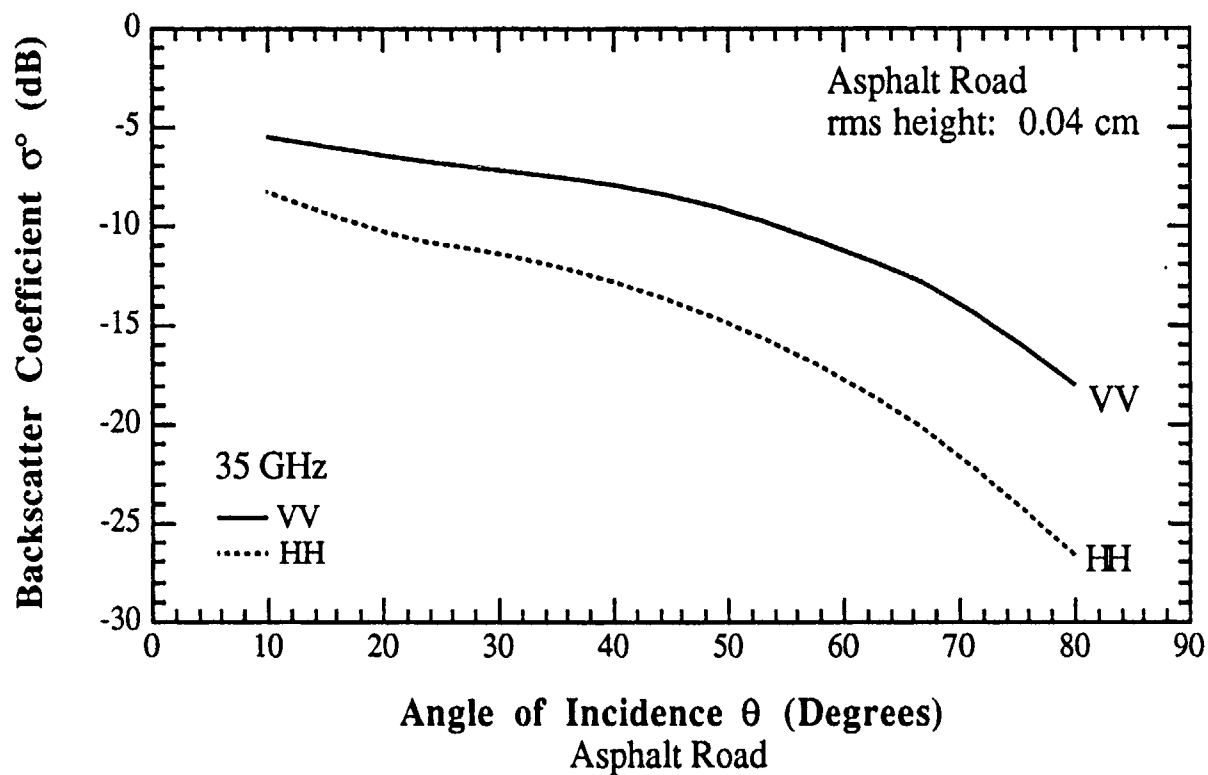


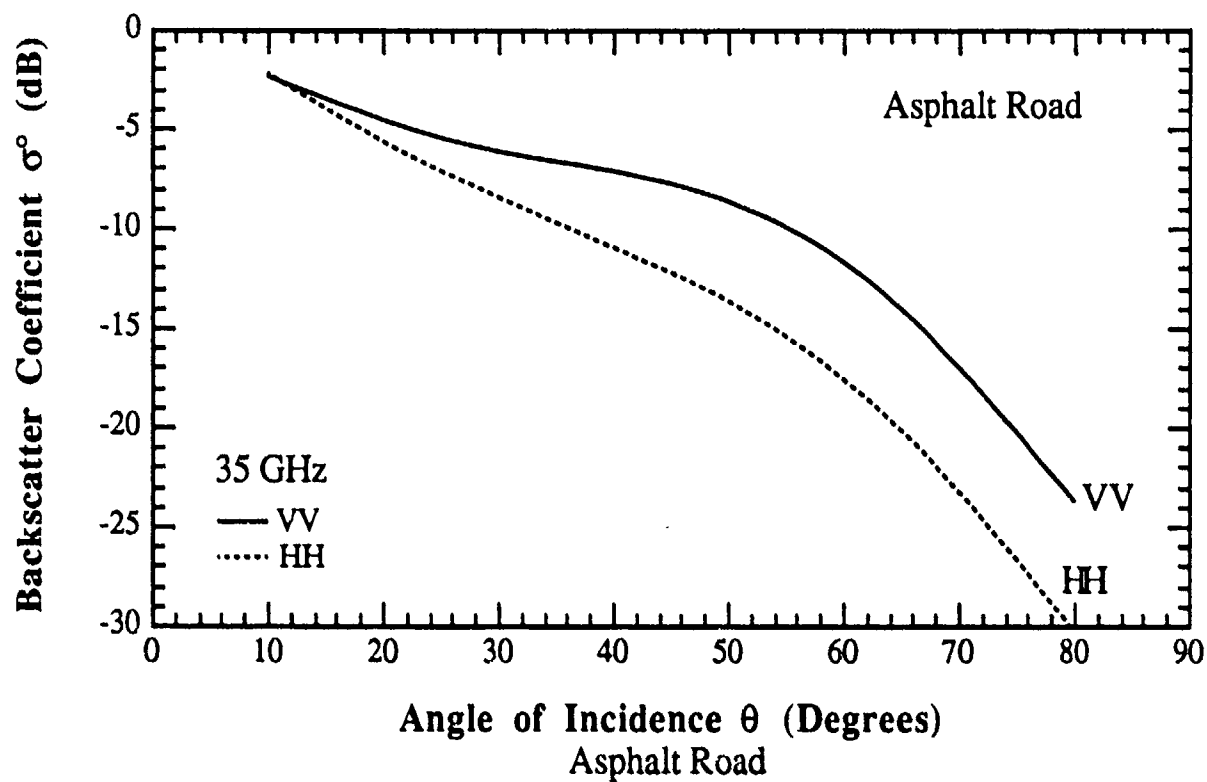
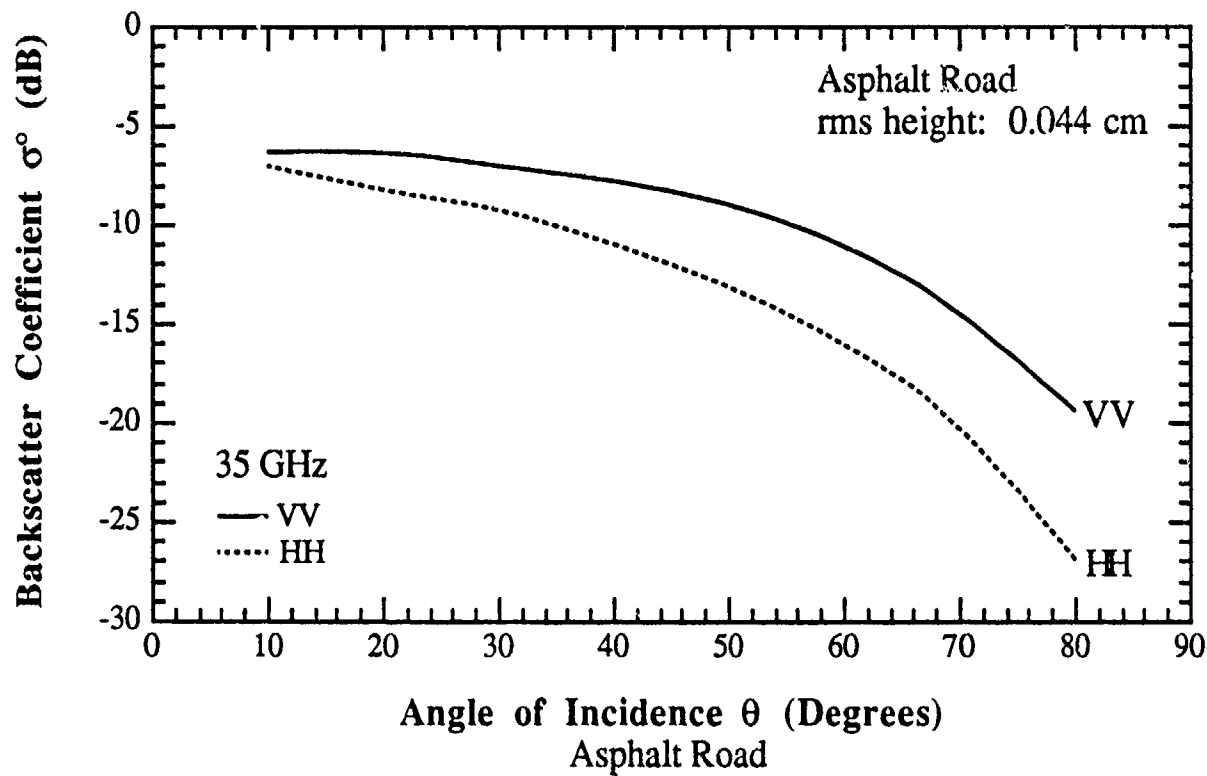


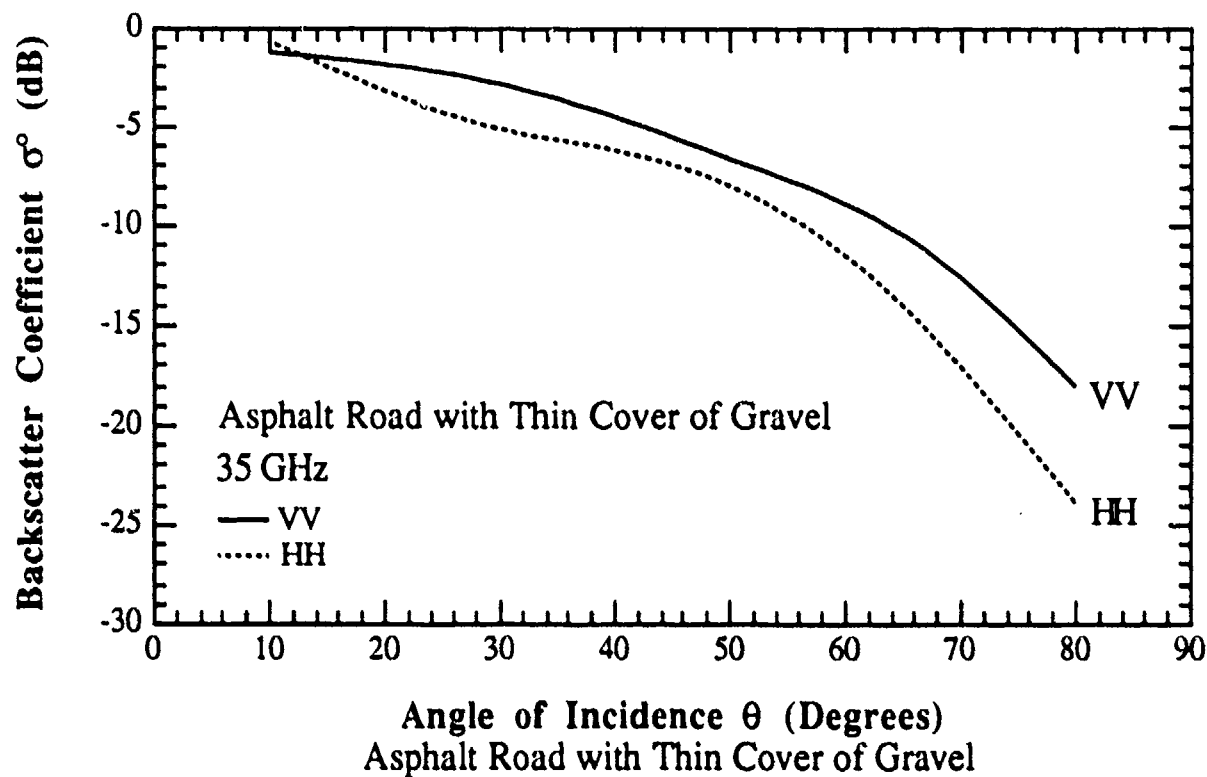
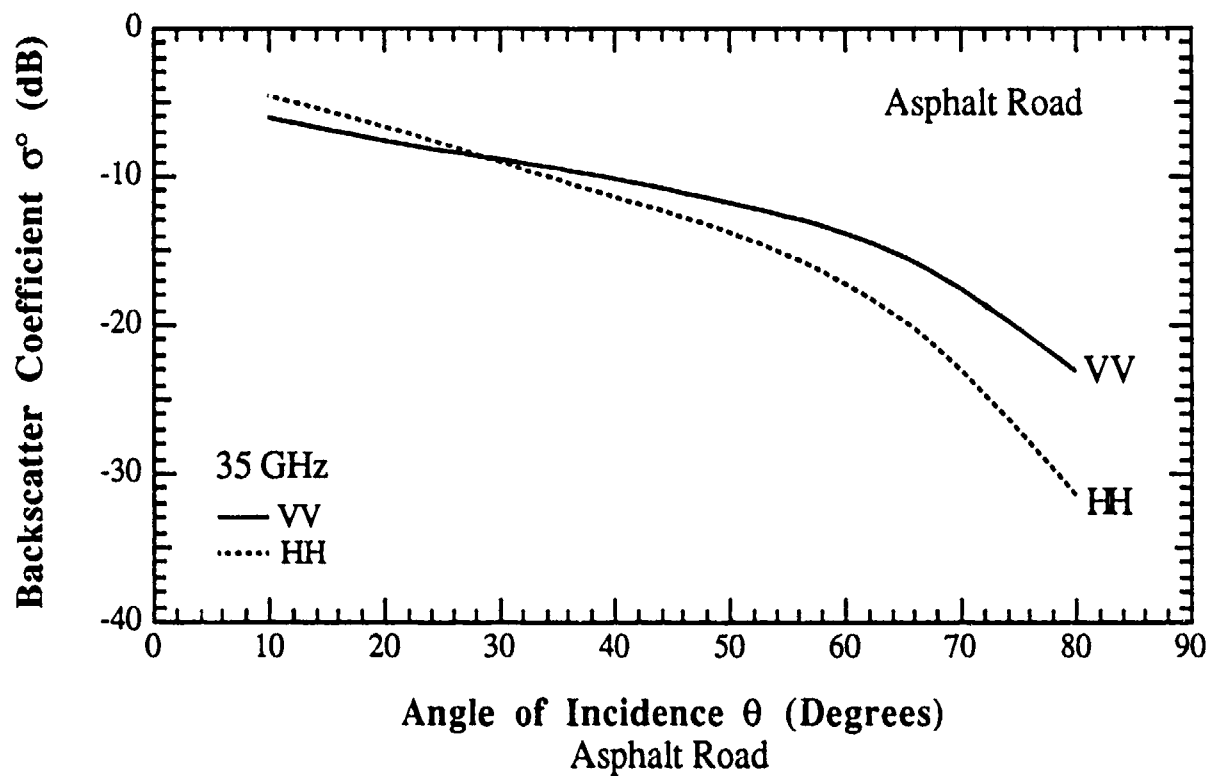


