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MILLIMETER - WAVE RADAR SCATTERING FROM TERRAIN: DATA HANDBOOK

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I. INTRODUCTION

This handbook provides plots of millimeter-wave (MMW) radar scattering data for terrain based on backscattering measurements made by the University of Michigan's Millimeter-Wave Polarimeter system during the 1987-1989 time period. It is planned to issue an updated version of this handbook in late 1990 that will include additional data acquired in 1990 as well as MMW scattering data reported in the literature by other institutions.

Measurements made in 1987 and early 1988 consisted of observations of the backscattering coefficient σ^o at 35 and 94 GHz. Later measurements included 140 GHz observations as well. Most of the data are presented in the form of plots of σ^o versus the incidence angle θ for each of the three principal linear polarization configurations: VV, HV, and HH, where H denotes horizontal polarization and V denotes vertical polarization. The radar measurements were often augmented with close-up observations of the target including such measurements as water content and surface roughness, where appropriate. For each data set, a summary of these observations and a photograph of the target scene are provided.

The Millimeter-Wave Polarimeter is a mobile truck-mounted radar system capable of making observations from a 20 m high platform at any incidence angle between 0^o (nadir) and 80^o. 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 1 shows a photograph of the system in operation and Figure 2 shows a close-up of the antenna platform. Table 1 provides a summary of the present system specifications and Appendix A includes a paper reprint that describes the system operation in more detail, although some of the specifications given in Appendix A are somewhat out of date.

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.

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

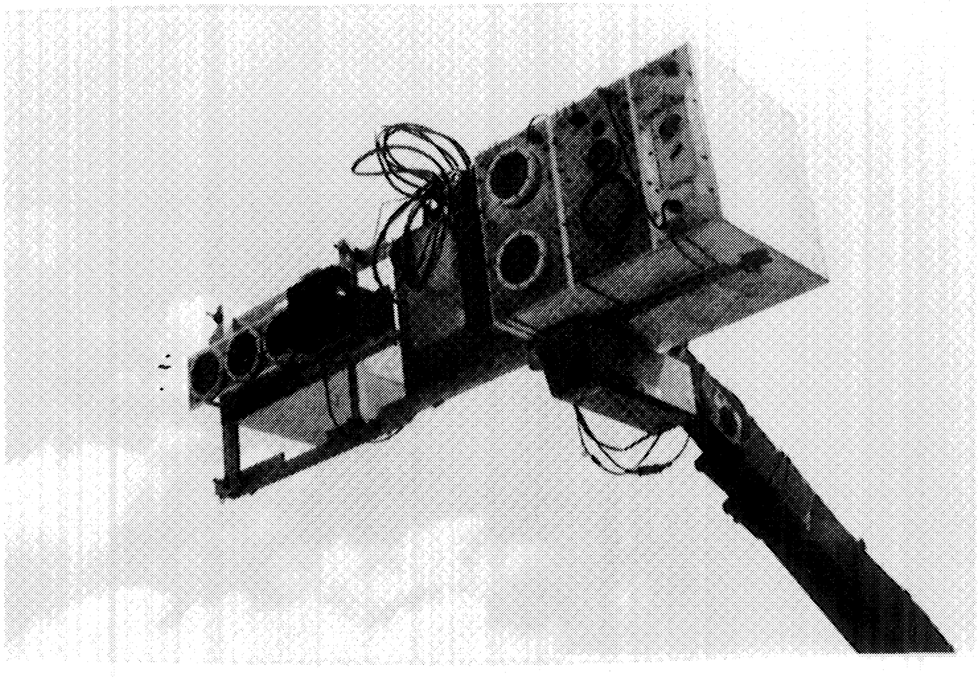


Fig. 2 Close-up view of the RF sections, showing the 35, 94, and 140 GHz radars on the right side, and radiometers at the same operating frequencies on the left side.

Table 1. Millimeter-wave Polarimeter system parameters.

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

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 σ^o.

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.

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 %.

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.

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 Vegetation 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.

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.

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

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.

II. 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.

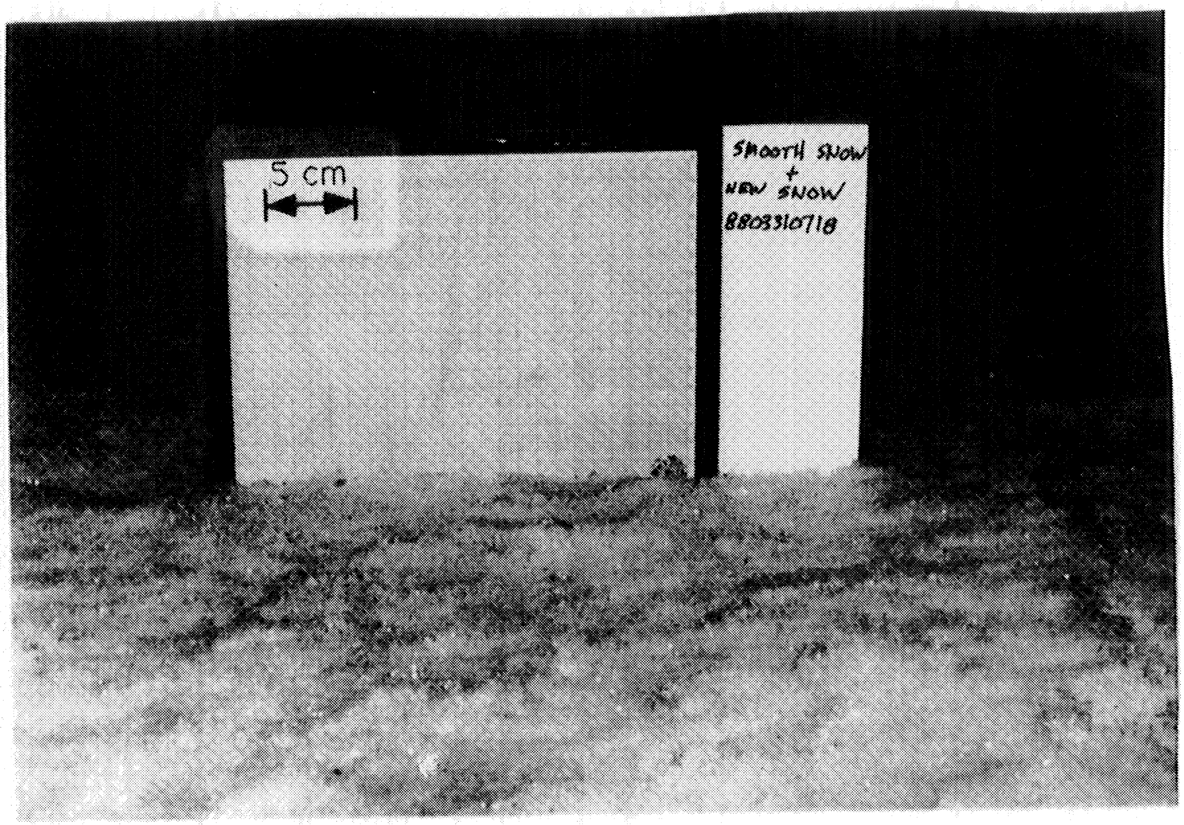
The following chart is included in order to give a more complete overview of the characteristics of the data:

Data Set Code	A (smooth surface)	B (slightly rough surface)	C (very rough surface)	D (heavily metamorphosed)	E (unmetamorphosed fresh)	F (small crystal size)	G (large crystal size)
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

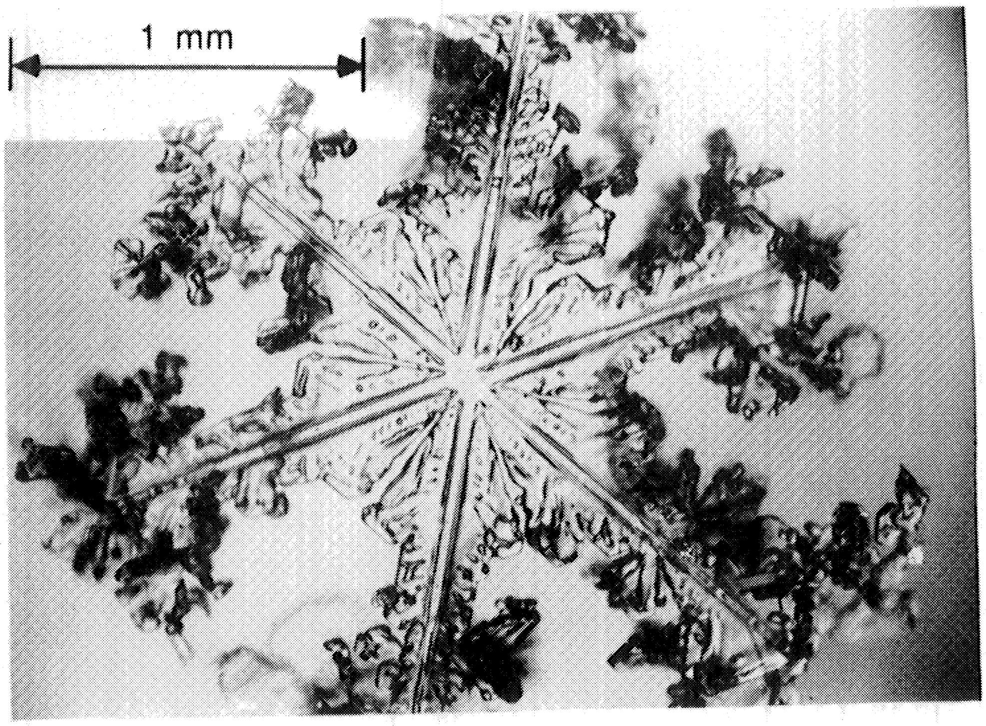
Dry snow
Data set code: 880329(S)
Depth: 20-30 cm
LWC: 0 %
Surface RMS height: 1 cm
Density: 0.3 to 0.4 gm/cm^3
Ice crystal diameter: 1 to 4 mm
Surface temperature: -2.0 C
Description: smooth snow surface



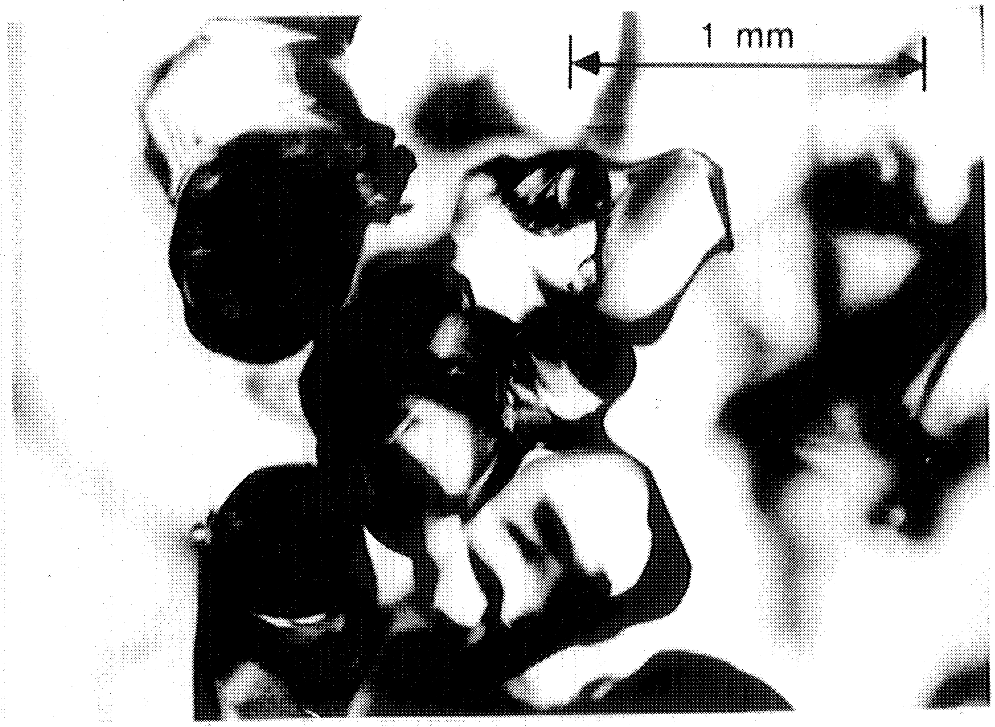
Surface roughness profile with 1 cm grid

MMW DATA FOR DRY SNOW

880329(S)



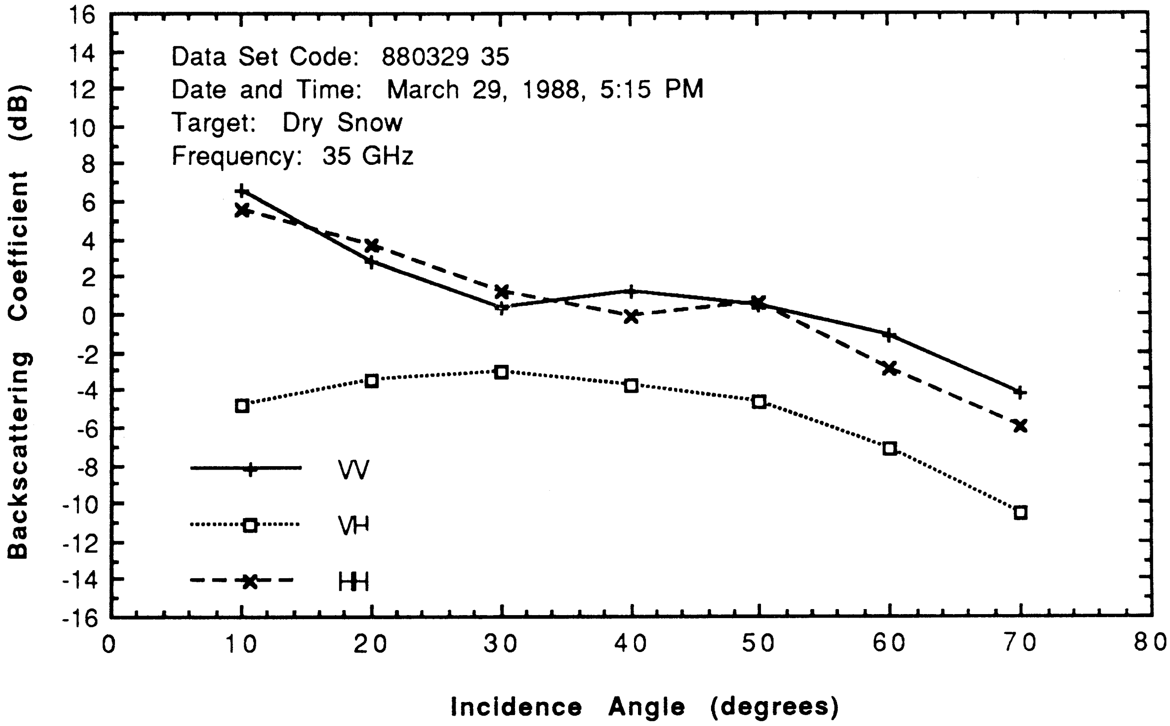
Snow crystal from surface



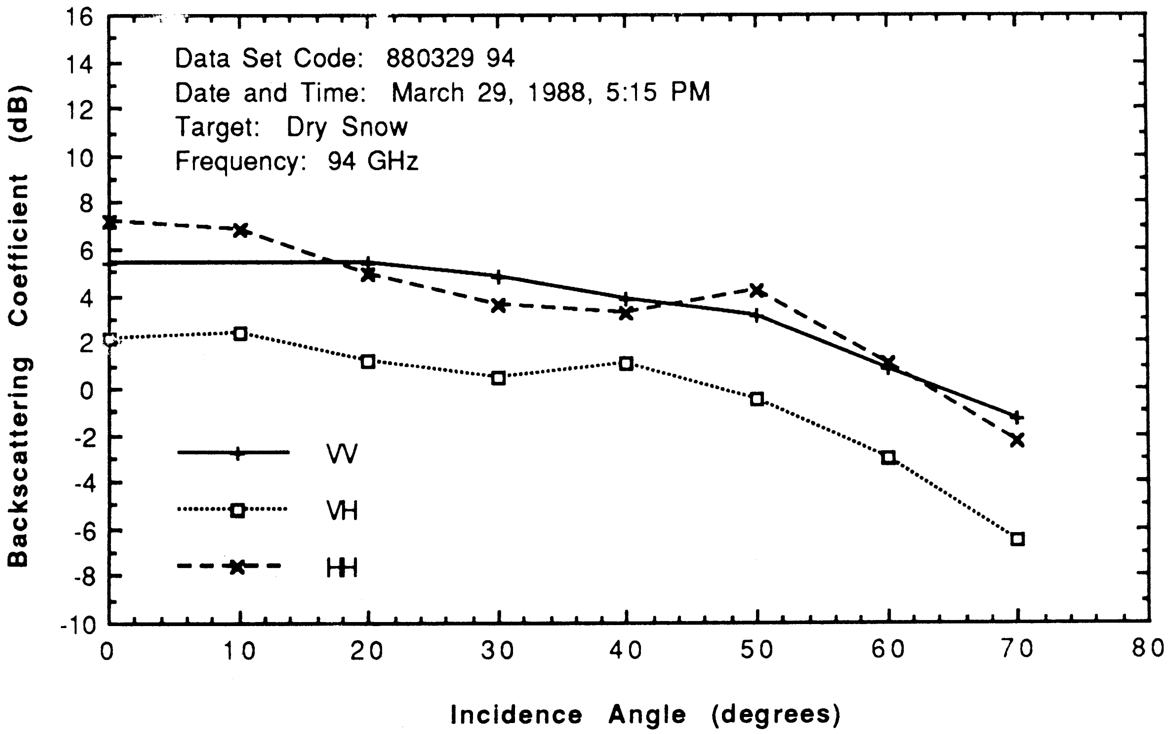
Metamorphosed crystal from middle of snowpack

MMW DATA FOR DRY SNOW

880329(S)



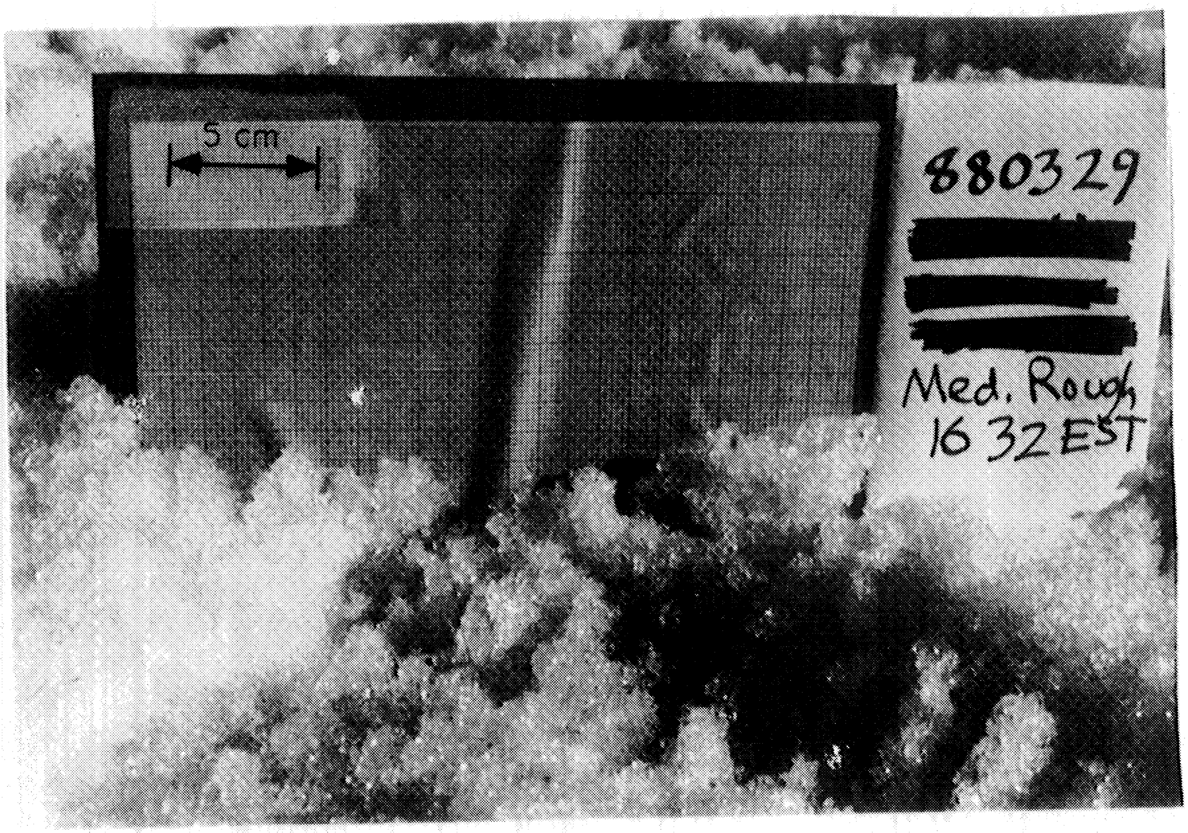
Smooth snow at Houghton



Smooth snow at Houghton

B. Slightly Rough Surface

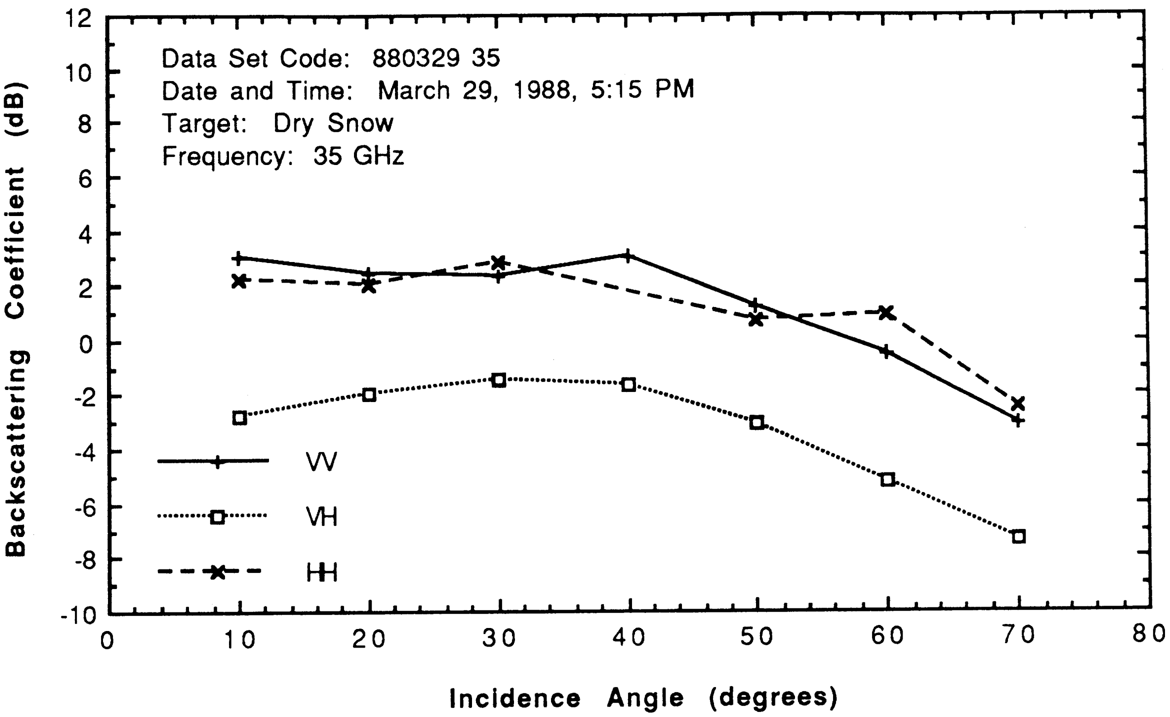
Dry snow
Data set code: 880329 (SR)
Depth: 20 to 30 cm
LWC: 0%
Surface RMS height: 1 cm
Density: 0.3 to 0.4 gm/cm^3
Ice crystal diameter: 1 to 4 mm
Surface temperature: 0 C
Description: snowpack of highly metamorphosed snow with a slightly rough surface



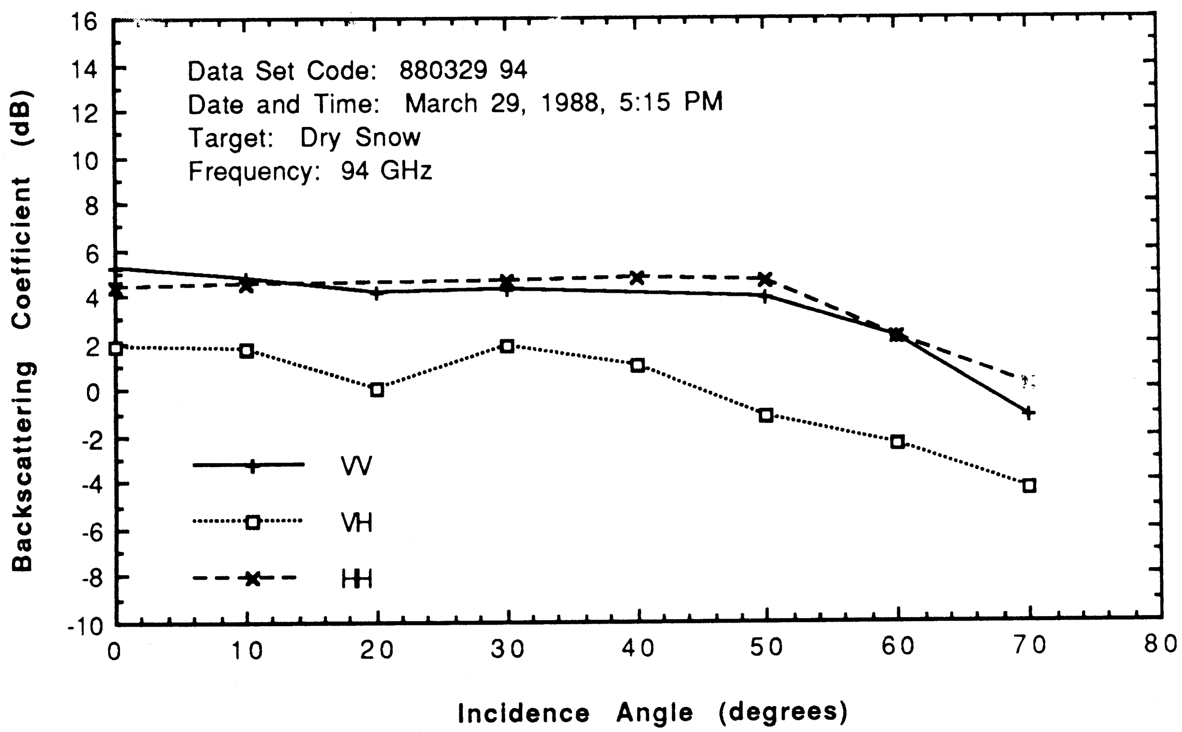
Surface roughness profile with 1 cm grid

MMW DATA FOR DRY SNOW

880329(SR)



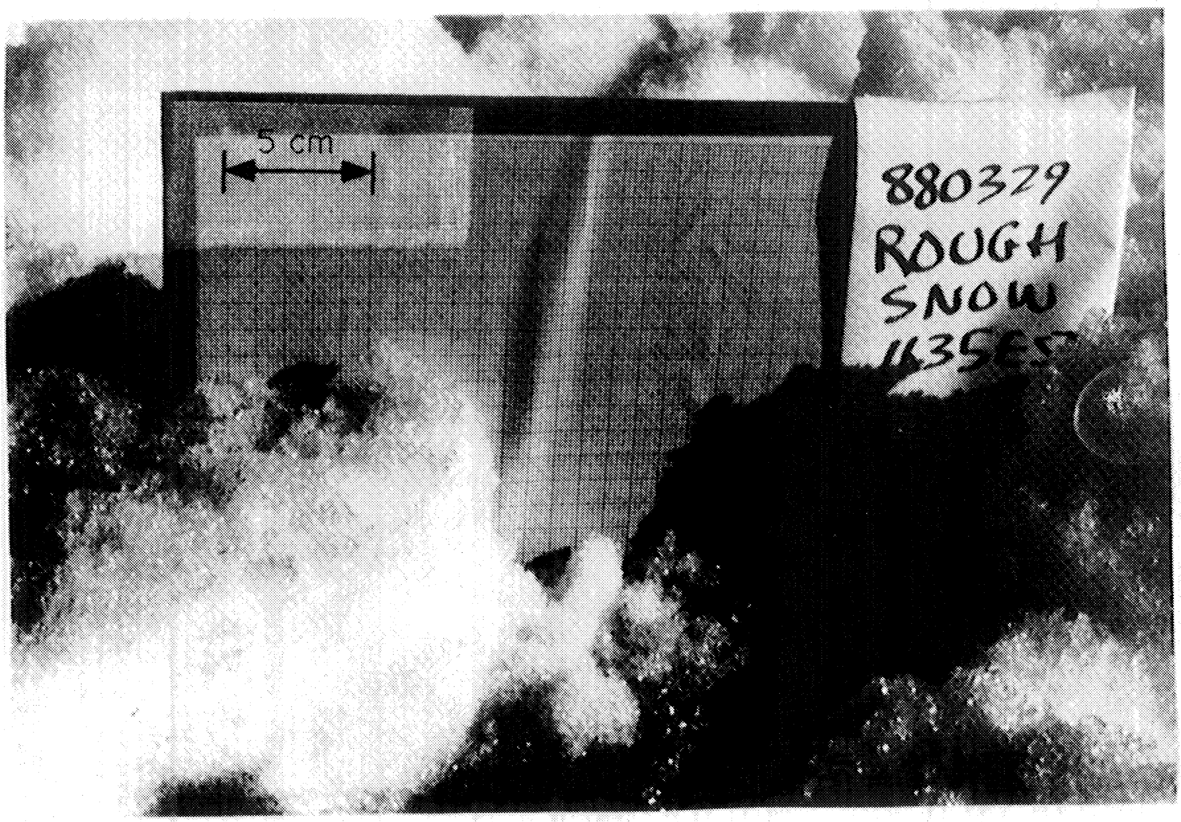
Slightly rough snow at Houghton



Slightly rough snow at Houghton

C. Very Rough Surface

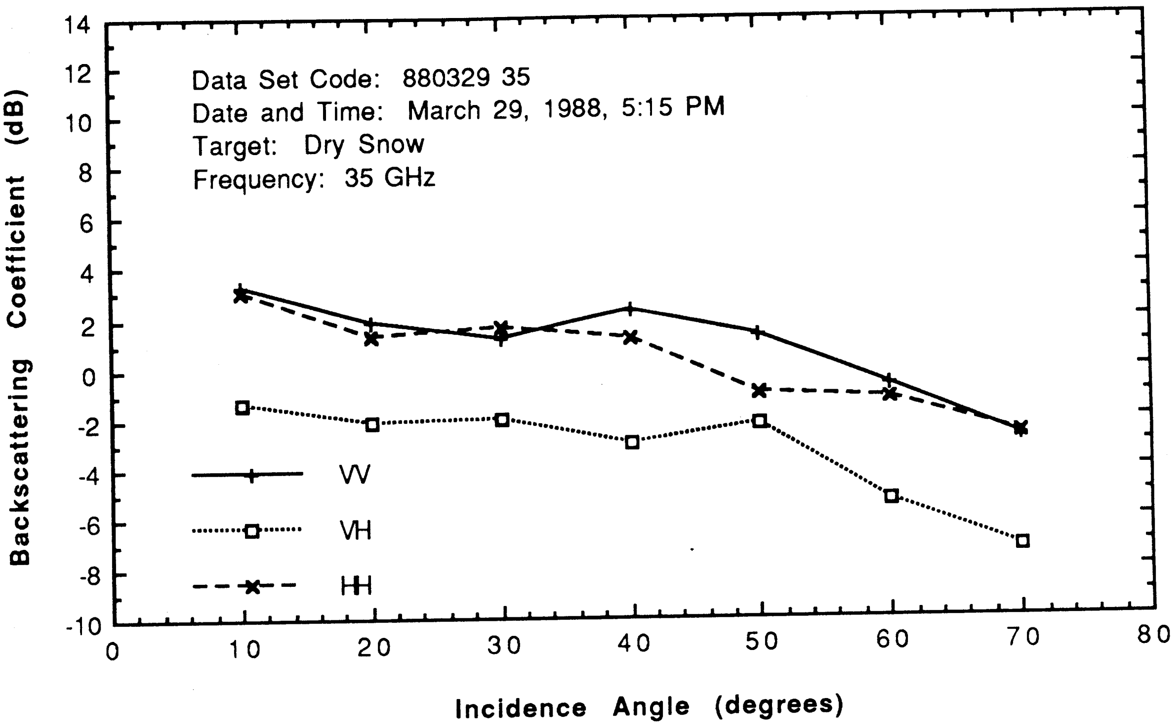
Dry snow
Data set code: 880329(VR)
Depth: 20 to 30 cm
LWC: 0%
Surface RMS height: 4 cm
Density: 0.3 to 0.4 gm/cm^3
Ice crystal diameter: 1 to 4 mm
Surface temperature: 0 C
Description: snowpack of highly metamorphosed snow with a rough surface



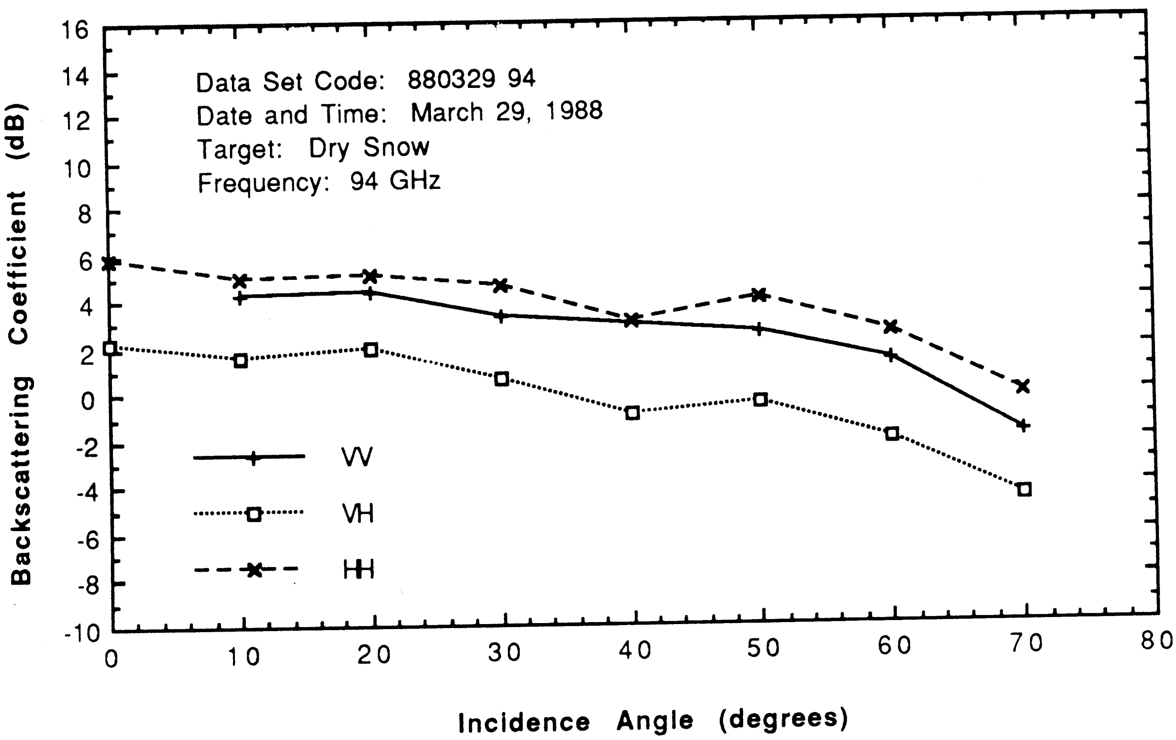
Surface roughness profile with 1 cm grid

MMW DATA FOR DRY SNOW

880329(VR)



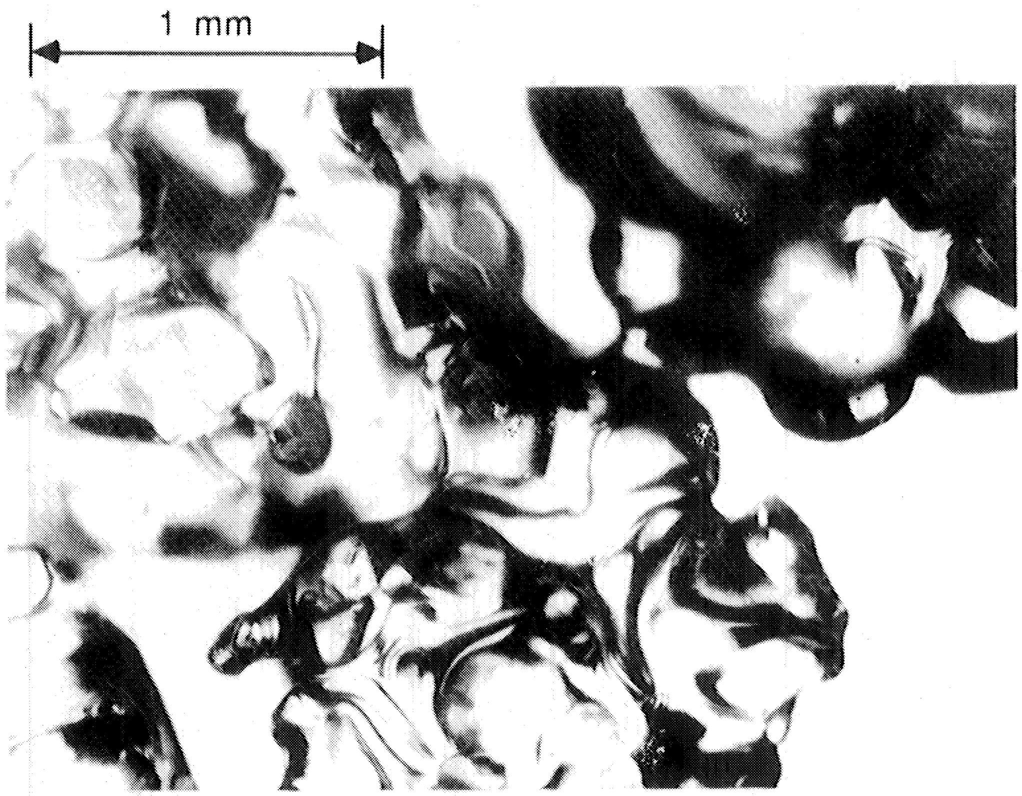
Very rough snow at Houghton



Very rough snow at Houghton

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^3
Ice crystal diameter: 2 to 4 mm
Surface temperature: -4.8 C
Description: heavily metamorphosed snow