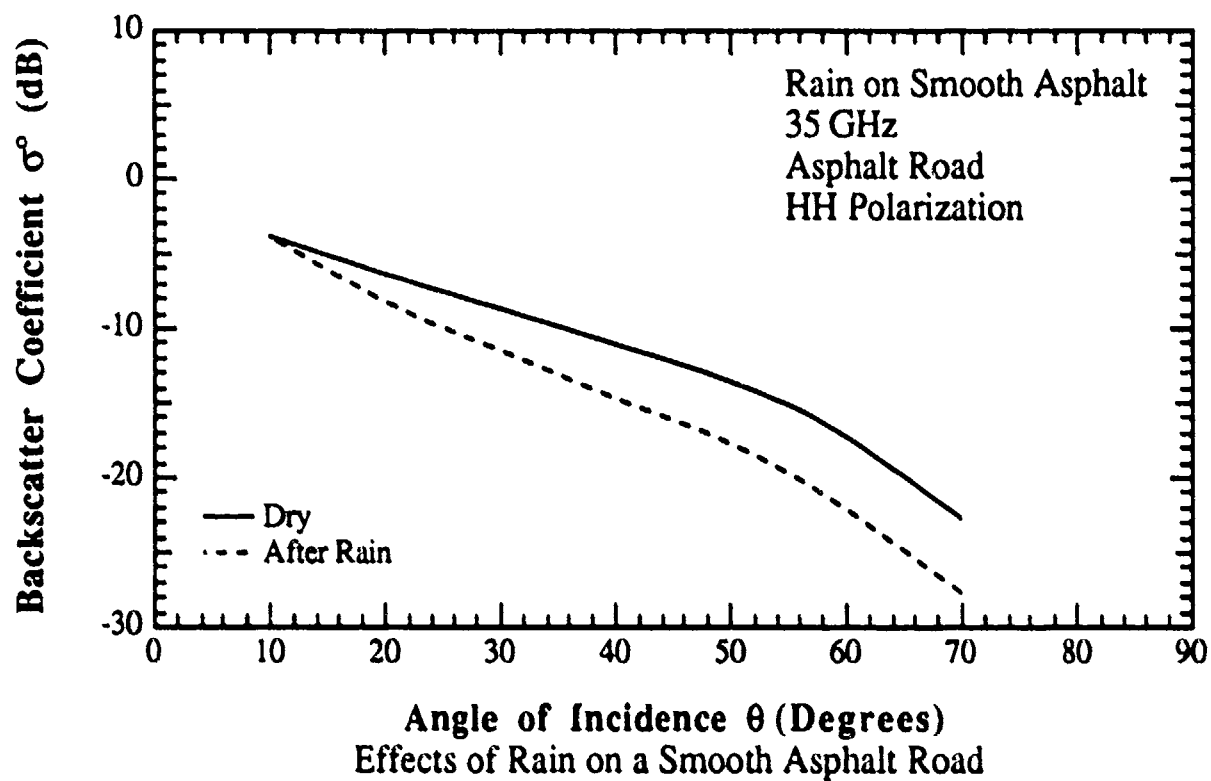
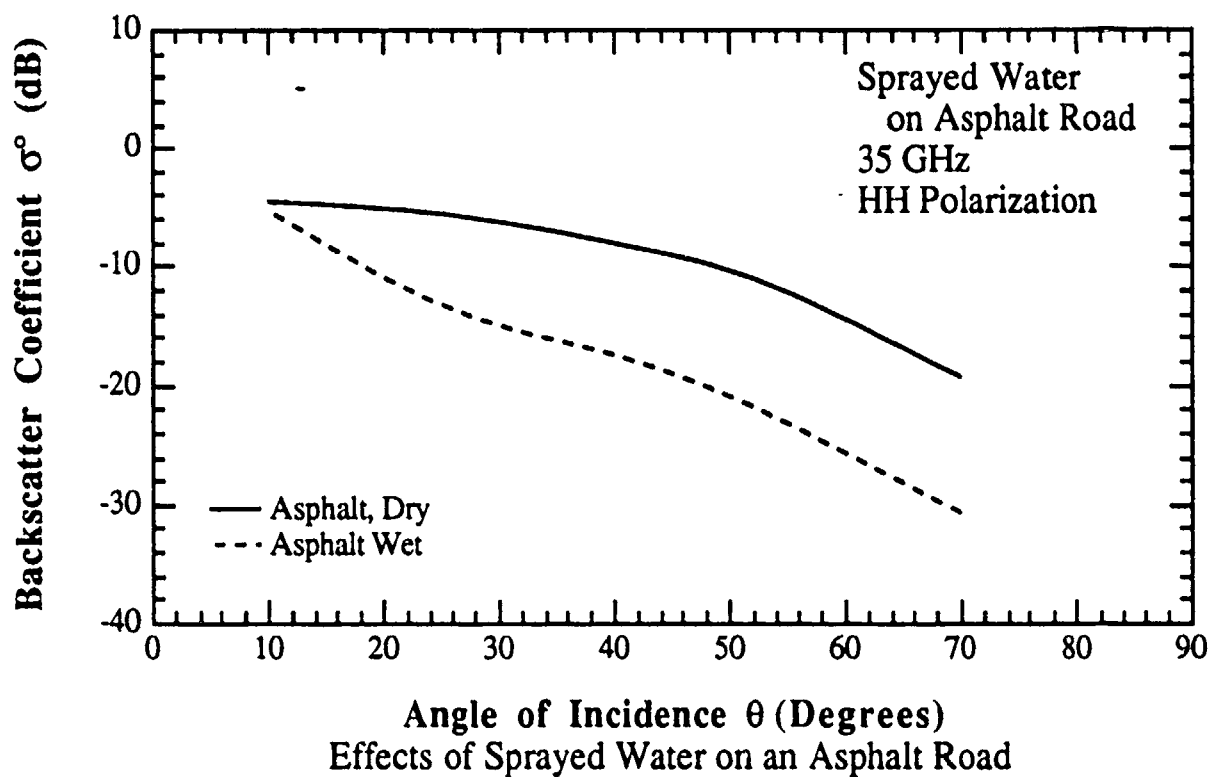
## 15. 35 GHz DATA FOR ROAD SURFACES

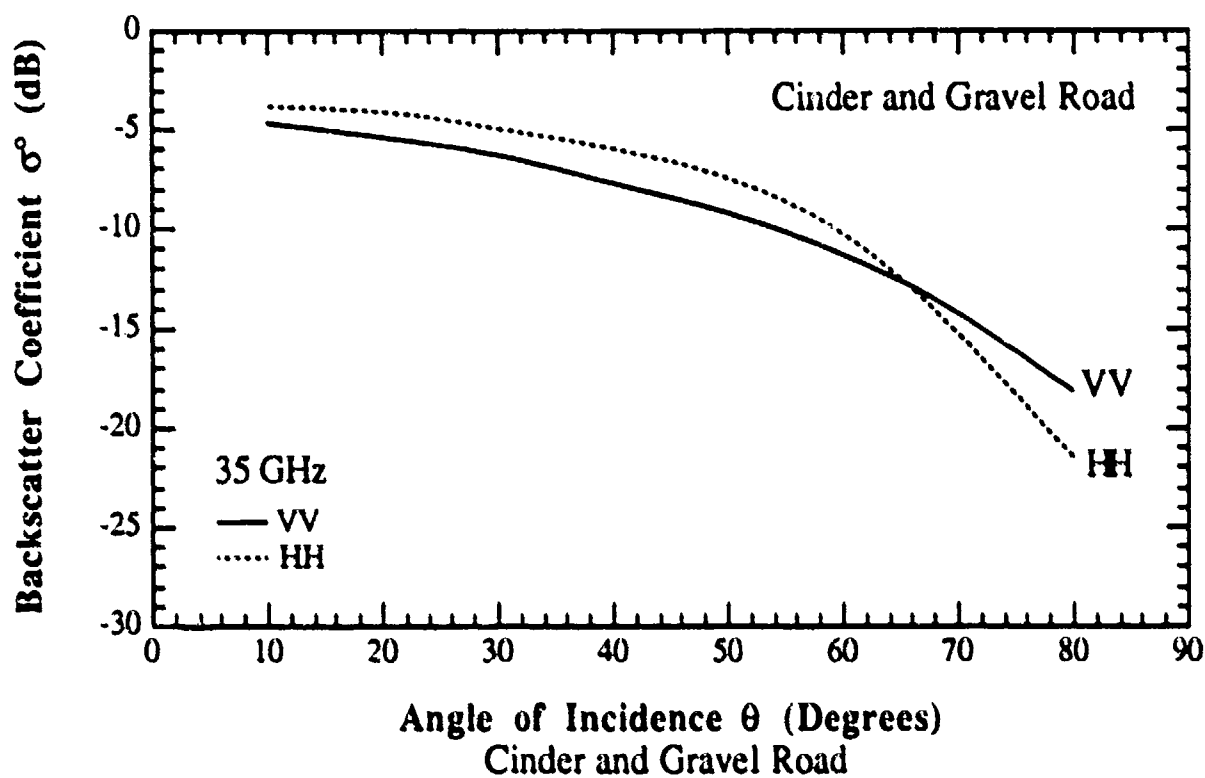
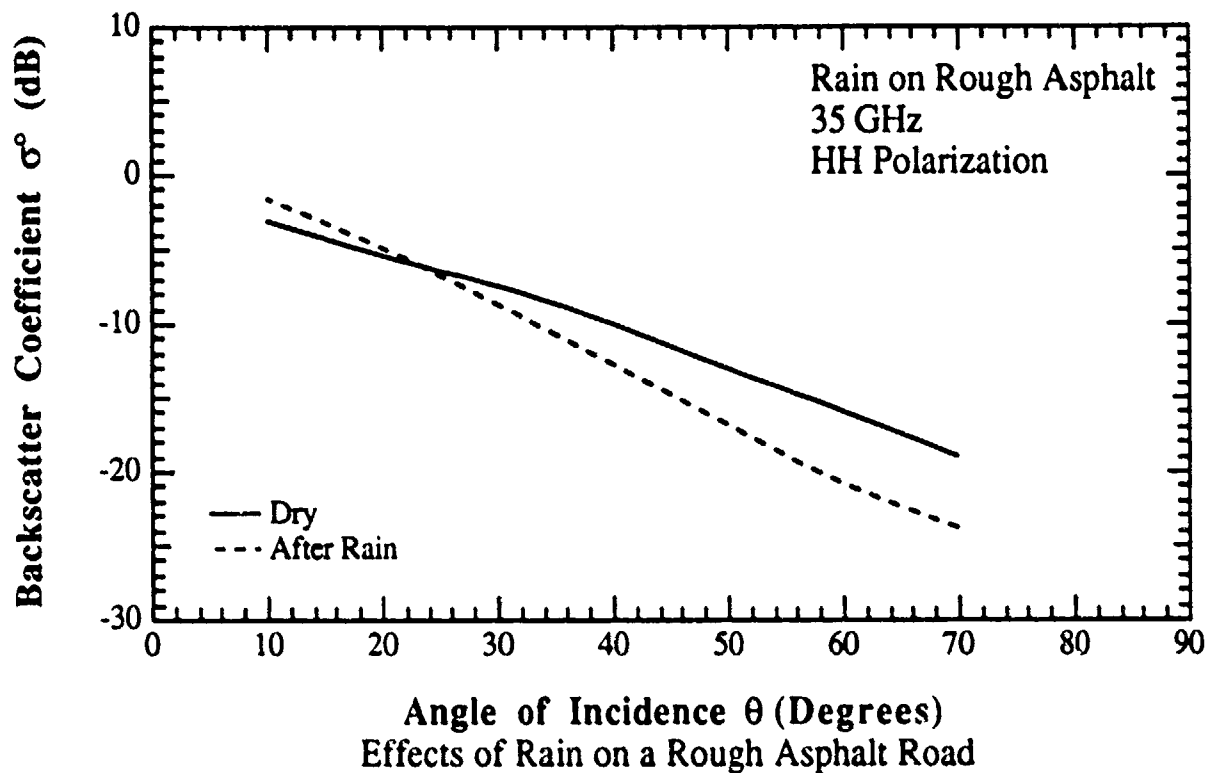
### A. Various Surfaces

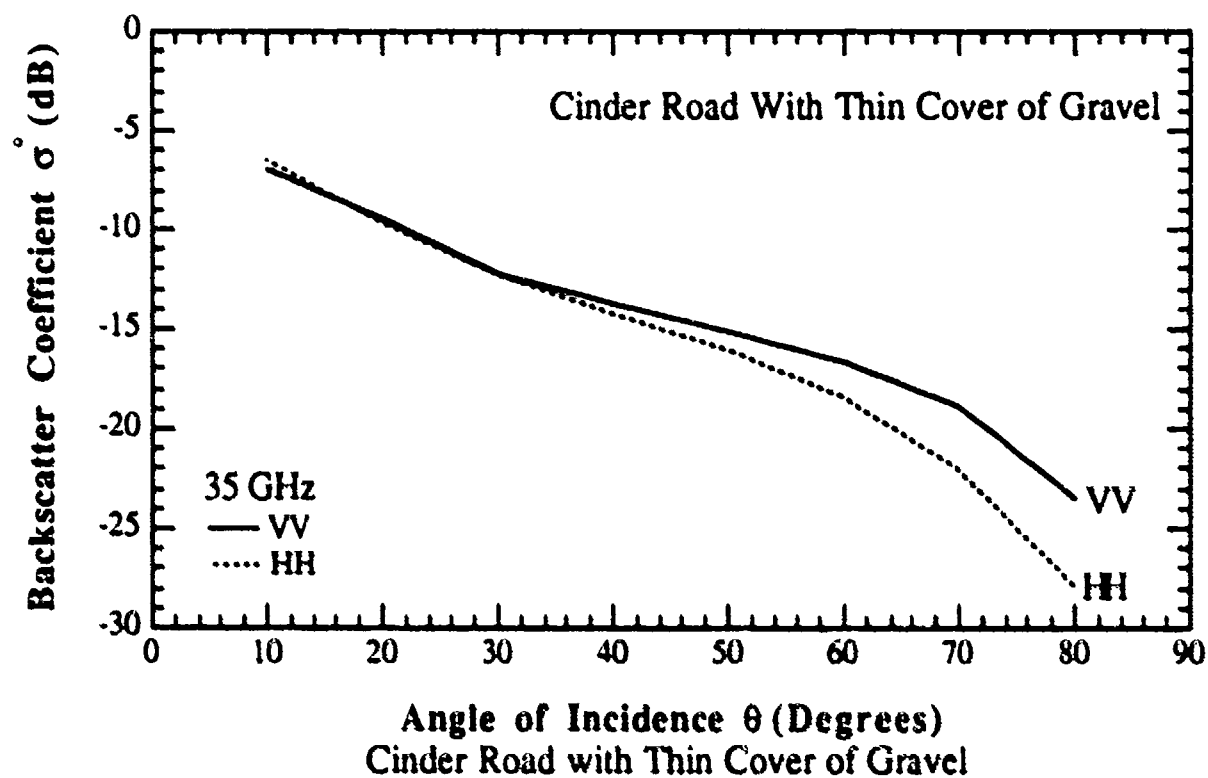
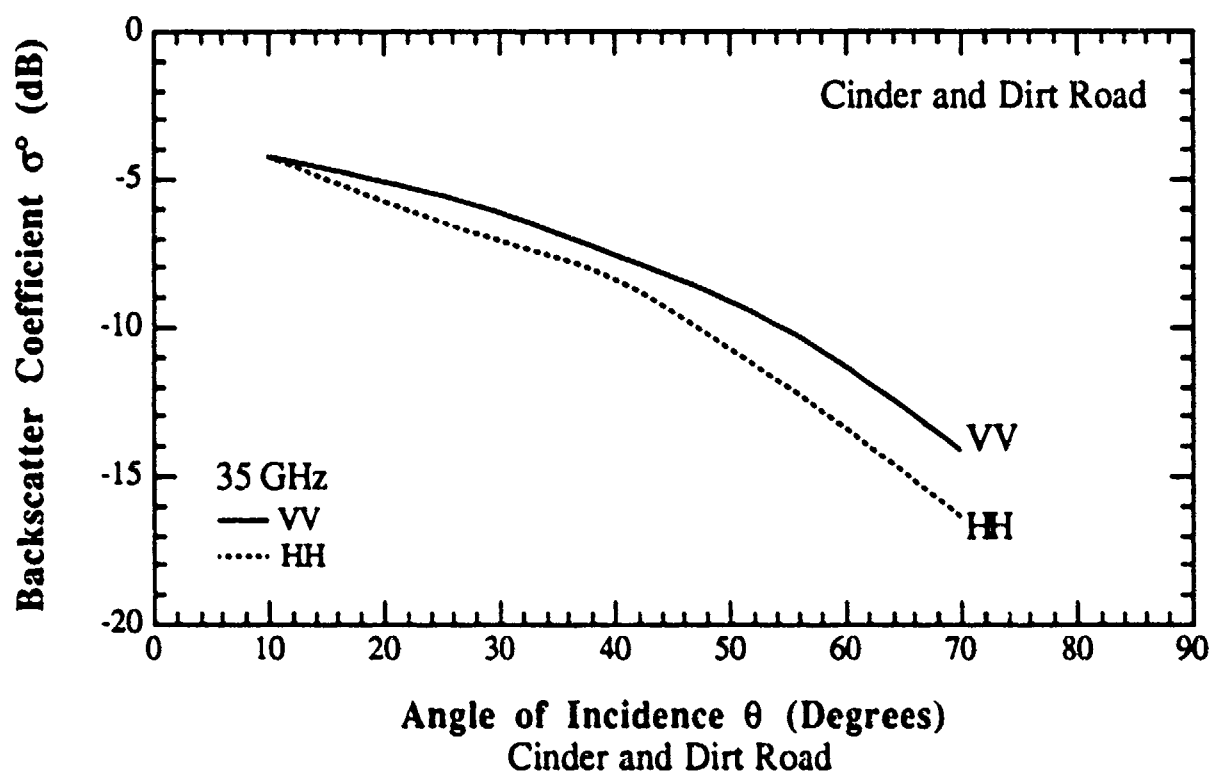