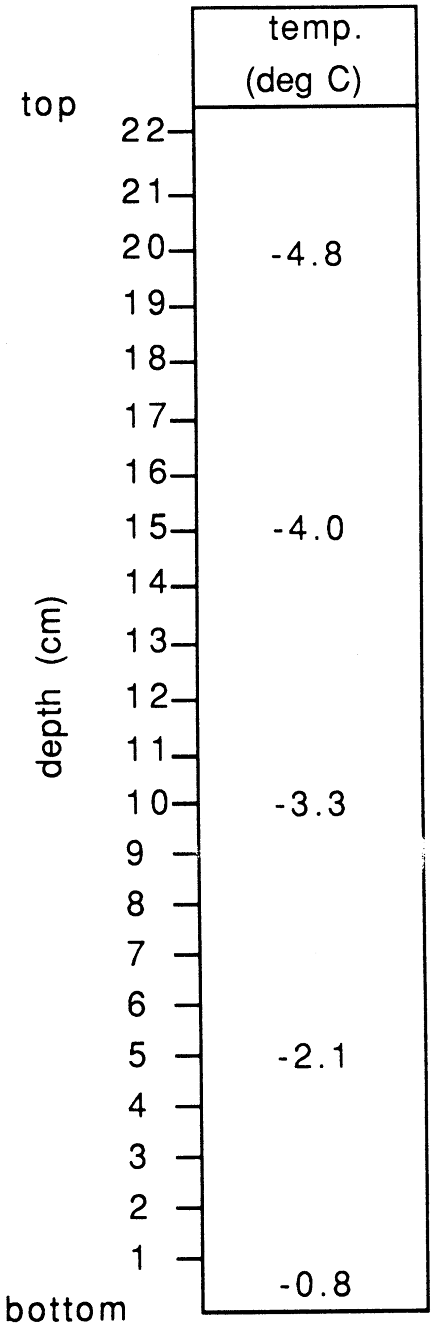


Metamorphosed crystal from top of the snowpack

MMW DATA FOR DRY SNOW

890210

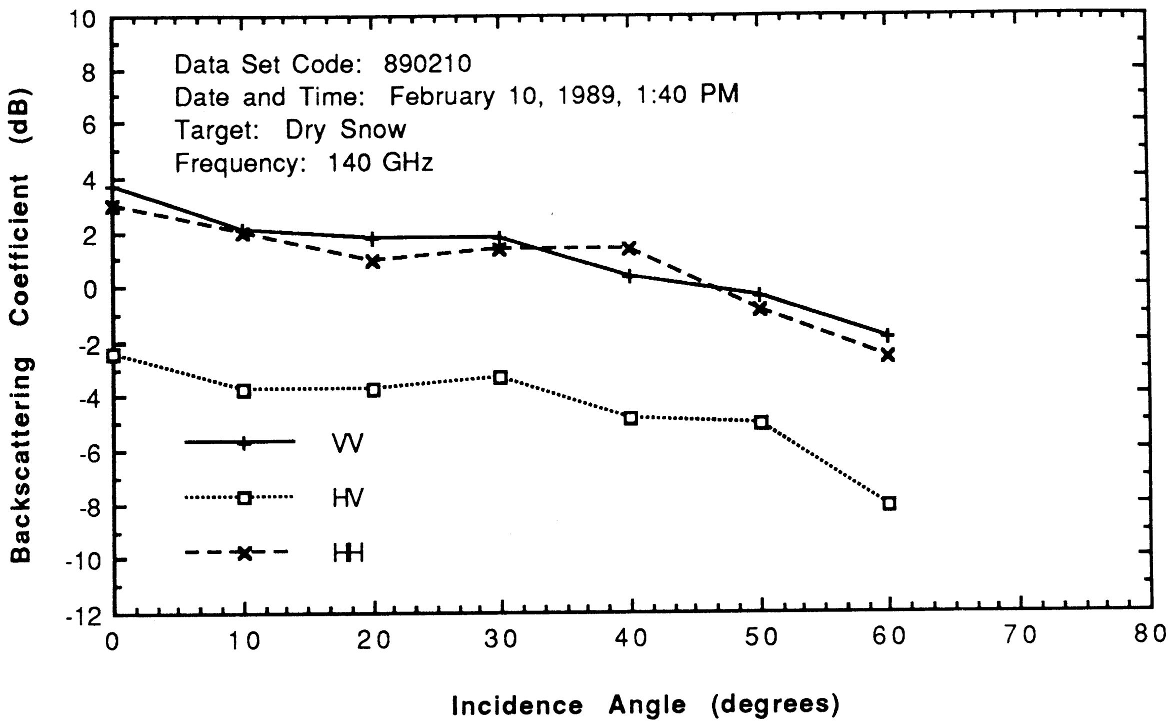
SNOW PIT PROFILE FOR 890210



air temperature: -4.4 C

MMW DATA FOR DRY SNOW

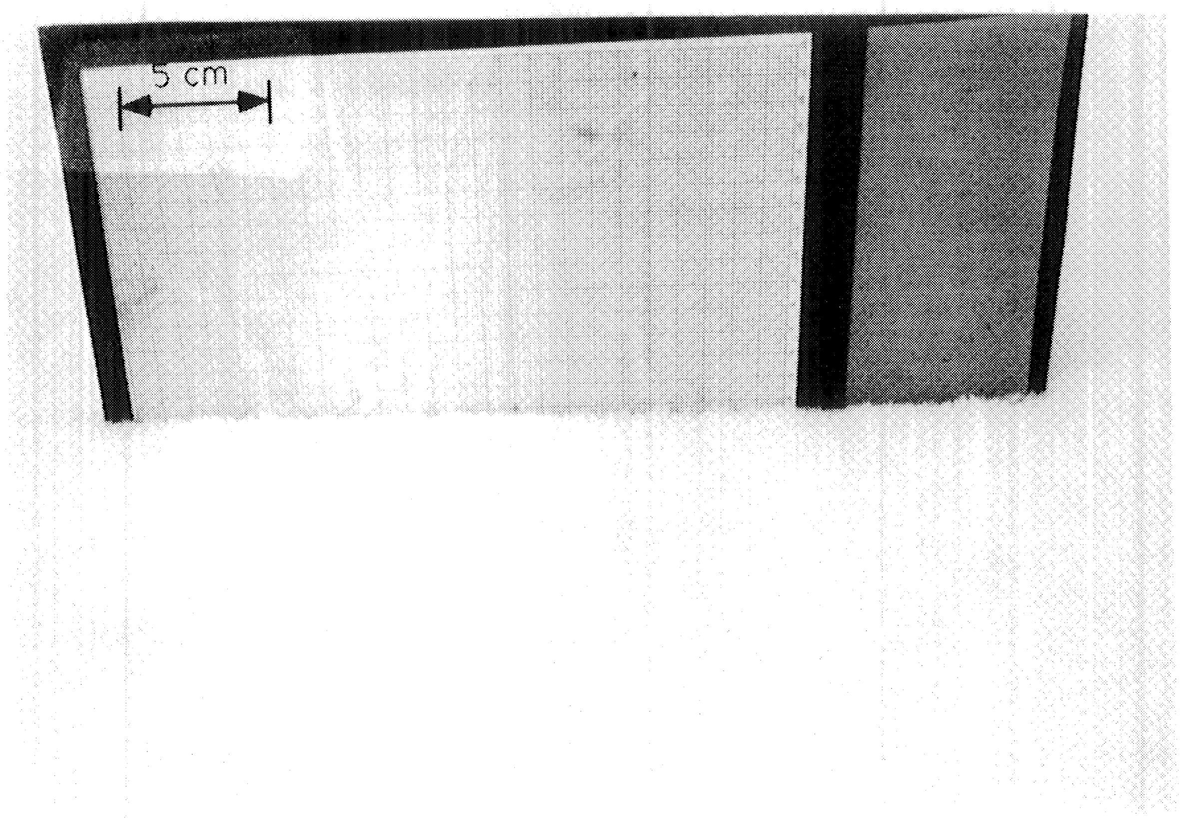
890210



Snow at Brighton

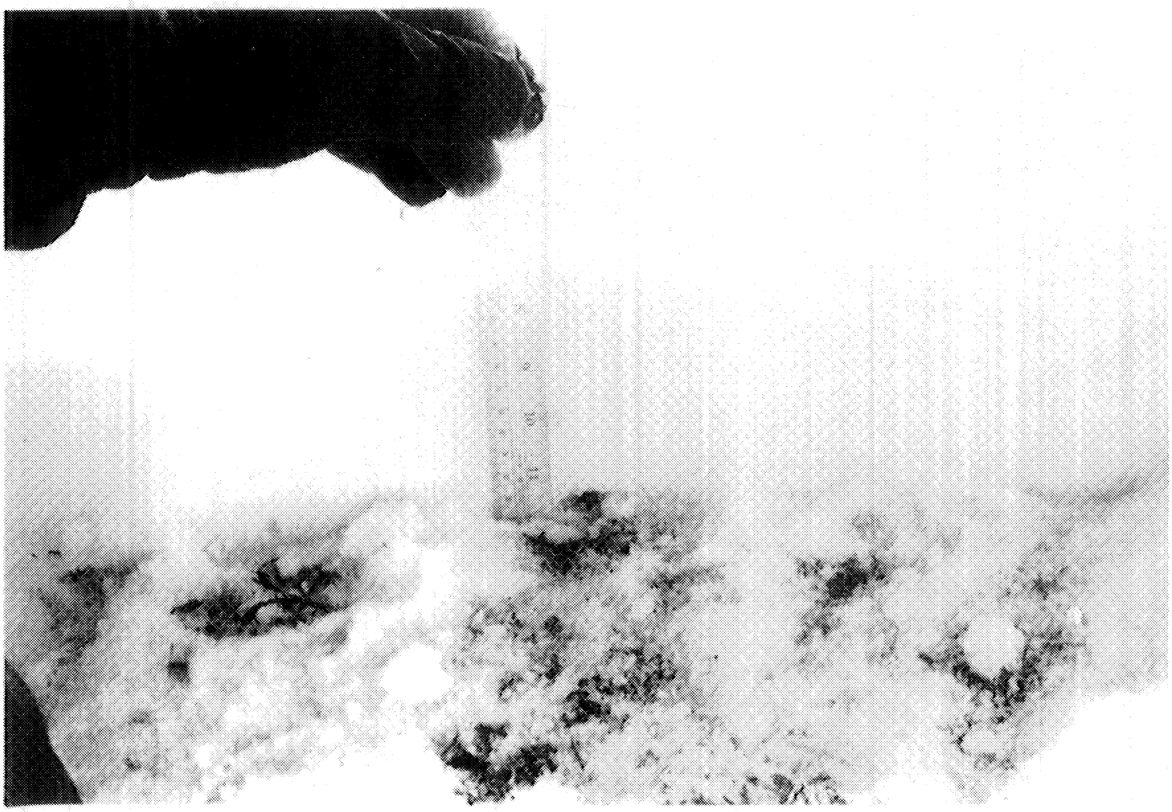
E. Unmetamorphosed Fresh Snow

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^3
Ice crystal diameter: 1 to 2 mm
Surface temperature: -7 C
Description: dry unmetamorphosed snow



Surface roughness profile with 1 cm grid

890223

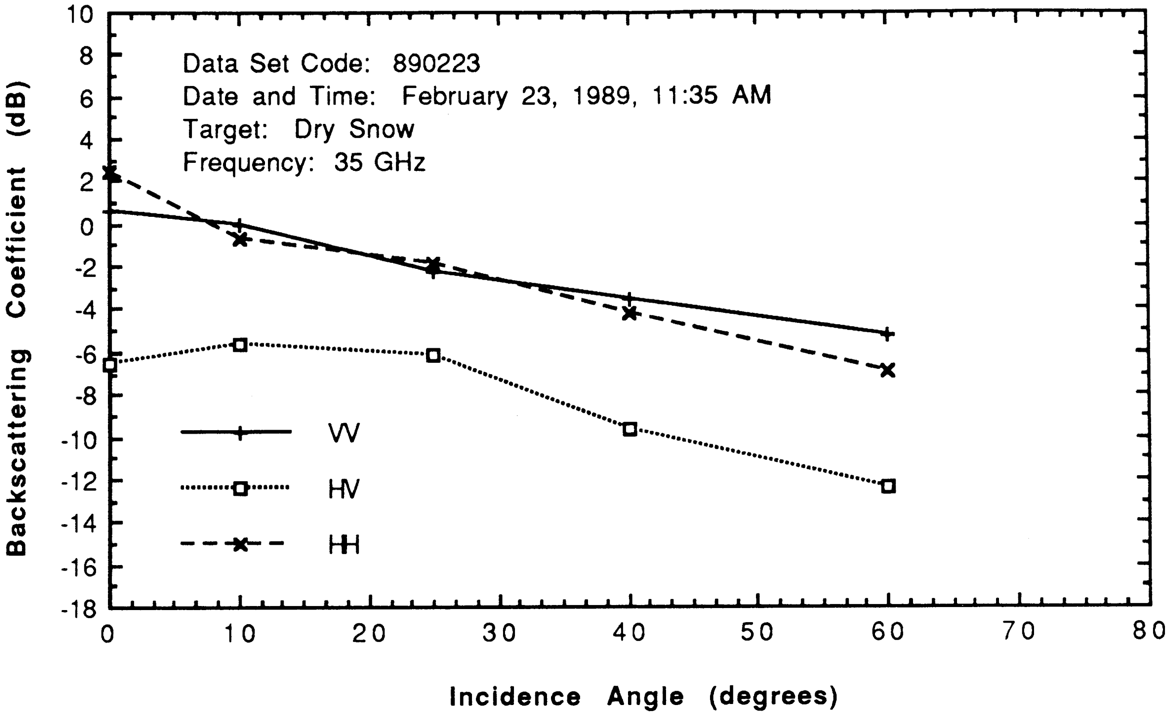


Snow pit

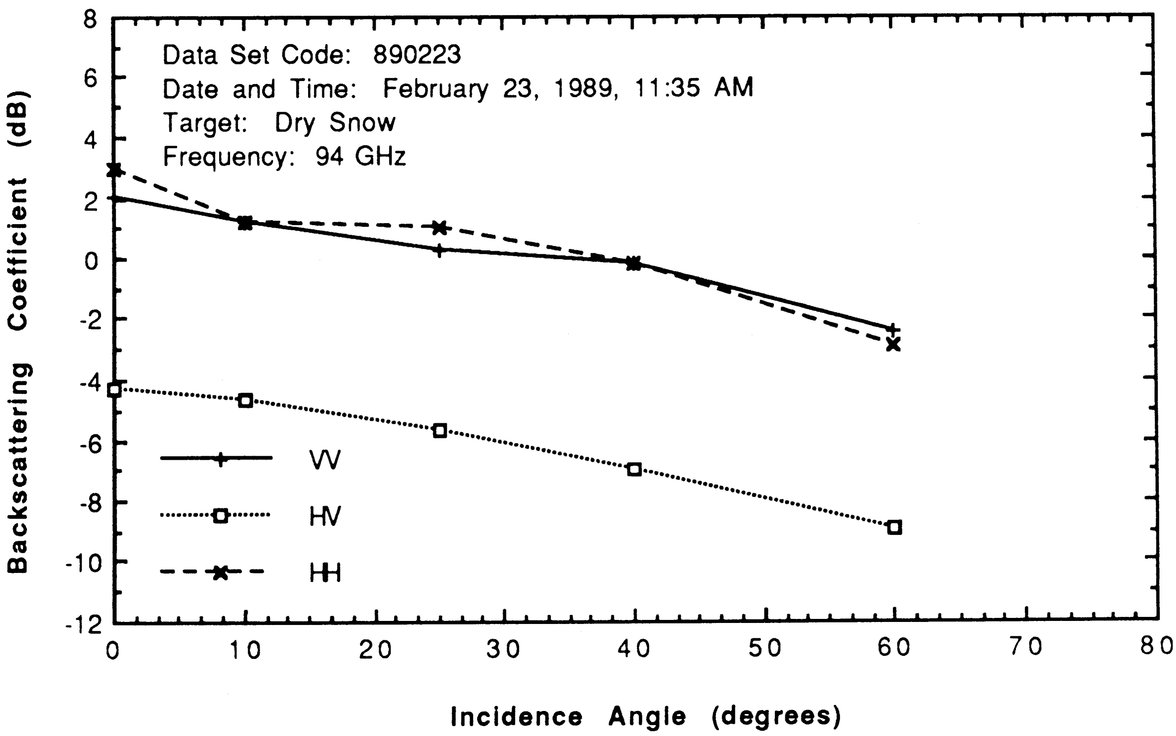
Data collection scene

MMW DATA FOR DRY SNOW

890223



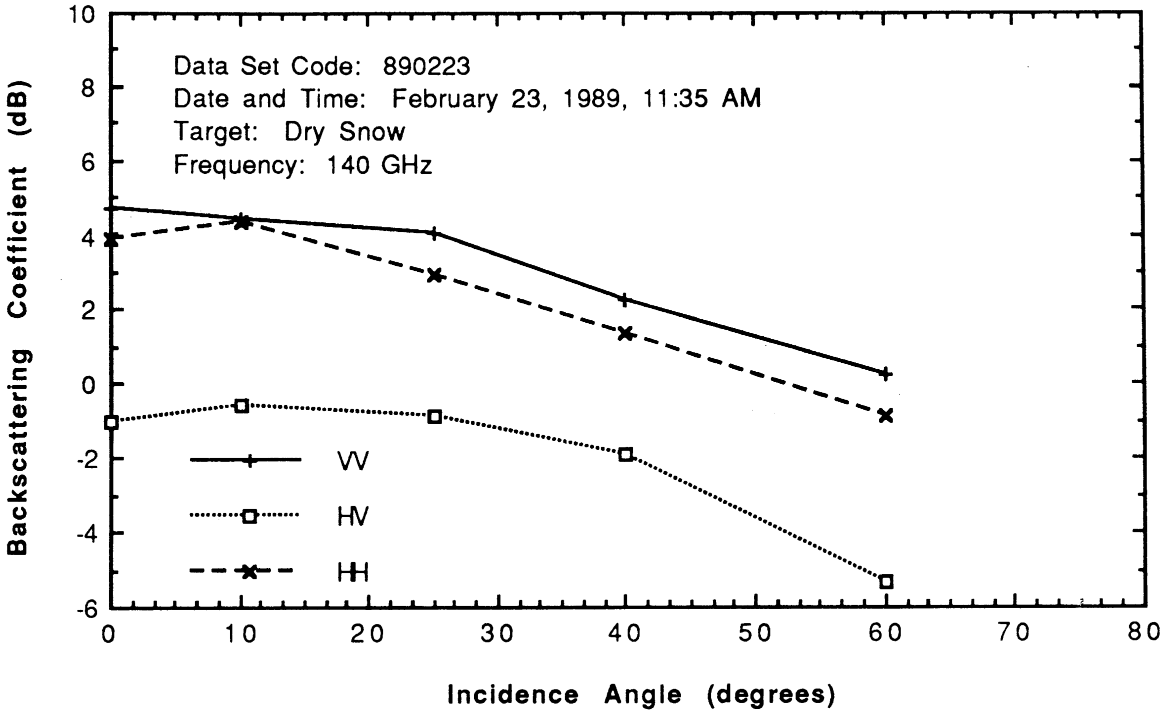
Dry snow at Brighton



Dry snow at Brighton

MMW DATA FOR DRY SNOW

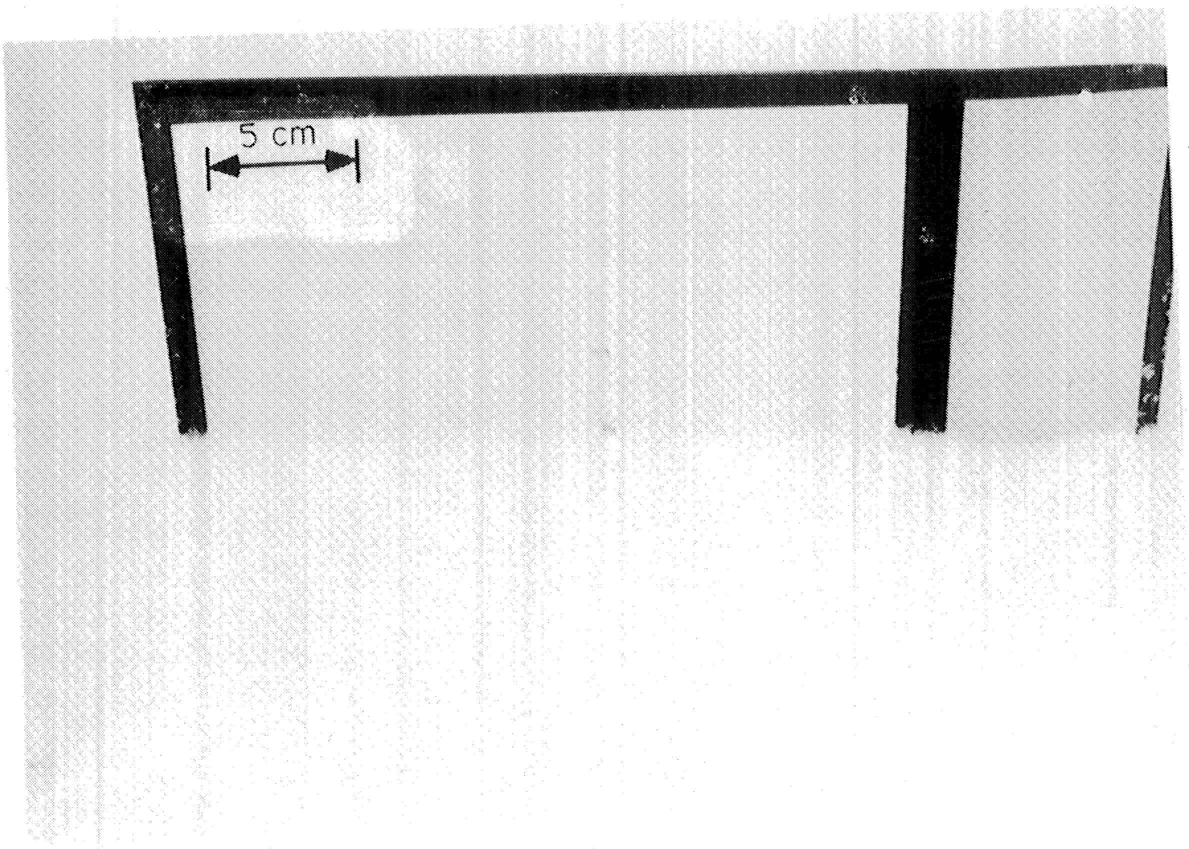
890223



Dry snow at Brighton

F. Small Crystal Size

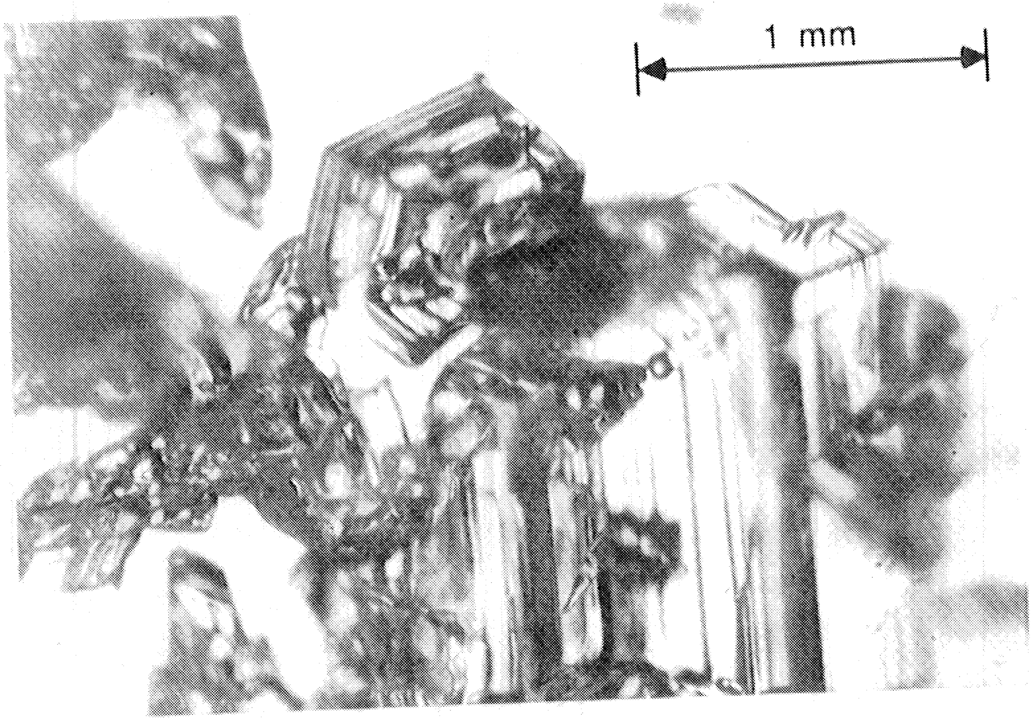
Dry snow
Data set code: 890302(sm)
Depth: 10 cm
LWC: 0 %
Surface RMS height: 0.15 cm
Density: 0.1 to 0.2 gm/cm^3
Ice crystal diameter: 1 mm
Surface temperature: -5 C
Description: smooth snow surface



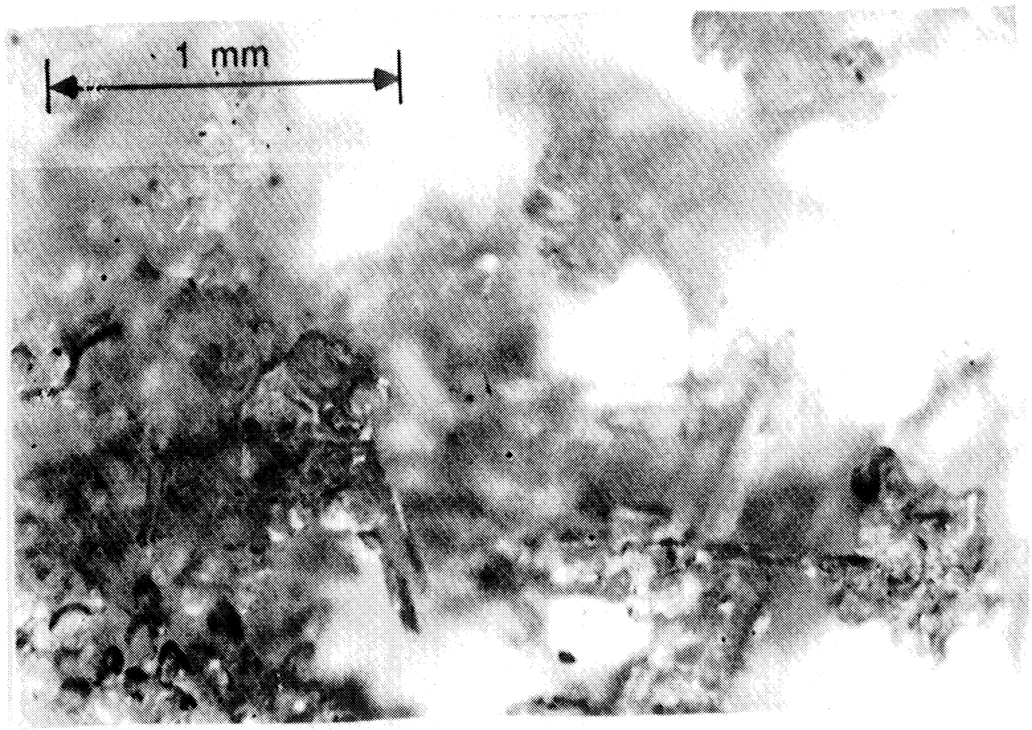
Surface profile with 1 cm grid

MMW DATA FOR DRY SNOW

890302(SM)



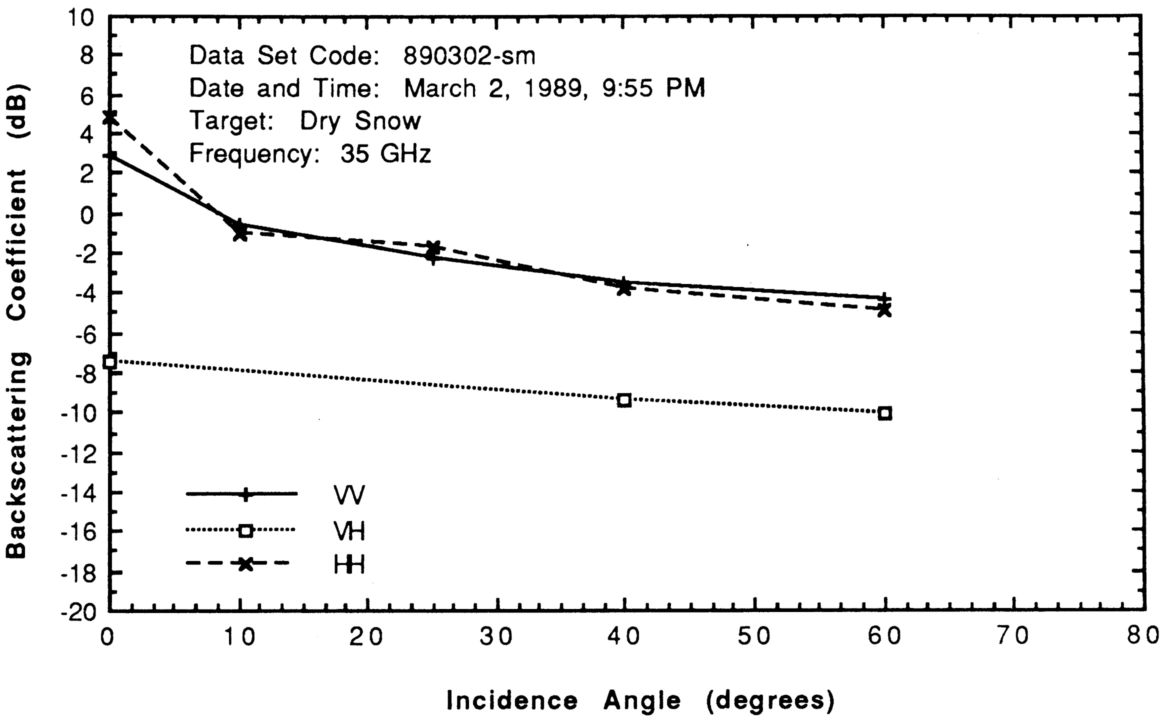
Snow crystals from surface



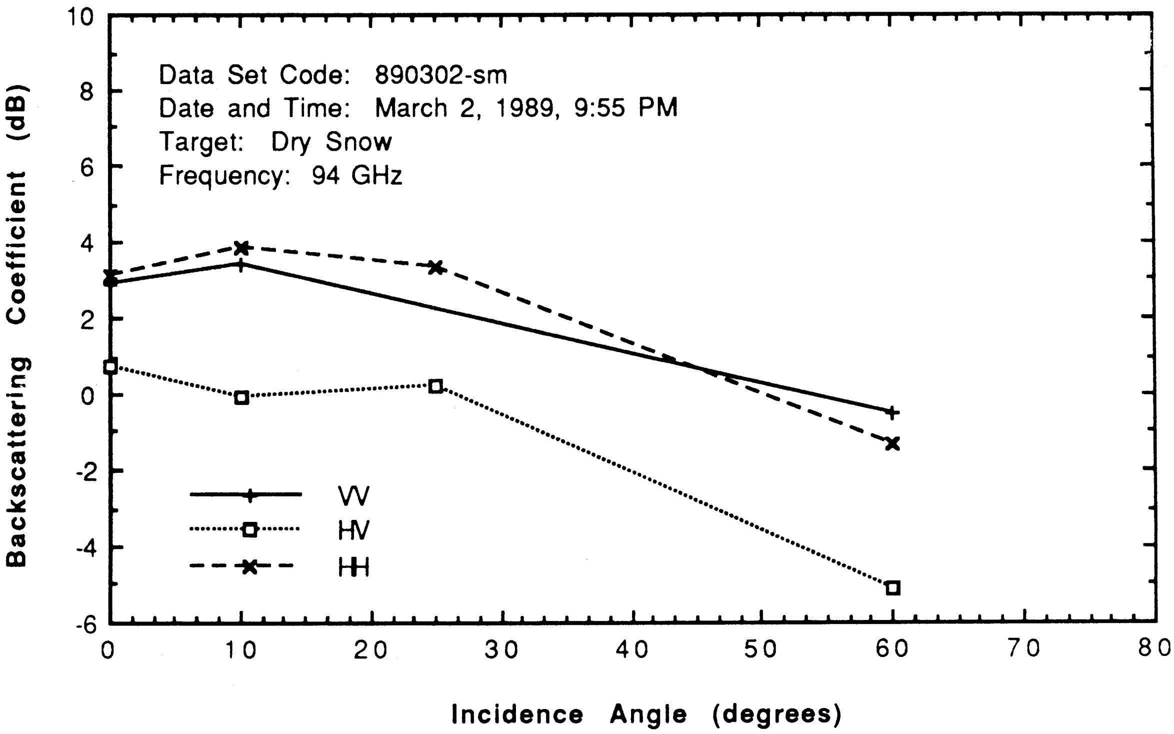
Snow crystals from bottom of snowpack

MMW DATA FOR DRY SNOW

890302(SM)



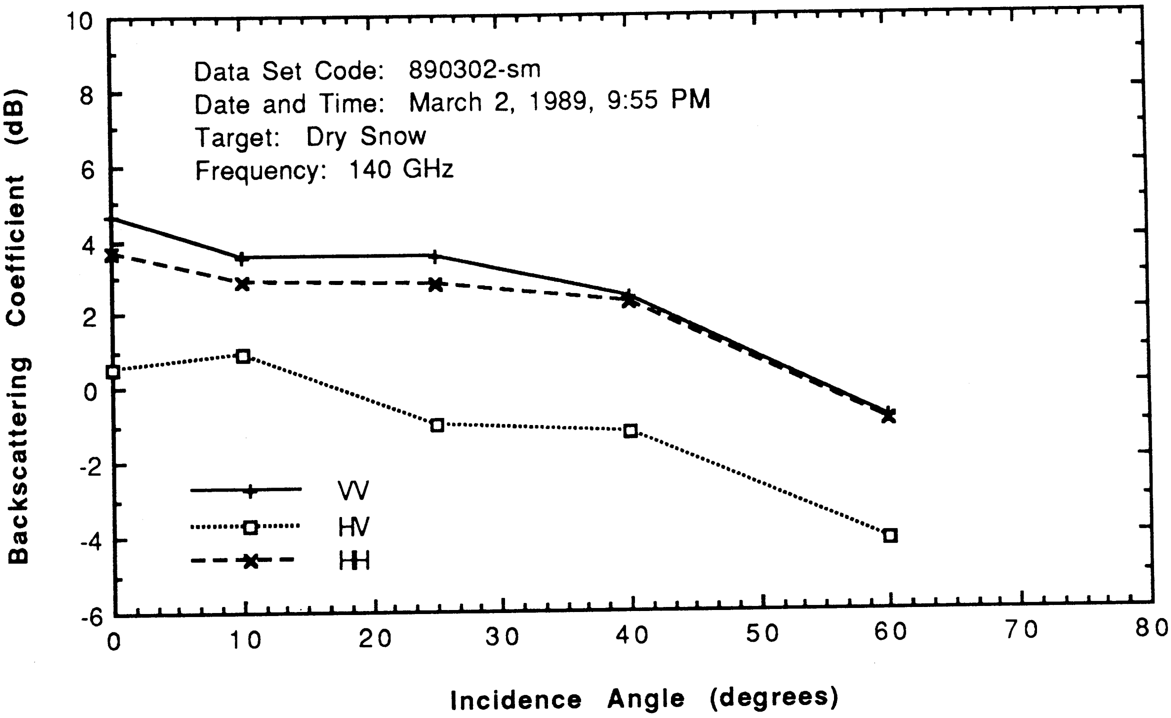
Small snow crystals at Brighton



Small snow crystals at Brighton

MMW DATA FOR DRY SNOW

890302(SM)

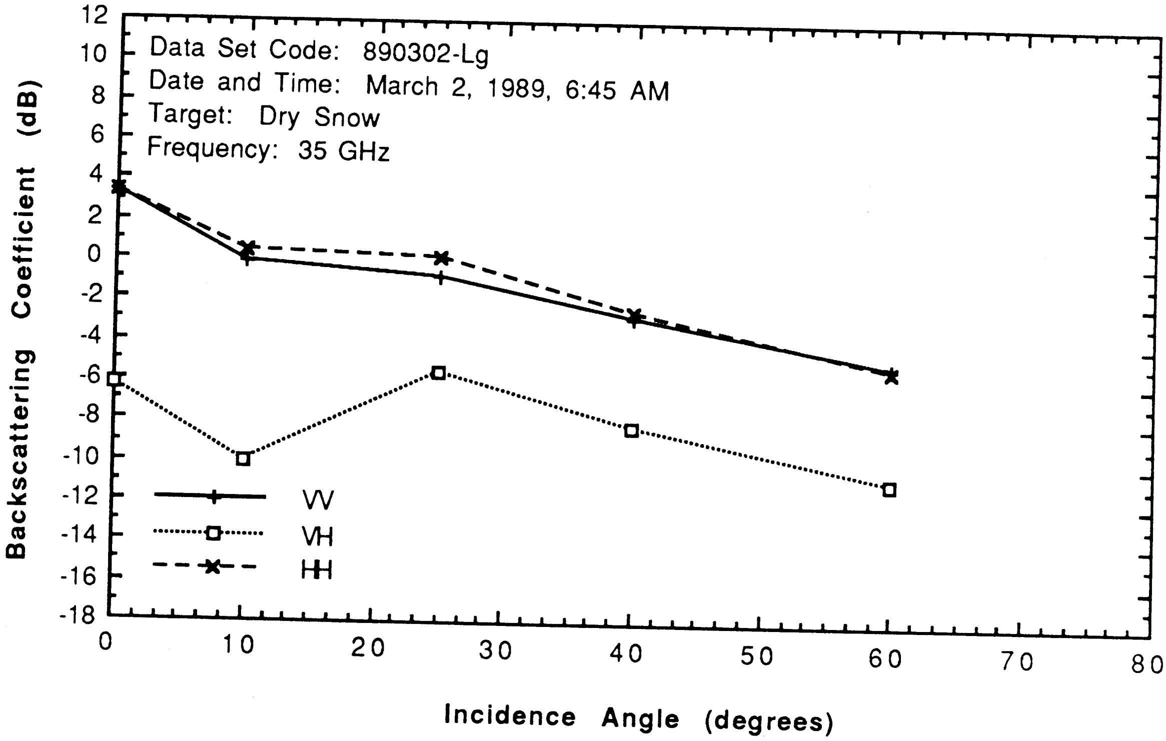


Small snow crystals at Brighton

G. Large Crystal Size

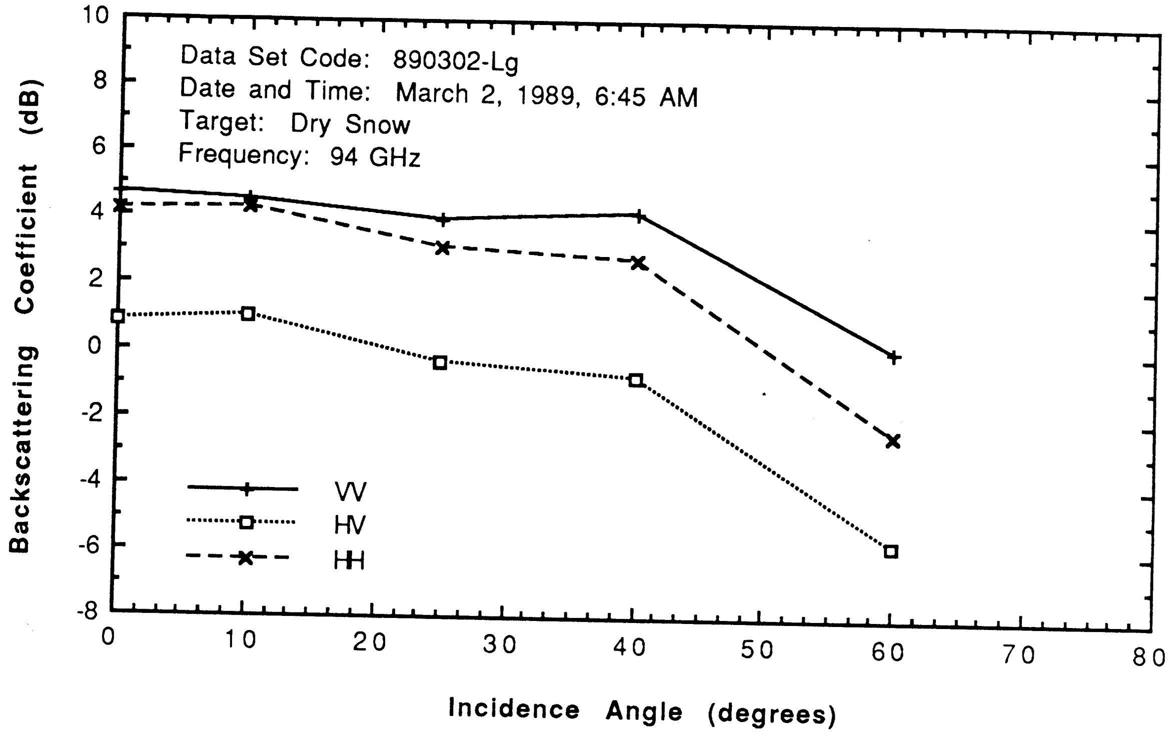
Dry snow
Data set code: 890302(Lg)
Depth: 10 cm
LWC: 0 %
Surface RMS height: 0.15 cm
Density: 0.1 to 0.2 gm/cm^3
Ice crystal diameter: 2 to 2.5 mm
Surface temperature: -5 C
Description: fresh smooth snow surface

890302(LG)



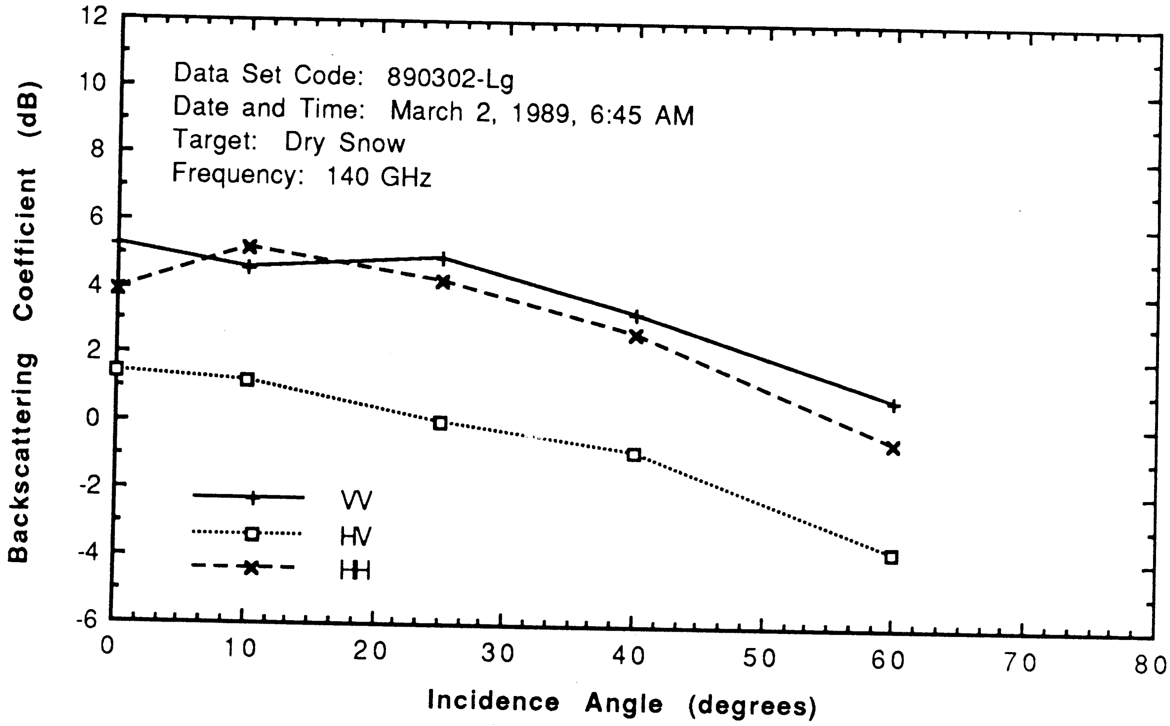
Large snow crystals at Brighton

MMW DATA FOR DRY SNOW



Large snow crystals at Brighton

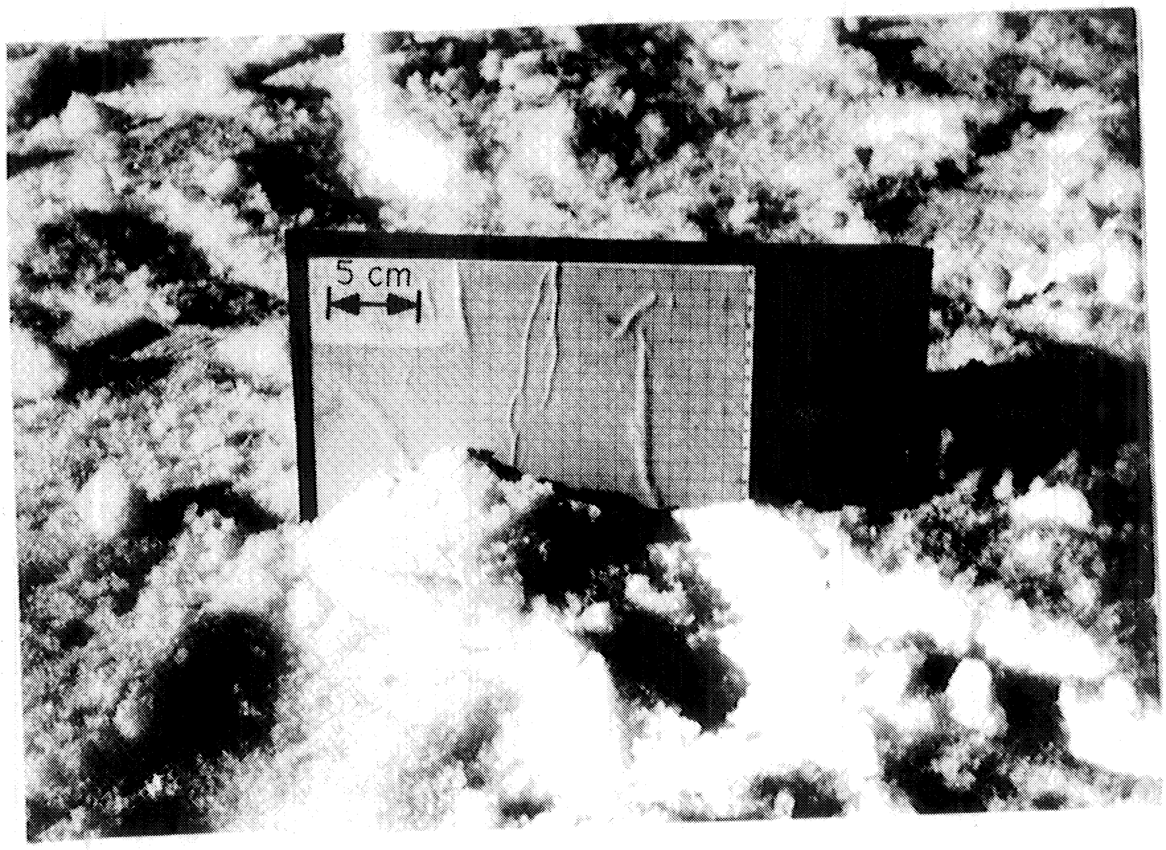
890302(LG)



Large snow crystals at Brighton

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^3
Ice crystal diameter: 2 to 4 mm
Surface temperature: -10 to -12 C
Description: dry, slightly metamorphosed snow

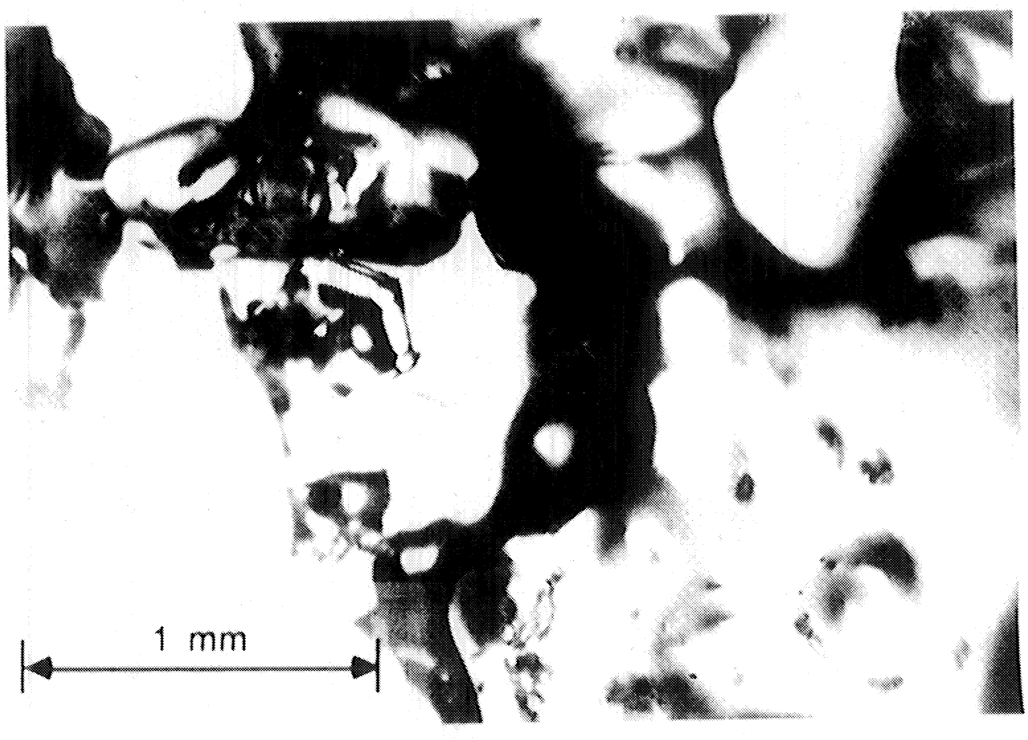


Surface roughness profile with 1 cm grid

MMW DATA FOR DRY SNOW

890307(RO)

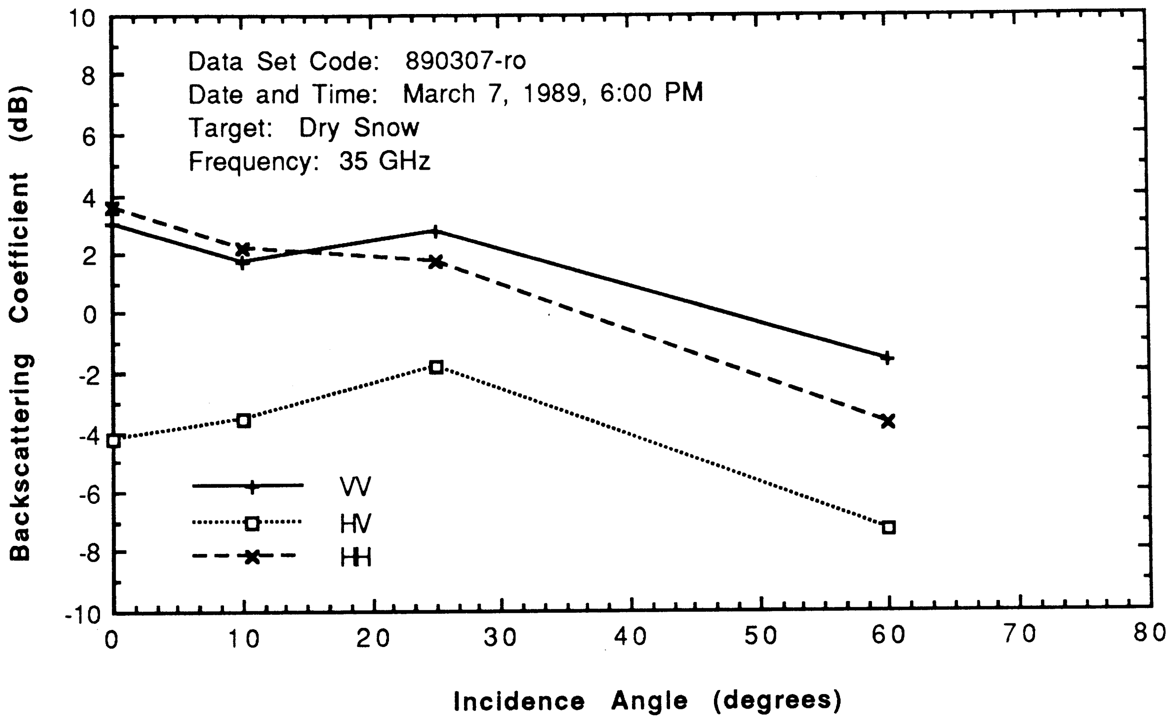
Data collection scene



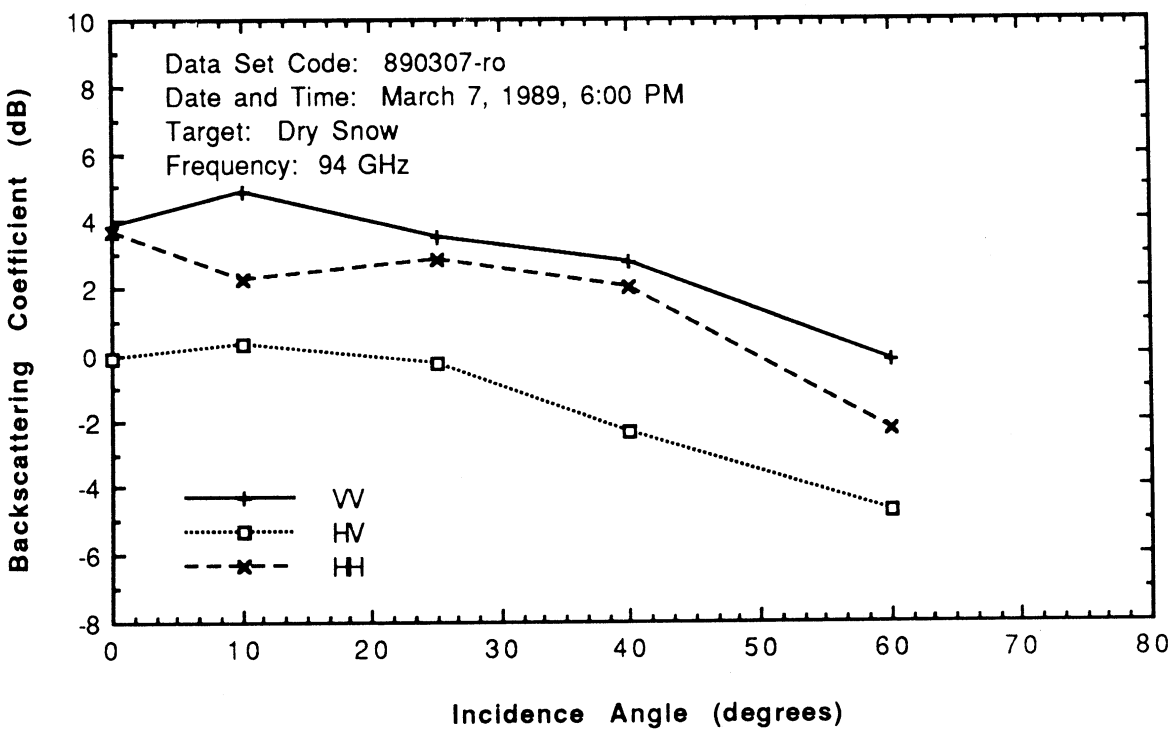
Snow crystals from surface

MMW DATA FOR DRY SNOW

890307(RO)



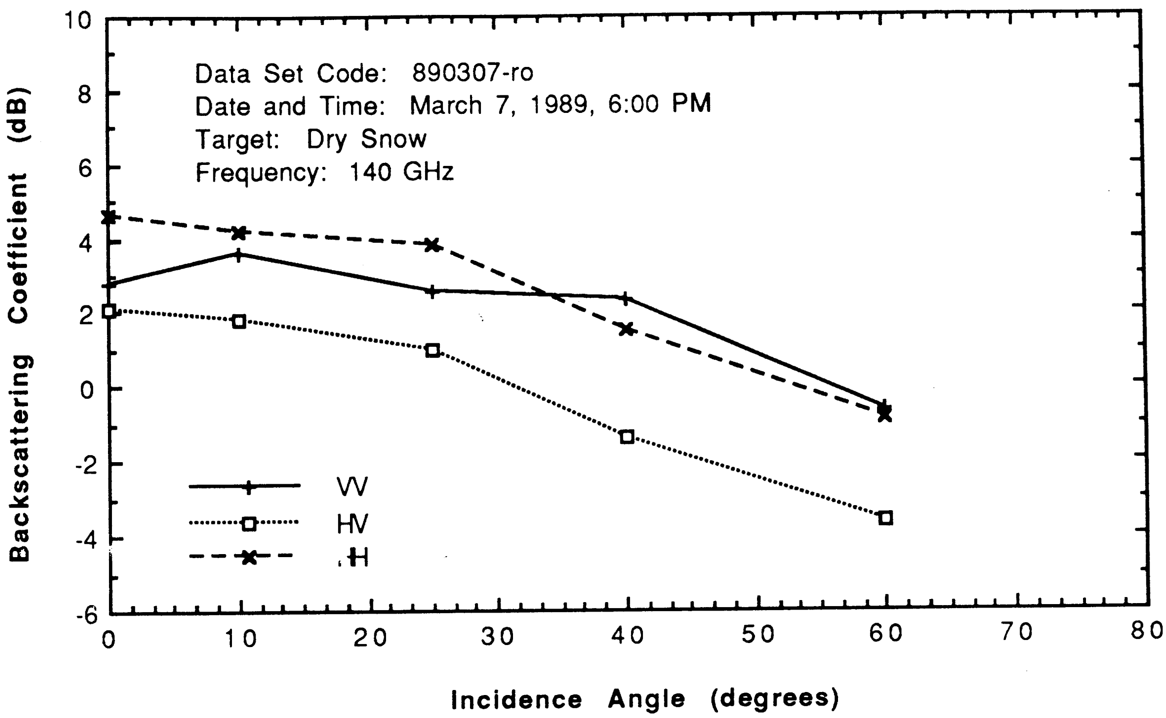
Dry rough metamorphosed snow at Brighton



Dry rough metamorphosed snow at Brighton

MMW DATA FOR DRY SNOW

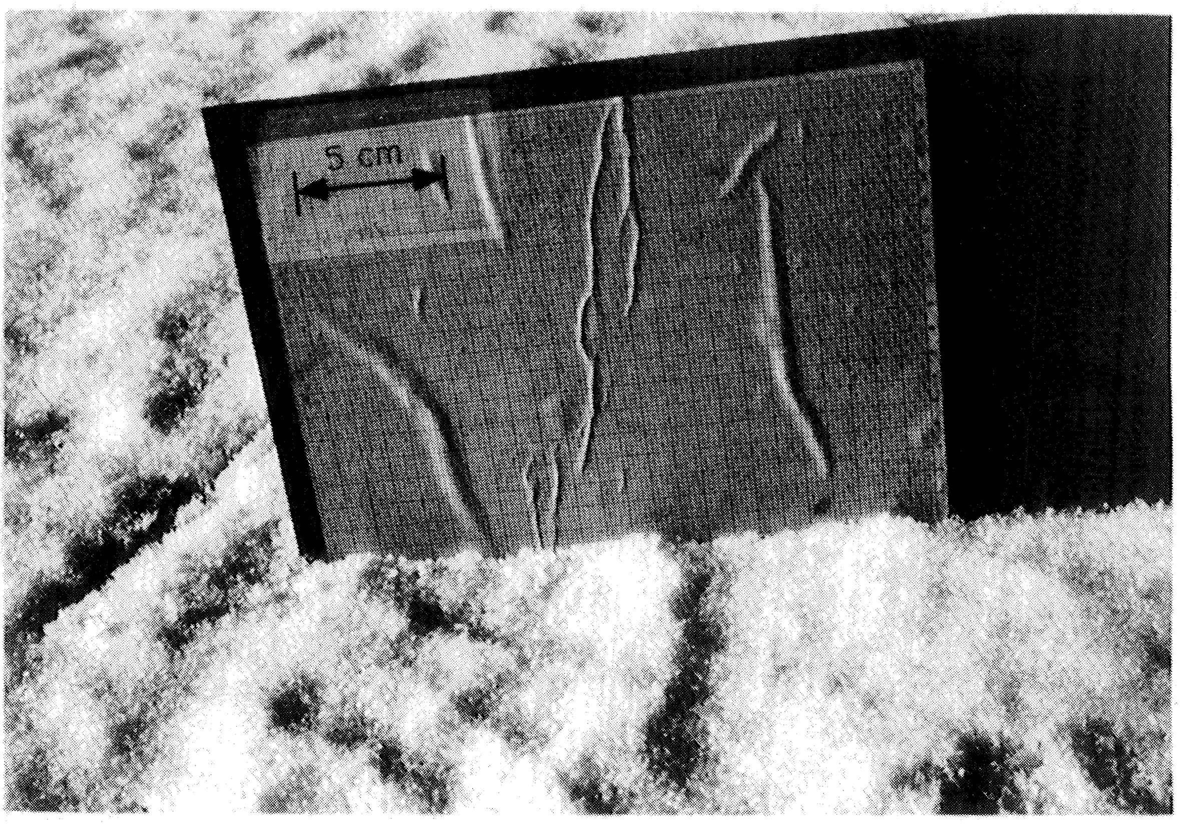
890307(RO)



Dry rough metamorphosed snow at Brighton

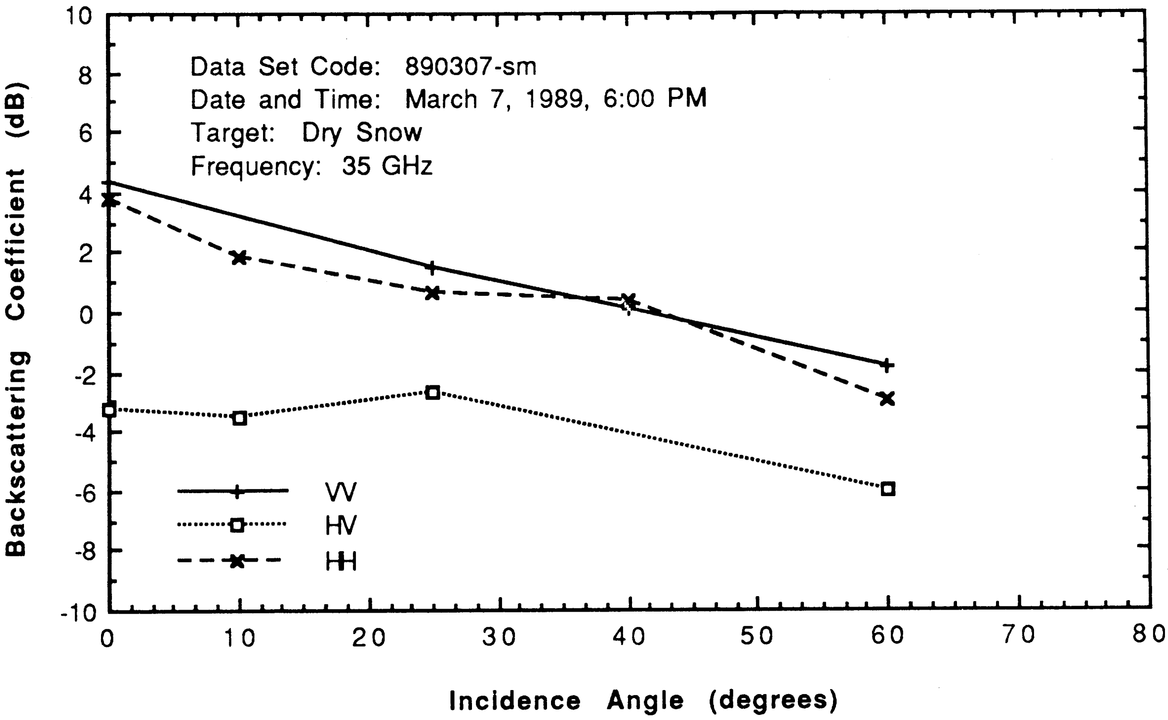
I. Large Crystal Size with Smooth Surface

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^3
Surface temperature: -10 to -12 C
Description: dry slightly metamorphosed snow

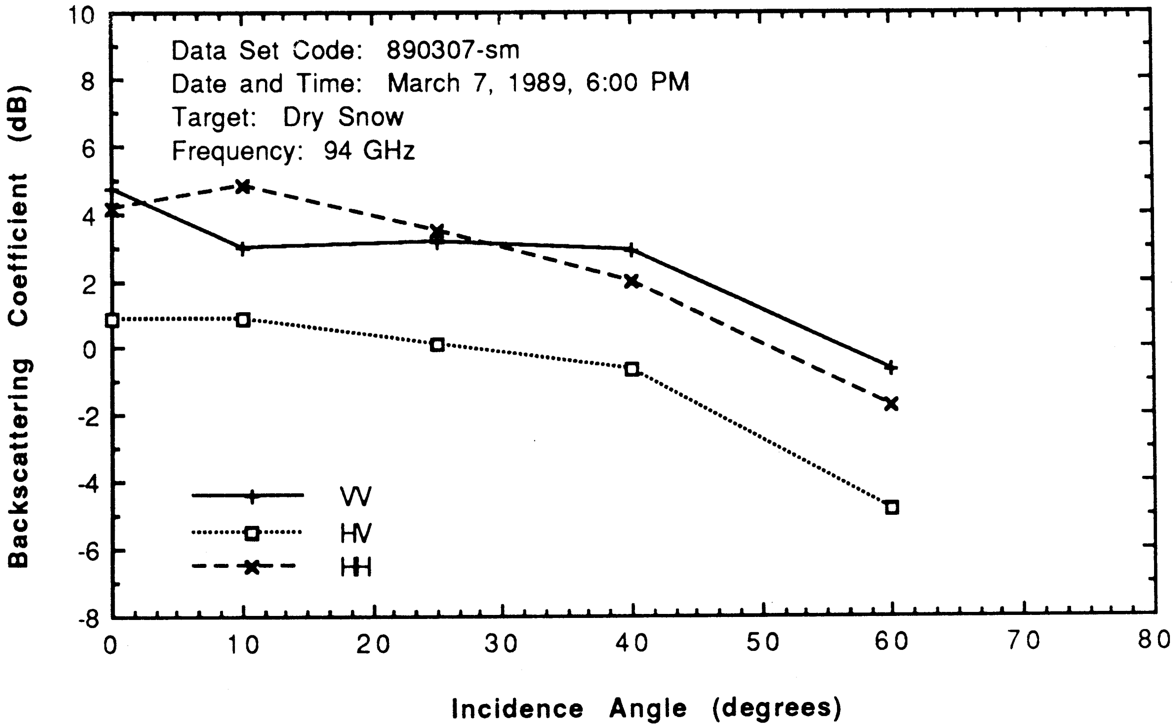


MMW DATA FOR DRY SNOW

890307(SM)



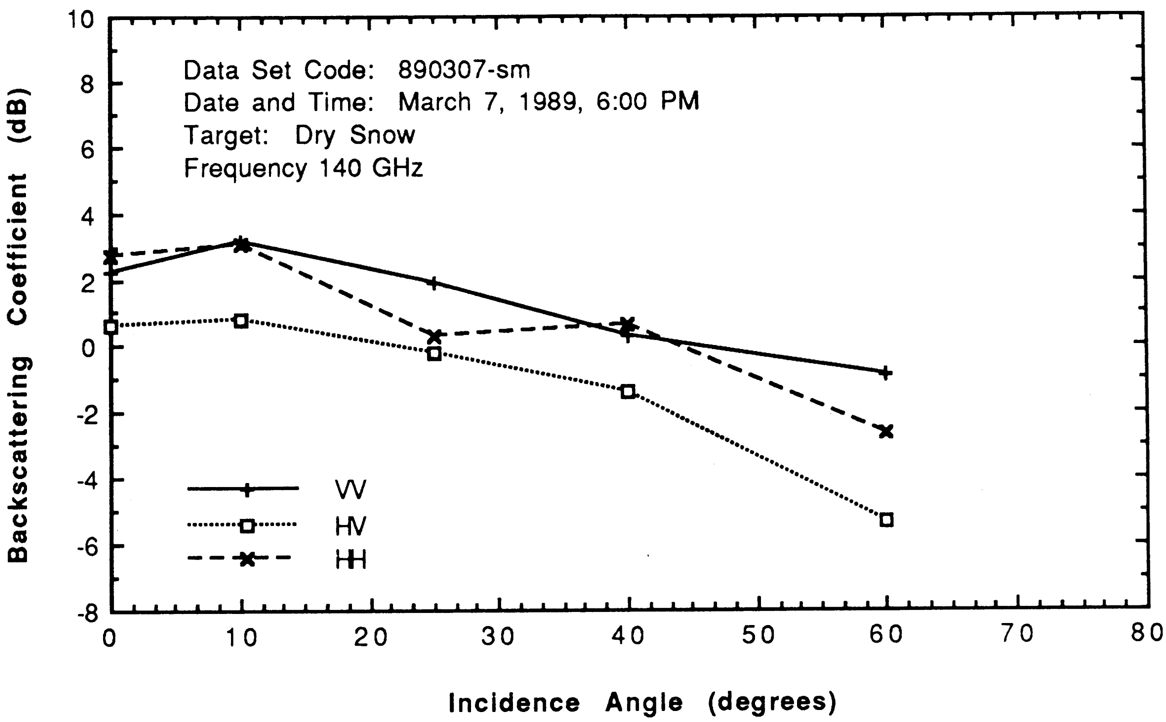
Dry smooth metamorphosed snow at Brighton



Dry smooth metamorphosed snow at Brighton

MMW DATA FOR DRY SNOW

890307(Sm)



Dry smooth metamorphosed snow at Brighton

III. MMW DATA FOR WET SNOW

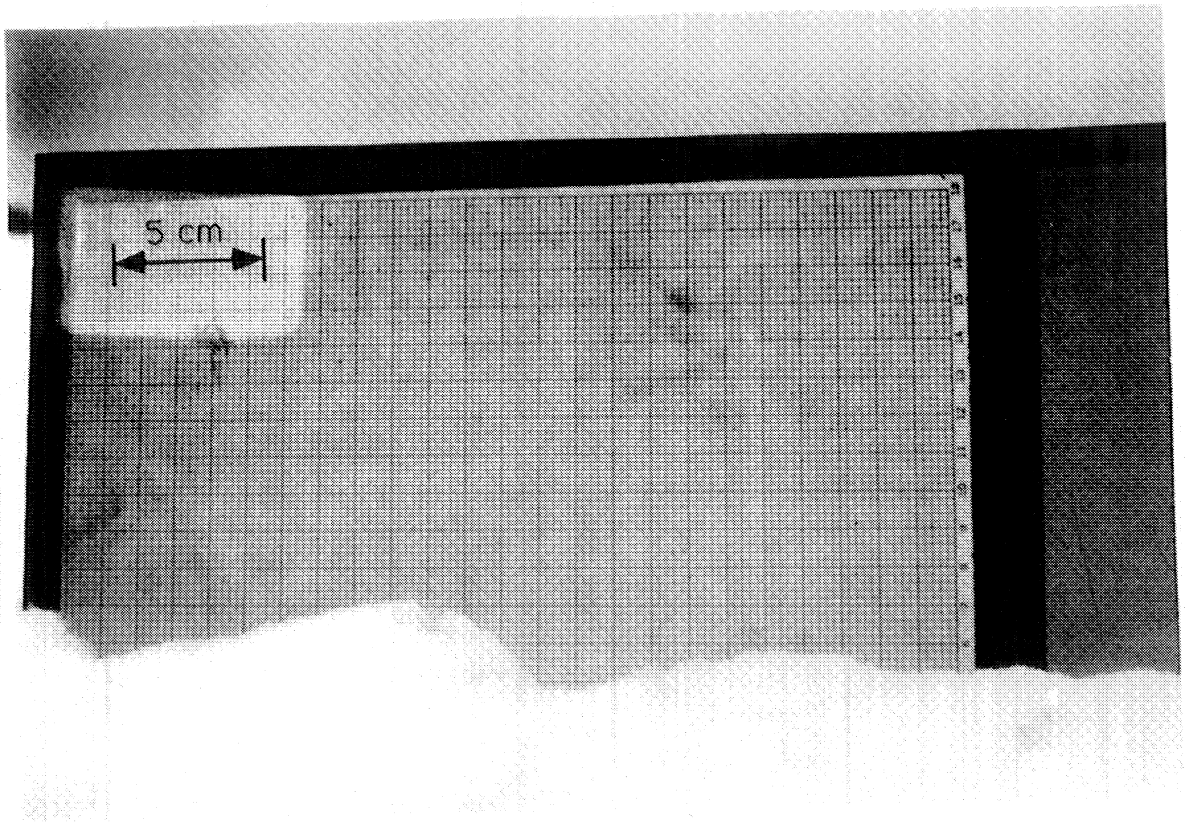
As in the previous chapter on Dry Snow, the following chart is included in order to give a more complete overview of the characteristics of the data:

	manmade wet	slightly wet with smooth surface	wet w/ smooth surface	very wet with rough surface	very wet with 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				

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^3
Ice crystal diameter: 2 to 4 mm
Surface temperature: 0.0 C
Description: manmade wet snow

Snowmaking scene

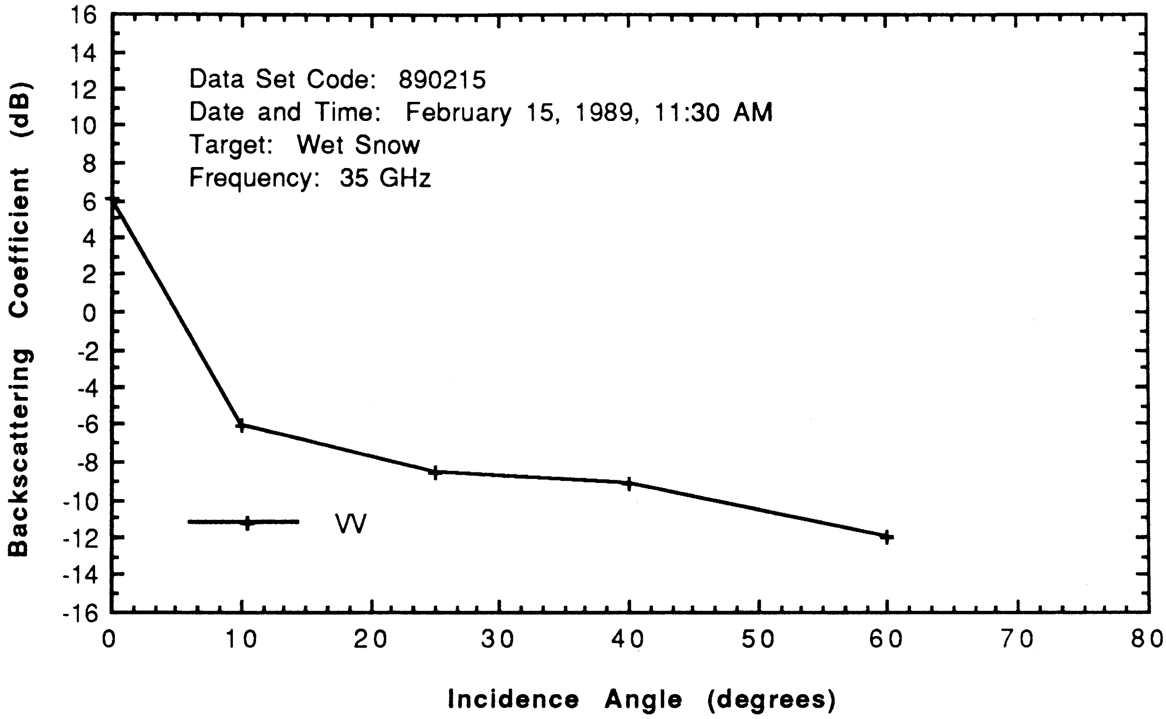


Surface roughness profile with 1 cm grid

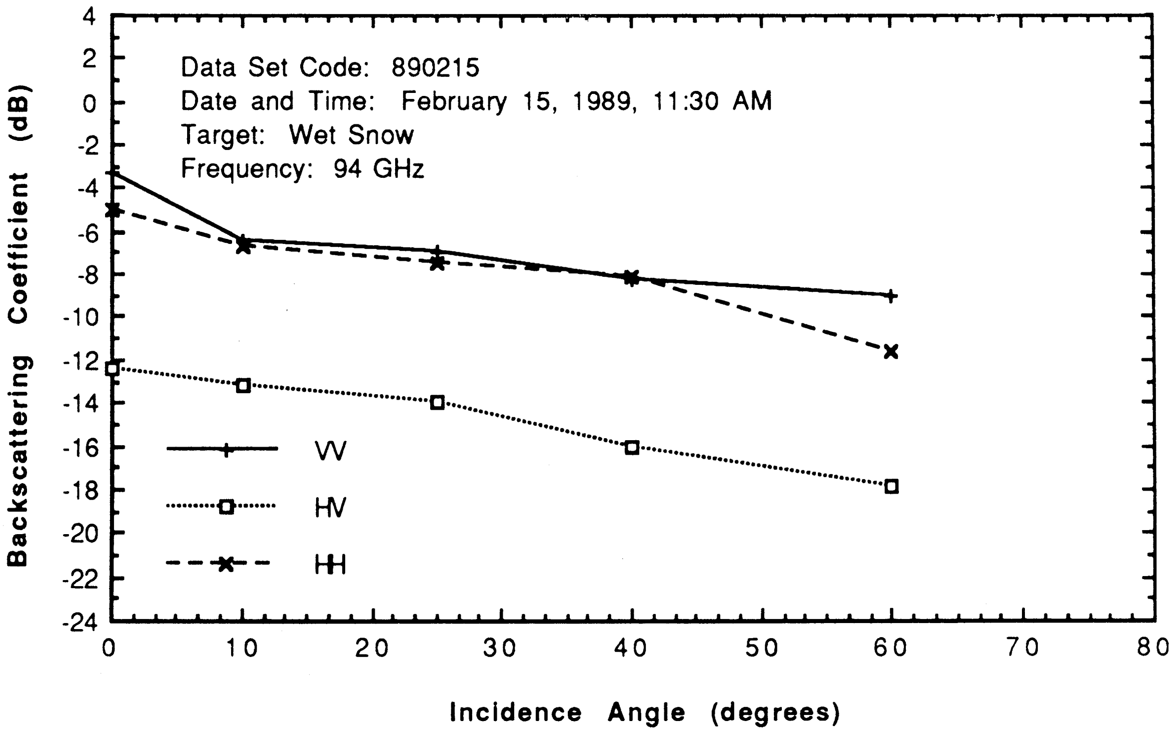
Data collection scene

MMW DATA FOR WET SNOW

890215



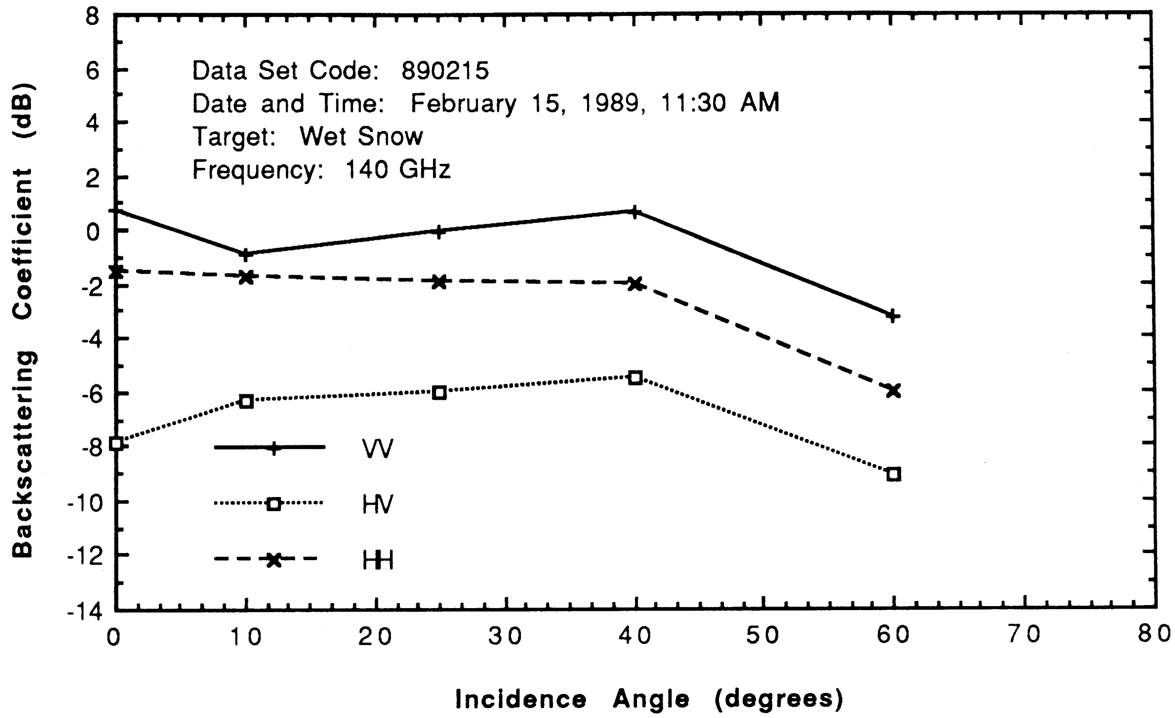
Wet snow at Brighton



Wet snow at Brighton

MMW DATA FOR WET SNOW

890215

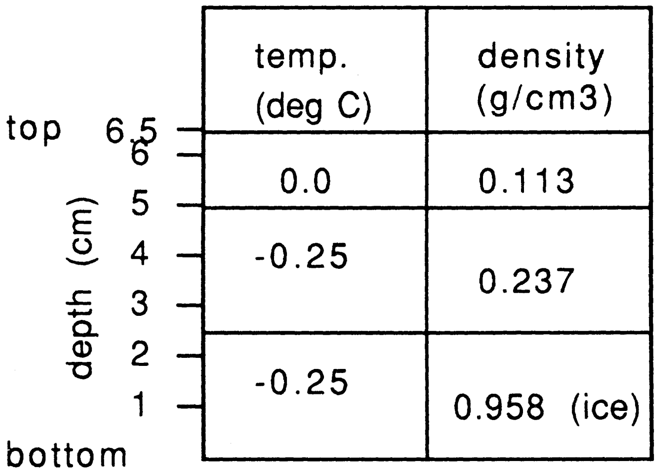


Wet snow at Brighton

B. Slightly Wet Snow with Smooth Surface

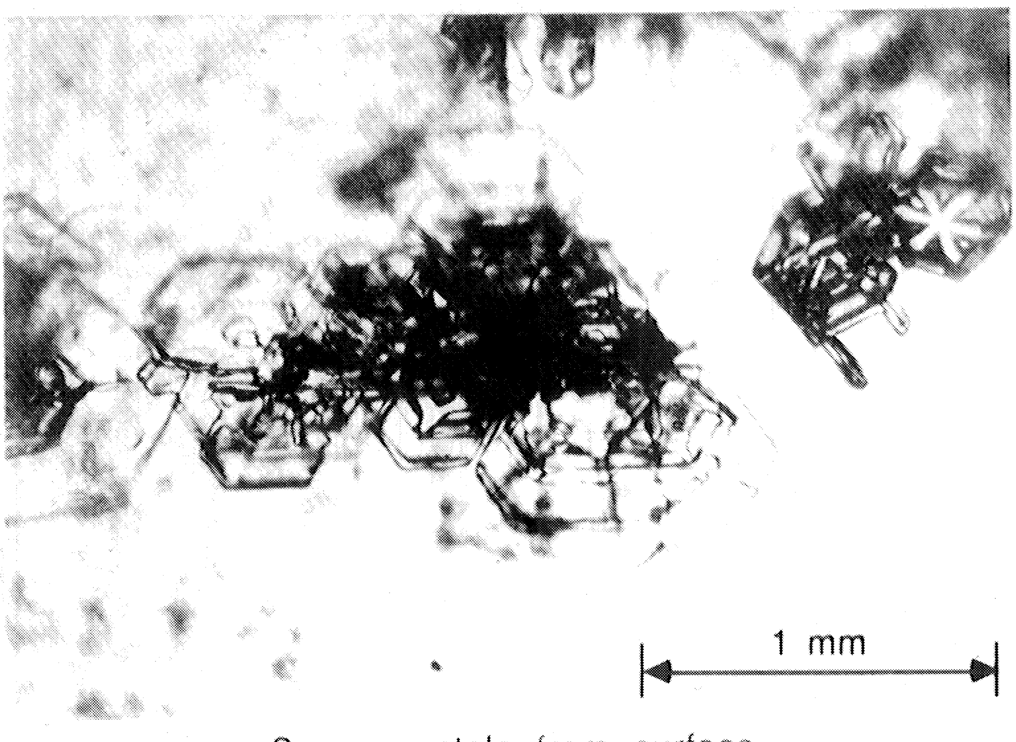
Data set code: 890220
Depth: 6.5 cm
LWC (at 2:08 PM): 0 %
LWC (at 4:23 PM): 1.88 %
Surface RMS height: 0.11 cm
Density: 0.1 to 1.0 gm/cm^3
Ice crystal diameter: 1 to 2 mm
Surface temperature: 0.0 C
Description: smooth, wet natural snow