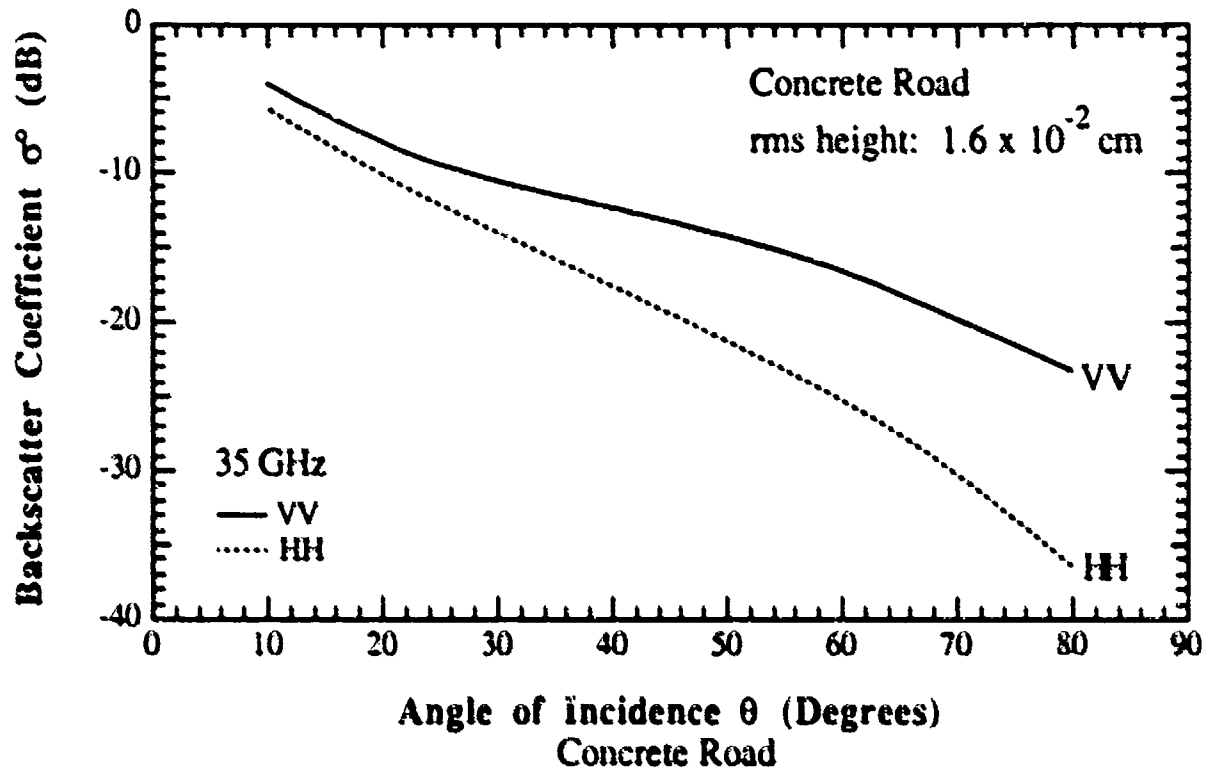
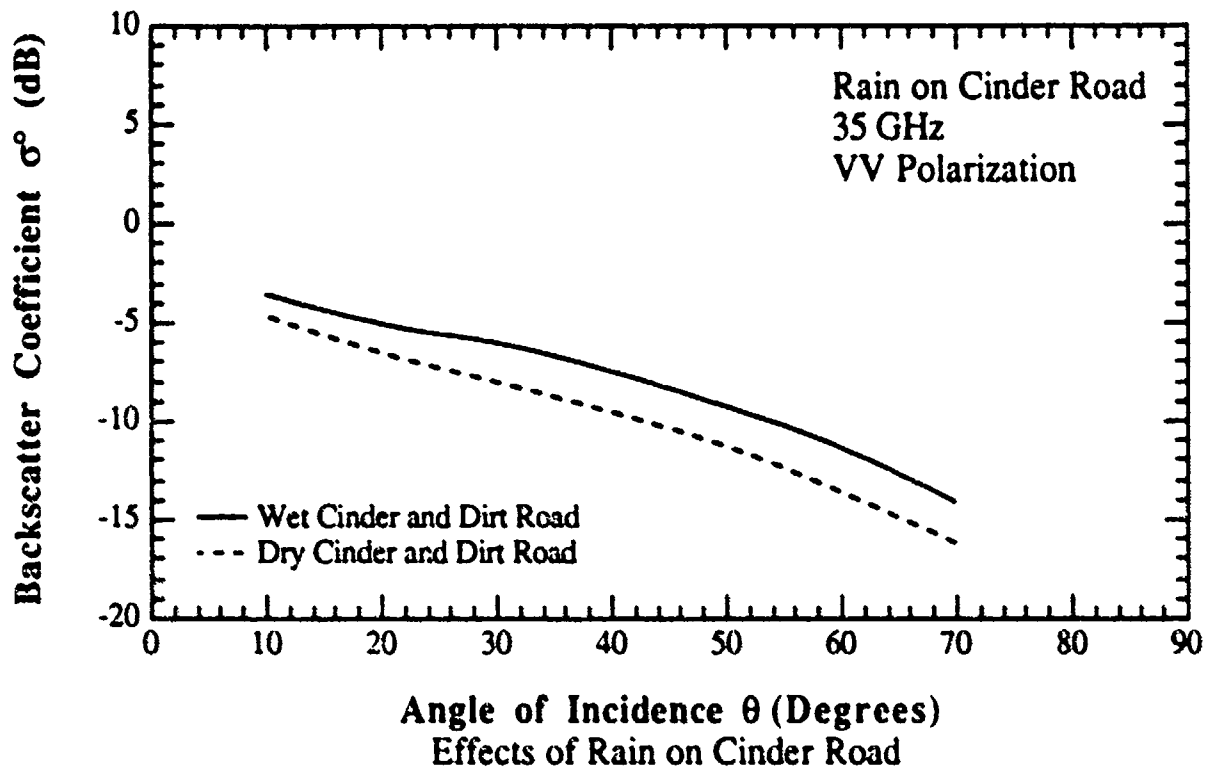


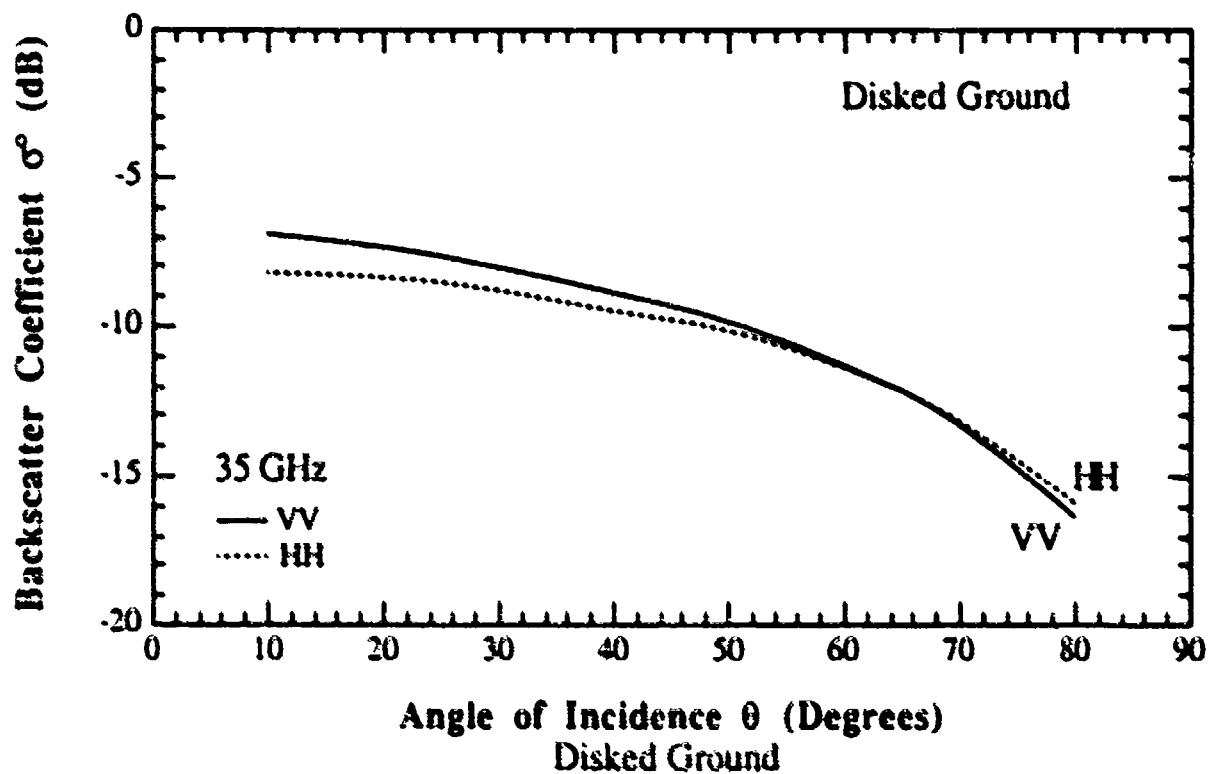
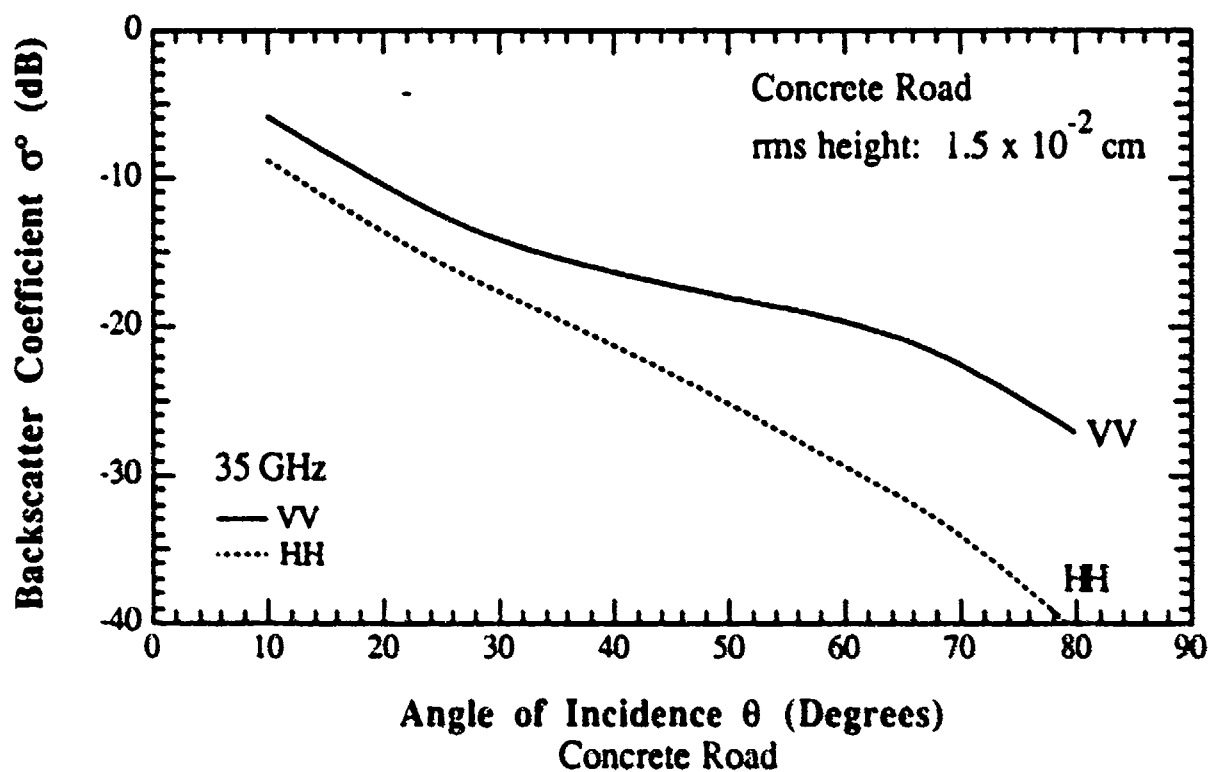


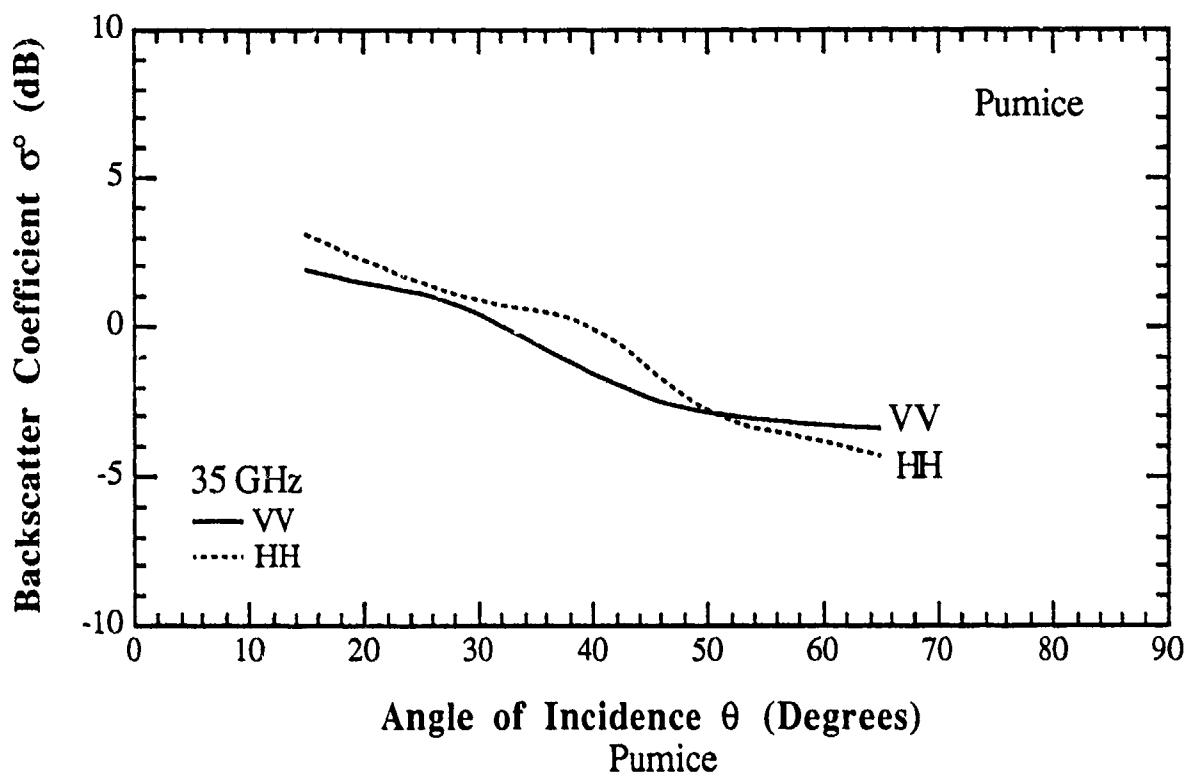
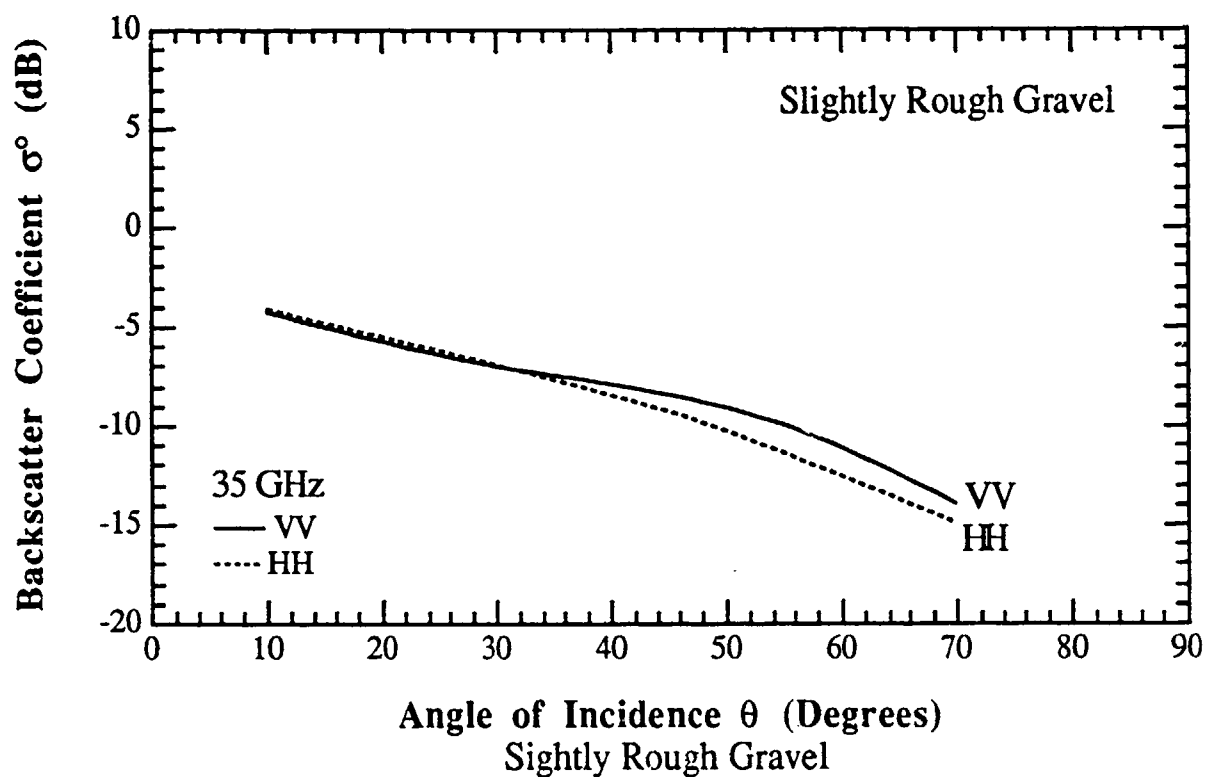


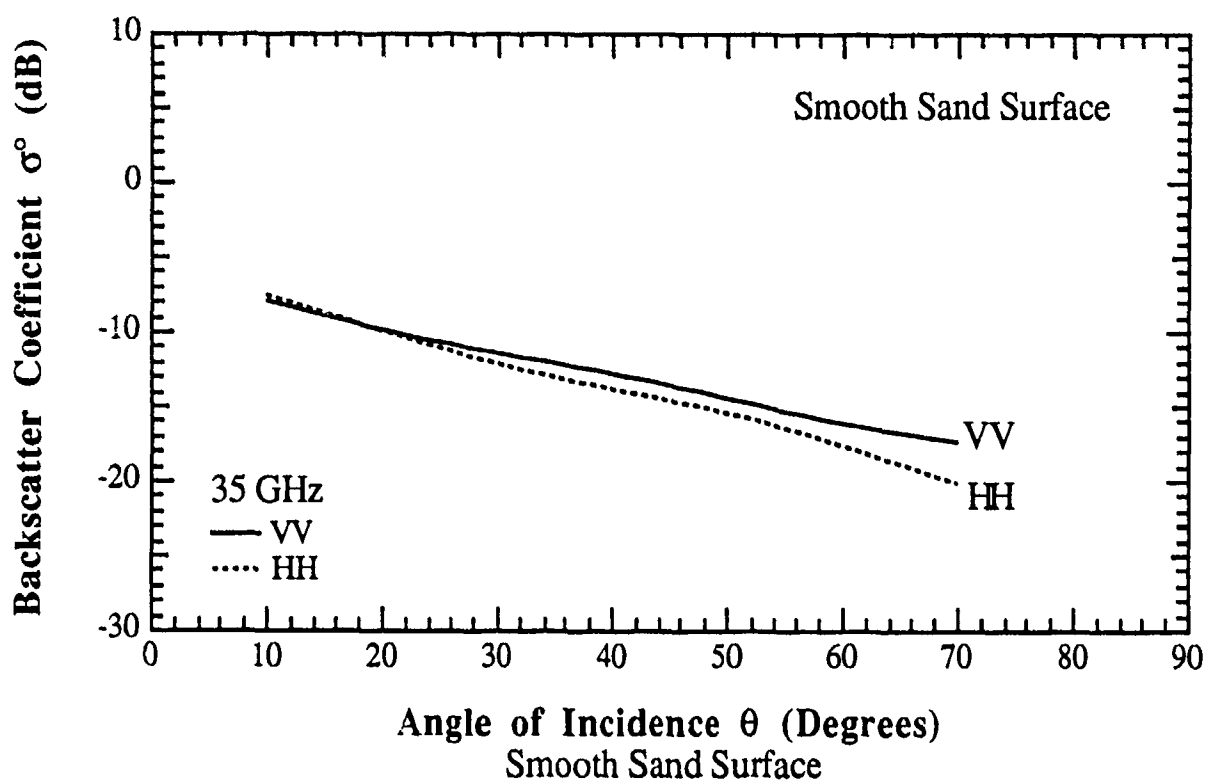
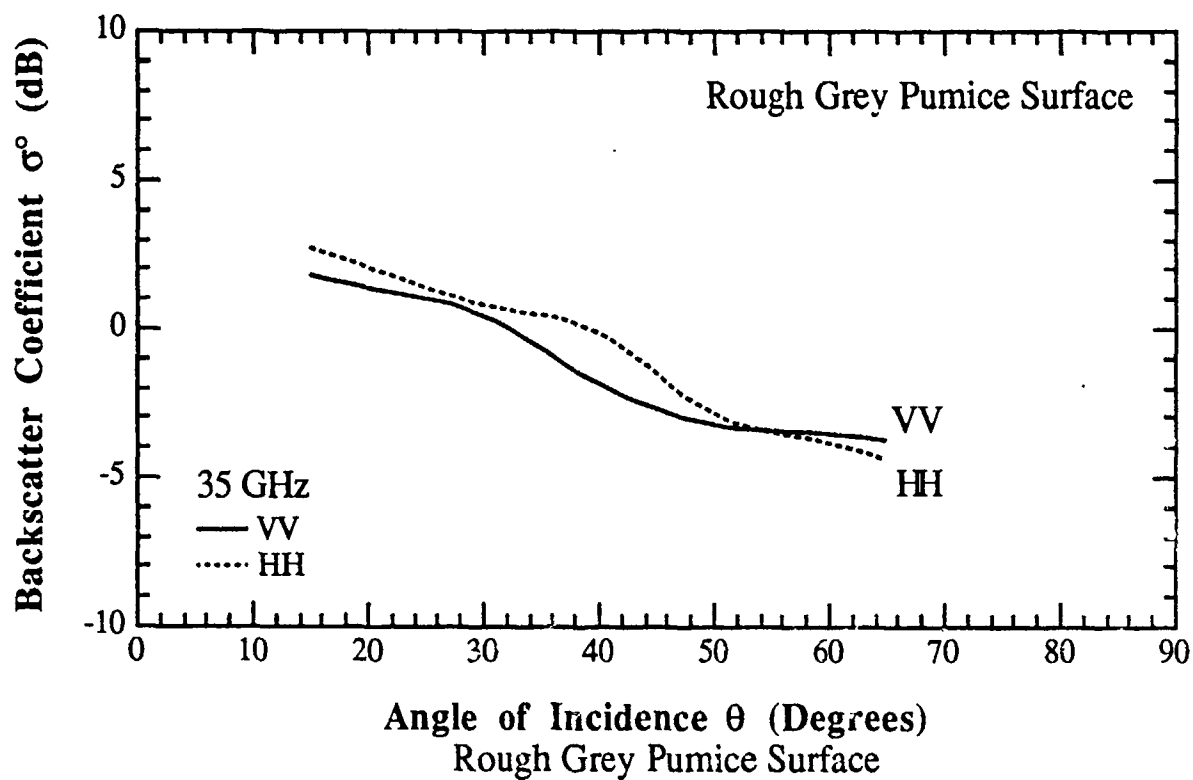


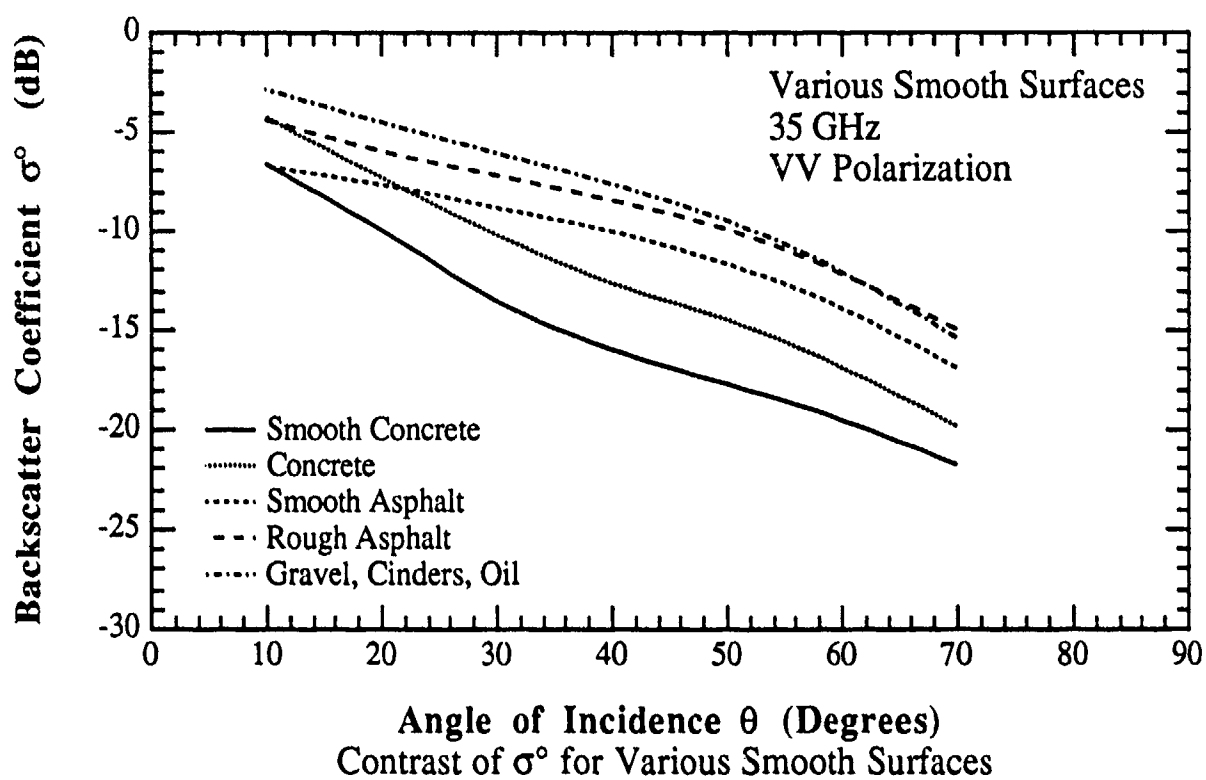
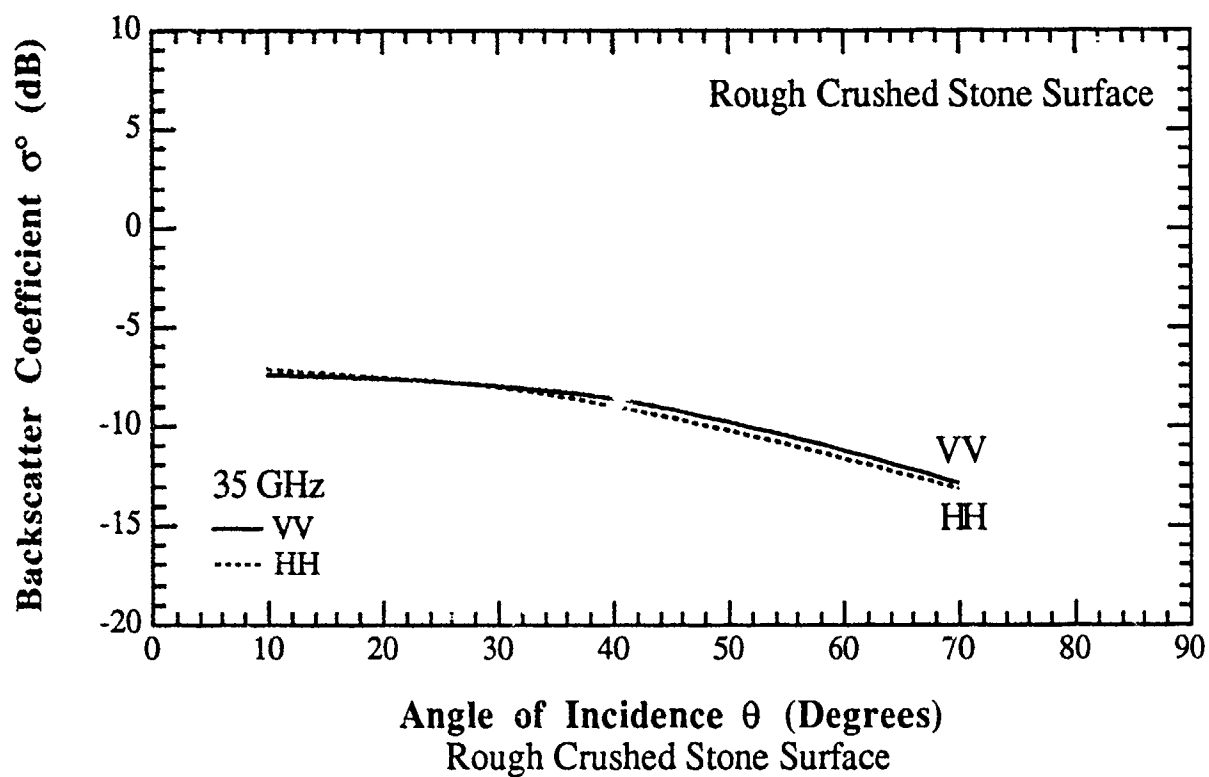