SNOW PIT PROFILE FOR 890220



air temperature: 1.1 C

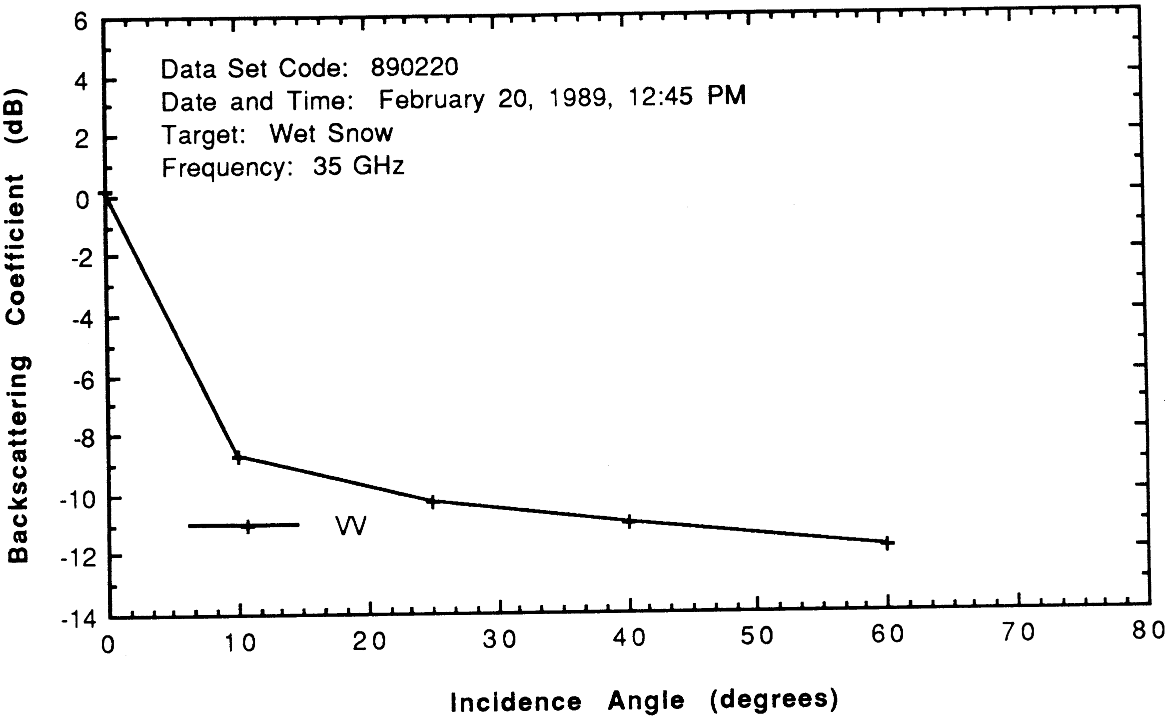
Data collection scene



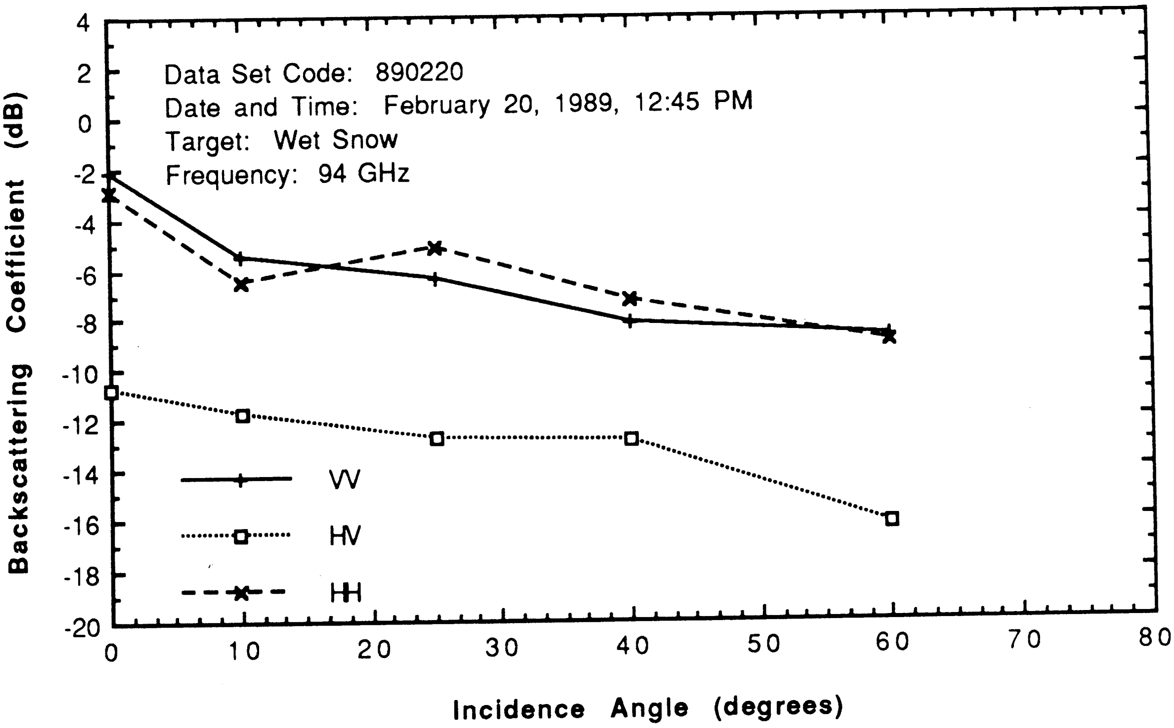
Snow crystals from surface

MMW DATA FOR WET SNOW

890220



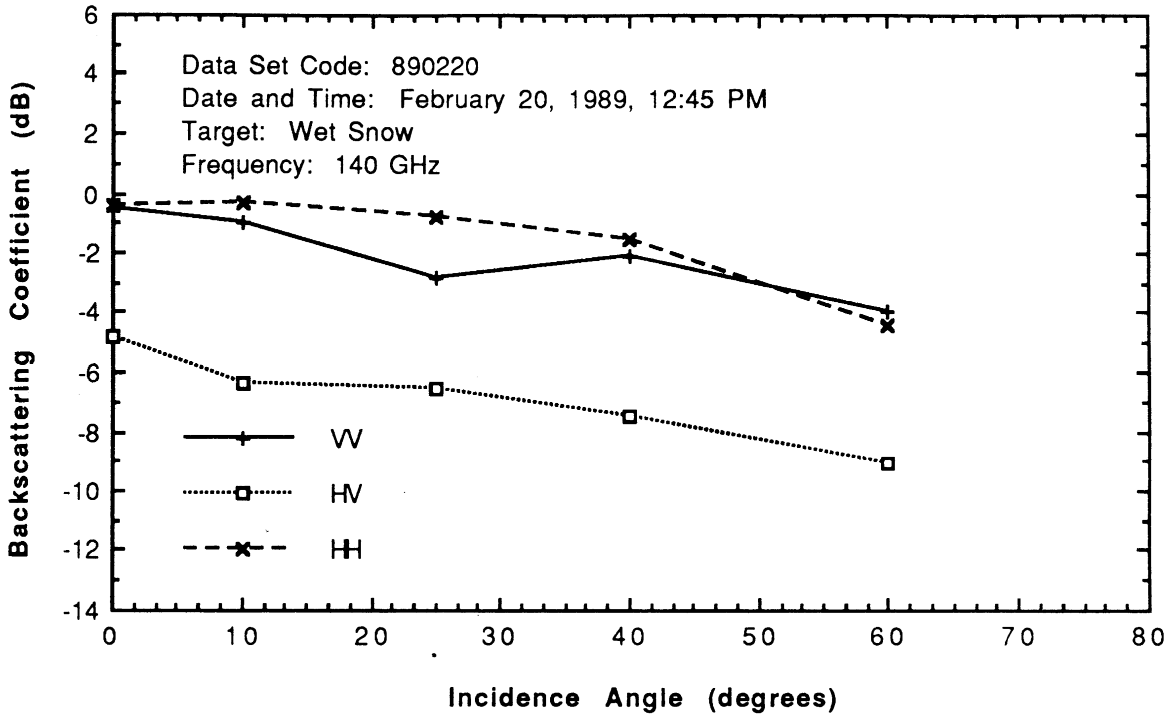
Wet snow at Brighton



Wet snow at Brighton

MMW DATA FOR WET SNOW

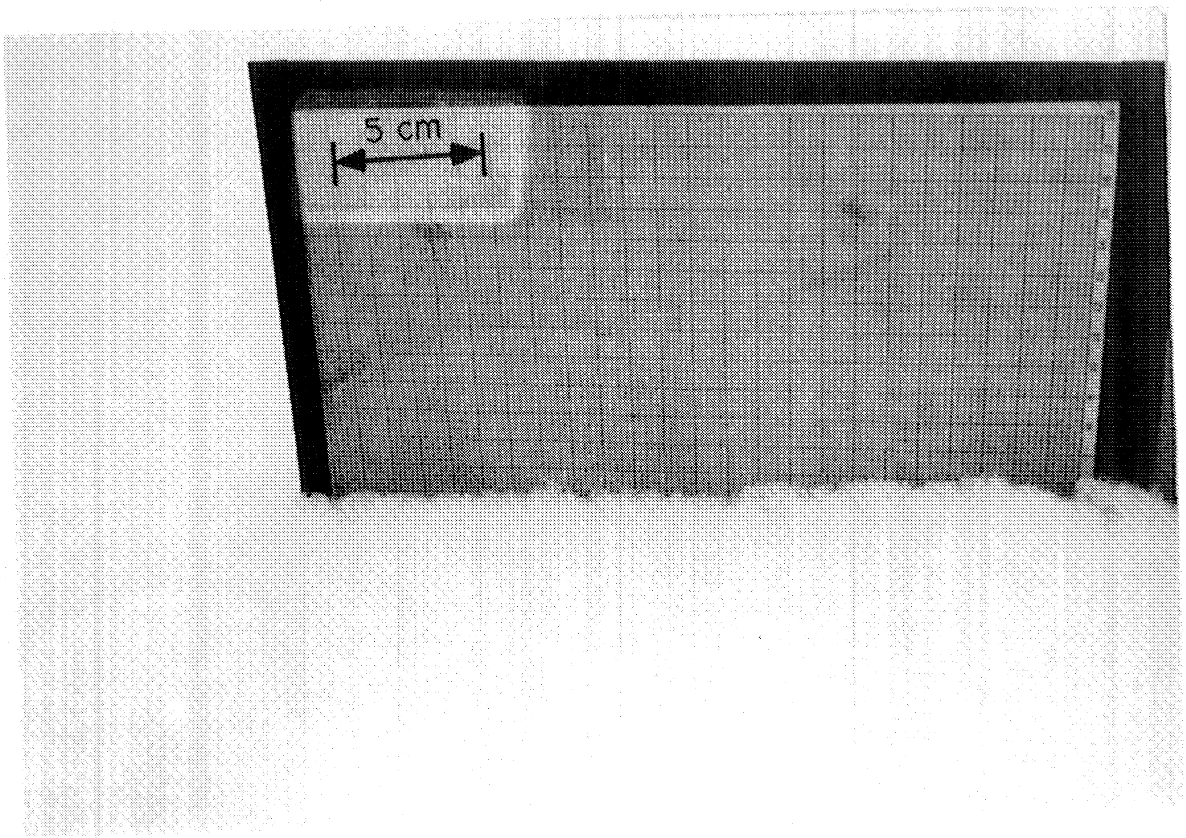
890220



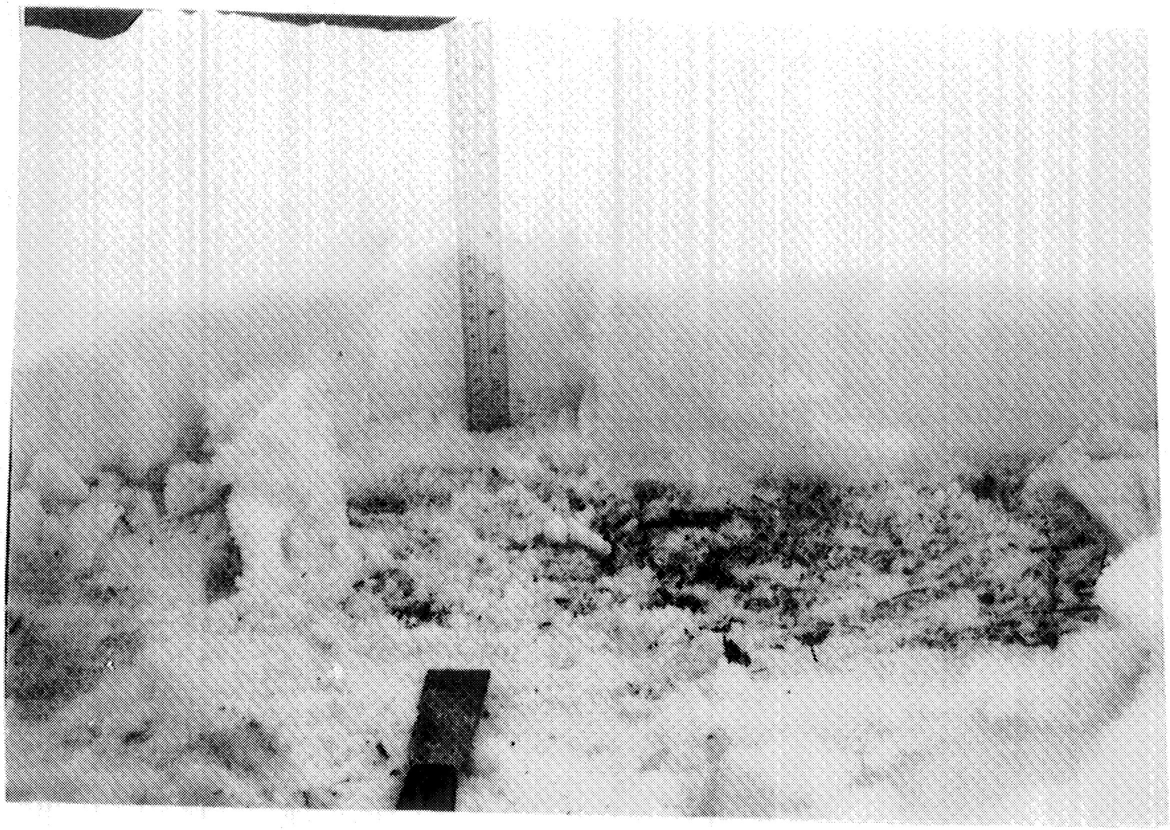
Wet snow at Brighton

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^3
Surface temperature: 1.0 C
Description: smooth, wet natural snow



Surface roughness profile with 1 cm grid

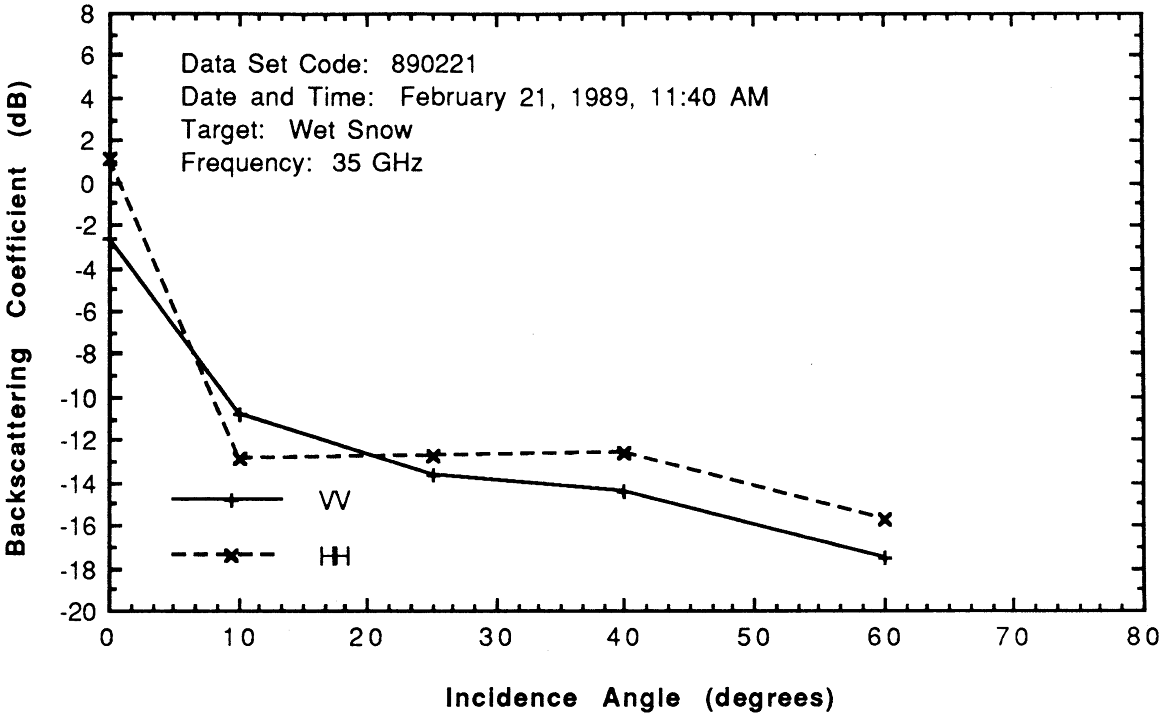


Snow pit

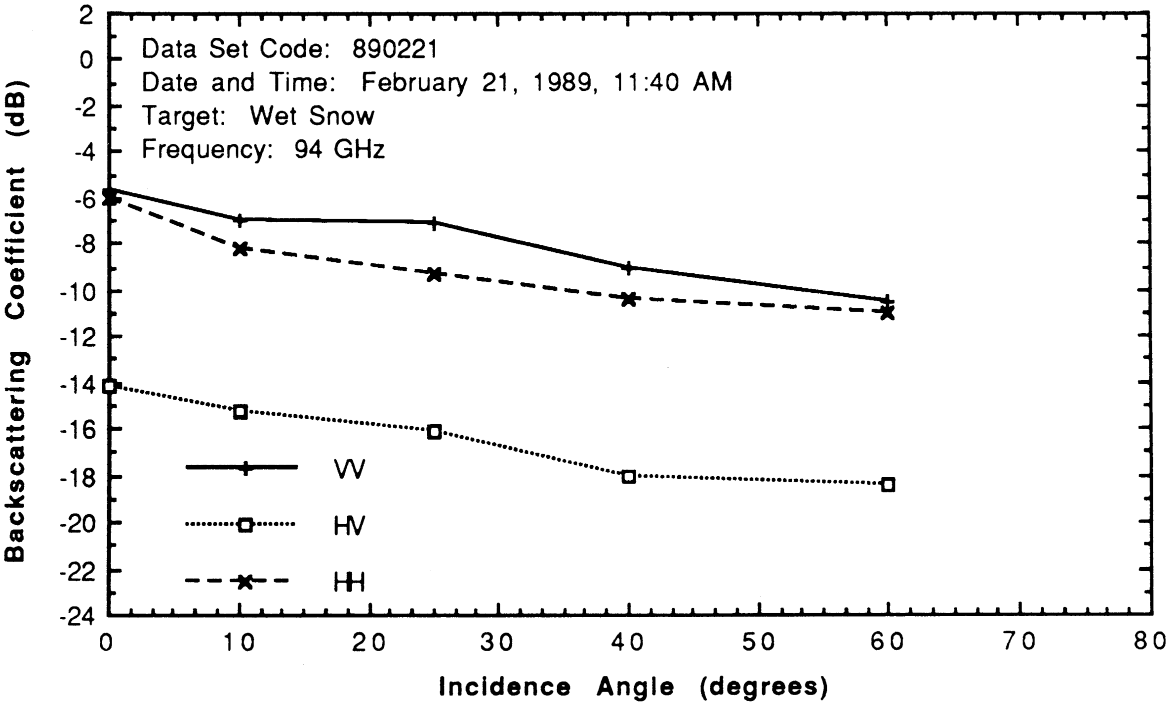
Data collection scene

MMW DATA FOR WET SNOW

890221



Wet snow at Brighton

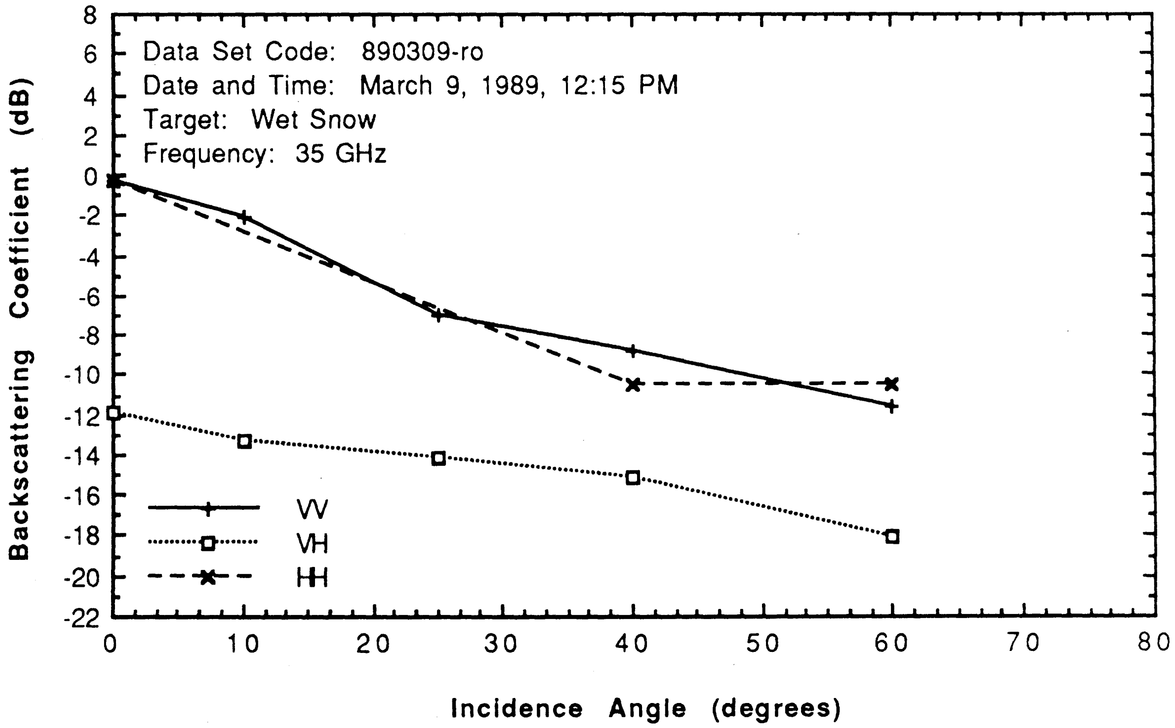


Wet snow at Brighton

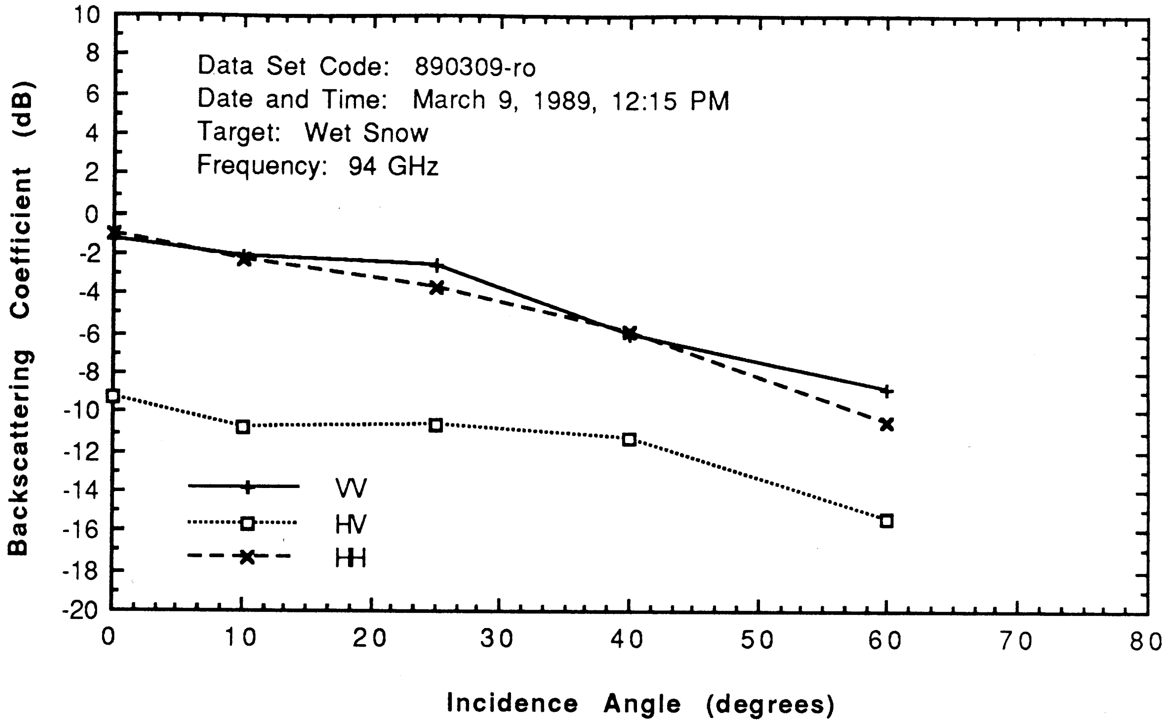
D. Very Wet Snow with rough Surface

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
Surface RMS height: 0.15 cm
Density: 0.42 gm/cm^3
Ice crystal diameter: 2 to 4 mm
Surface temperature: 4 to 6 C
Description: rough, wet snow

890309(RO)

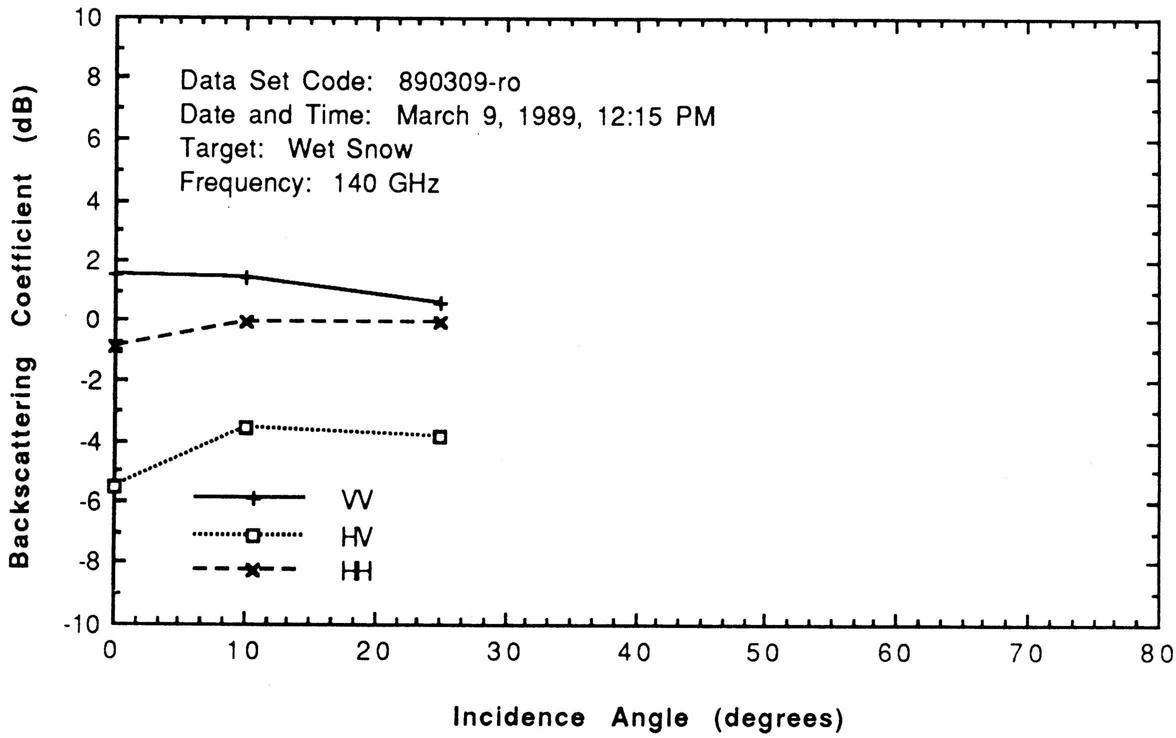


Wet rough metamorphosed snow at Brighton



Wet rough metamorphosed snow at Brighton

890309(RO)

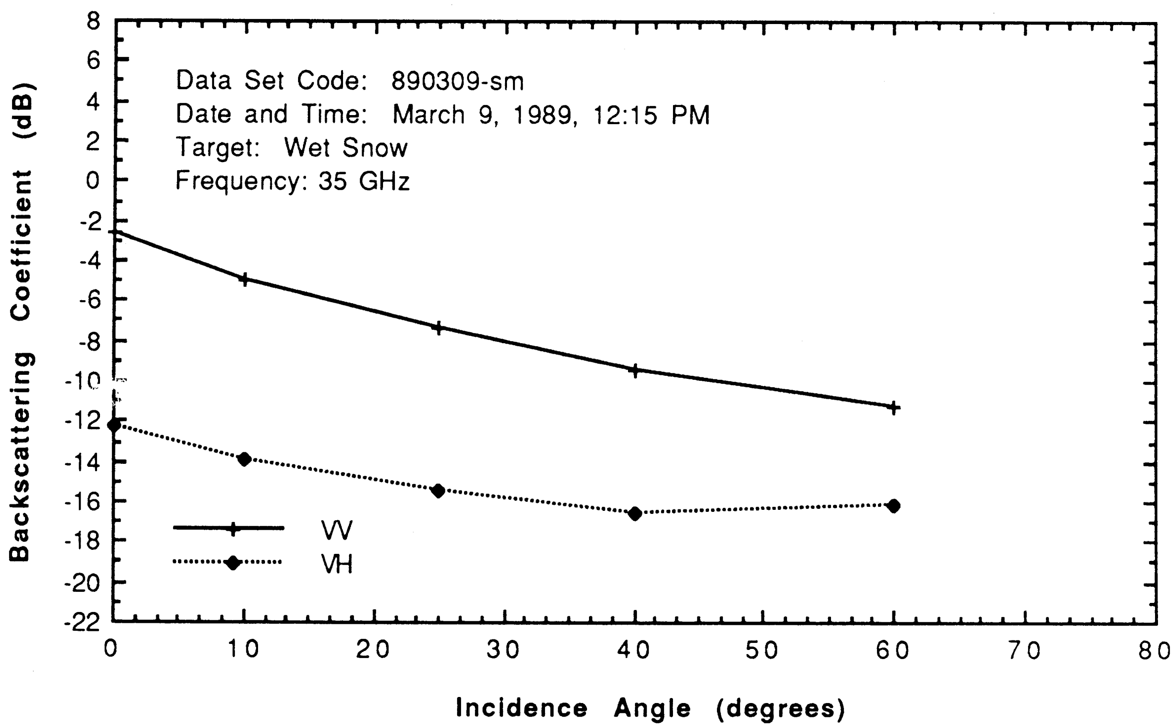


Wet rough metamorphosed snow at Brighton

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^3
Ice crystal diameter: 2 to 4 mm
Surface temperature: 4 to 6 C
Description: wet, smooth snow

890309(SM)

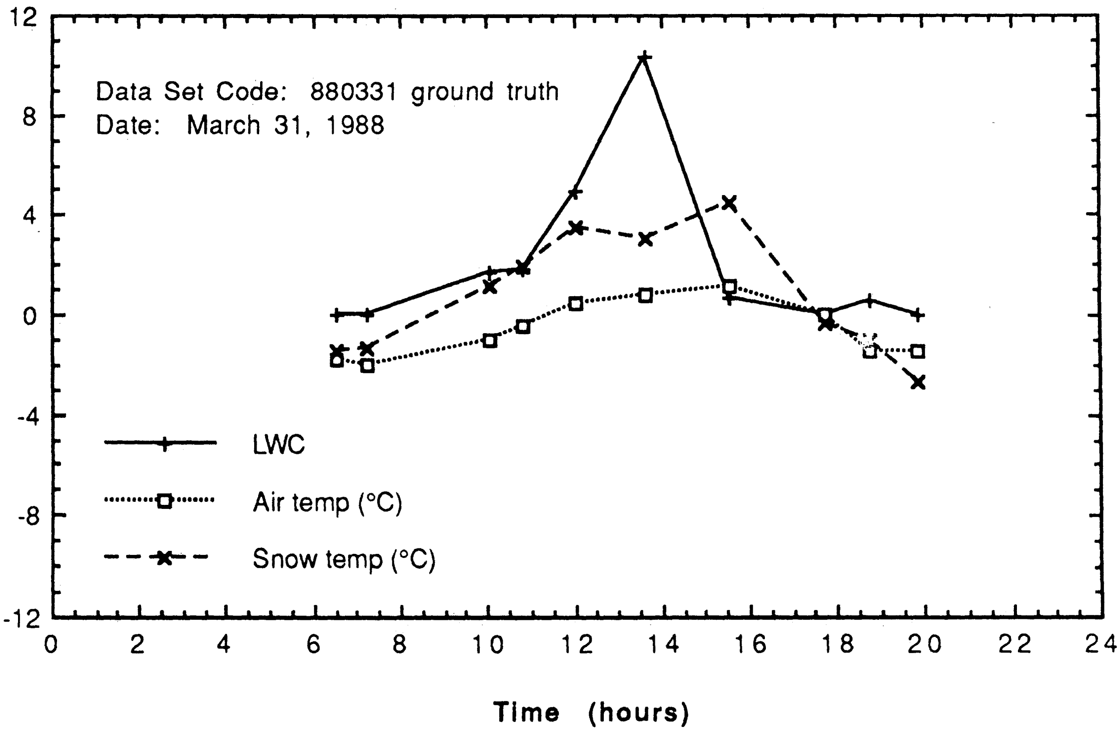


Wet smooth metamorphosed snow at Brighton

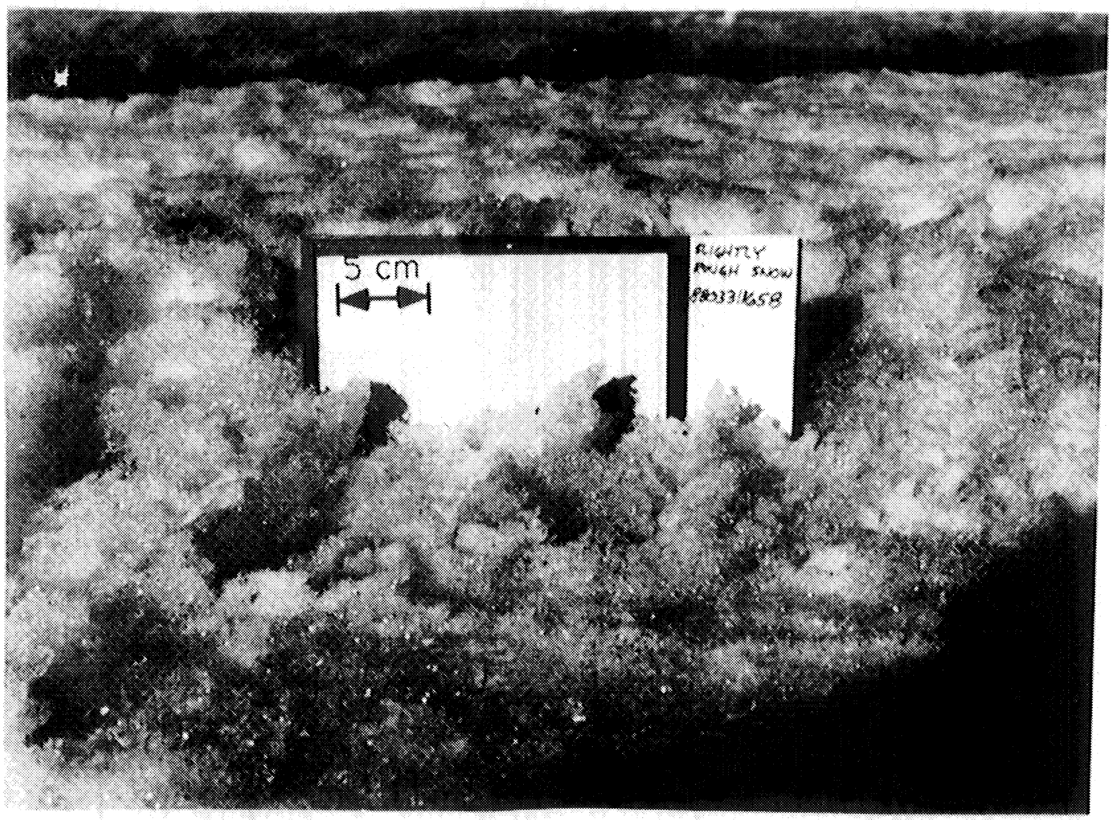
IV. MMW DIURNAL DATA FOR SNOW

A. 31 March, 1988

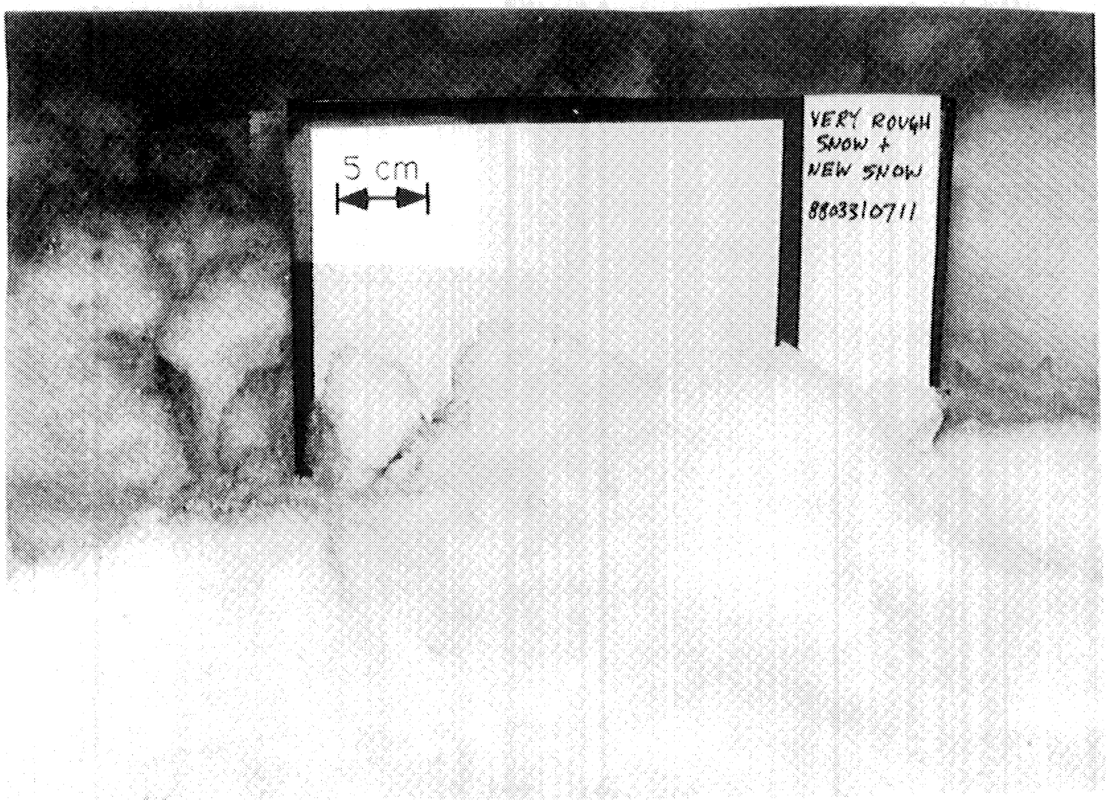
Snow
Data set code: 880331
Depth: ~ 71 cm
LWC: 0 to 10.2 %
Smooth surface RMS height: 0.49 cm
Slightly rough surface RMS height: 0.88 cm
Very rough surface RMS height: 1.98 cm
Density: surface: 0.39 gm/cm^3
15 cm depth: 0.50 gm/cm^3
30 cm depth: 0.54 gm/cm^3
45 cm depth: 0.53 gm/cm^3
60 cm depth: 0.58 gm/cm^3
71 cm depth (ground): 0.65 gm/cm^3
Ice crystal diameter: 0.5 to 1 mm
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



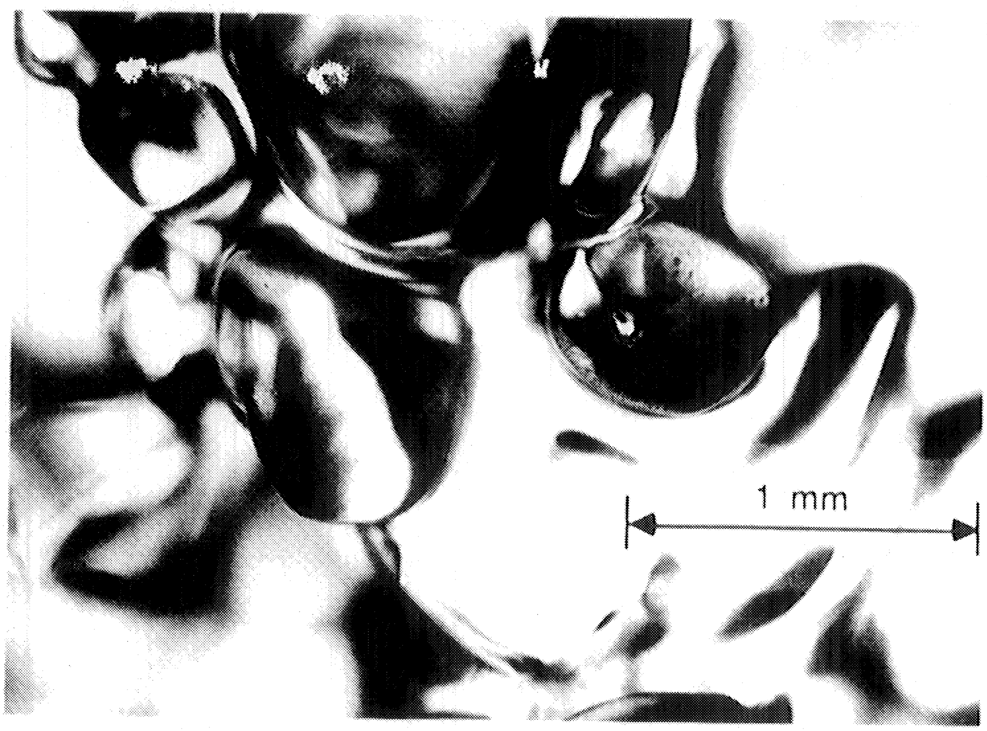
Surface roughness profile of smooth snow with 1 cm grid



Surface roughness profile of slightly rough snow with 1 cm grid



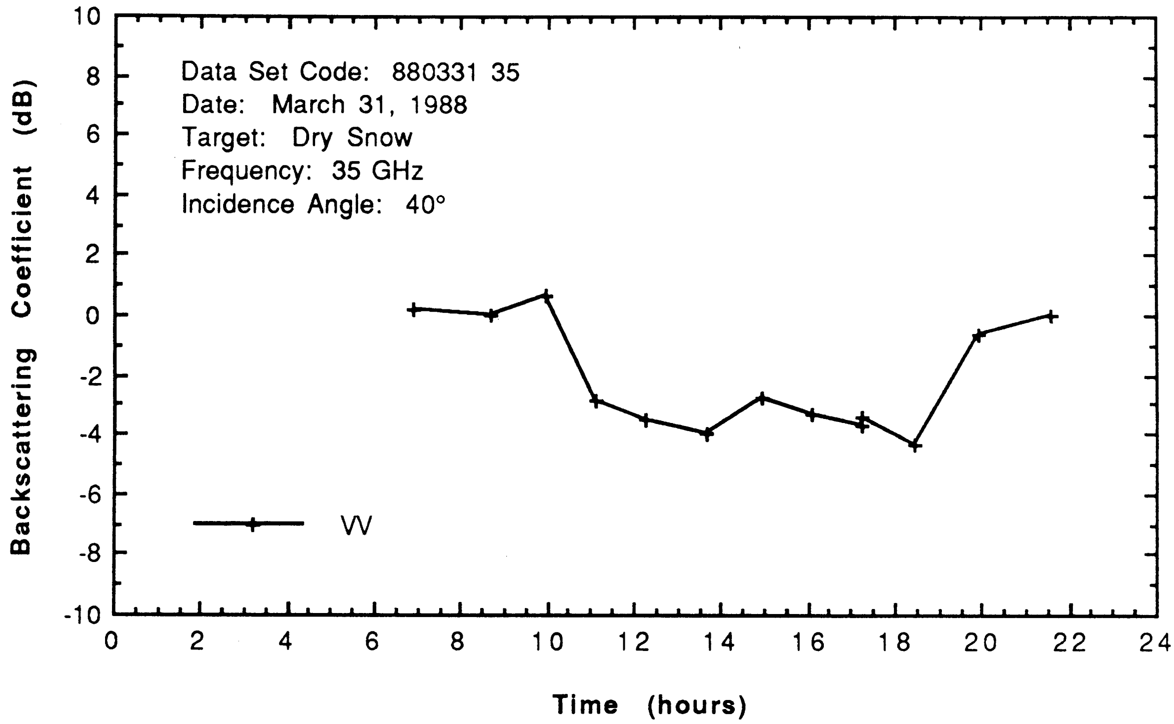
Surface roughness profile of very rough snow with 1 cm grid