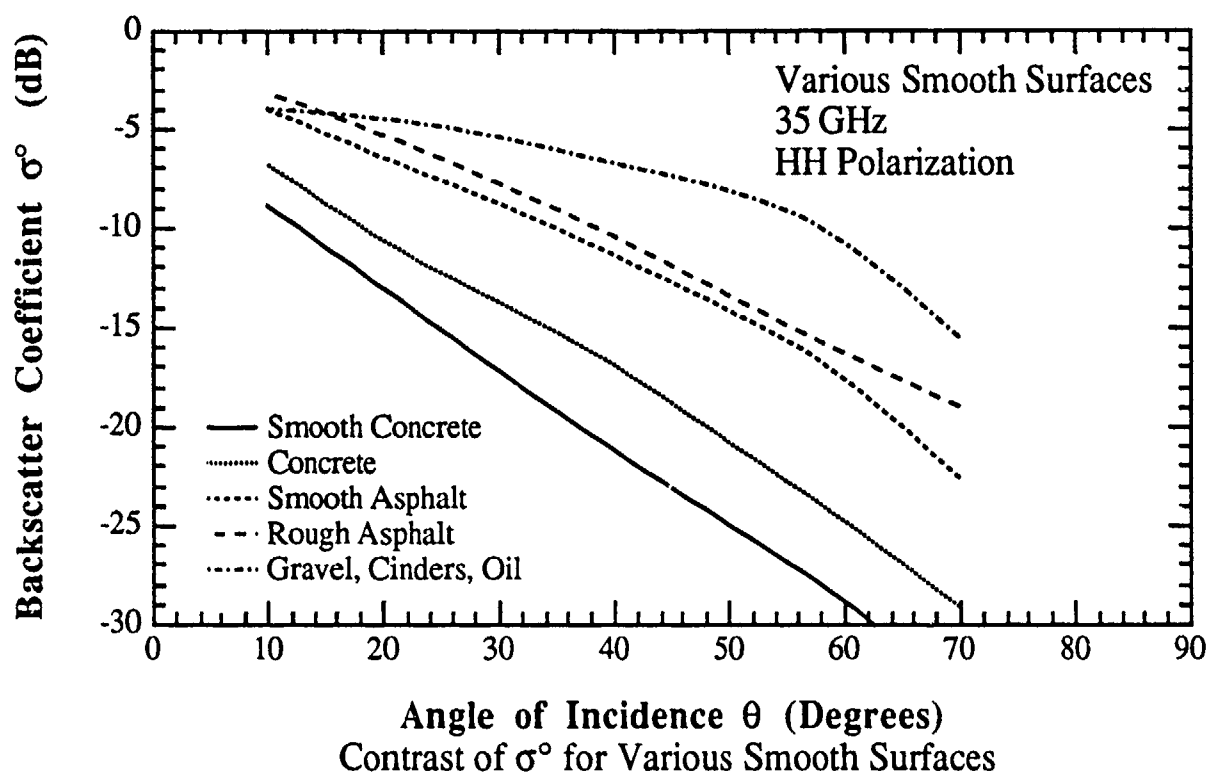




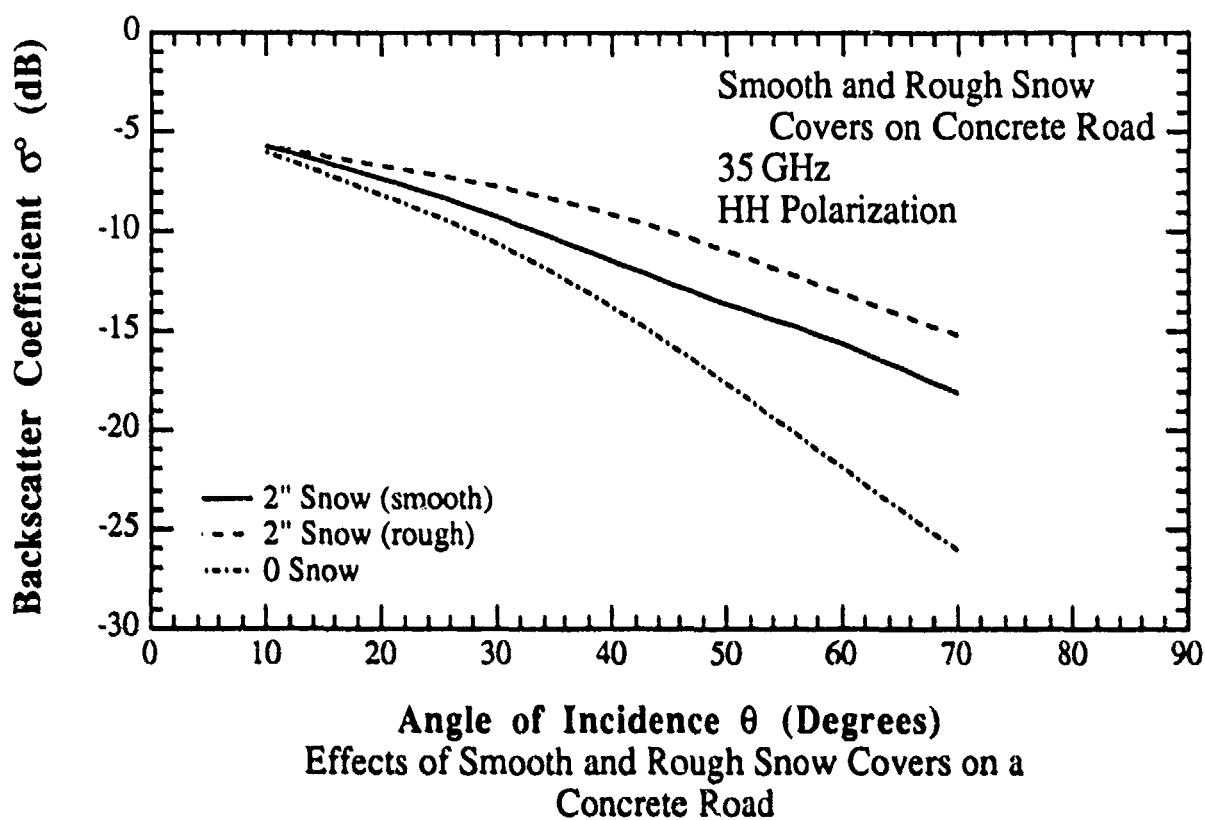
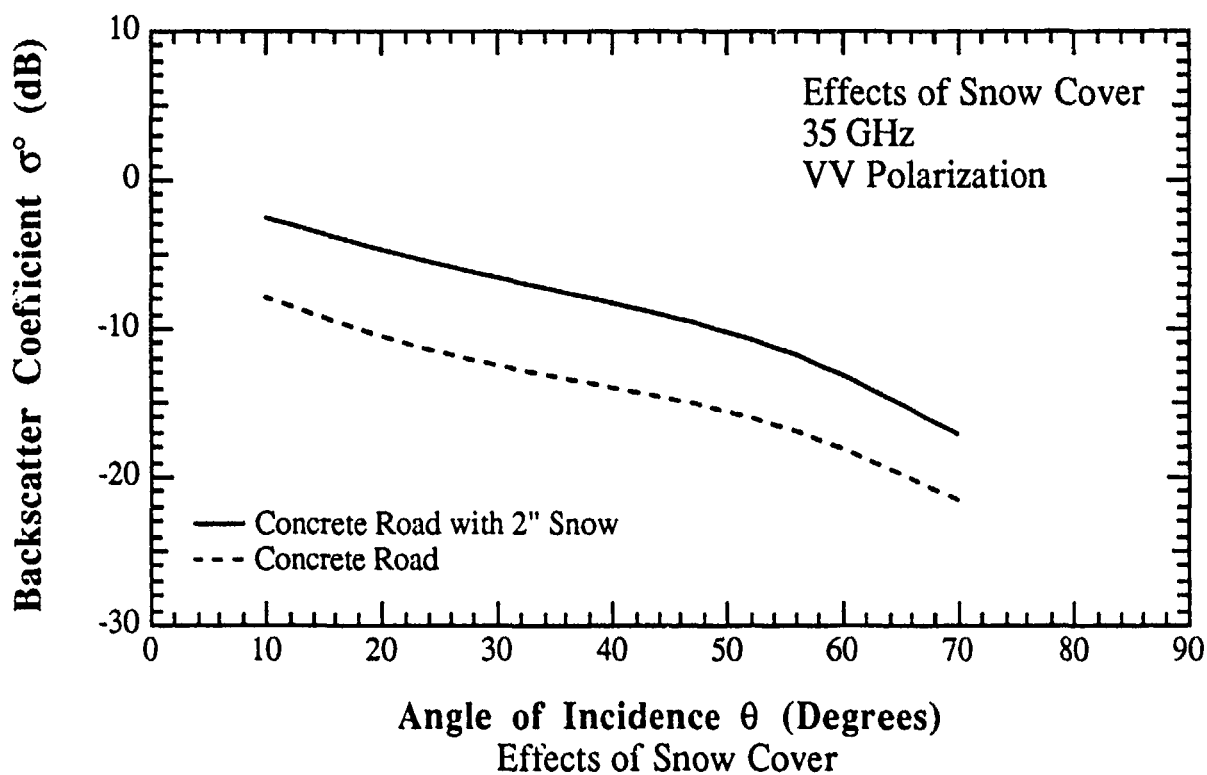


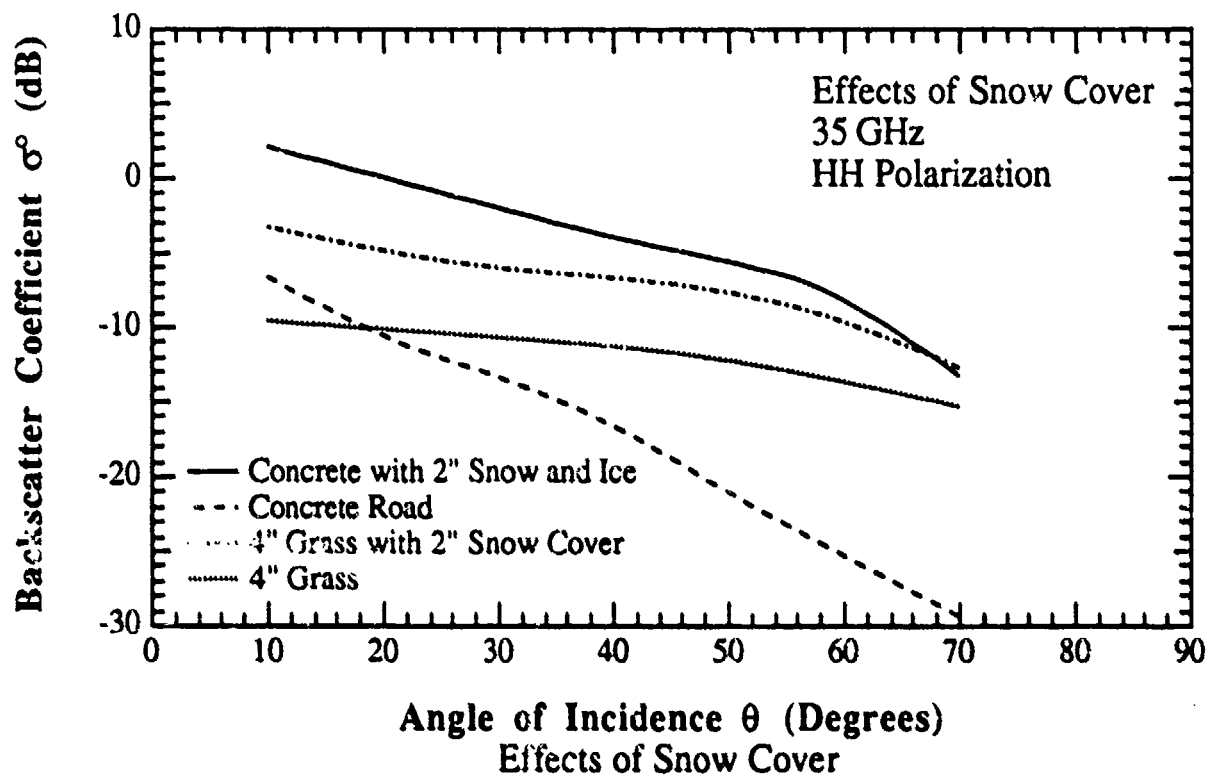
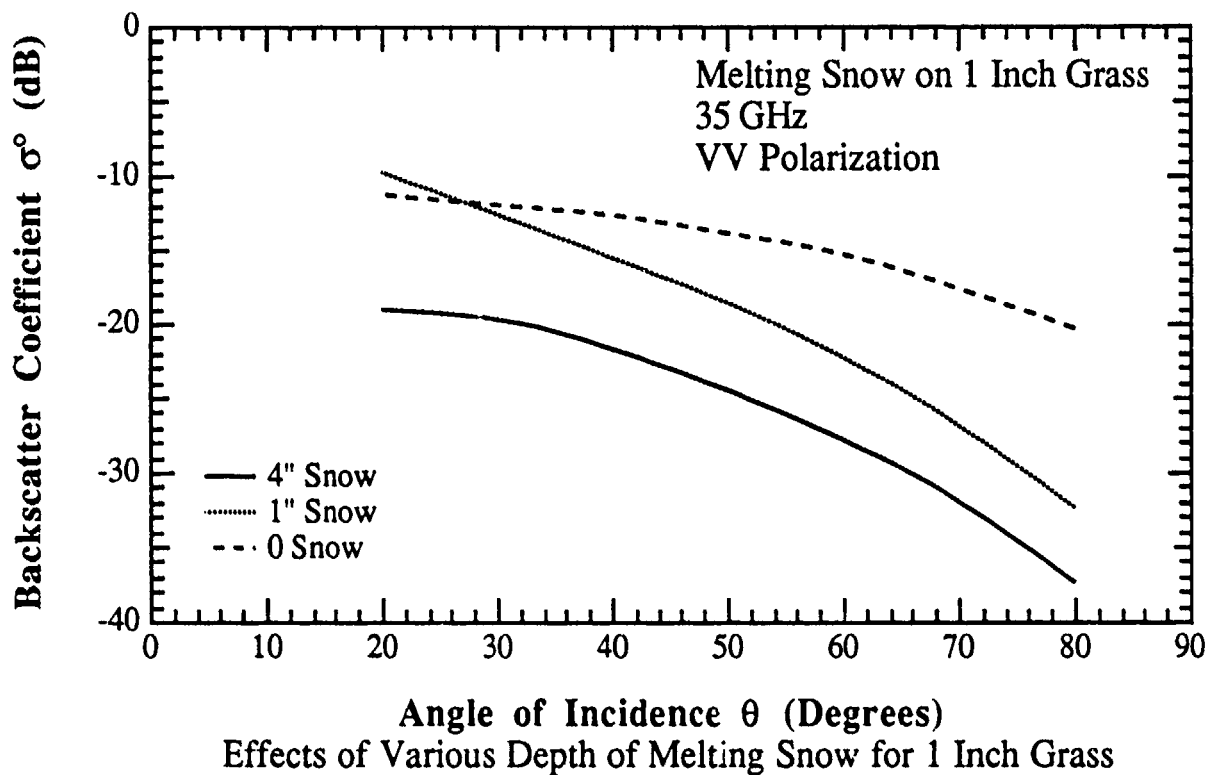