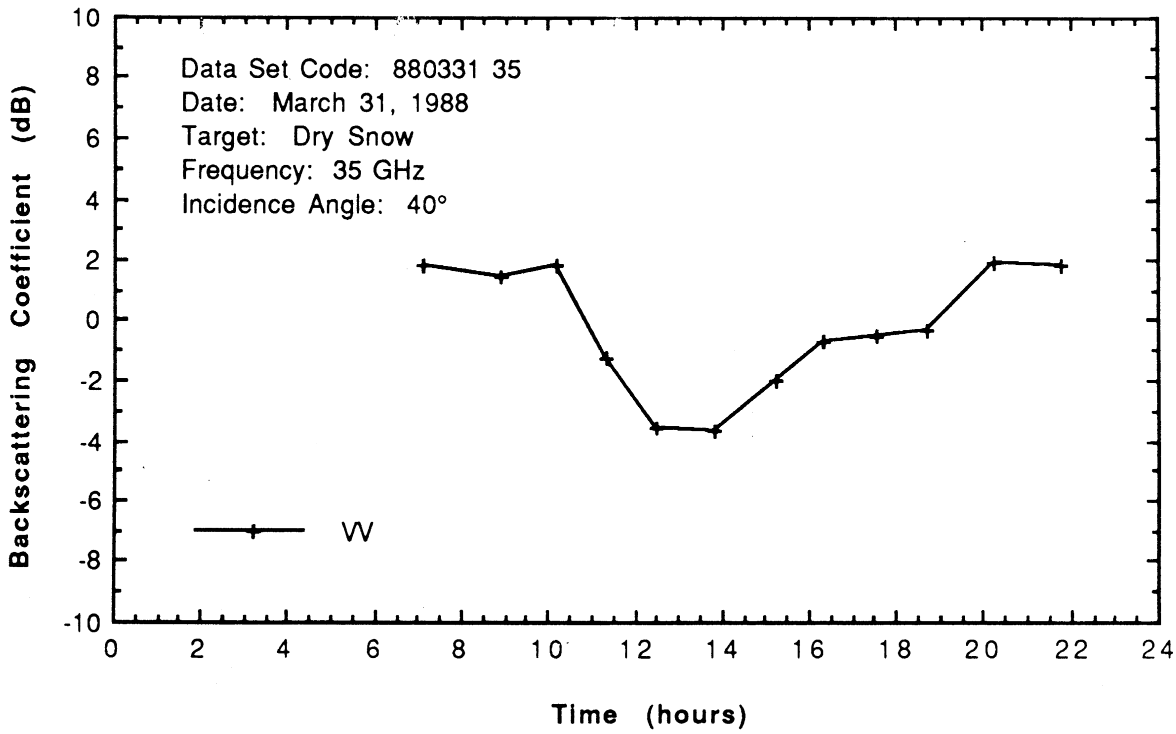
Snow crystals from surface

MMW DIURNAL DATA FOR SNOW

880331



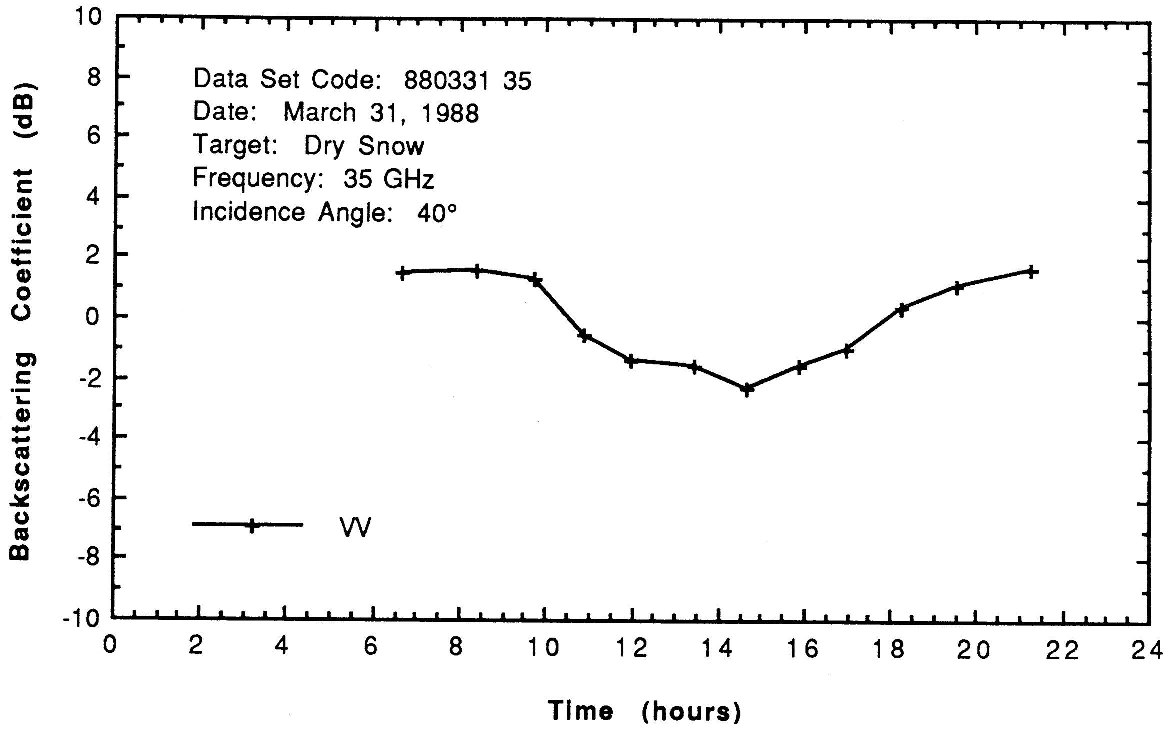
Houghton snow with smooth surface



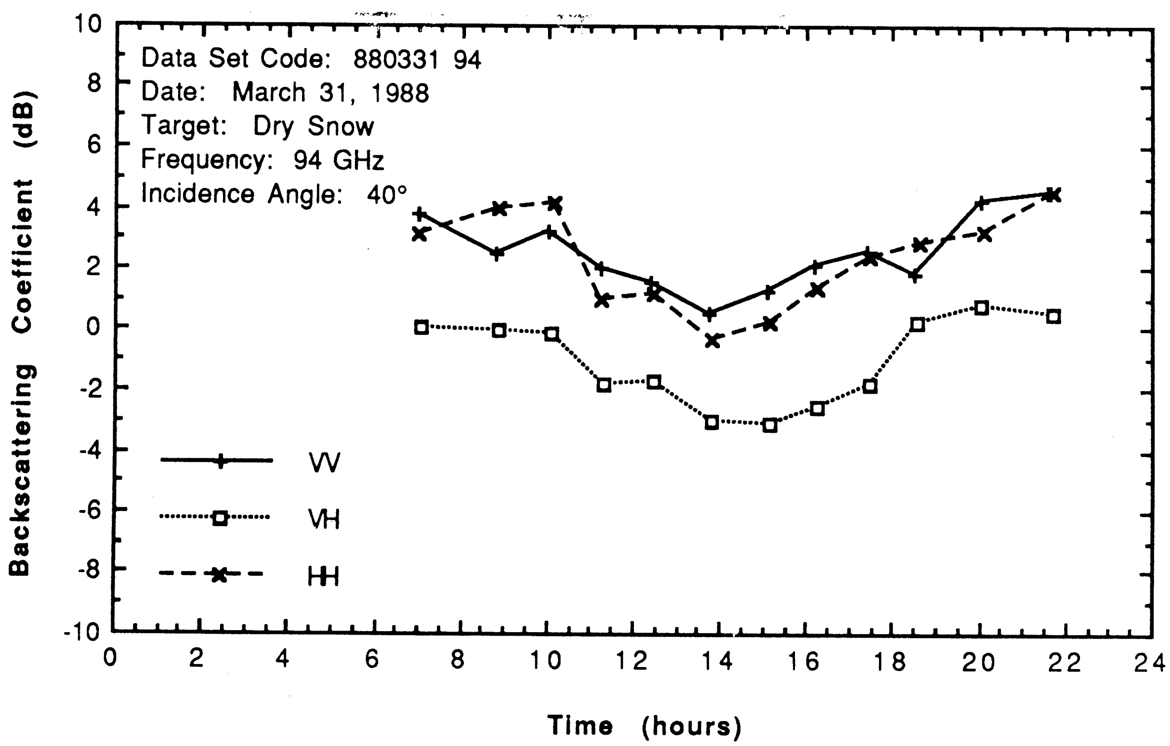
Houghton snow with slightly rough surface

MMW DIURNAL DATA FOR SNOW

880331

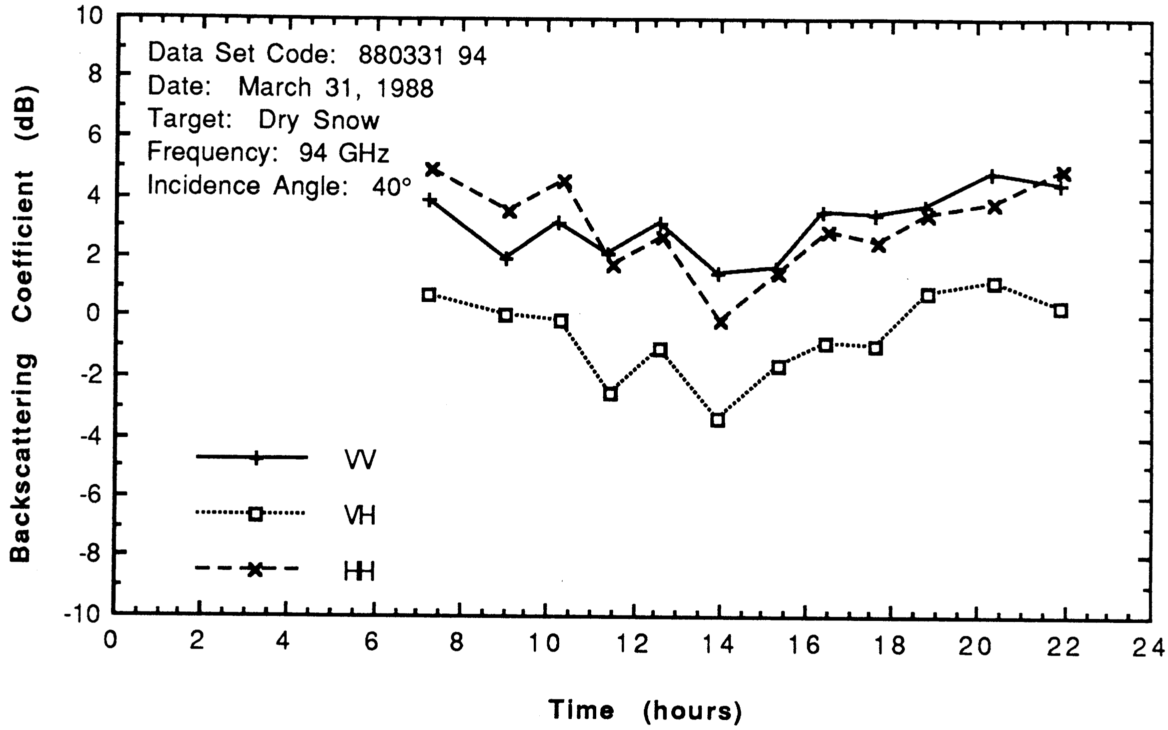


Houghton snow with very rough surface

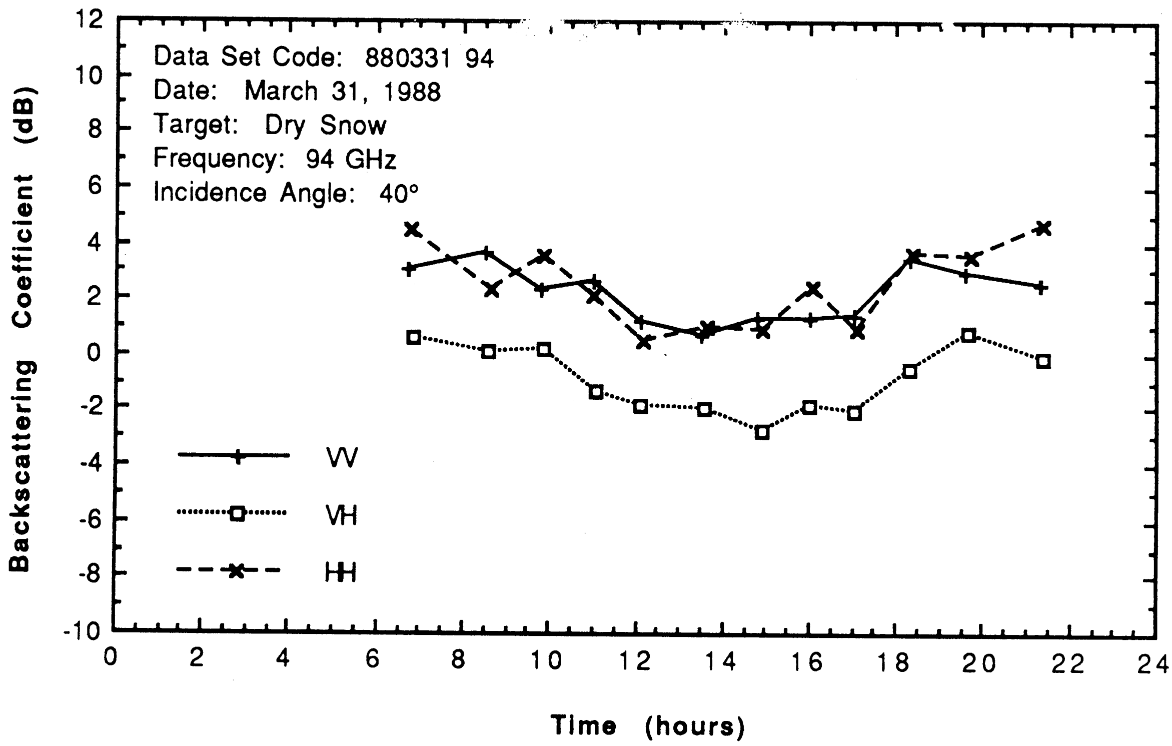


Houghton snow with smooth surface

MMW DIURNAL DATA FOR SNOW



Houghton snow with slightly rough surface



Houghton snow with very rough surface

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^3
Ice crystal diameter: 1 mm
Surface temperature: 0.0 C to -9.0 C
Description: partially metamorphosed snow

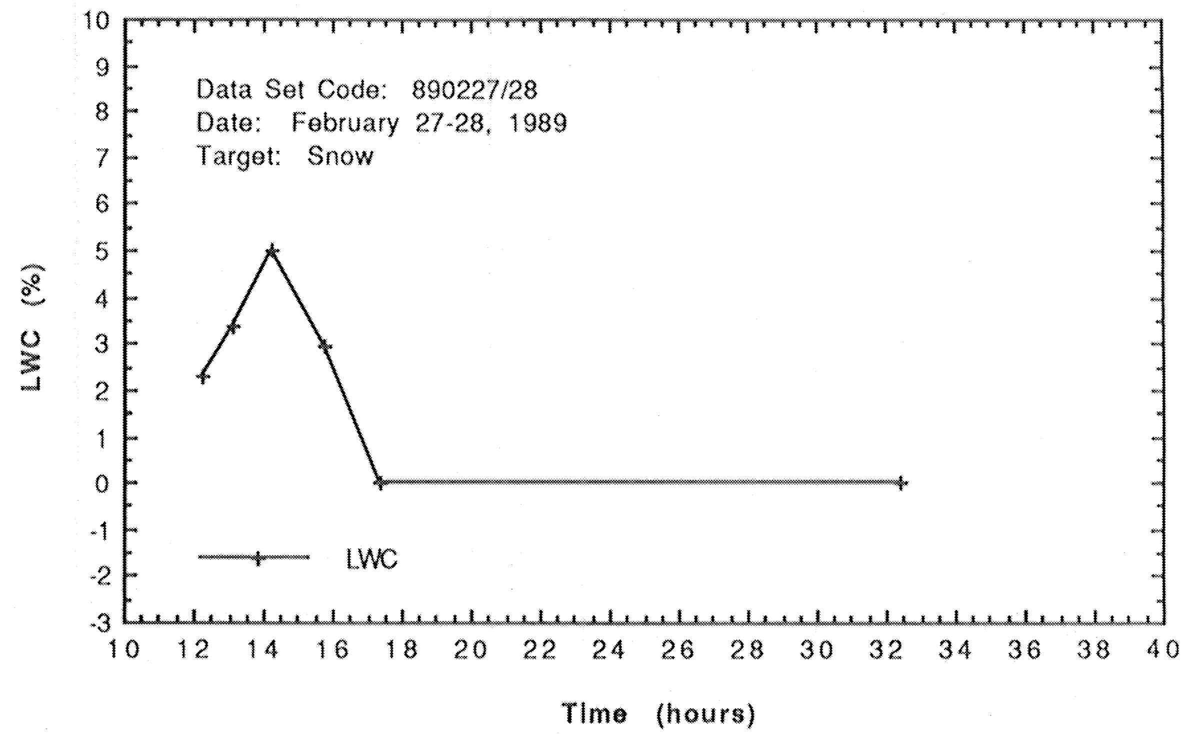
890227/28

SNOW PIT TEMPERATURE PROFILE (°C)

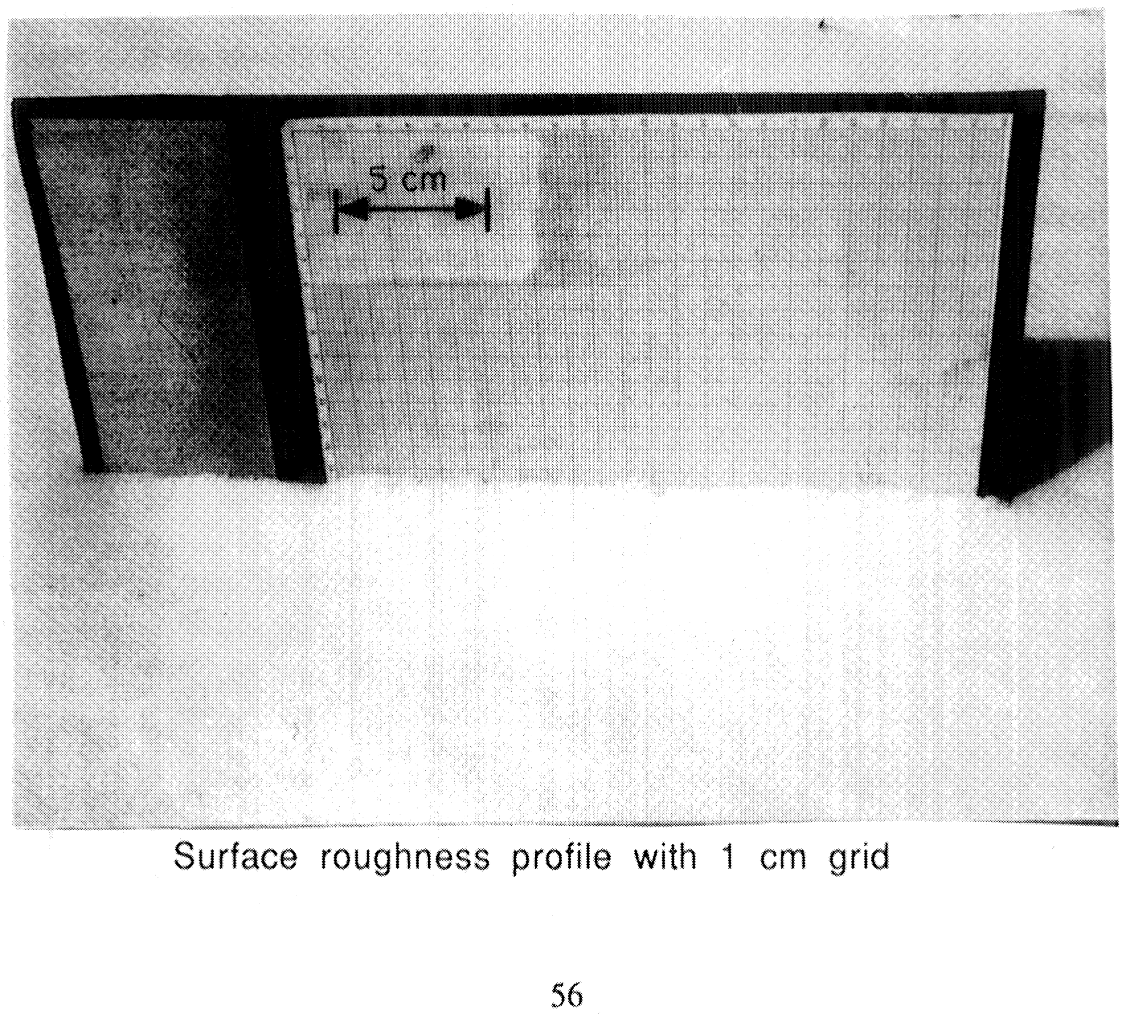
Time	depth (cm)	1400	1445	1540	1655	1800	1900	2100	2302	0100	0300	0500	0605	0803
Top	9.5 / 9			0.0	-2.0	-4.0	-3.5	-6.5	-6.5	-6.3	-8.5	-9.0	-7.5	-7.0
	8	0.0	0.0											
	7													
	6													
	5	-0.6	-0.3	-0.3	-0.5	-1.1	-4.0	-5.5	-5.5	-4.0	-5.0	-6.5	-4.5	-5.7
	4													
	3													
	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



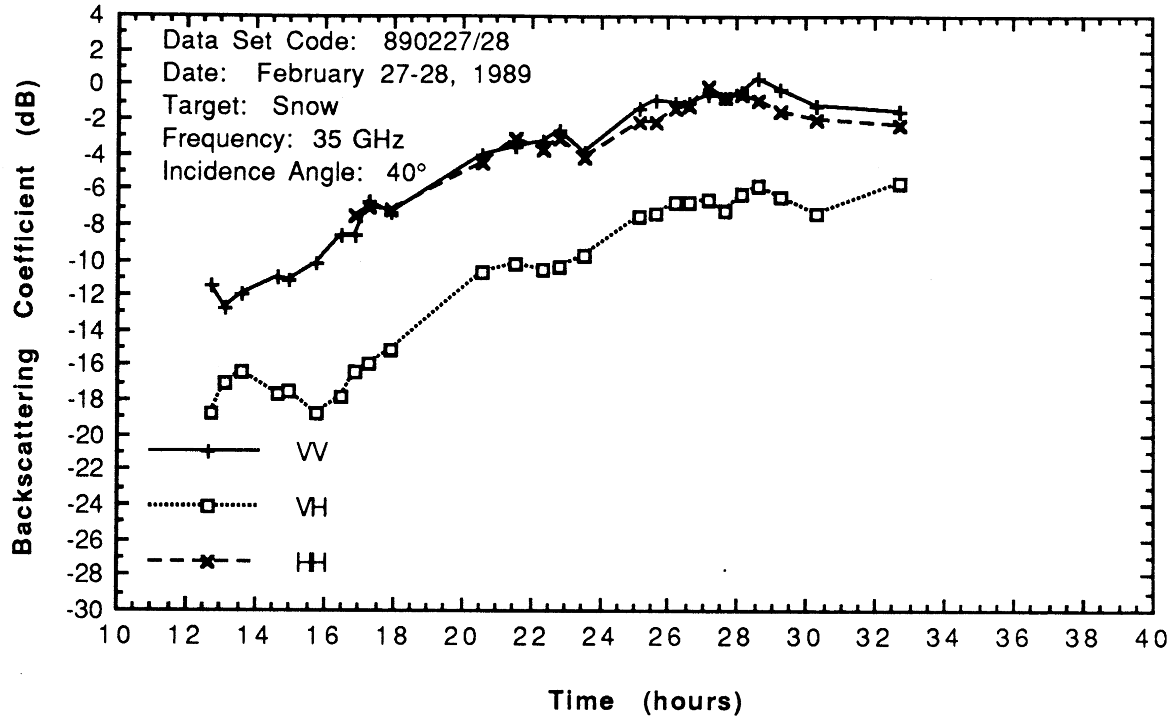
Liquid water content during snow diurnal at Brighton



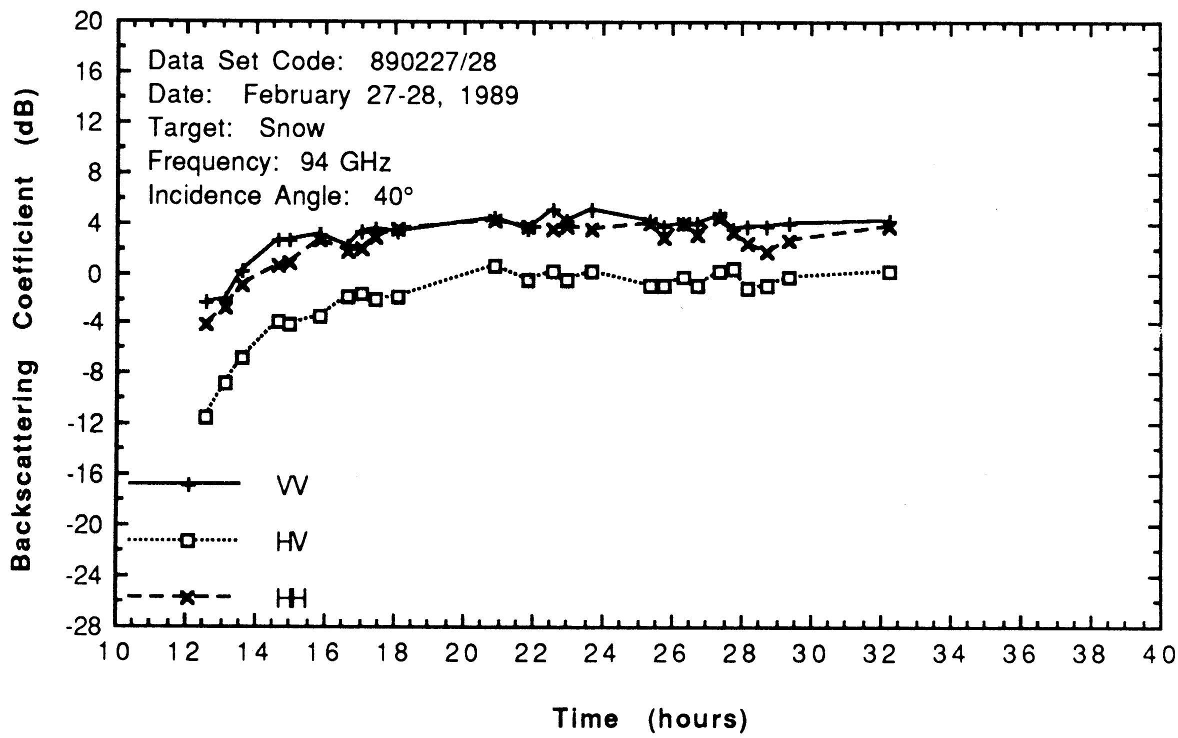
Surface roughness profile with 1 cm grid

MMW DIURNAL DATA FOR SNOW

890227/28



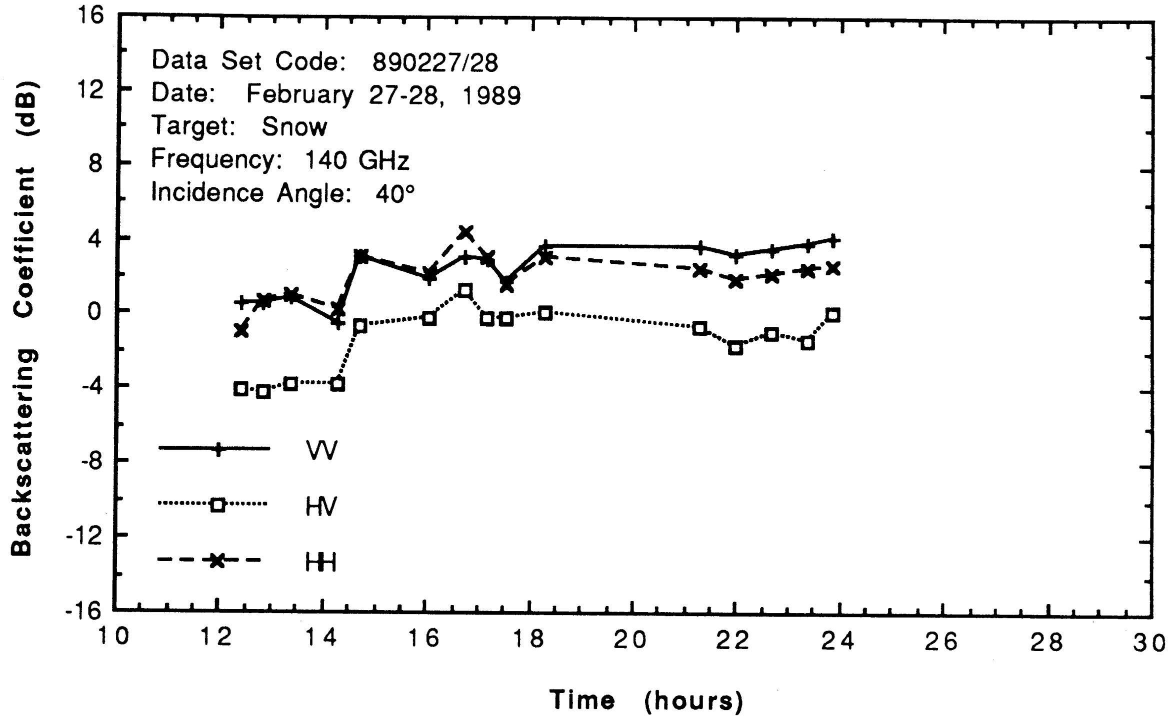
Snow diurnal at Brighton



Snow diurnal at Brighton

MMW DIURNAL DATA FOR SNOW

890227/28



Snow diurnal at Brighton

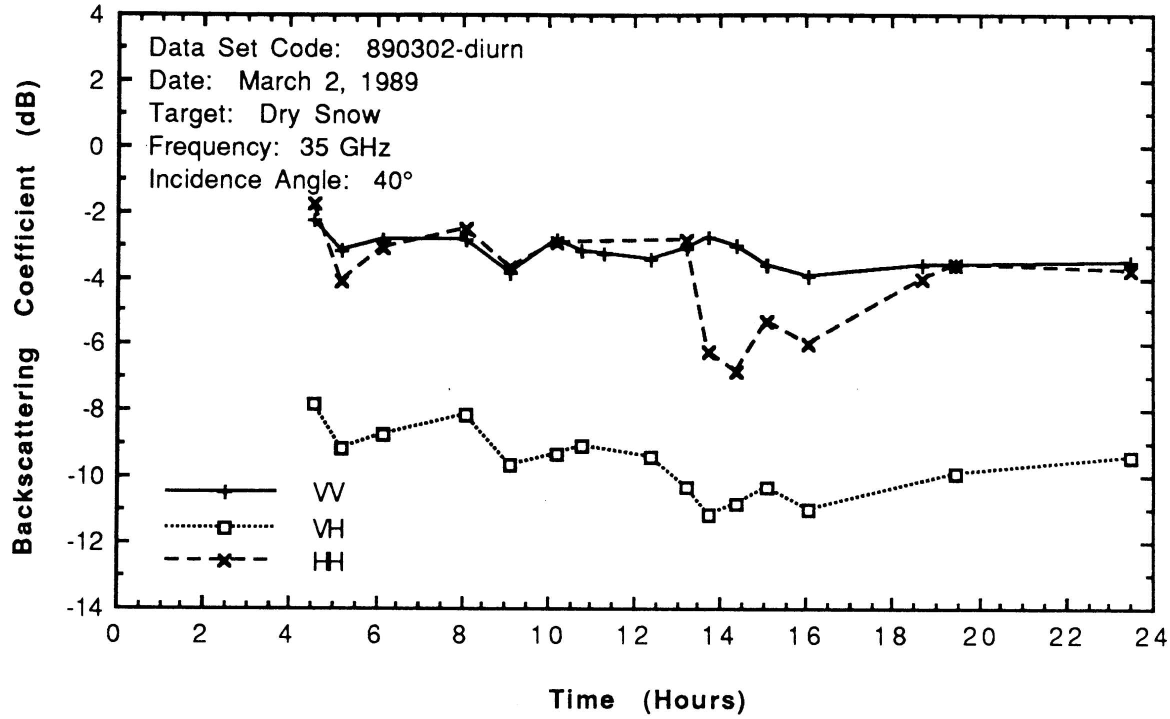
C. 2 March, 1985

Snow
Data Set code: 890302
Depth: 10 cm
LWC: 0%
Surface RMS height: 0.15 cm
Density: 0.1 to 0.2 gm/cm^3
Ice crystal diameter: 2 to 2.5 mm
Surface temperature: -4 C to -5 C
Description: partially metamorphosed snow

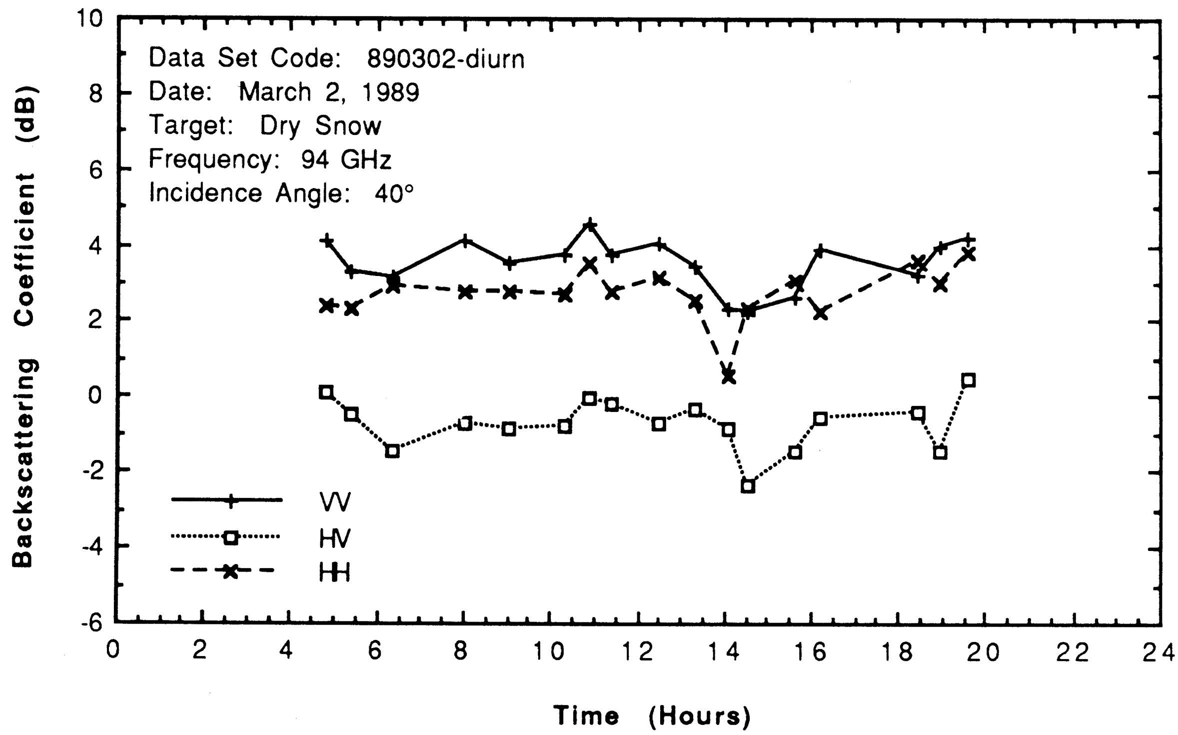
SNOW PIT TEMPERATURE PROFILE (°C)

depth (cm) / Time	0400	0500	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600
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

depth (cm) / Time	1700	1800	1900	2100	1400	1500	1600	1700	1800	1900	2100
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



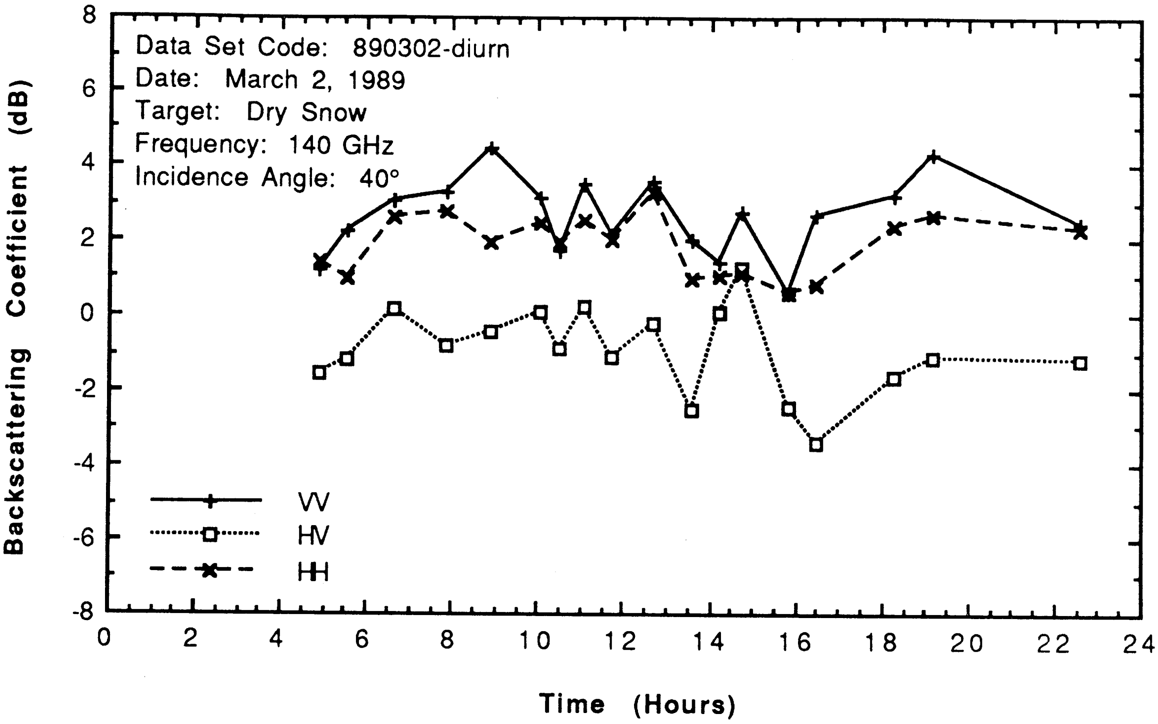
Snow diurnal at Brighton



Snow diurnal at Brighton

MMW DIURNAL DATA FOR SNOW

890302

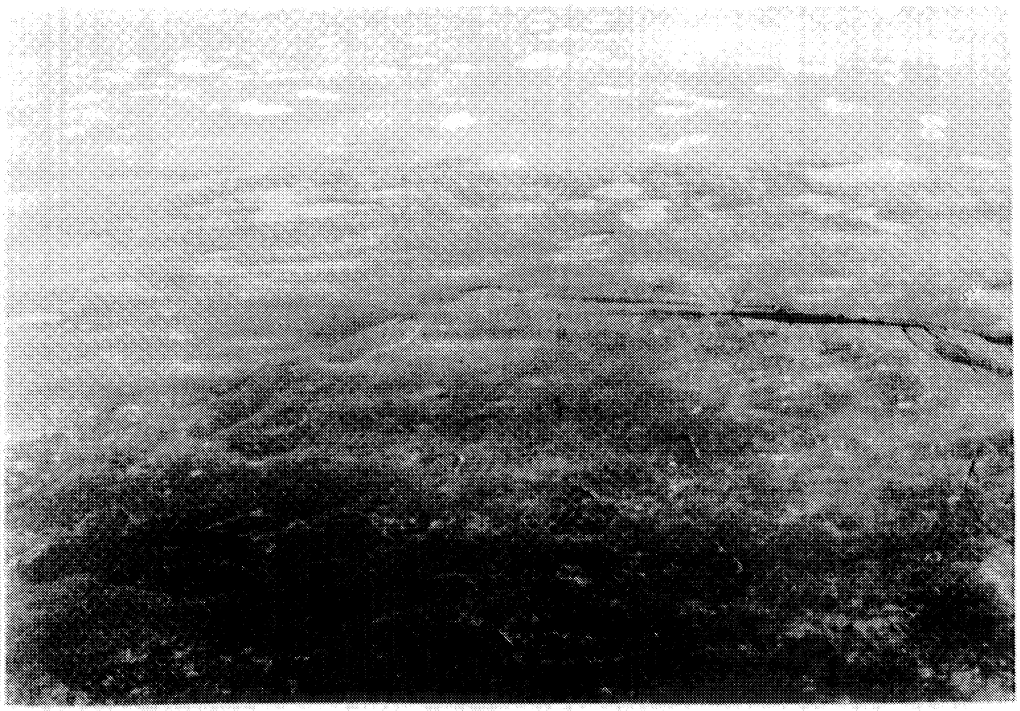


Snow diurnal at Brighton

V. MMW DATA FOR ICE-COVERED GROUND

V. MMW DATA FOR ICE-COVERED GROUND

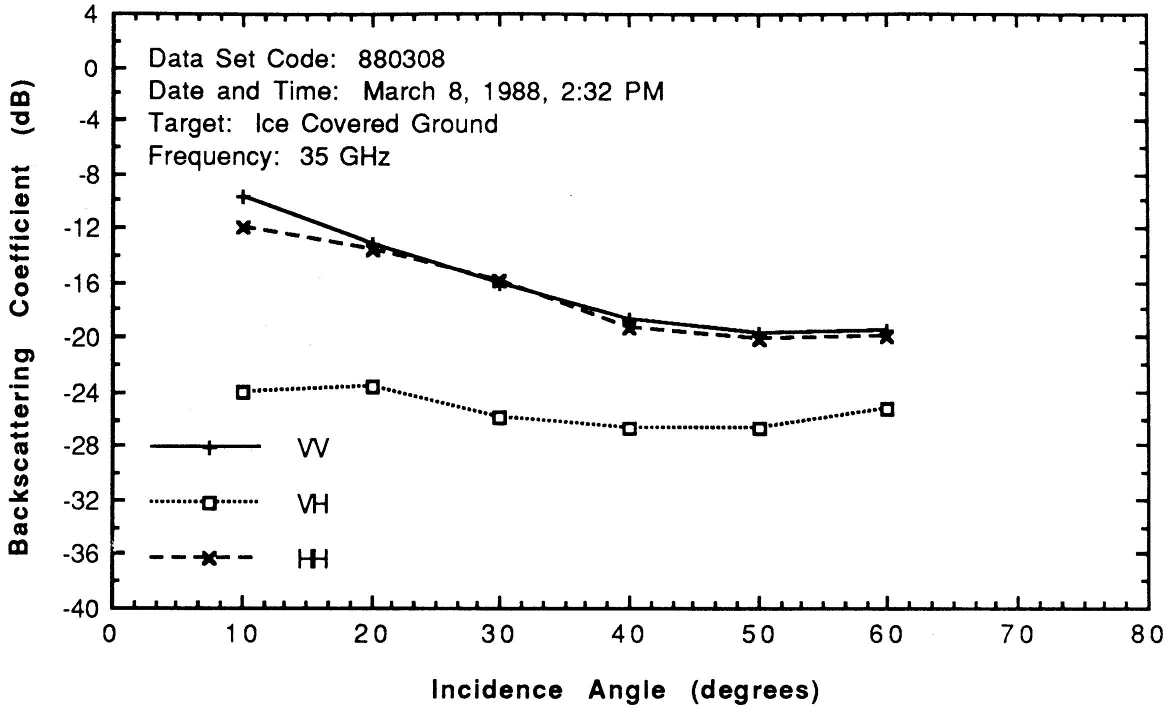
Data set code: 880308
Depth: 3 to10 cm
Surface RMS height: 1 mm
Surface temperature: 0 C
Description: ice formed by the freezing of sheet-flooded terrain, about 10% of the surface was covered by pools of water