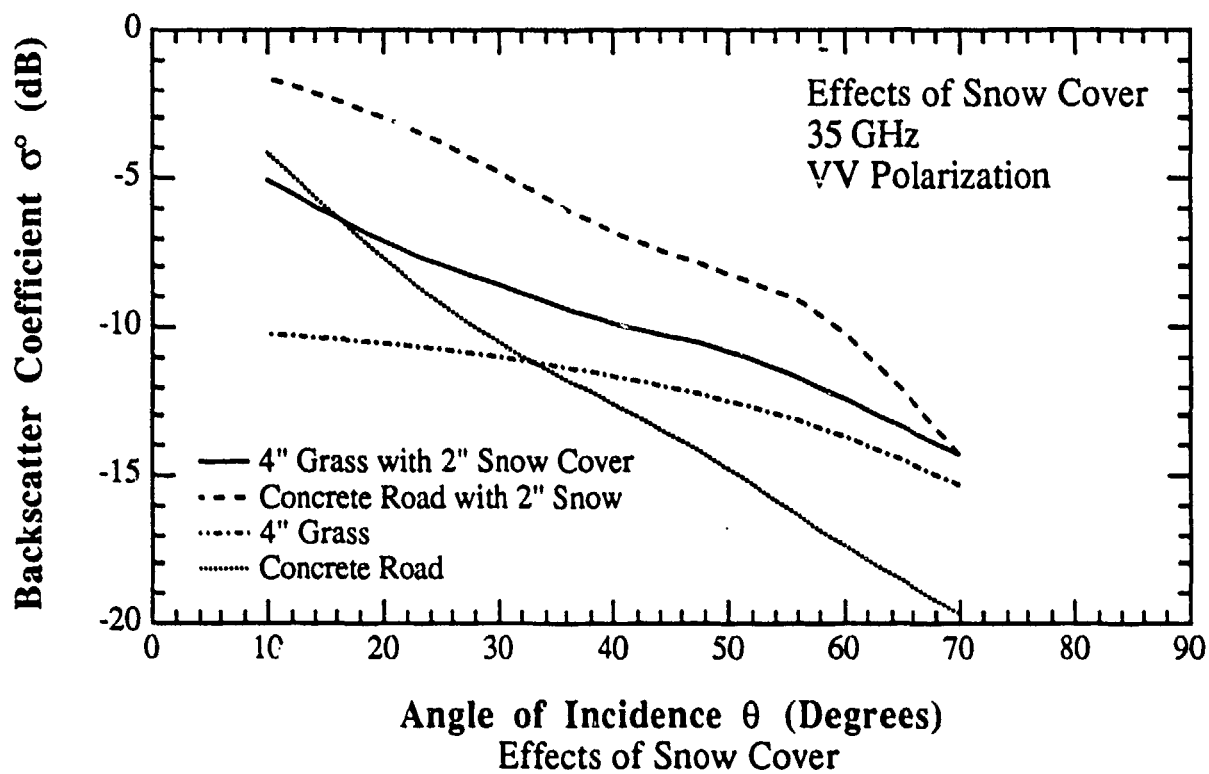




## B. Various Surfaces With Snow Cover

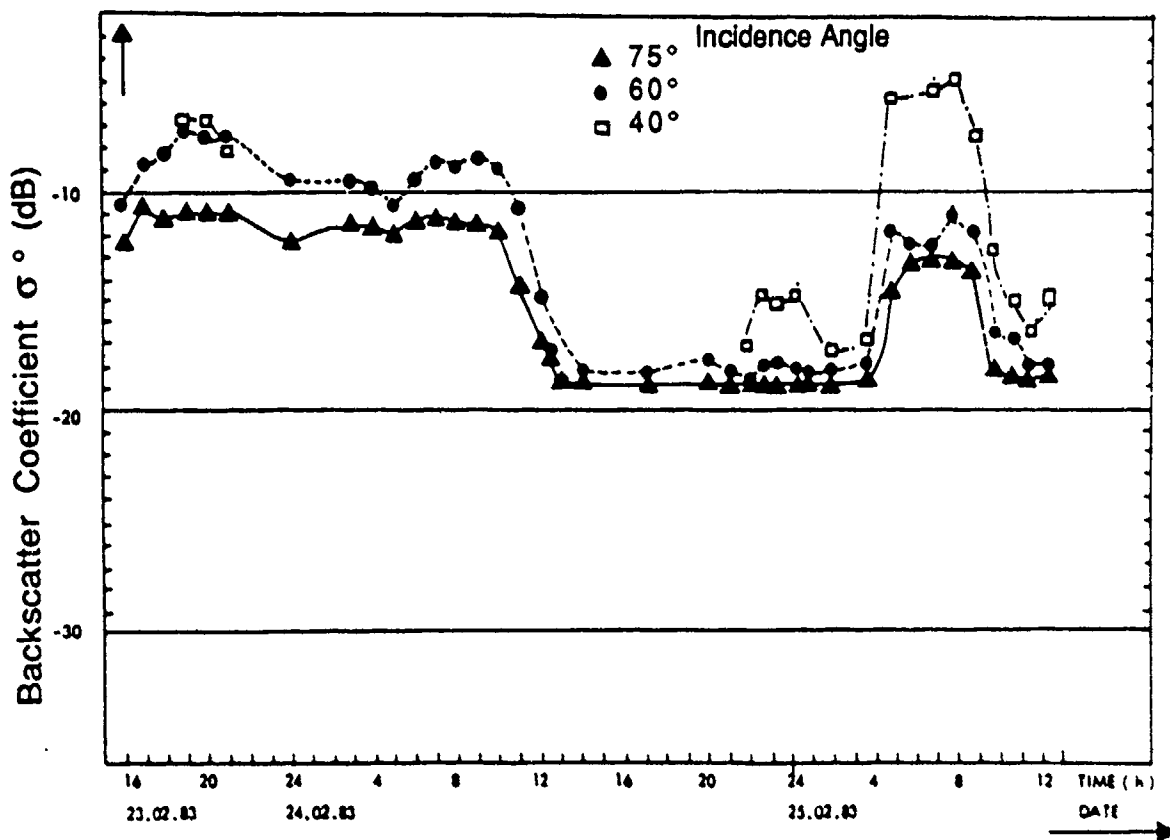




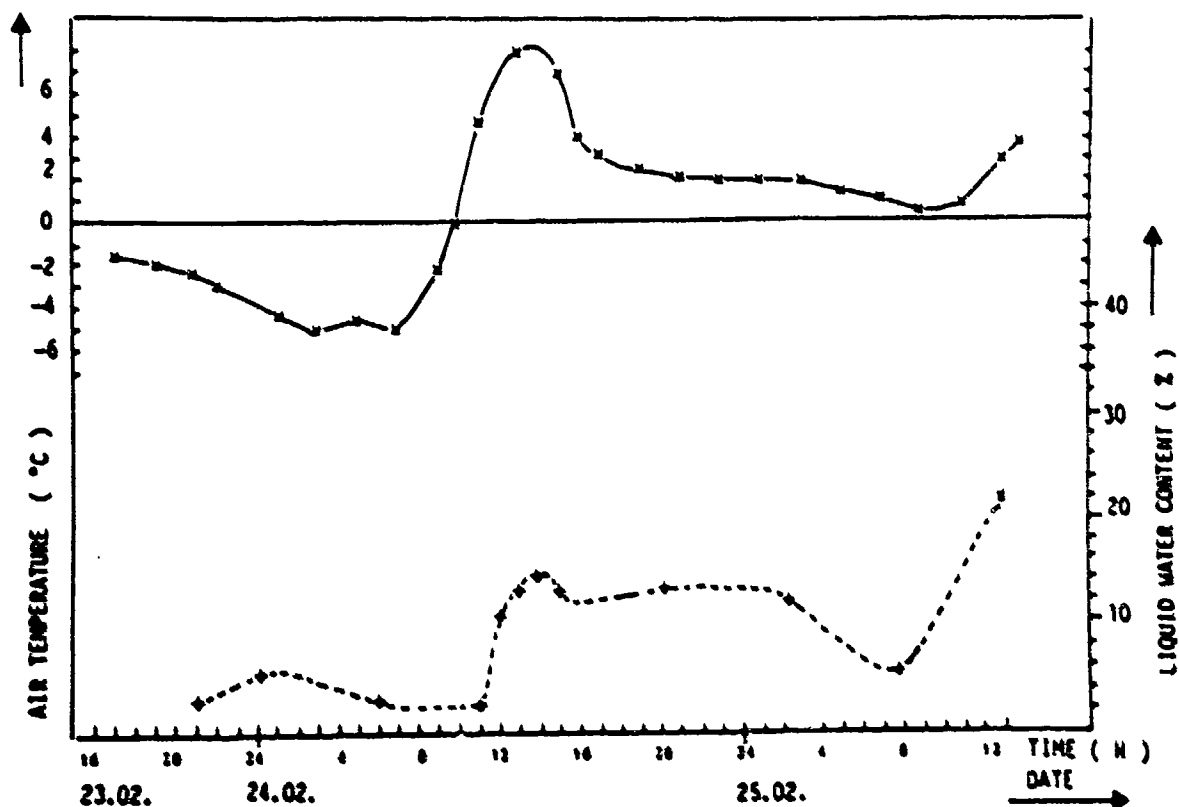


## **PART V. OTHER MMW DATA**

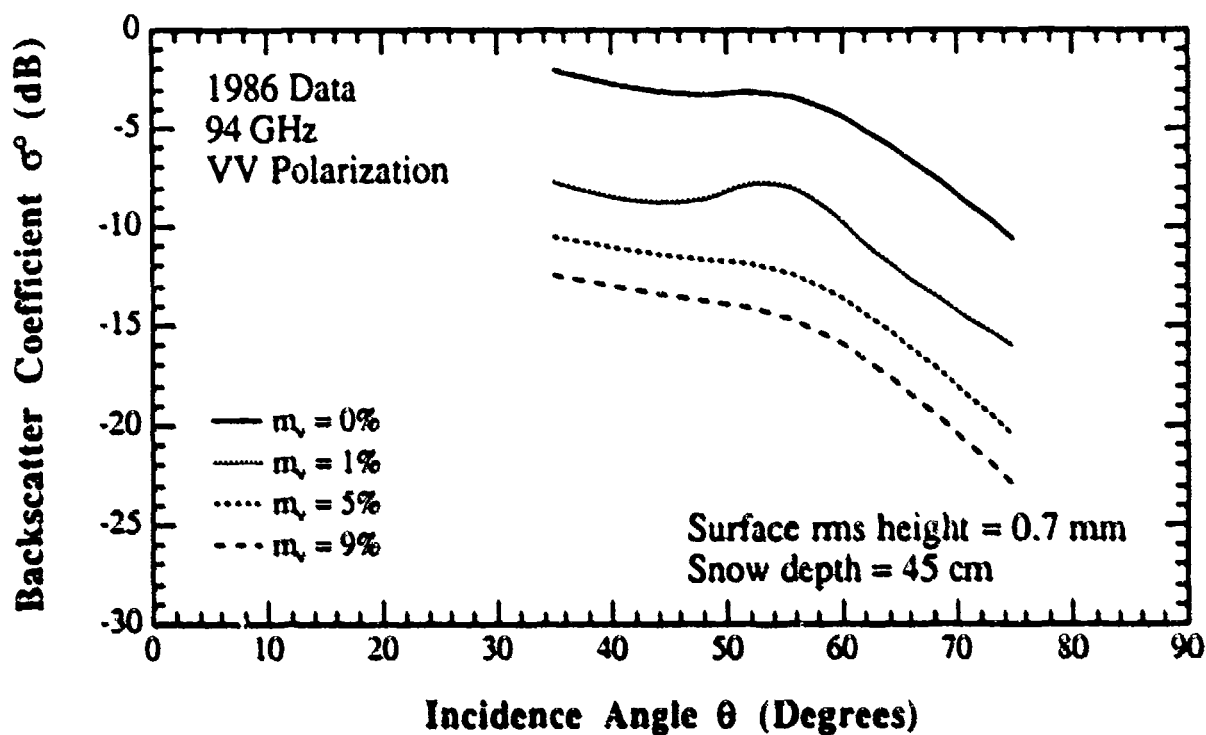
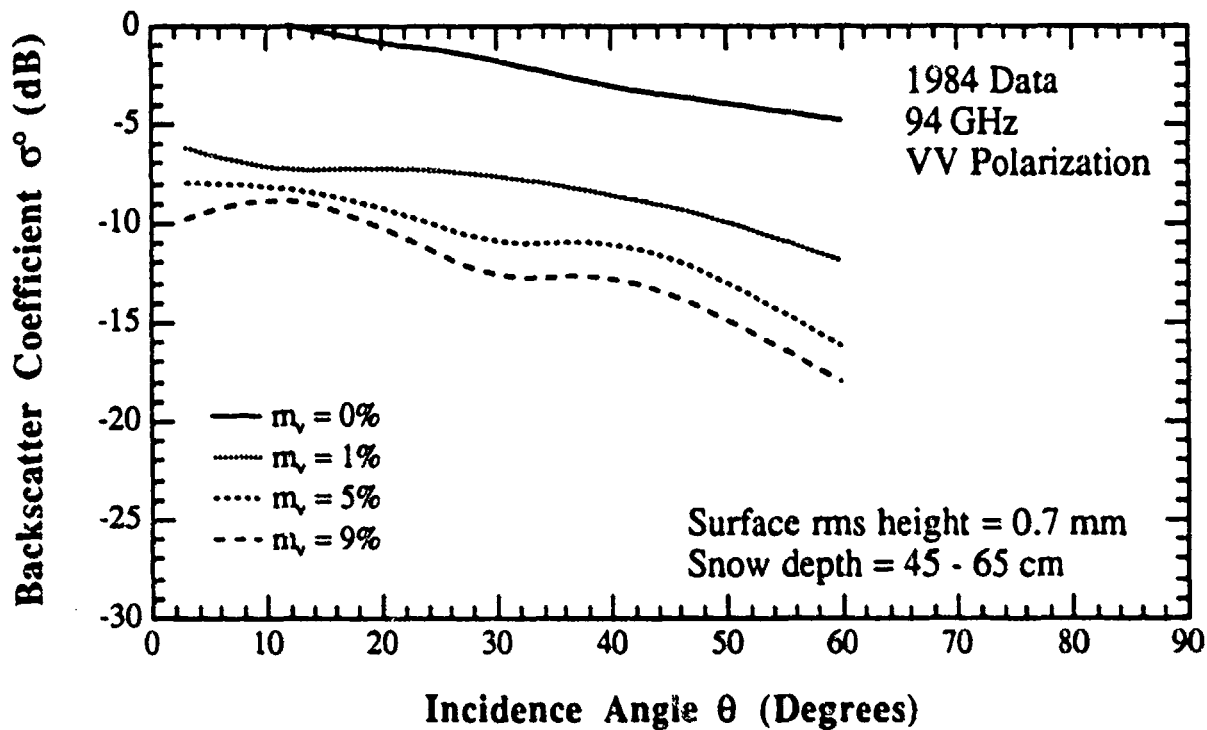
This part of the Handbook includes MMW data reported by organizations other than those covered in previous chapters of this Handbook. The data, the majority of which was extracted from plots published in scientific journals, do not include measurements that lack adequate ground-truth information or whose accuracy cannot be ascertained.