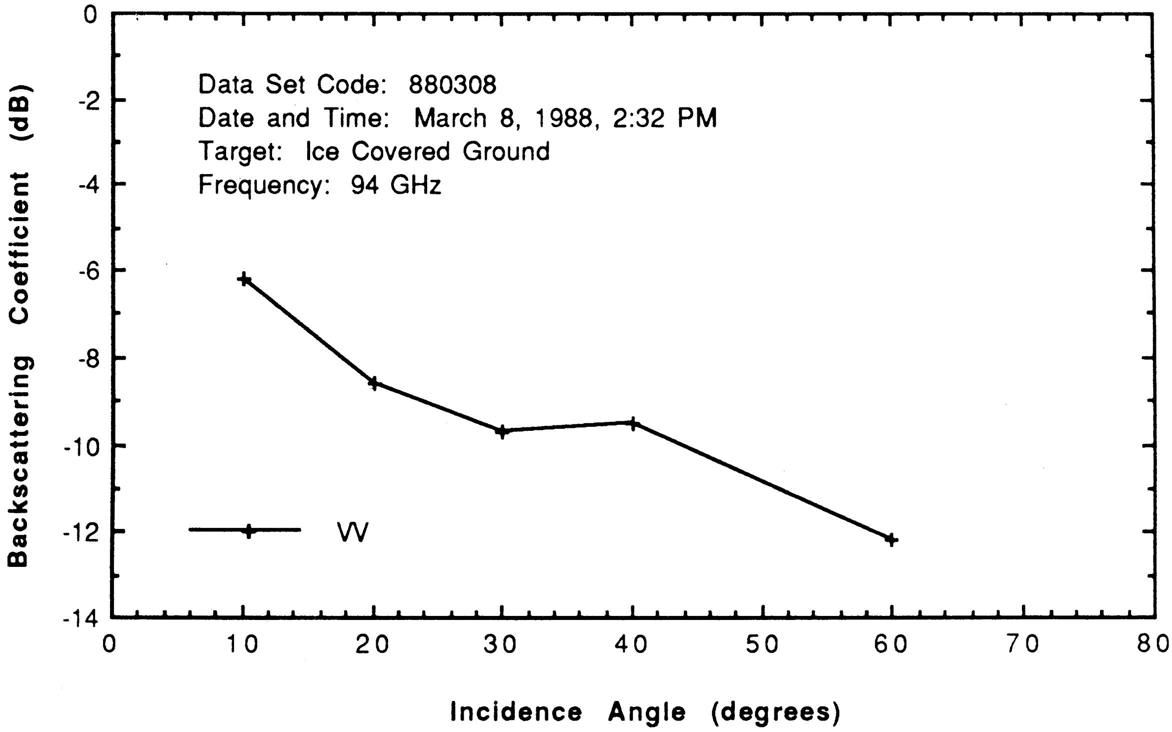
Ice covered ground

MMW DATA FOR ICE-COVERED GROUND

880308



Ice

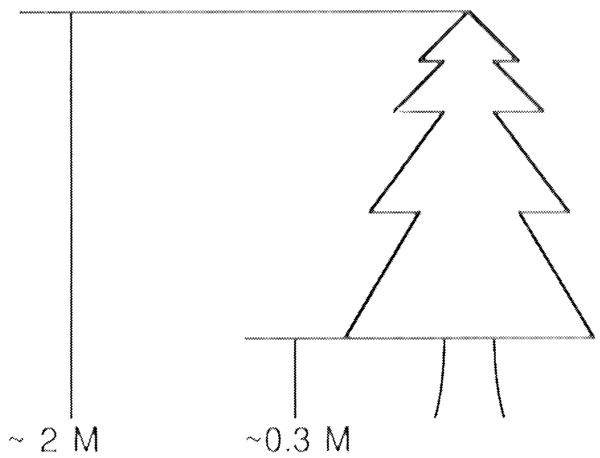


Ice

VI. MMW DATA FOR TREE CANOPIES

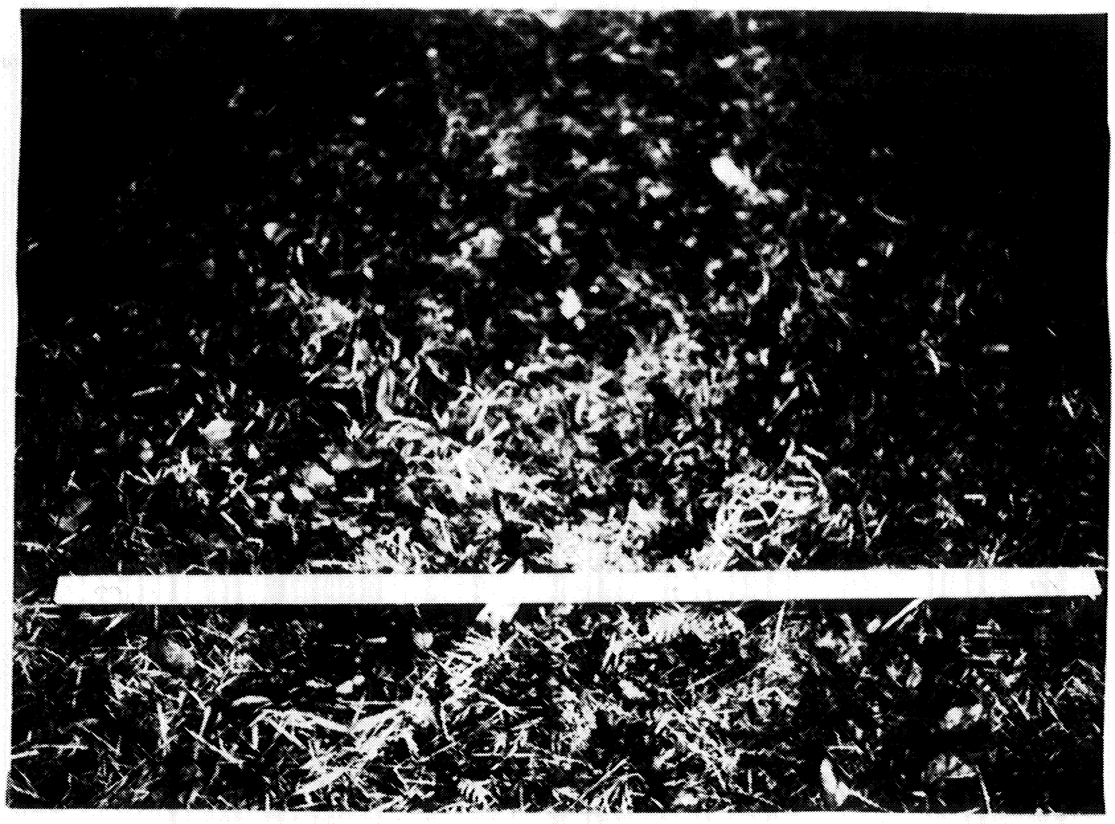
A. Cedar Trees

Cedar trees
Data set code: 871111
Tree density: 0.07 trees/m^2
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



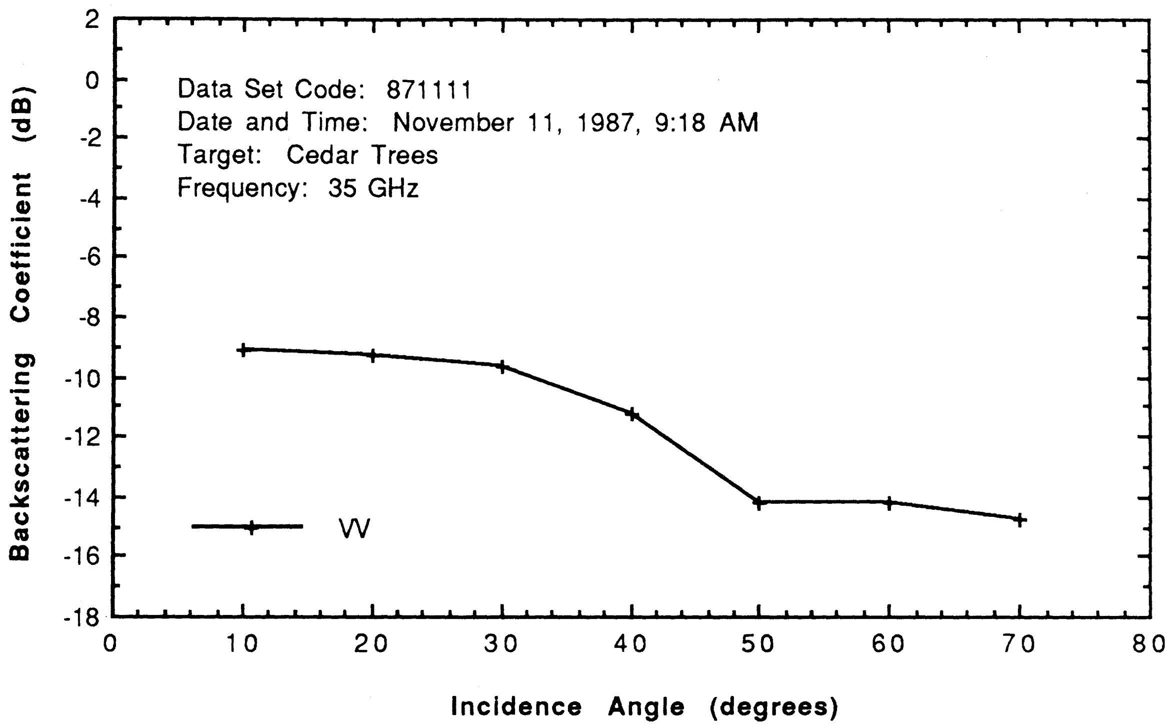
Cedar trees

Needles of Cedar trees

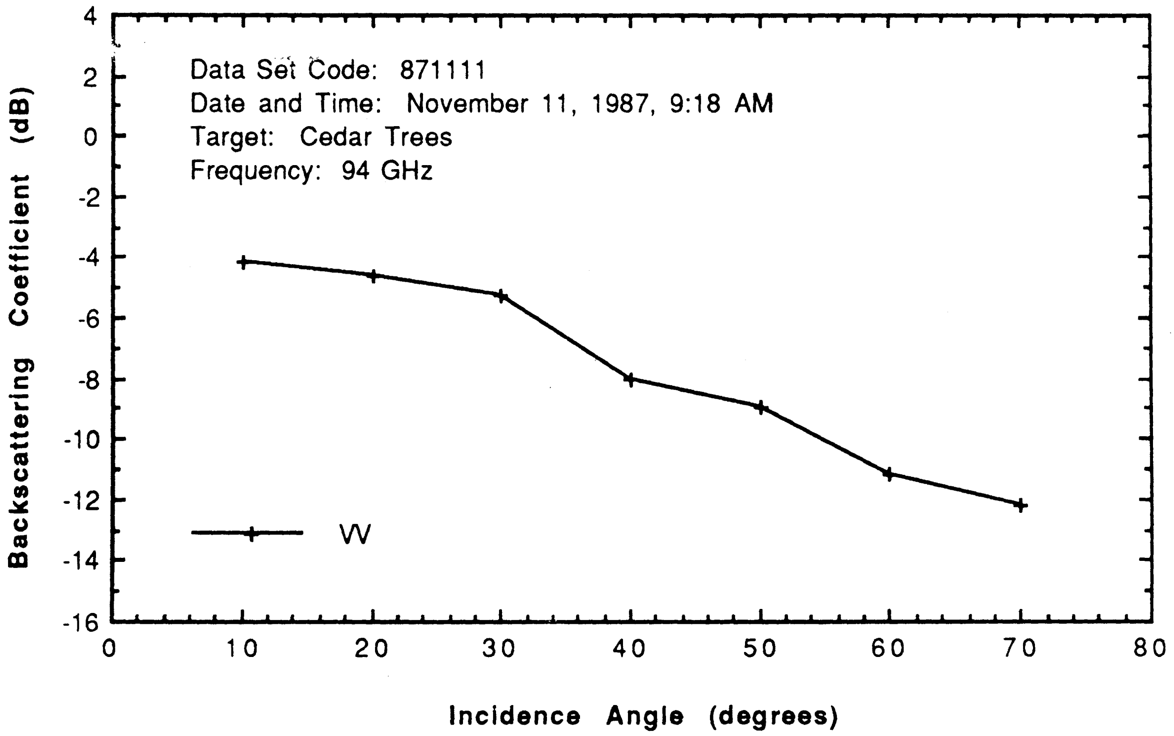


Ground cover beneath Cedar trees

871111



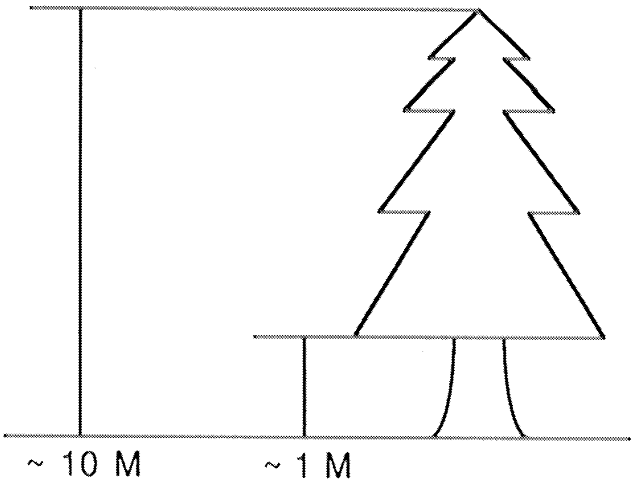
Cedars at Arboretum

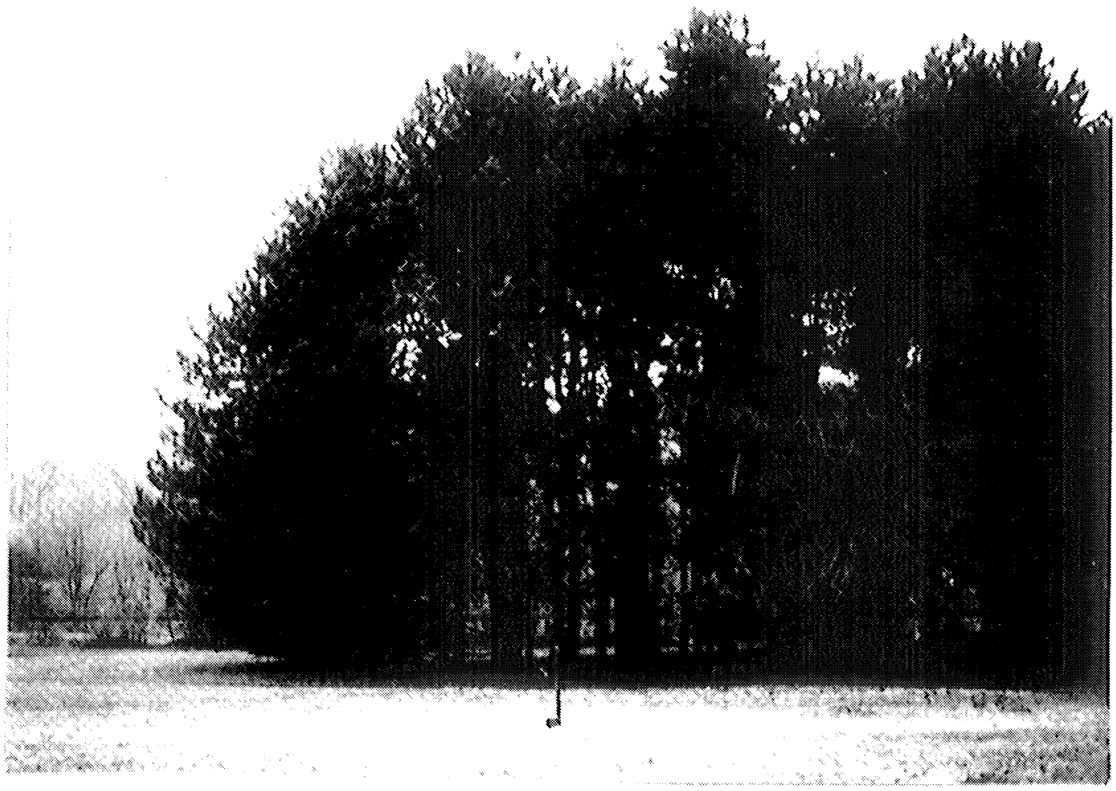


Cedars at Arboretum

B. Red Pine

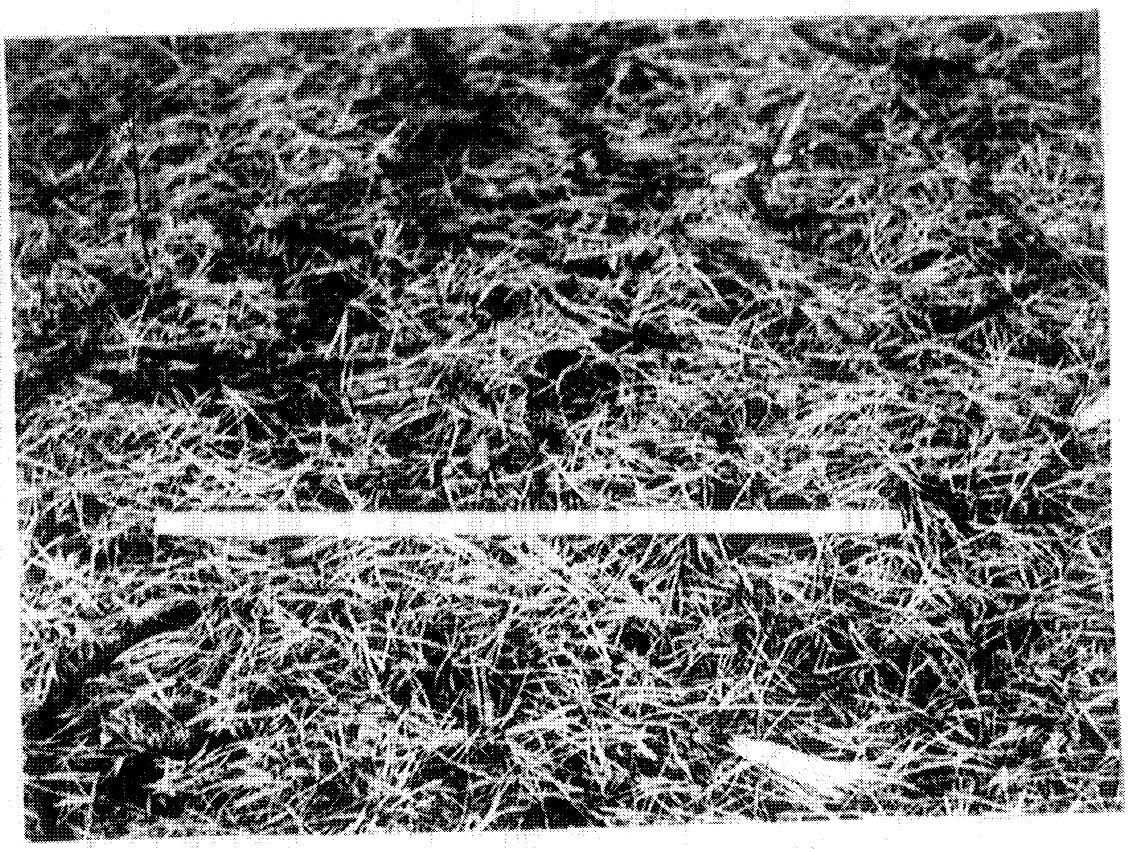
5 -11 November, 1987
Data set code: 871105
Tree density: 0.14 trees/m^2
Average leaf (or needle) dimensions: 10 to 15 cm
Leaf moisture content: ~70 %
Percent vegetation cover: 90 %
Percent cover of undergrowth: 100%
Moisture content of undergrowth: 35%
Description: Stand of mature red pines over dry, fallen needles





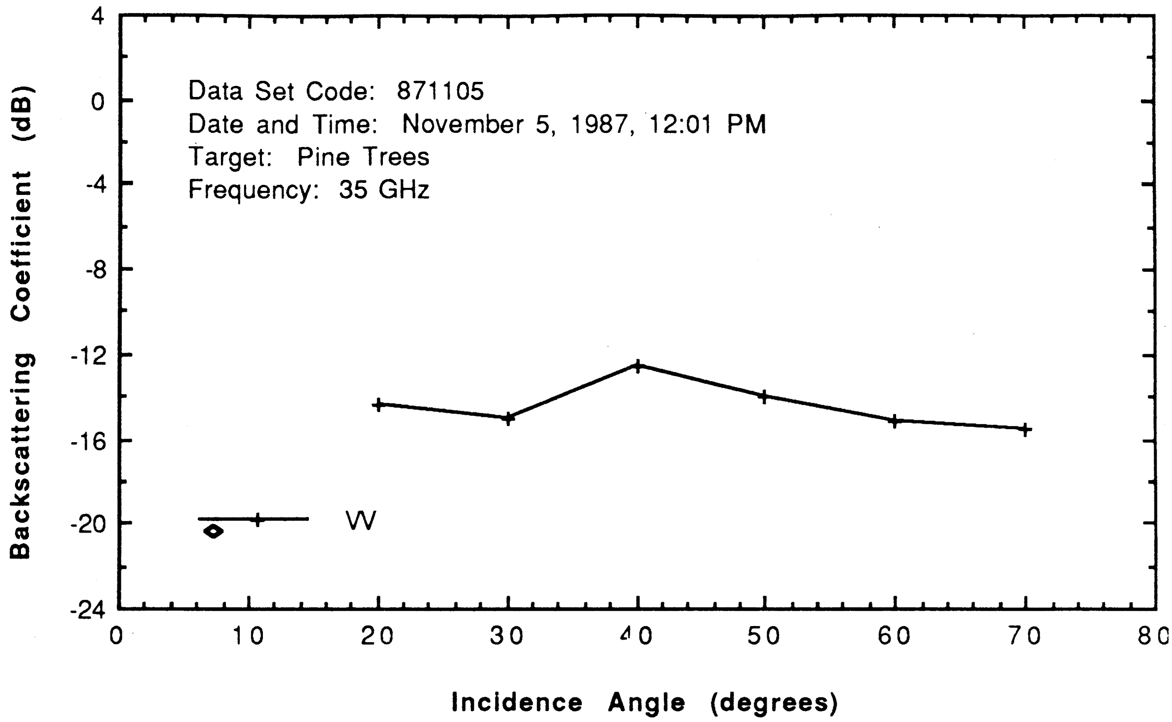
Red pines

Needles of Red Pines



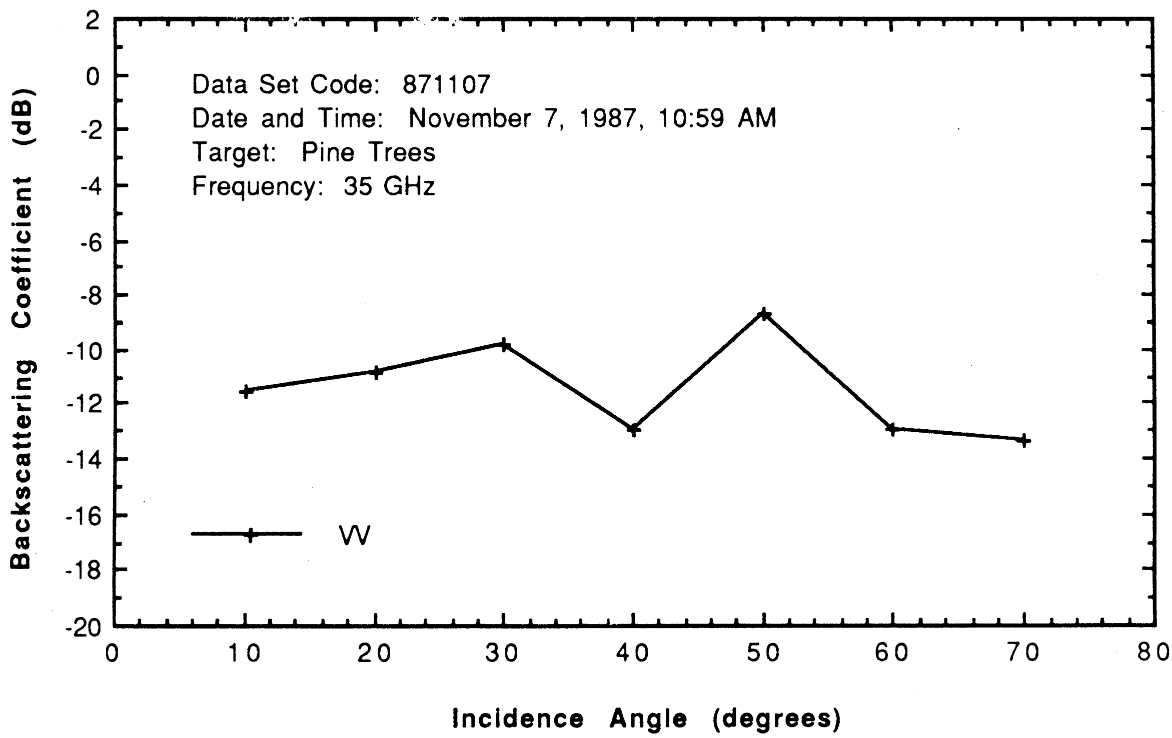
Ground cover beneath Red Pines

871105

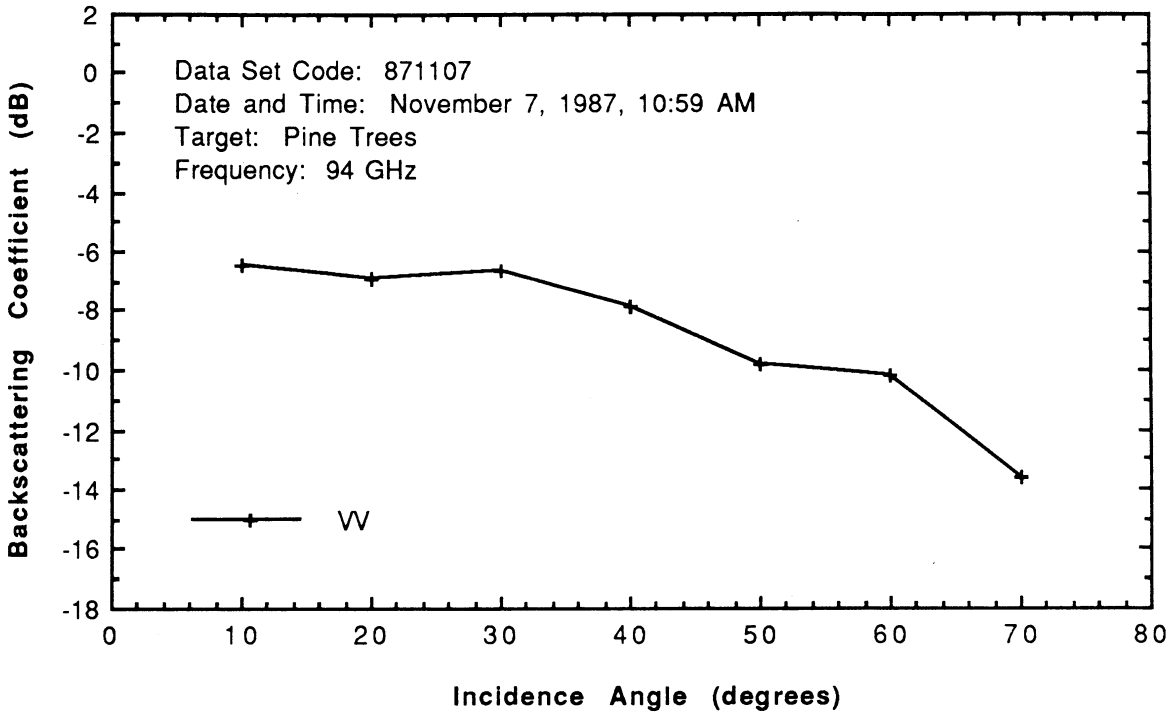


Red Pines at Arboretum
(5 November, 1987)

871107

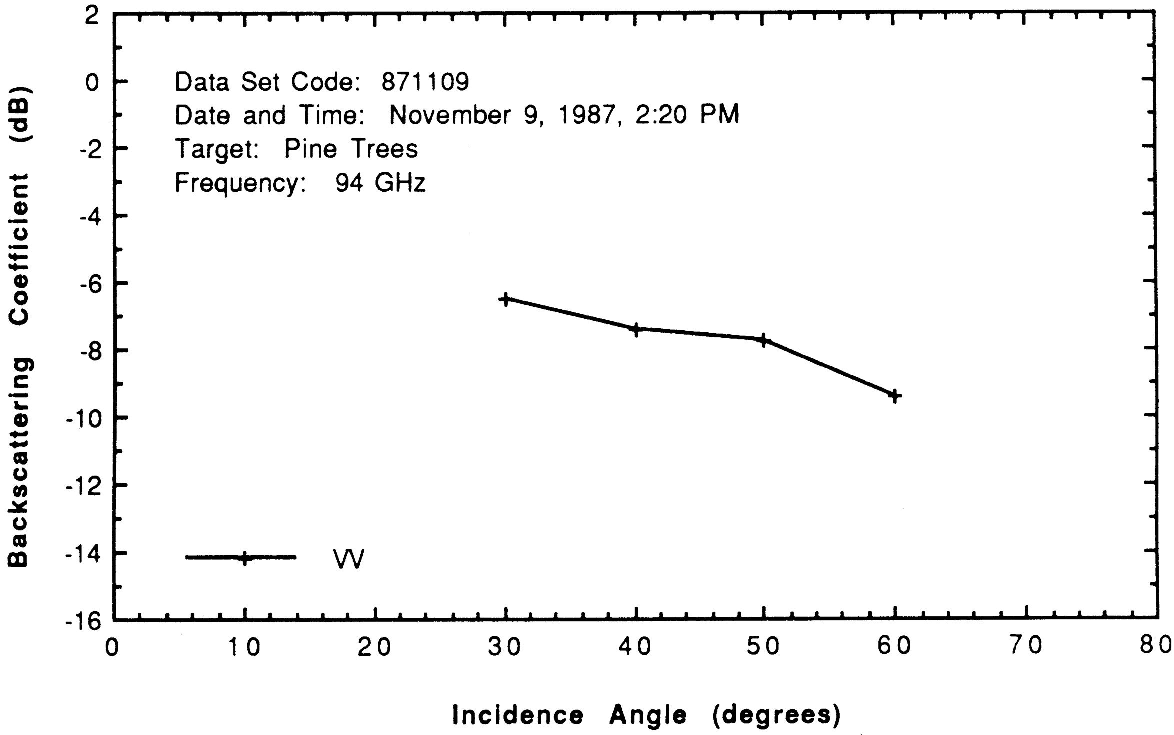


Red Pines at Arboretum
(7 November, 1987)

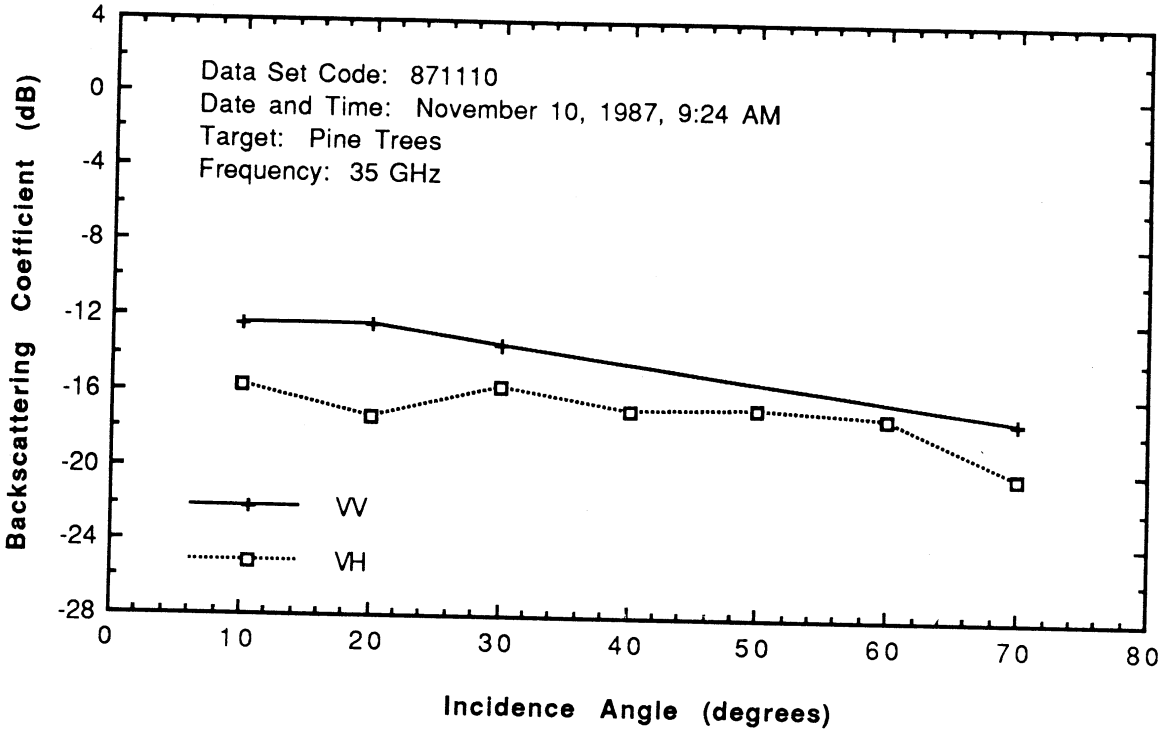


Red Pines at Arboretum
(7 November, 1987)

871109

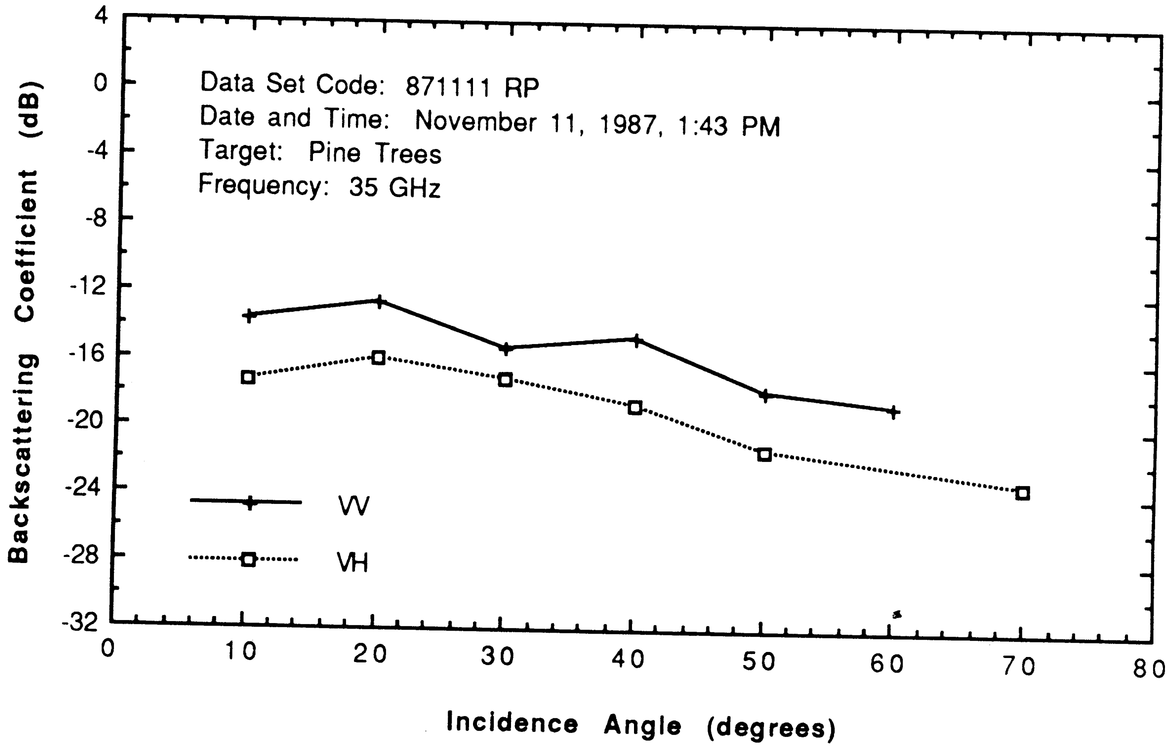


Red Pines at Arboretum
(9 November, 1987)



Red Pines at Arboretum
(10 November, 1987)

871111



Red Pines at Arboretum
(11 November, 1987)

C. Apple Trees

Data set code: 880811

Tree density: 0.1 trees/m^2

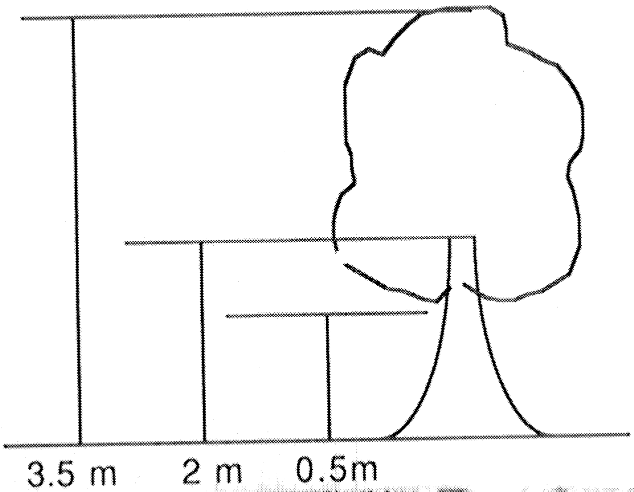
Average leaf (or needle) dimensions: 4 by 8 cm