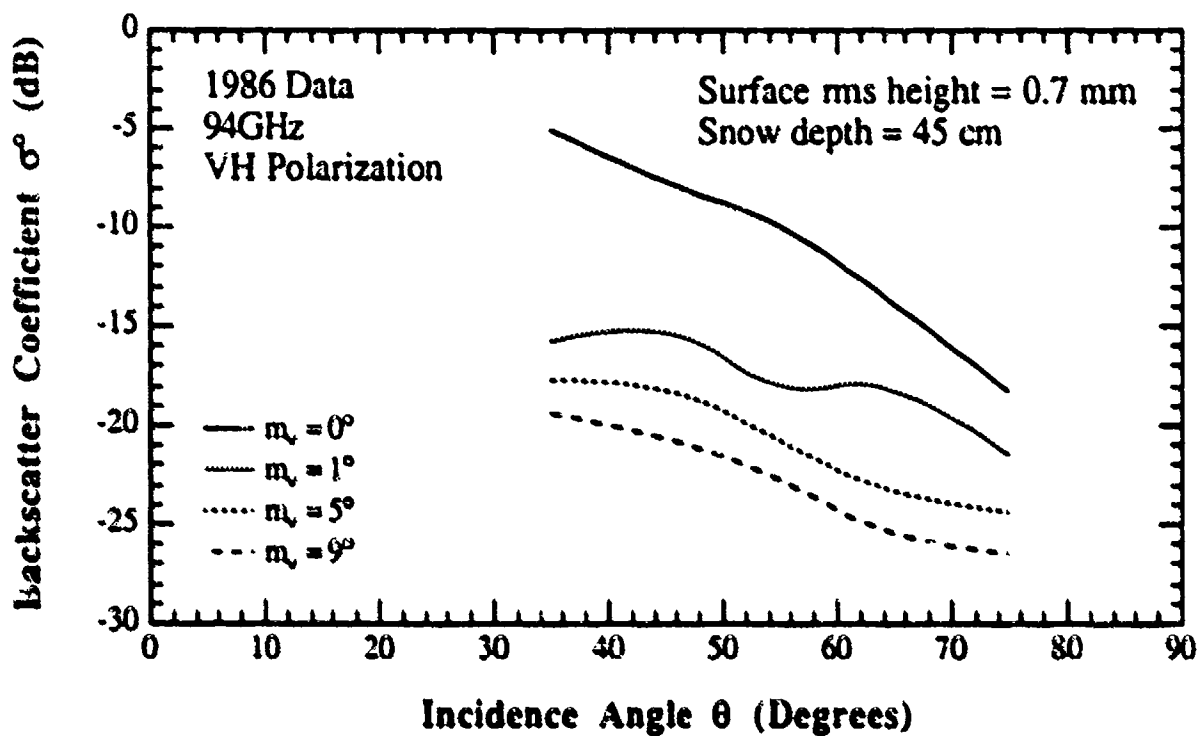
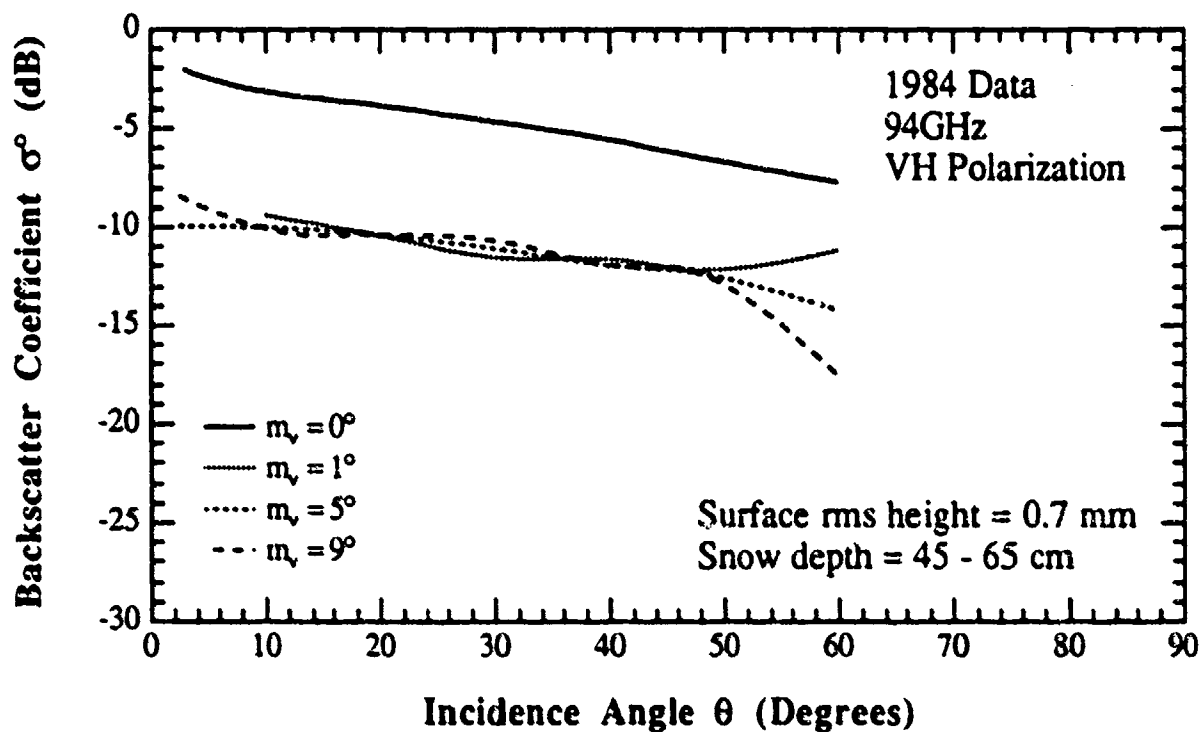
Diurnal variation of reflectivity for a metamorphic snow state at 94 GHz



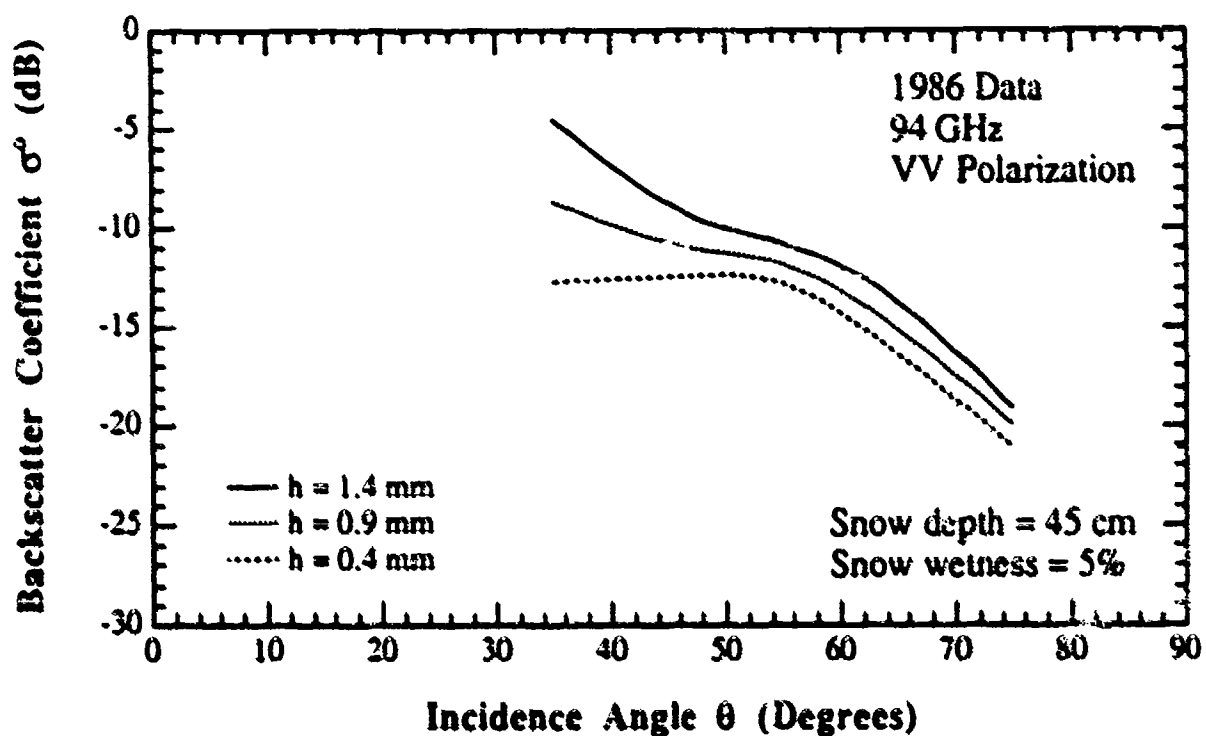
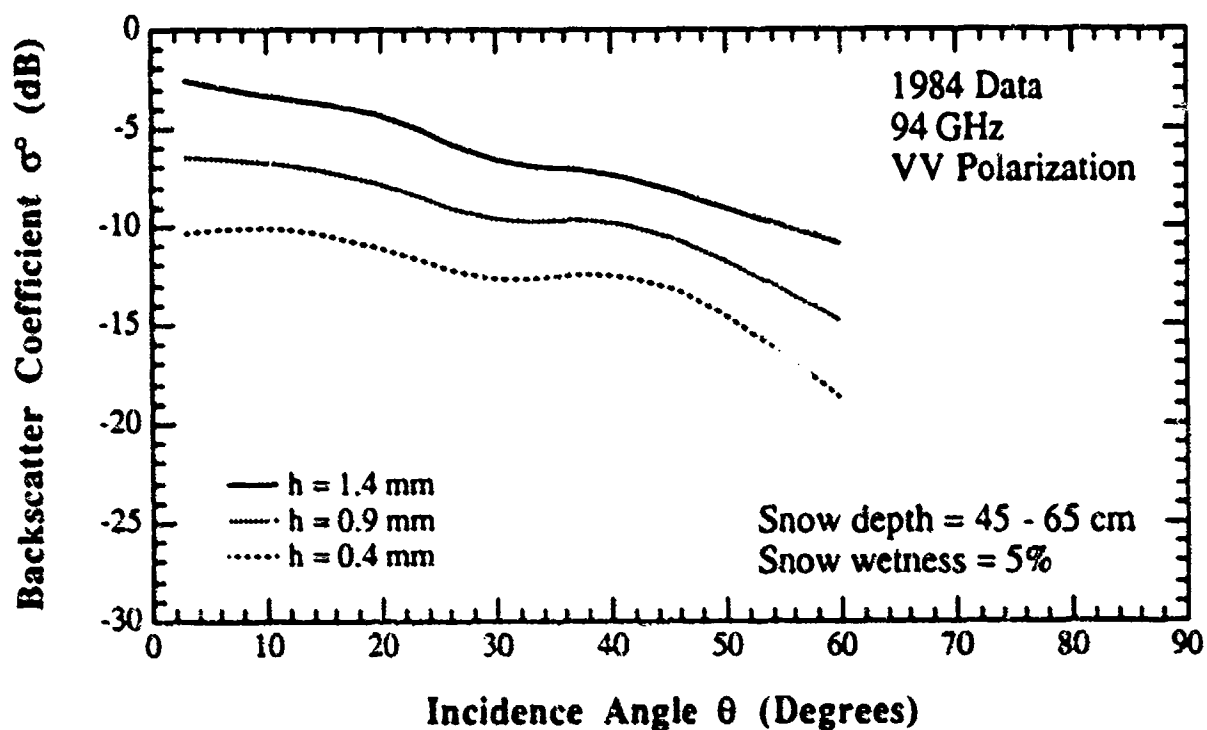
Diurnal variation of air temperature and liquid water content of snow from 23/2 to 25/2/82. From [23].



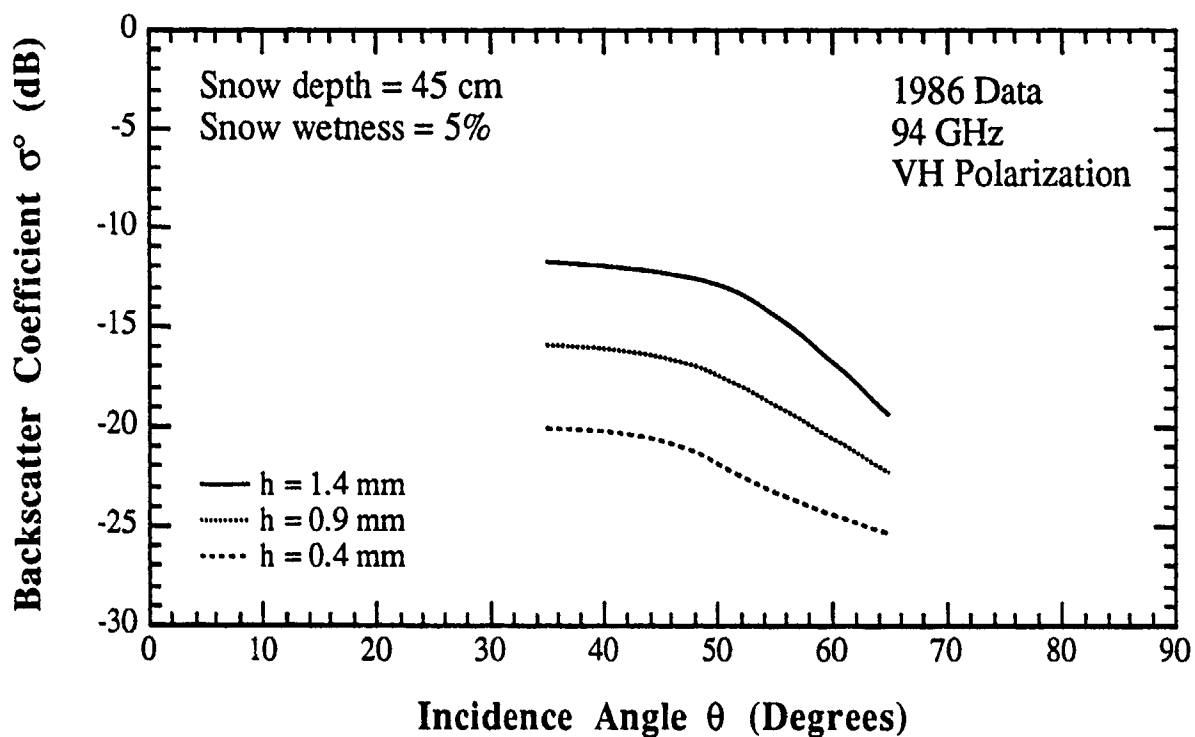
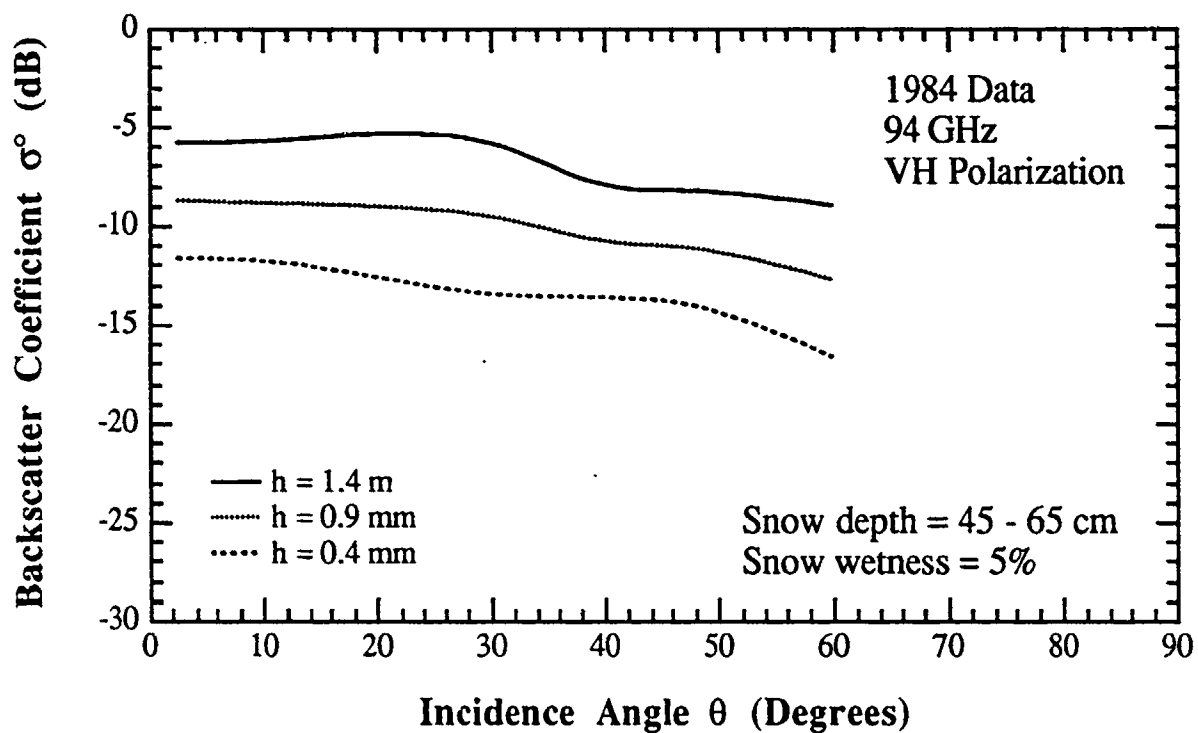
VV - Polarized Backscatter of Snow Measured in 1984 and 1986 for Various Liquid Water Contents  $m_v$ . From [24,25].