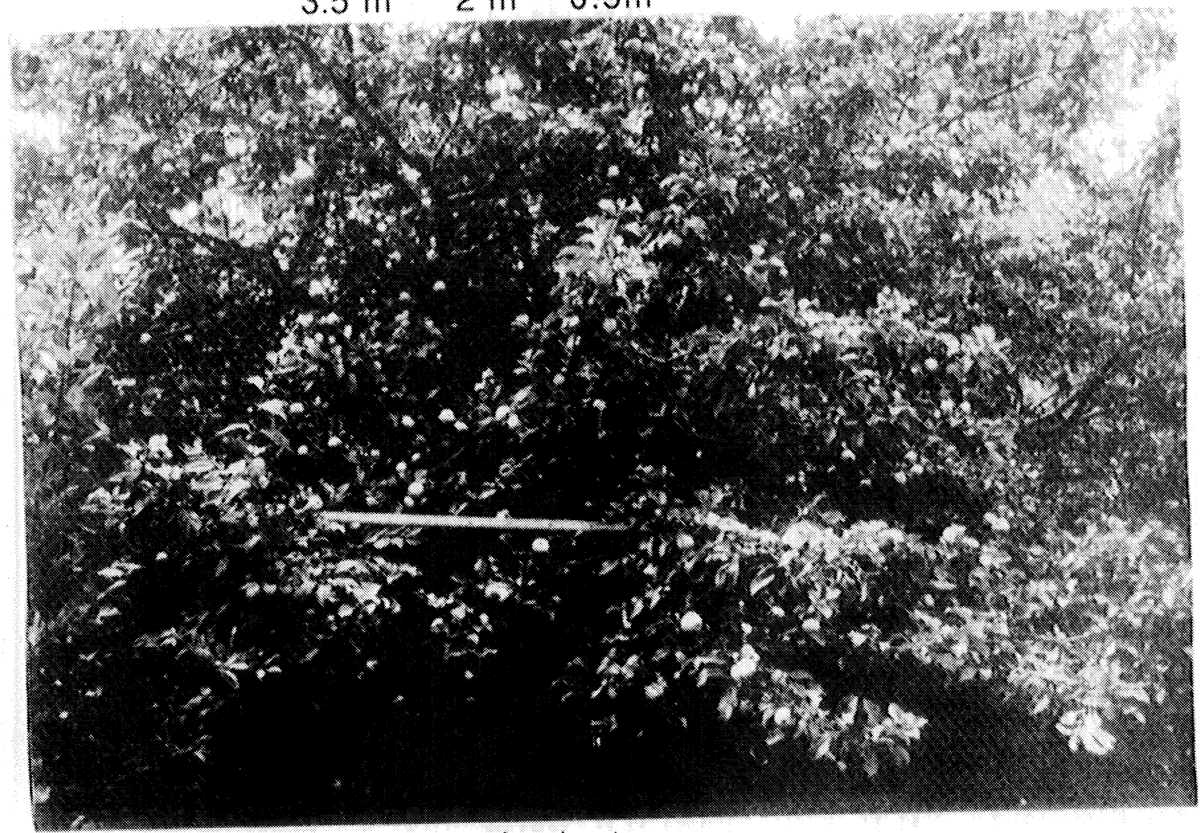
Leaf moisture content: ~80 %

Percent vegetation cover: 90%

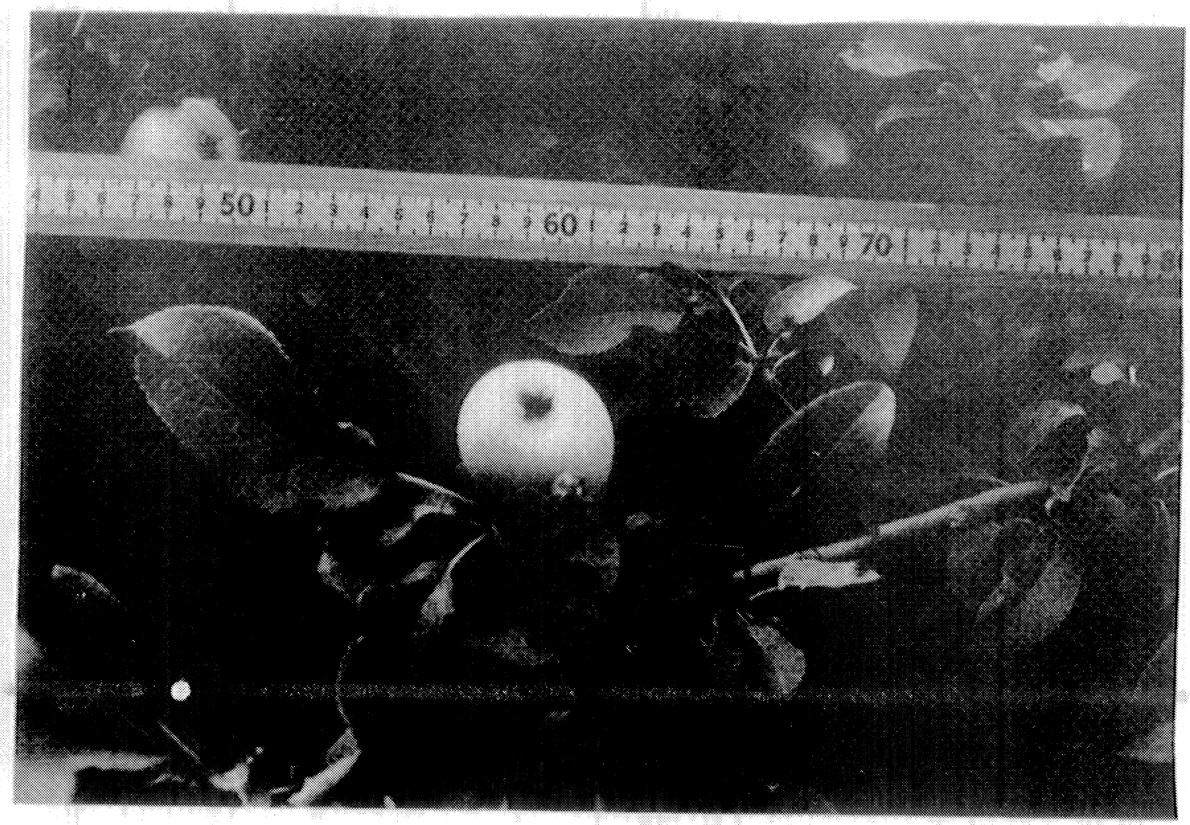
Percent cover of undergrowth: 100%

Moisture content of undergrowth: 80%



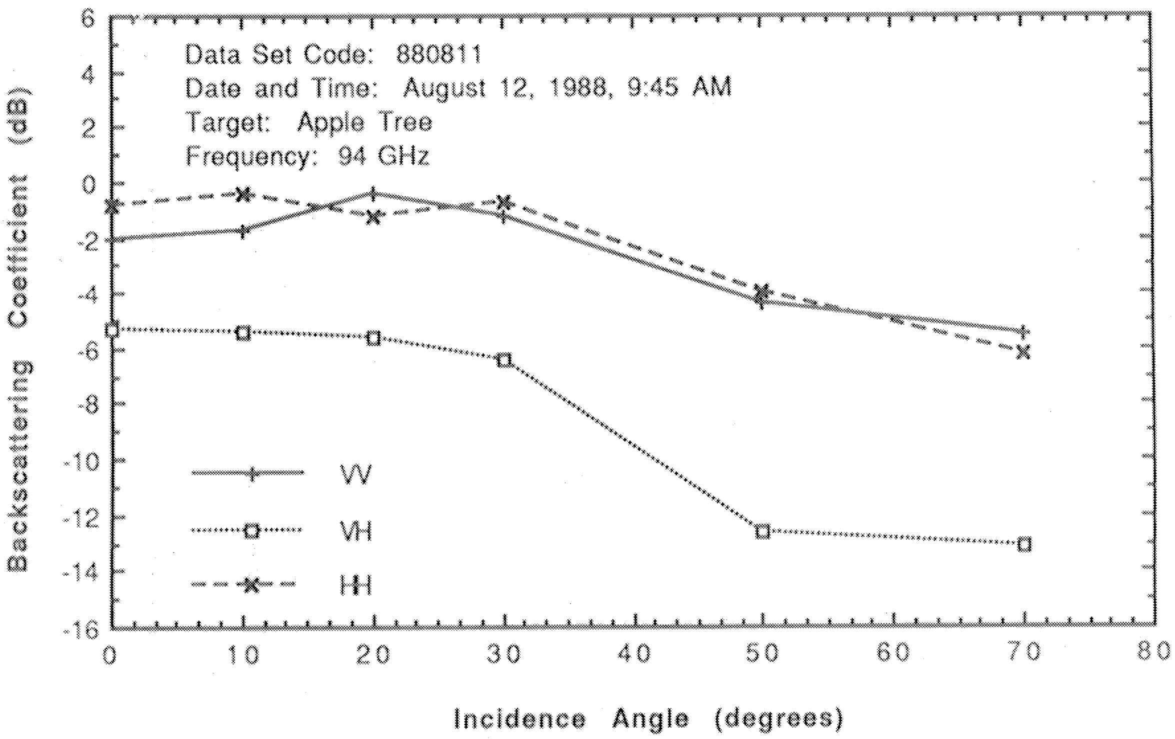


Apple tree



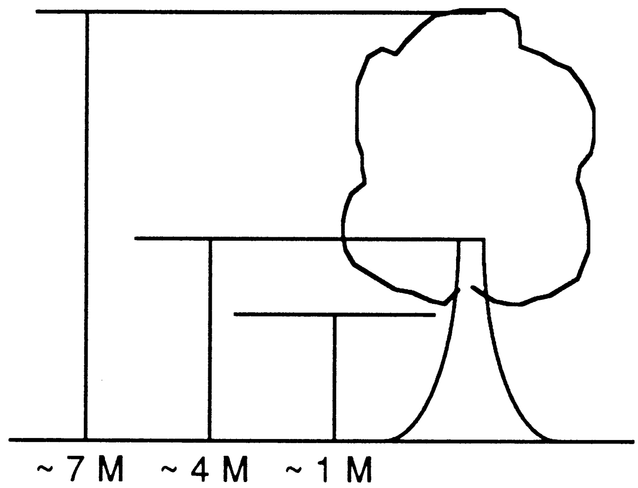
Leaves of apple tree

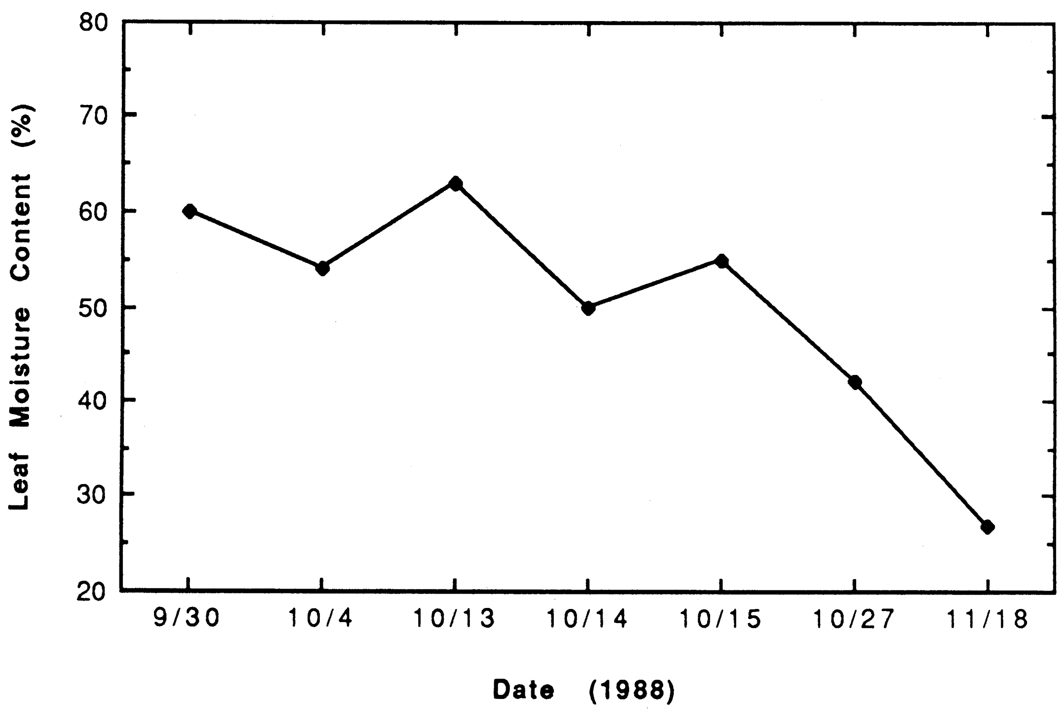
880811



D. Bur Oak

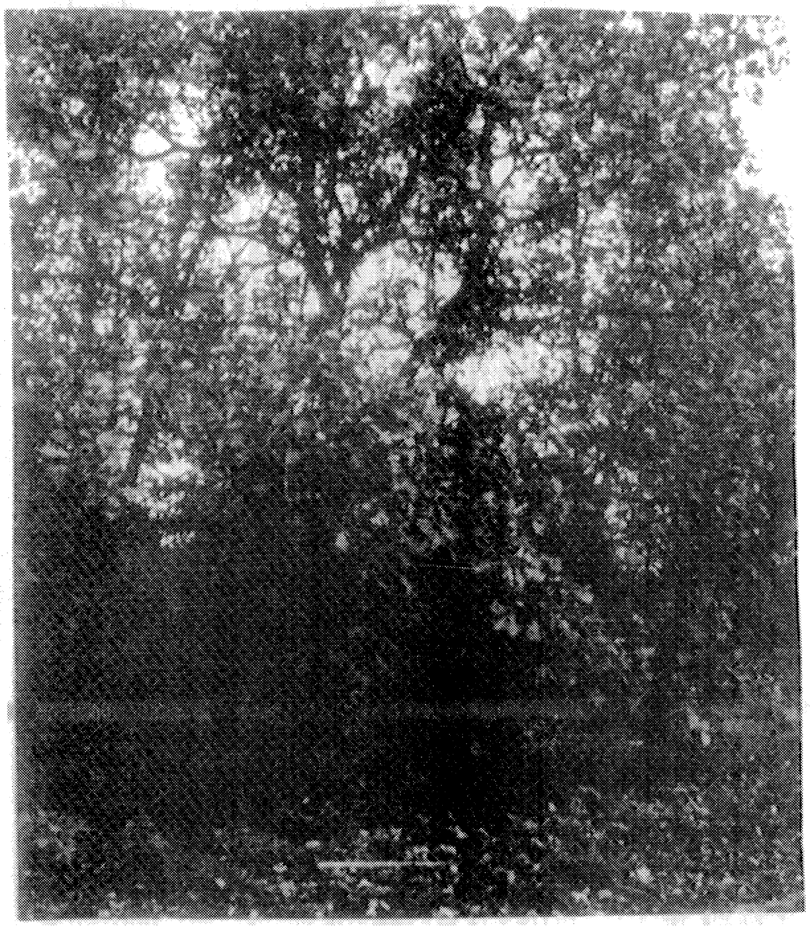
Bur Oak (Quercus macrocarpa)
Data set code: 880930-1027
Tree density: 0.09 trees/m^2
Average leaf (or needle) dimensions: 8 by 12 cm
Moisture content of undergrowth: ~ 70%
Percent cover of undergrowth: 100%
Percent vegetationcover: 95%
Description: Stand of mature oak trees over low ground cover



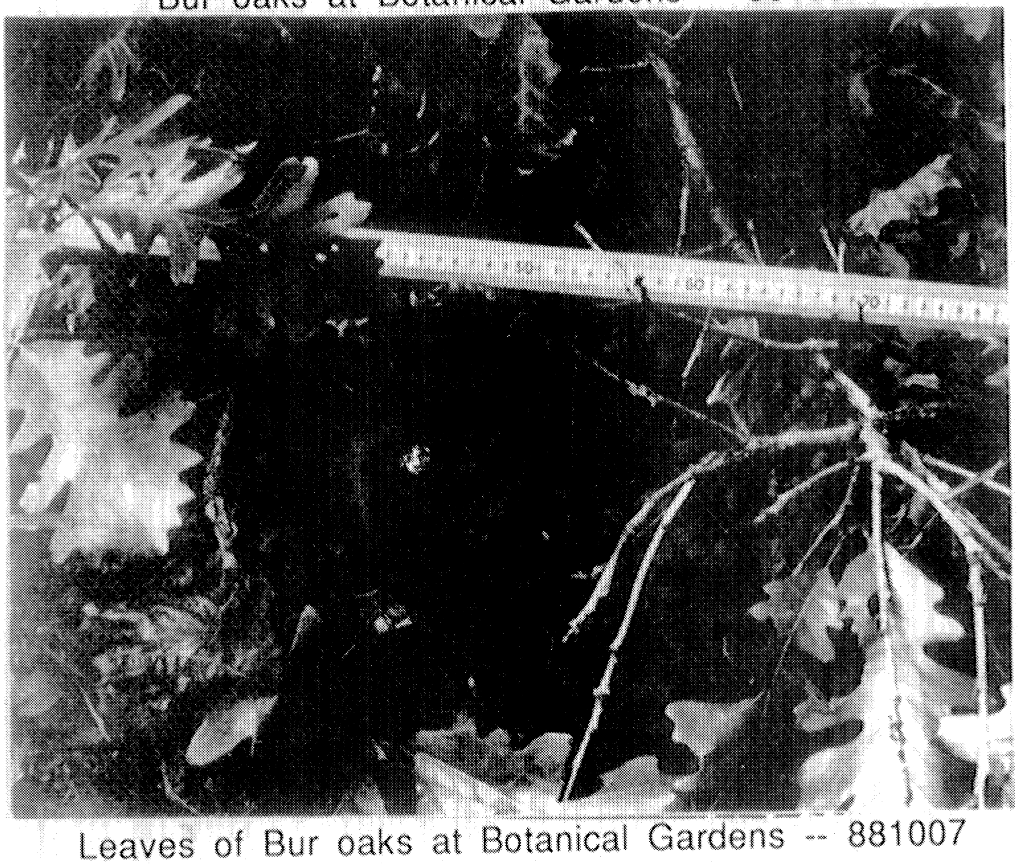


Bur oaks at Botanical Gardens -- 880930

Leaves of Bur oaks at Botanical Gardens -- 880930

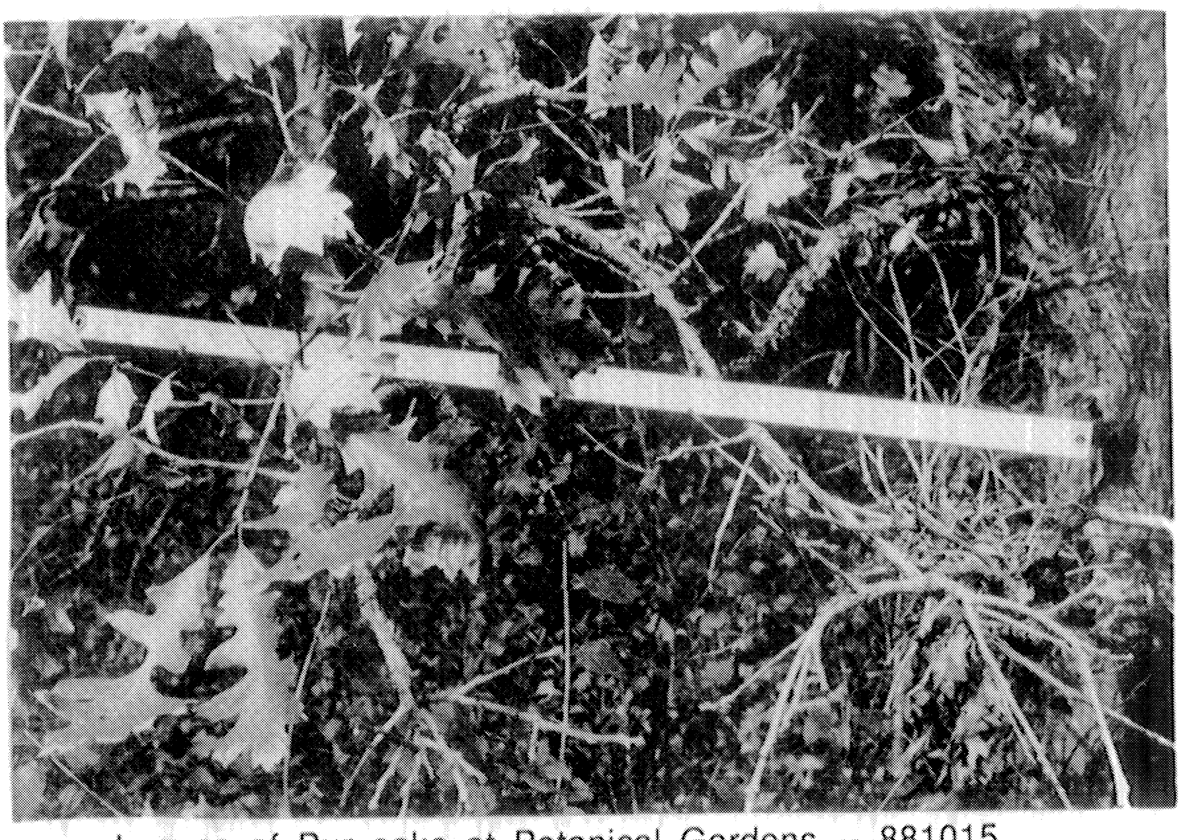


Bur oaks at Botanical Gardens -- 881007

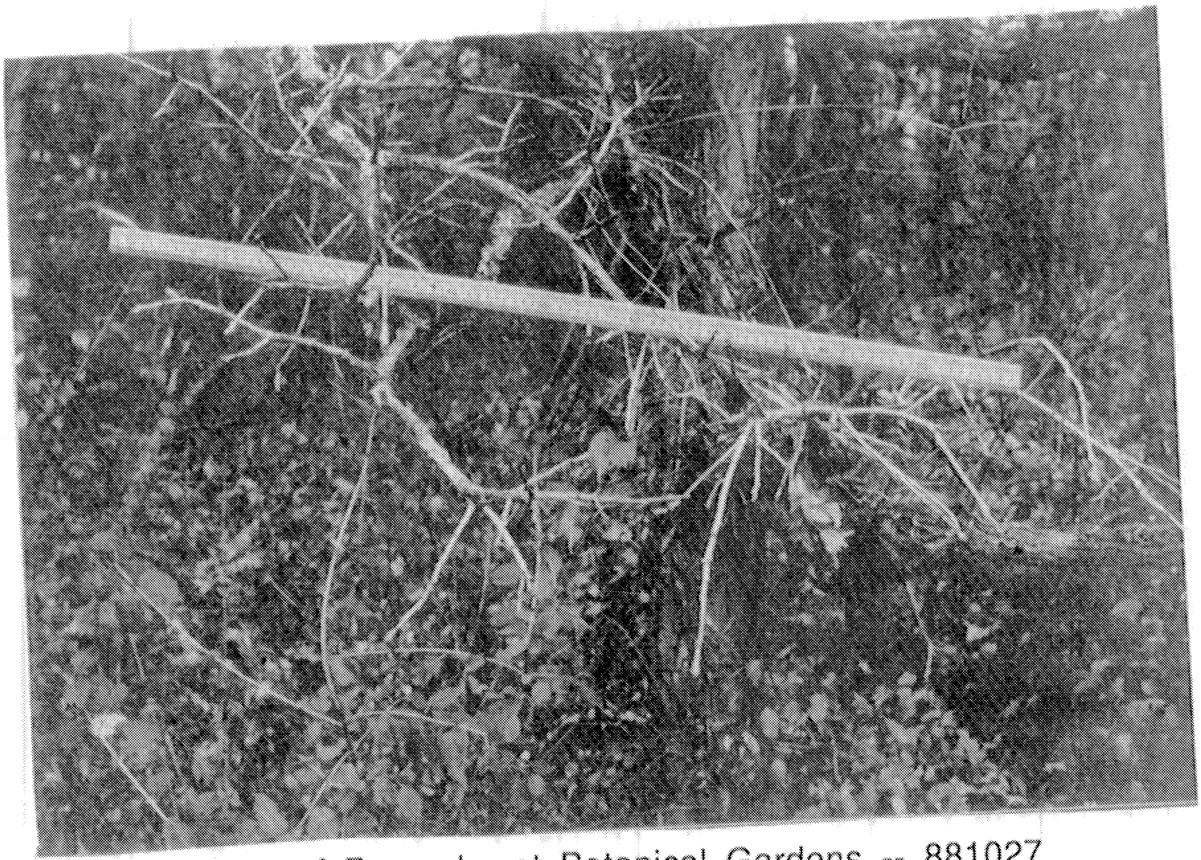


Leaves of Bur oaks at Botanical Gardens -- 881007

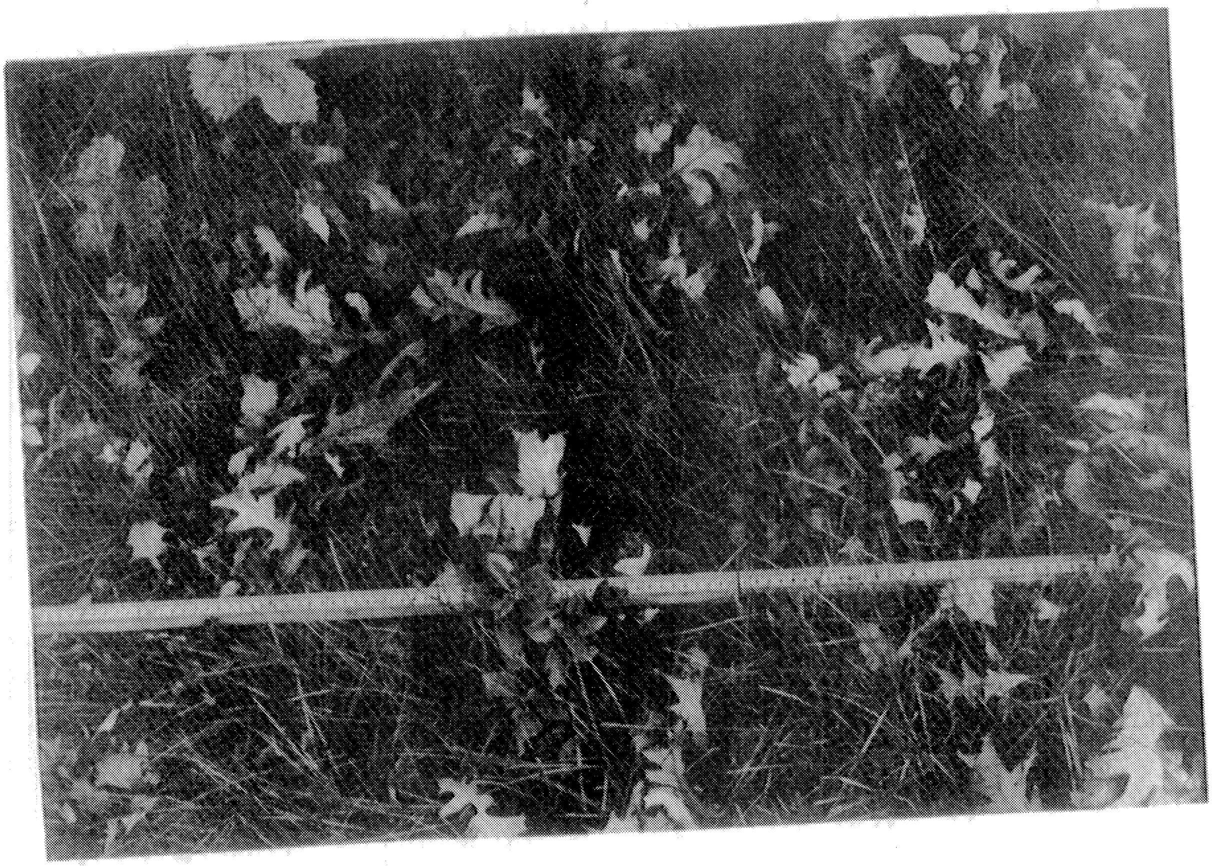
Bur oaks at Botanical Gardens -- 881015



Leaves of Bur oaks at Botanical Gardens -- 881015

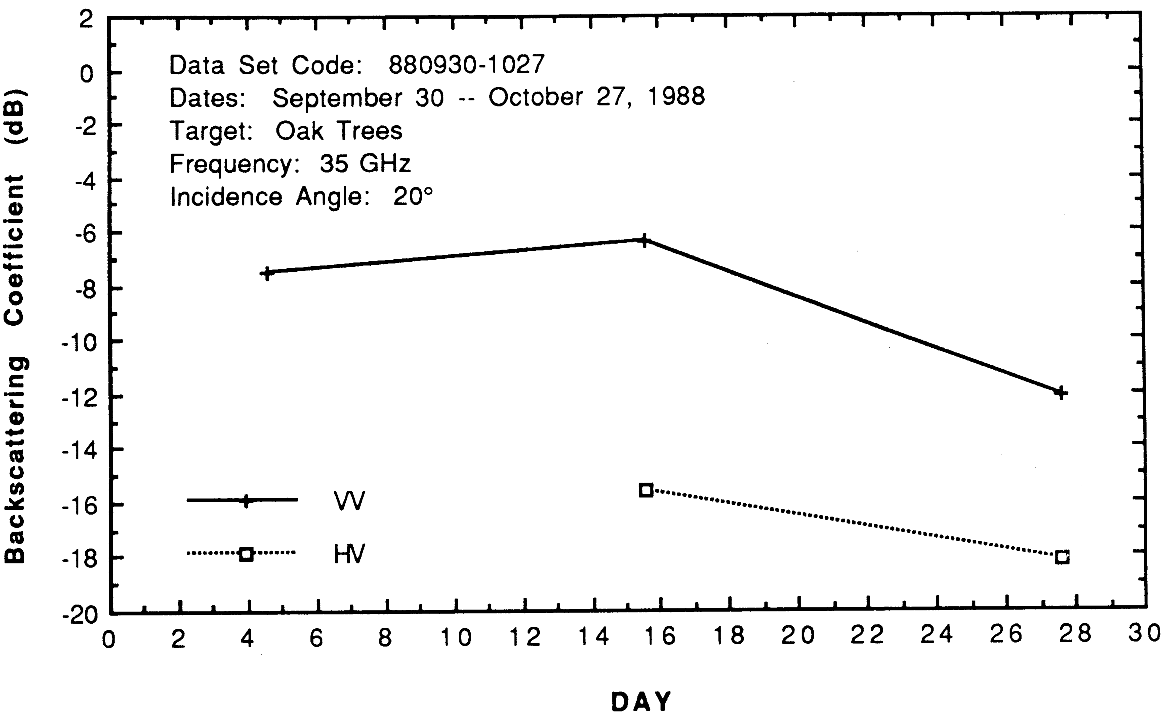


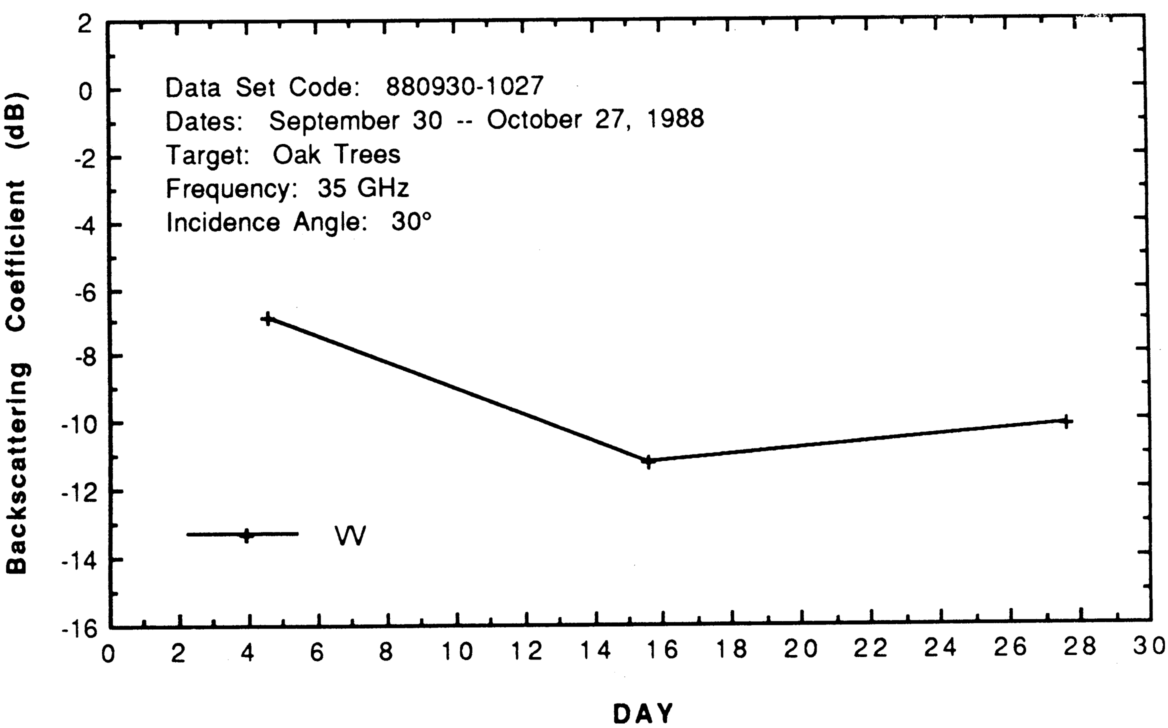
Leaves of Bur oaks at Botanical Gardens -- 881027



Ground cover beneath Bur oaks at Botanical Gardens -- 881027

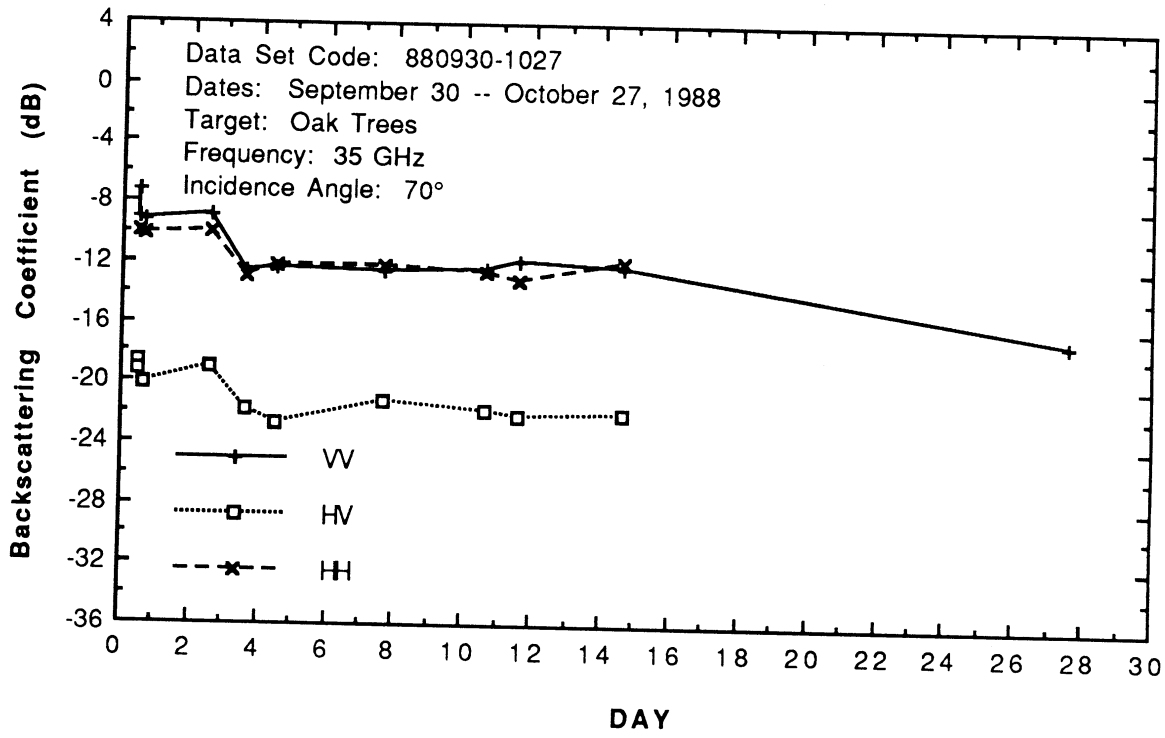
880930-1027



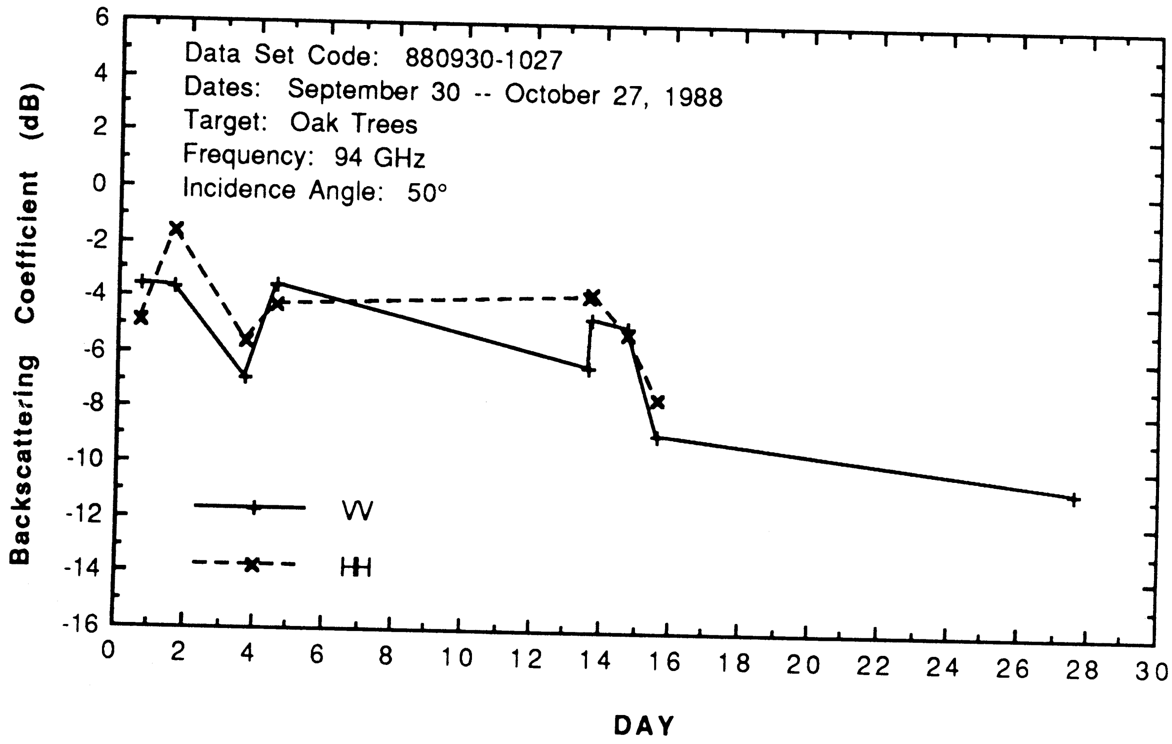


Bur Oaks (Quercus Macrocarpa)

880930-1027

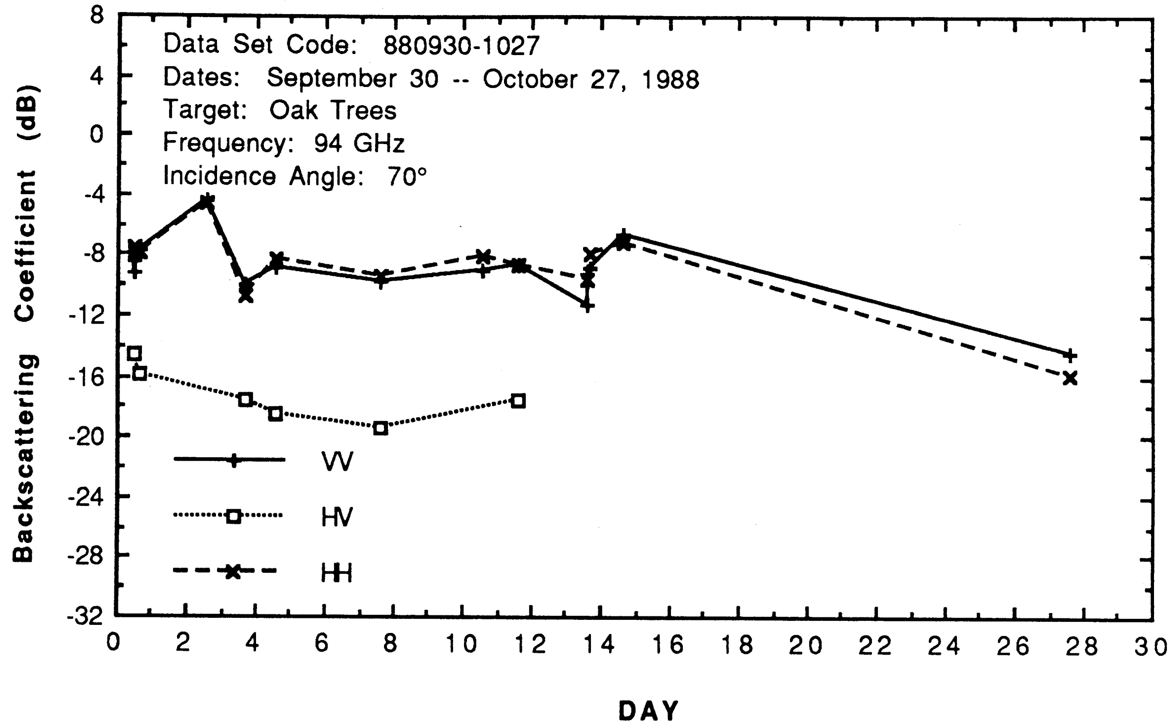


Bur Oaks (Quercus Macrocarpa)

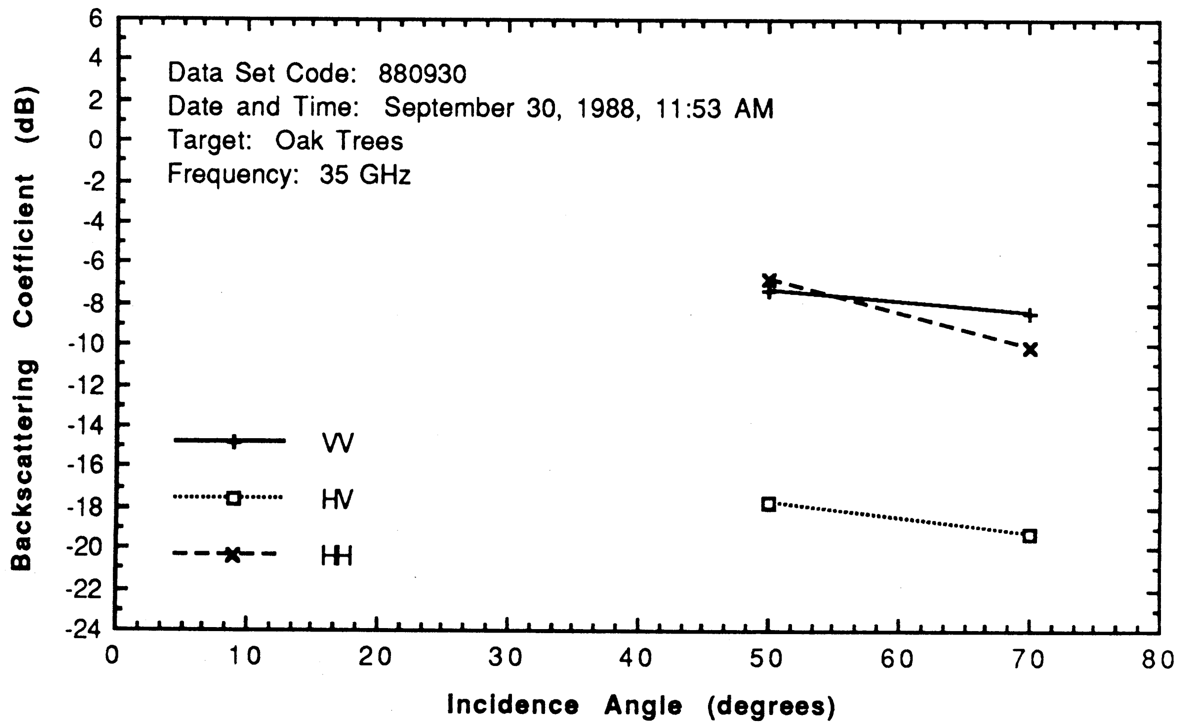


Bur Oaks (Quercus Macrocarpa)