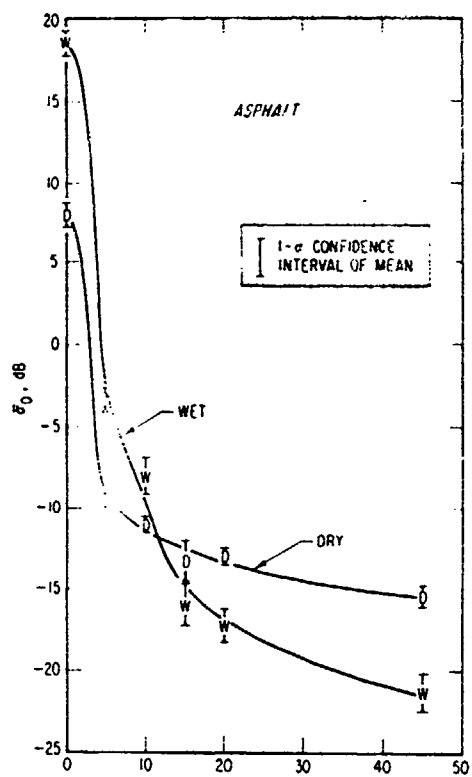
VH - Polarized Backscatter of Snow Measured in 1984 and 1986 for Various Liquid Water Contents  $m_v$ . From [24,25].



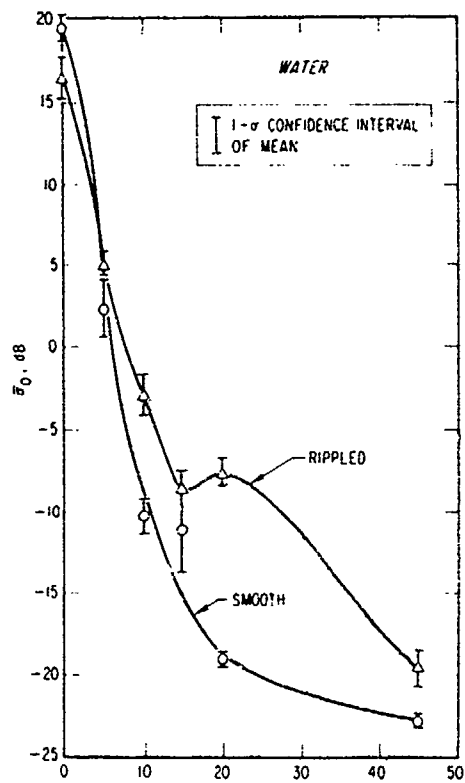
VV - Polarized Backscatter of Snow Measured in 1984 and 1986 Liquid Water Content of 5% and Various Surface Roughnesses ( $h$  = rms height). From [24,25].



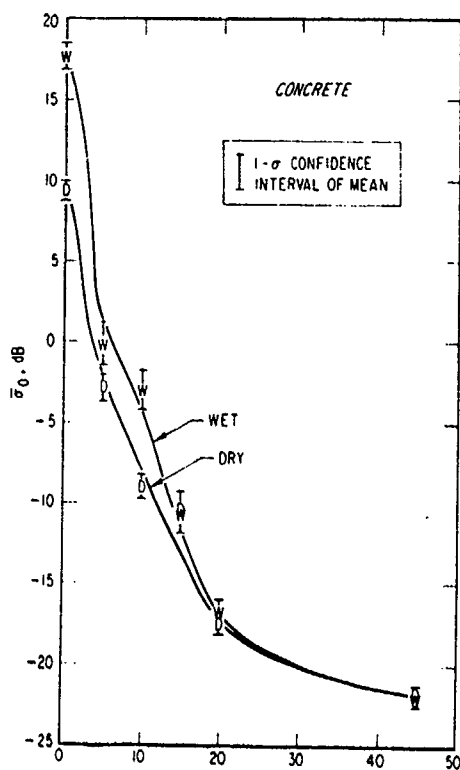
VH - Polarized Backscatter of Snow Measured in 1984 and 1986 Liquid Water Content of 5% and Various Surface Roughnesses ( $h$  = rms height). From [24,25].



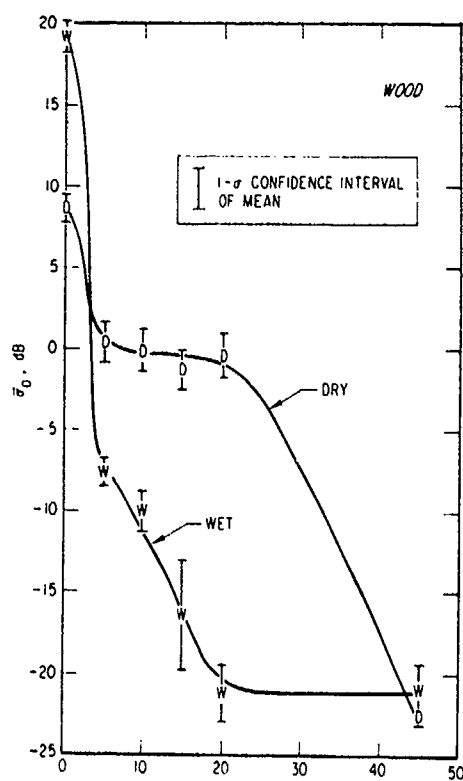
ANGLE OF INCIDENCE, deg  
Mean  $\sigma_0$  for wet and dry asphalt.



ANGLE OF INCIDENCE, deg  
Mean  $\sigma_0$  for smooth and rippled water.

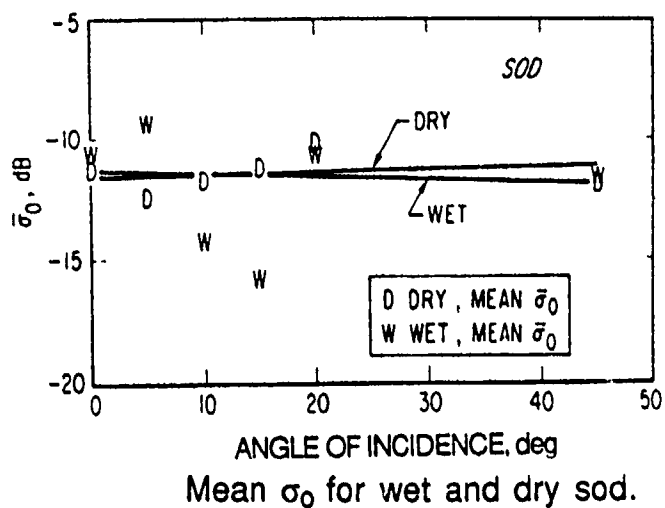
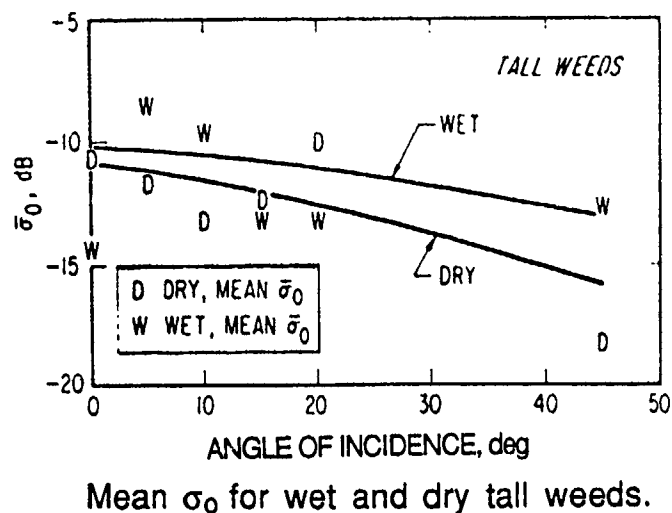
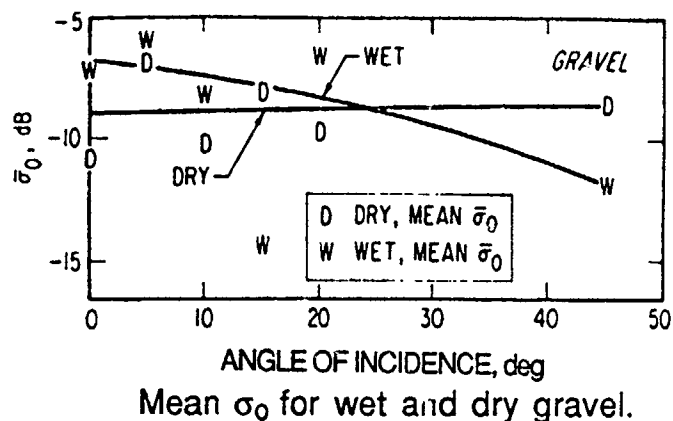


ANGLE OF INCIDENCE, deg  
Mean  $\sigma_0$  for wet and dry concrete.

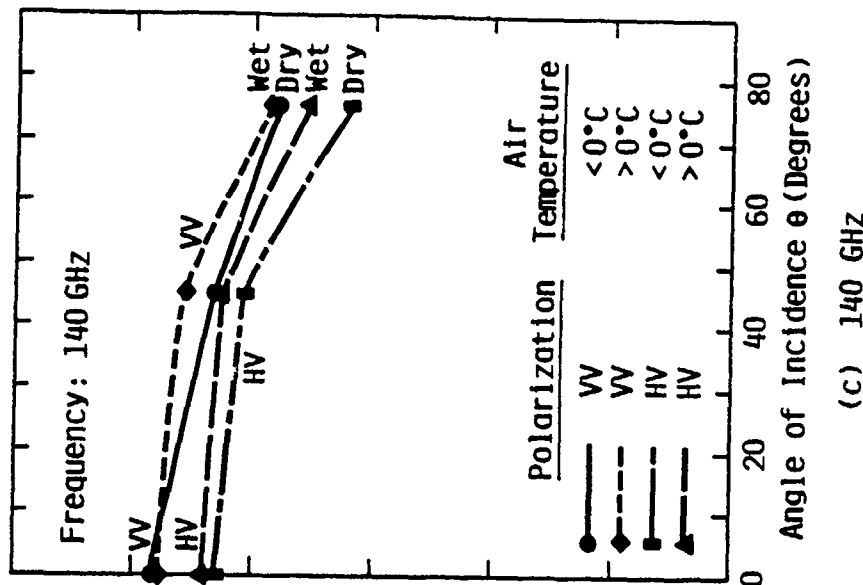
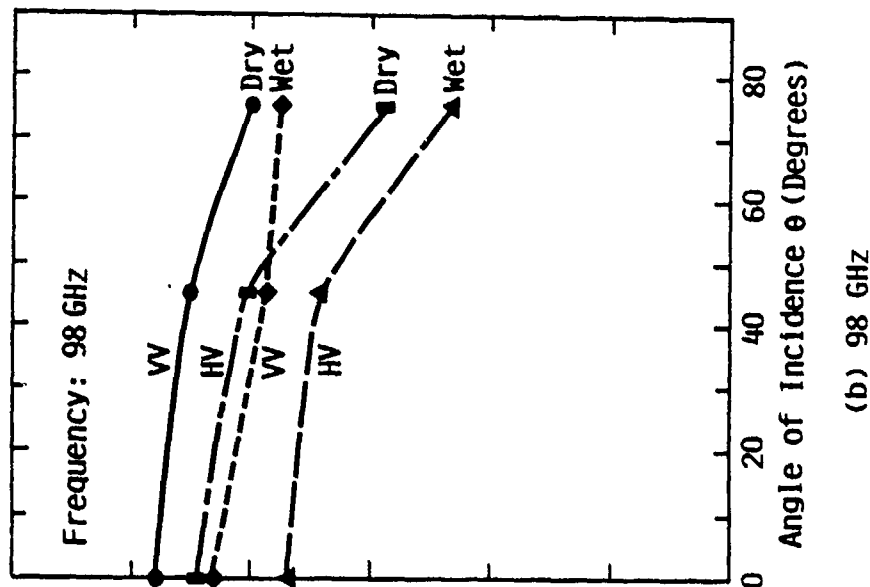
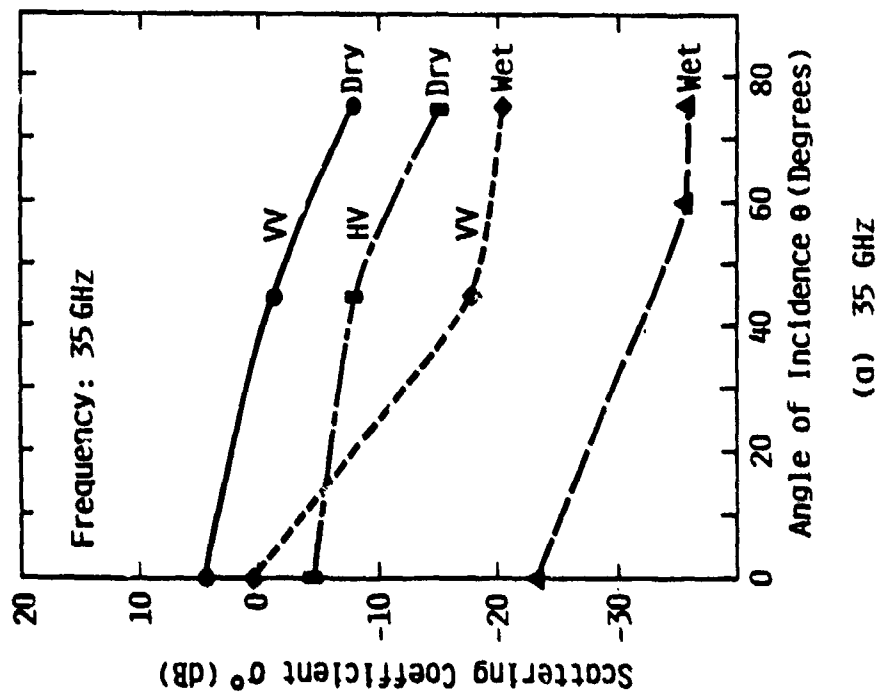


ANGLE OF INCIDENCE, deg  
Mean  $\sigma_0$  for wet and dry wood.

Backscattering Coefficient, Averaged over 40-90 GHz for various surfaces. From [26].



Backscattering Coefficient, Averaged over 40-90 GHz for various surfaces. From [26].



Backscattering Coefficient at (a) 35 GHz, (b) 98 GHz, and (c) 140 GHz for Dry and Wet Snow. From [28].

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