880930-1027

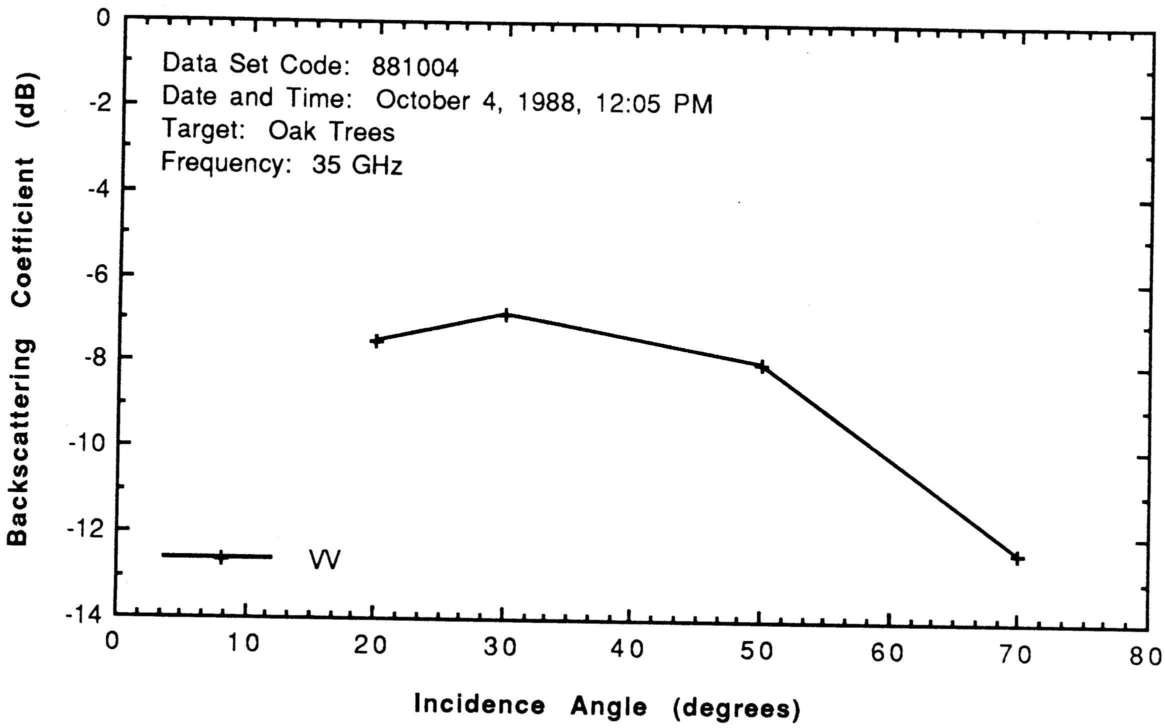


Bur Oaks (Quercus Macrocarpa)
880930

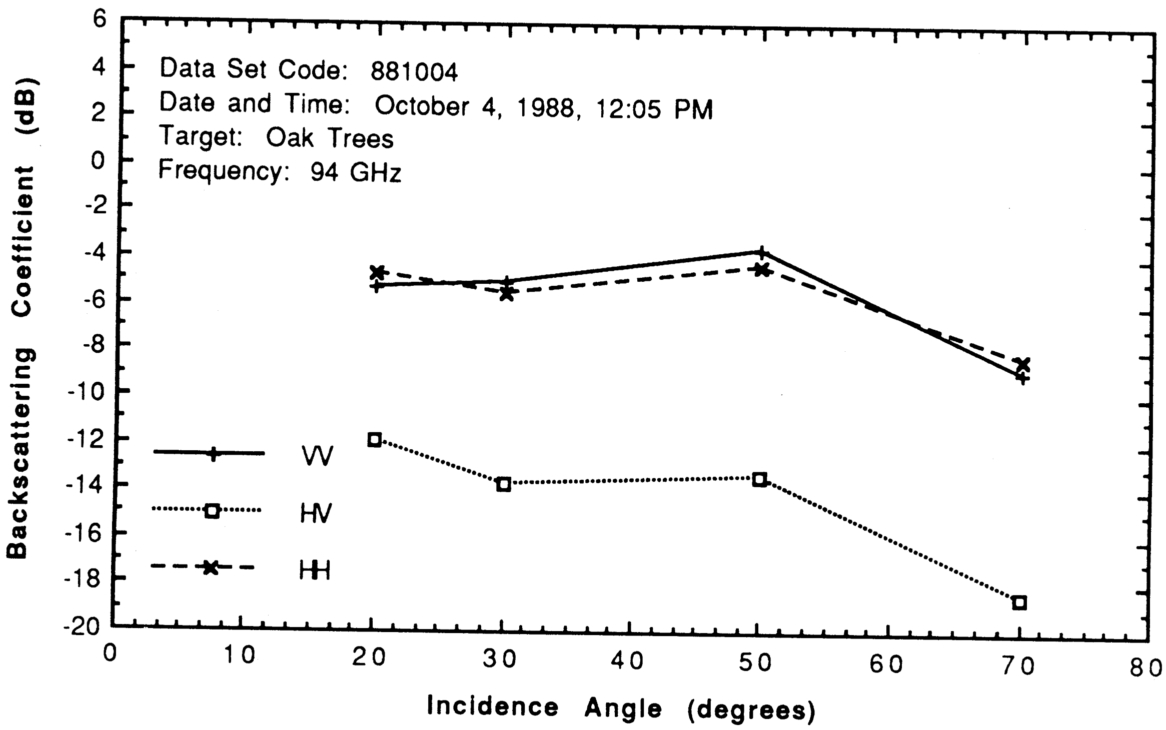


Bur Oaks (Quercus Macrocarpa)
Leaf Moisture Content = 59.7%

881004

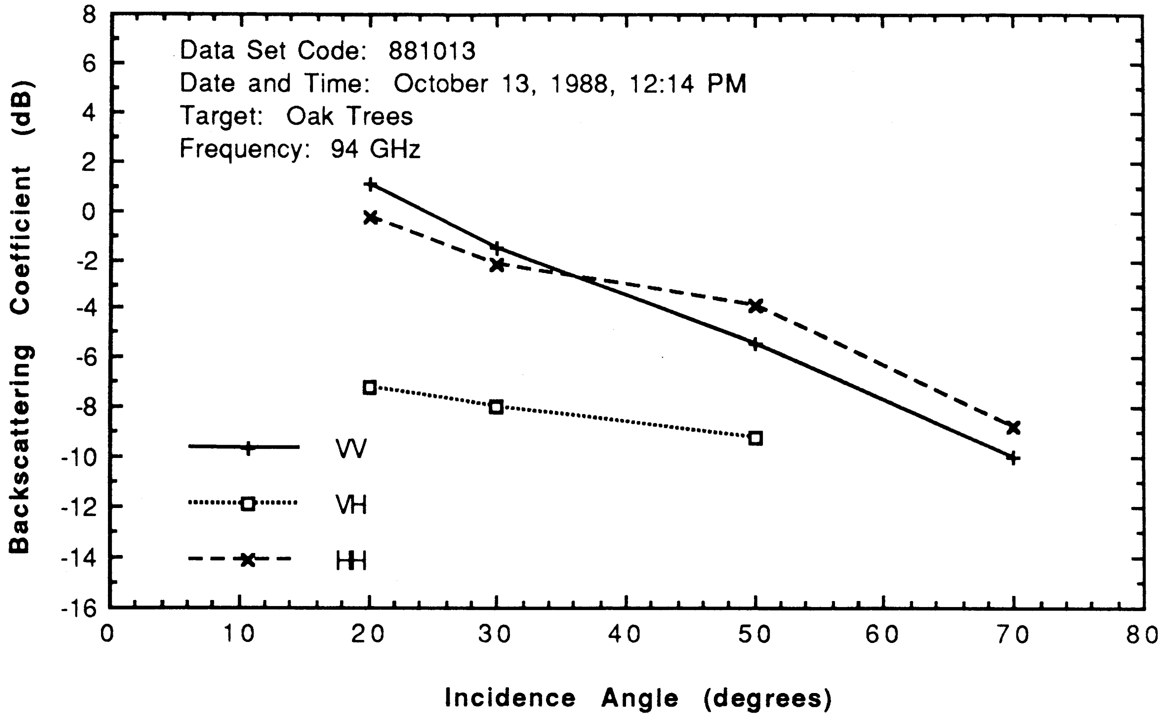


Bur Oaks (Quercus Macrocarpa)



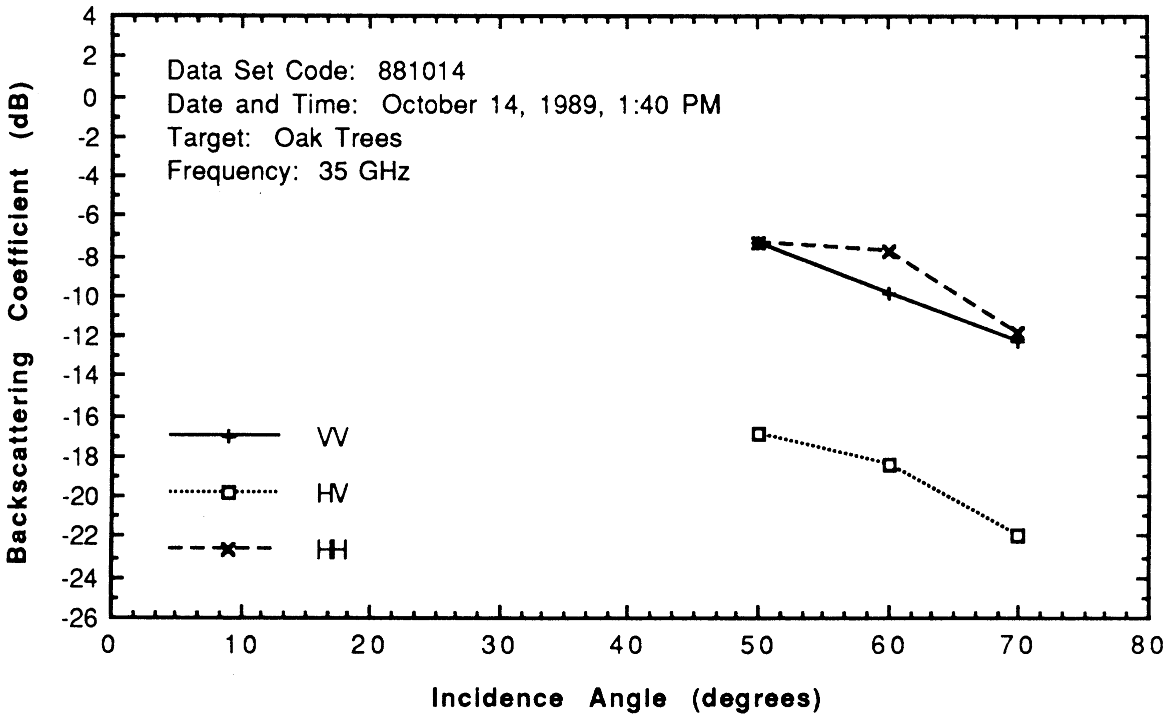
Bur Oaks (Quercus Macrocarpa)
Leaf Mositure Content = 54.2%

881013



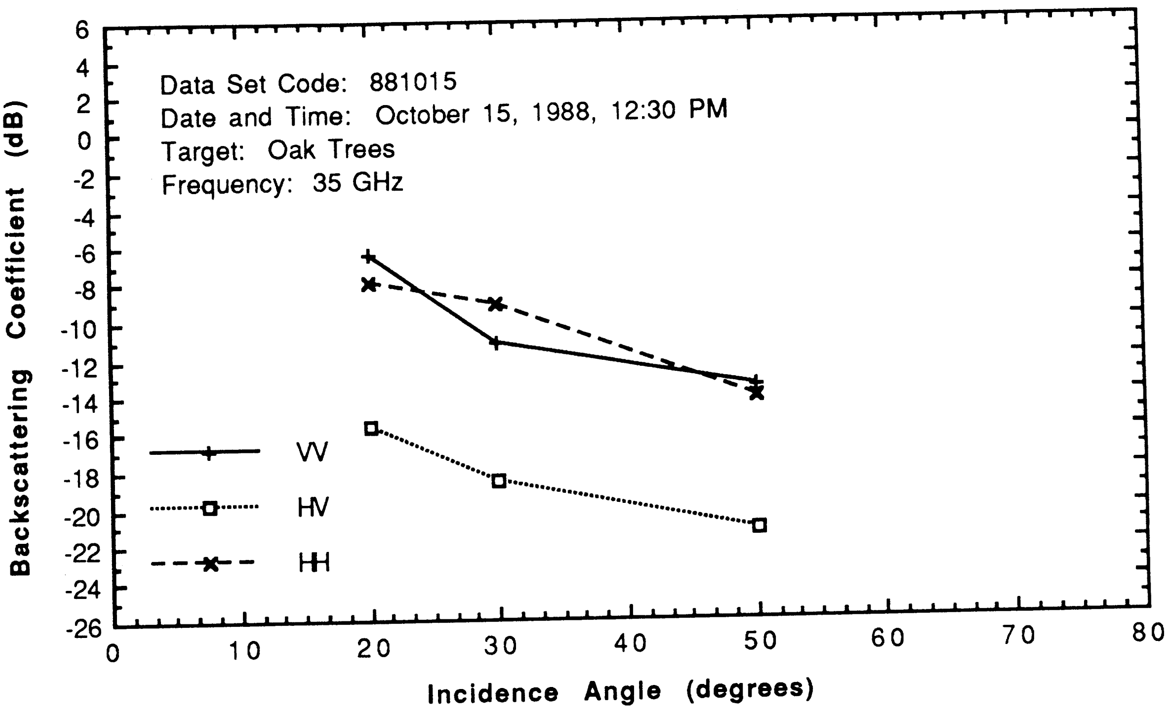
Bur Oaks (Quercus Macrocarpa)
Leaf Moisture Content = 63.4%

881014

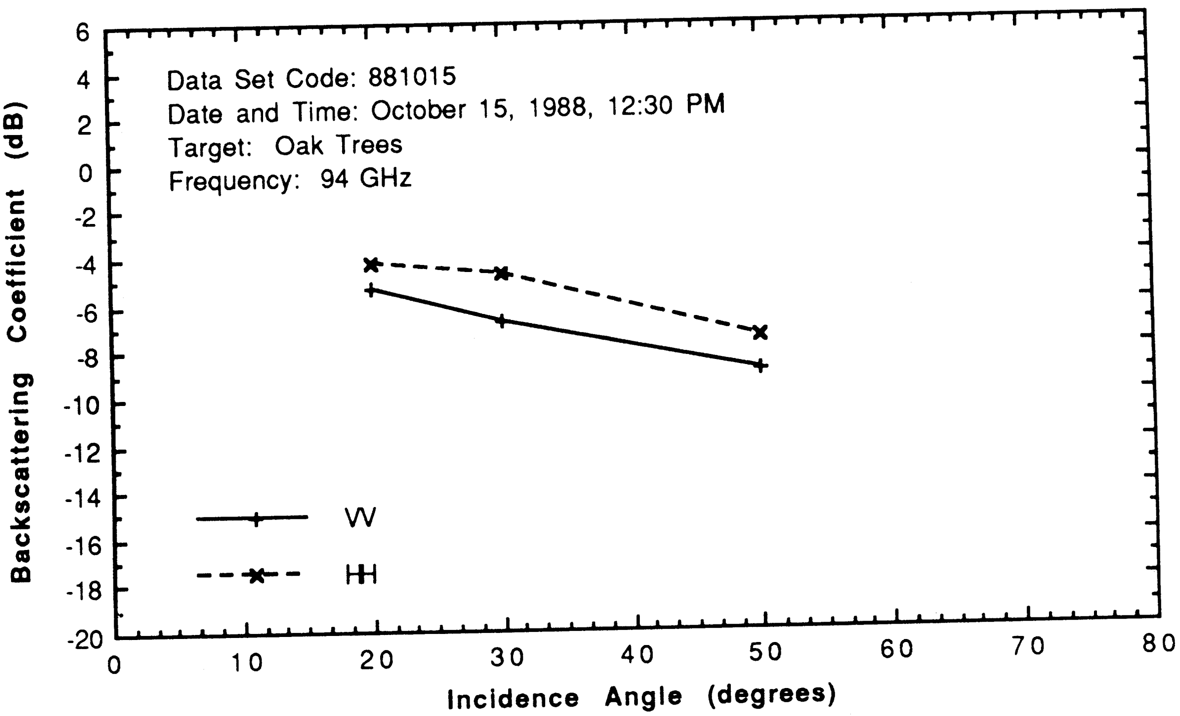


Bur Oaks (Quercus Macrocarpa)
Leaf Moisture Content = 50.1%

881015

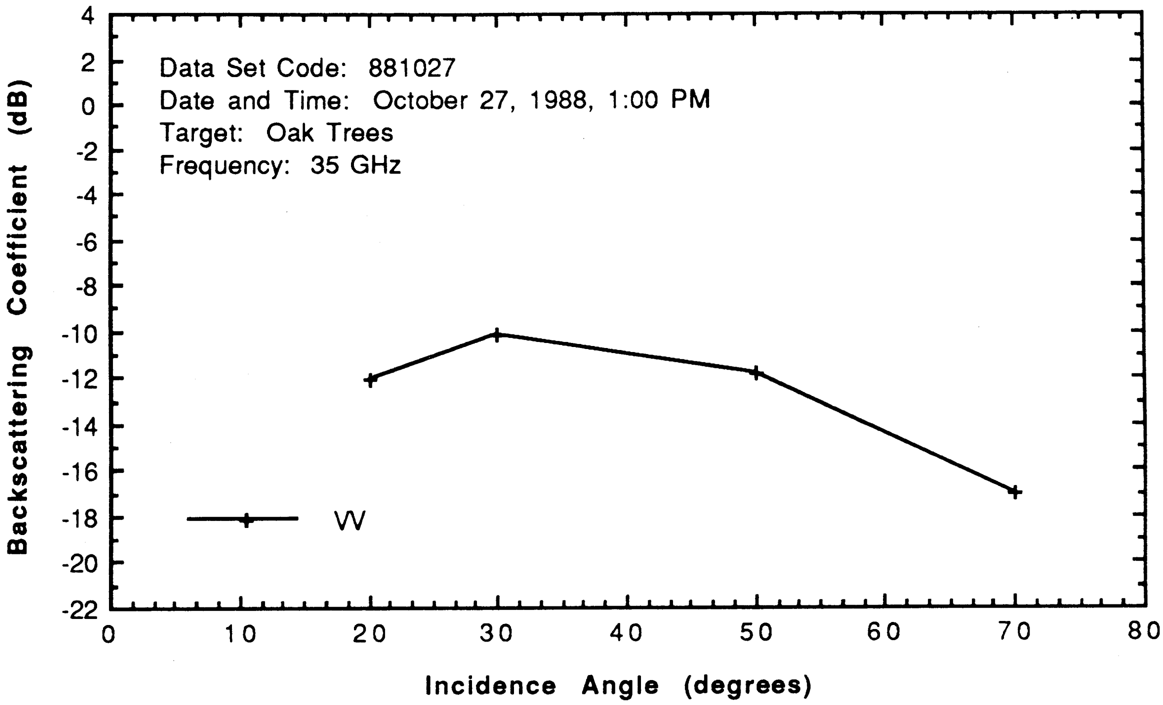


Bur Oaks (Quercus Macrocarpa)

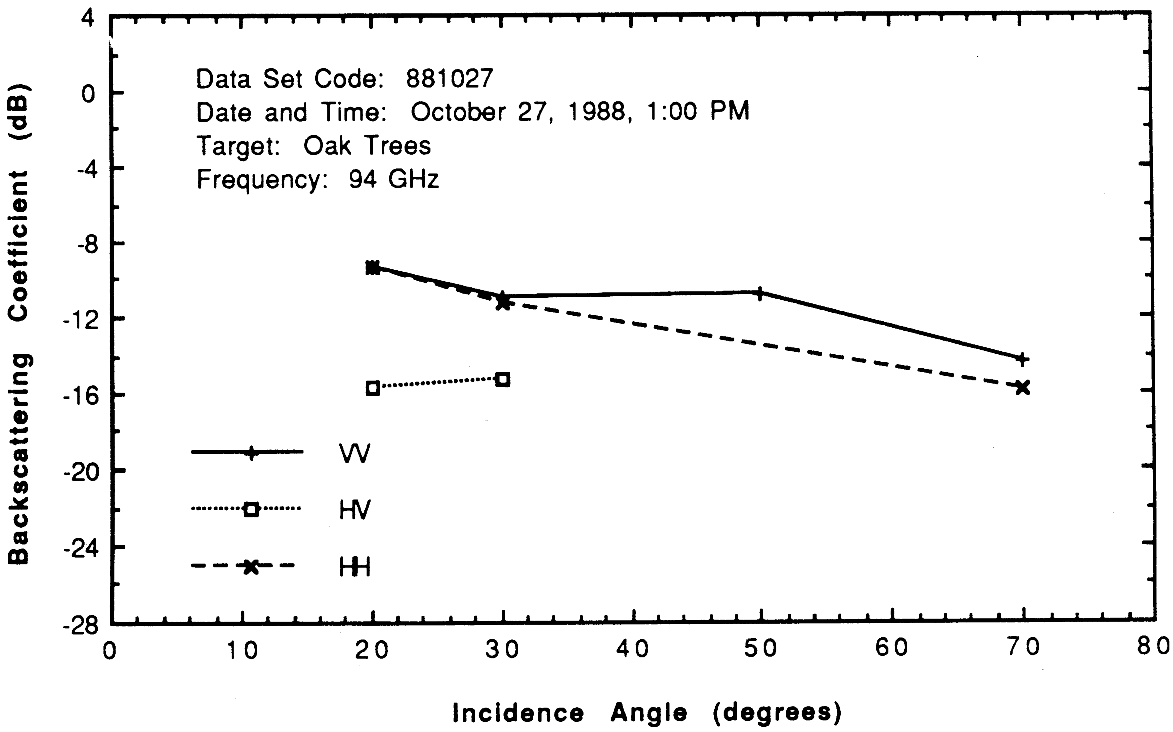


Bur Oaks (Quercus Macrocarpa)
Leaf Moisture Content = 55.2%

881027

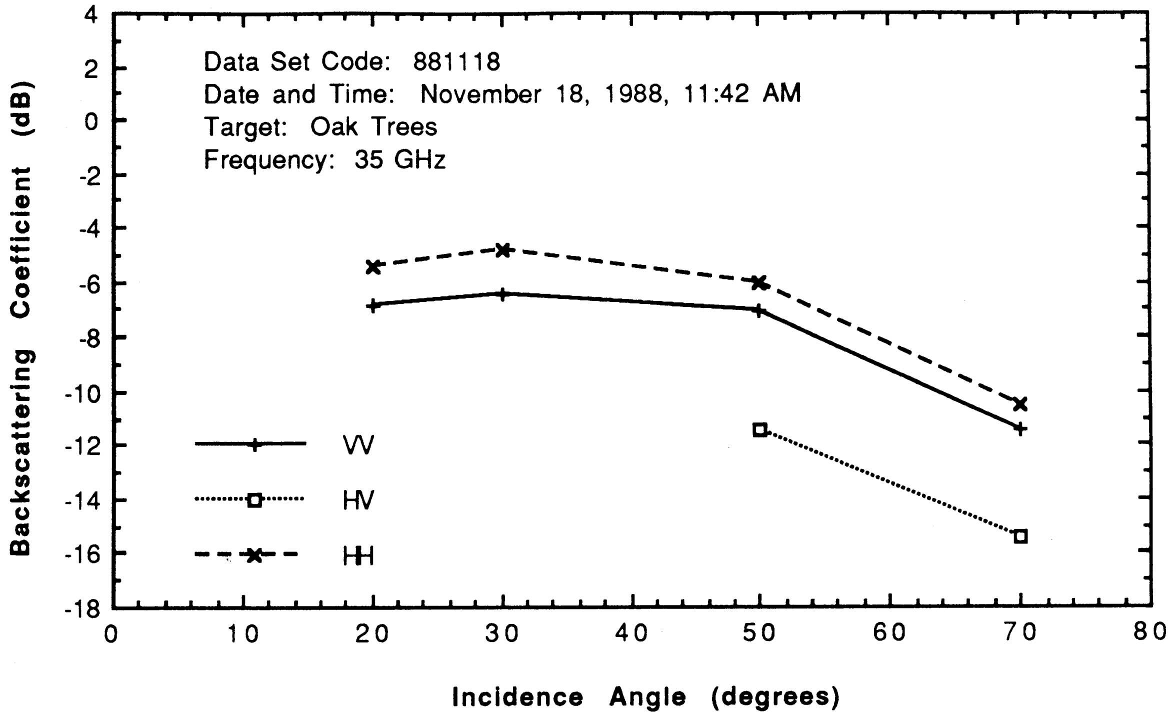


Bur Oaks (Quercus Macrocarpa)

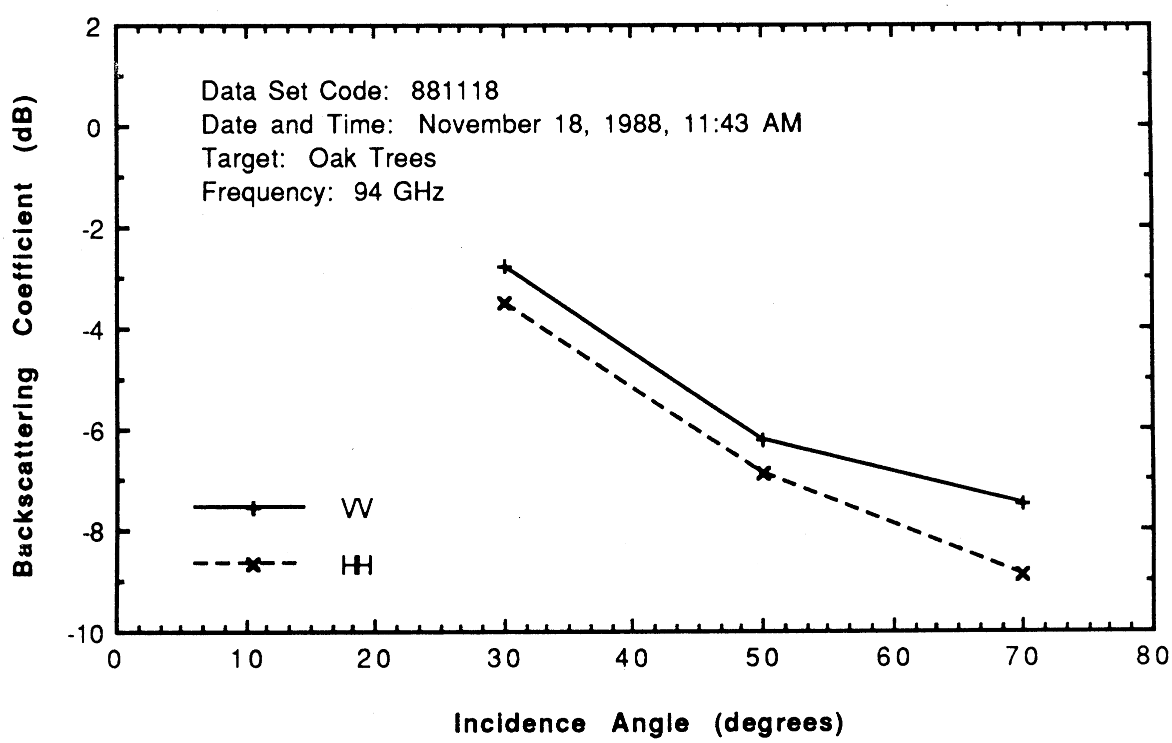


Leaf Moisture Content = 42%

881118

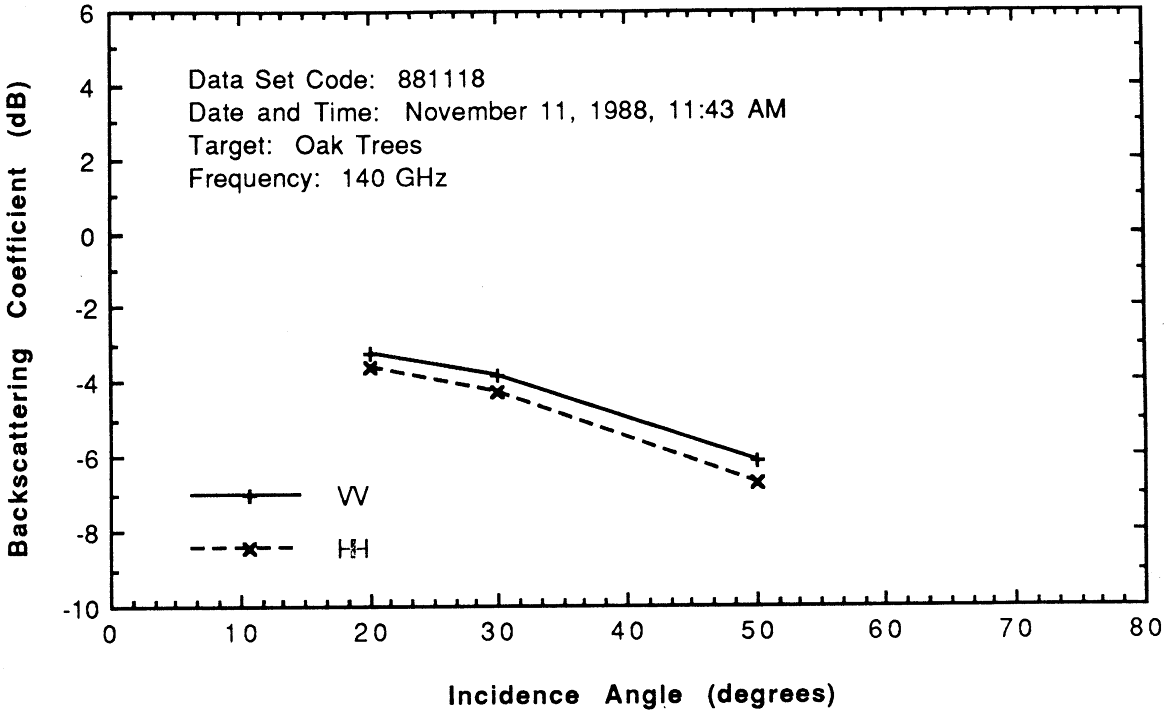


Bur Oaks (Quercus Macrocarpa)



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

881118



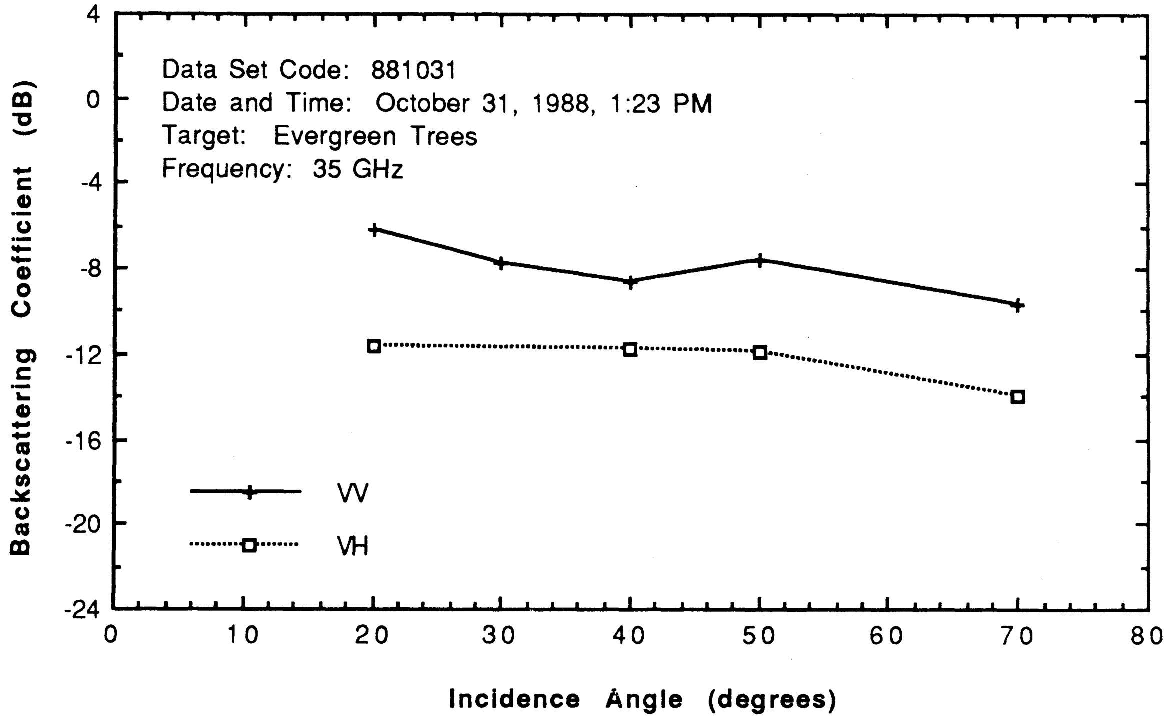
Oaks (Quercus Macrocarpa)
Leaf Moisture Content = 27%

E. Spruce Trees

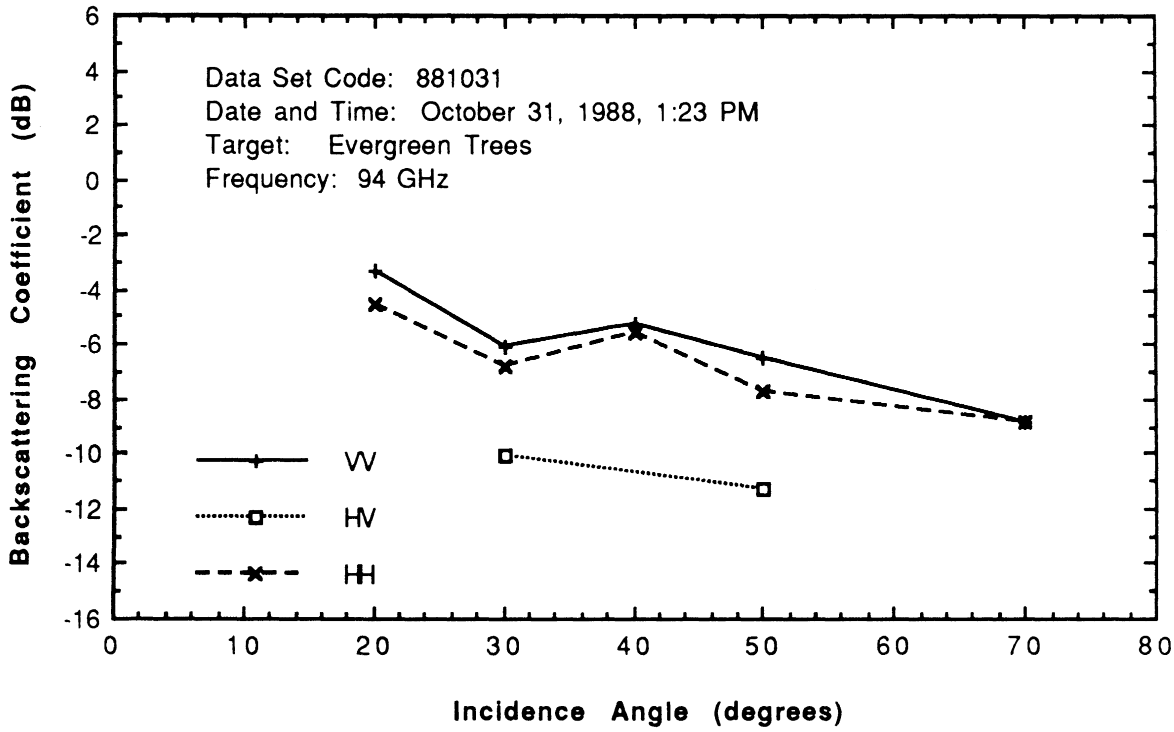
Spruce (Picea abies)
Data set code: 881031/881122
Tree density: 0.03 trees/m^2
Average needle dimensions: 2 cm
Leaf moisture content: 53.1%(881031); 56% (881122)
Percent vegetation cover (est.): 80 %
Percent cover of undergrowth: 100%
Moisture content of undergrowth:35%
Description: stand of mature spruce trees with weedy ground cover

Spruce trees

881031



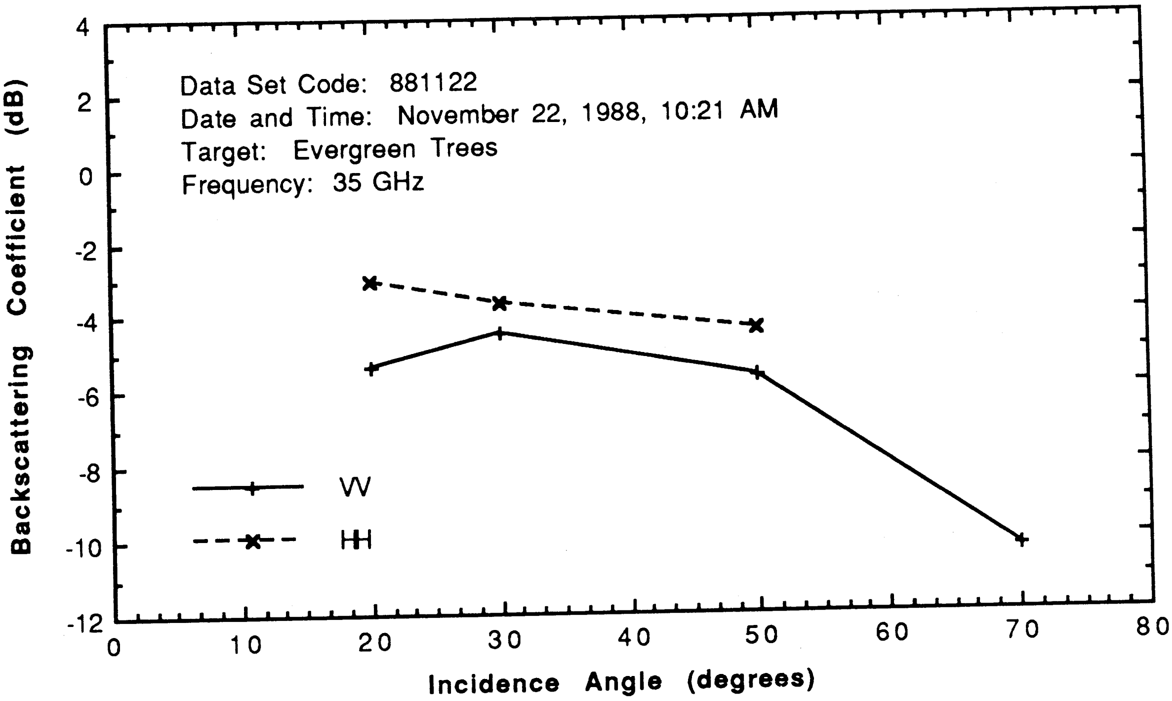
Norway Spruce (Picea Abies)



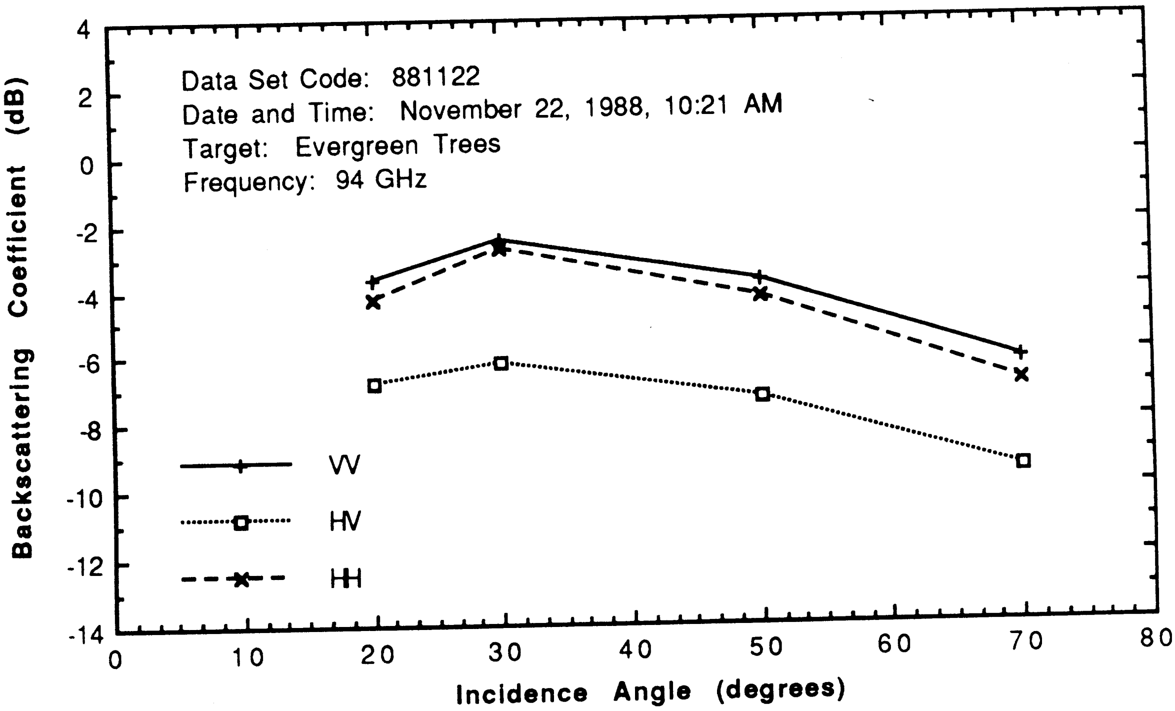
Norway Spruce (Picea Abies)

MMW DATA FOR TREE CANOPIES

881122



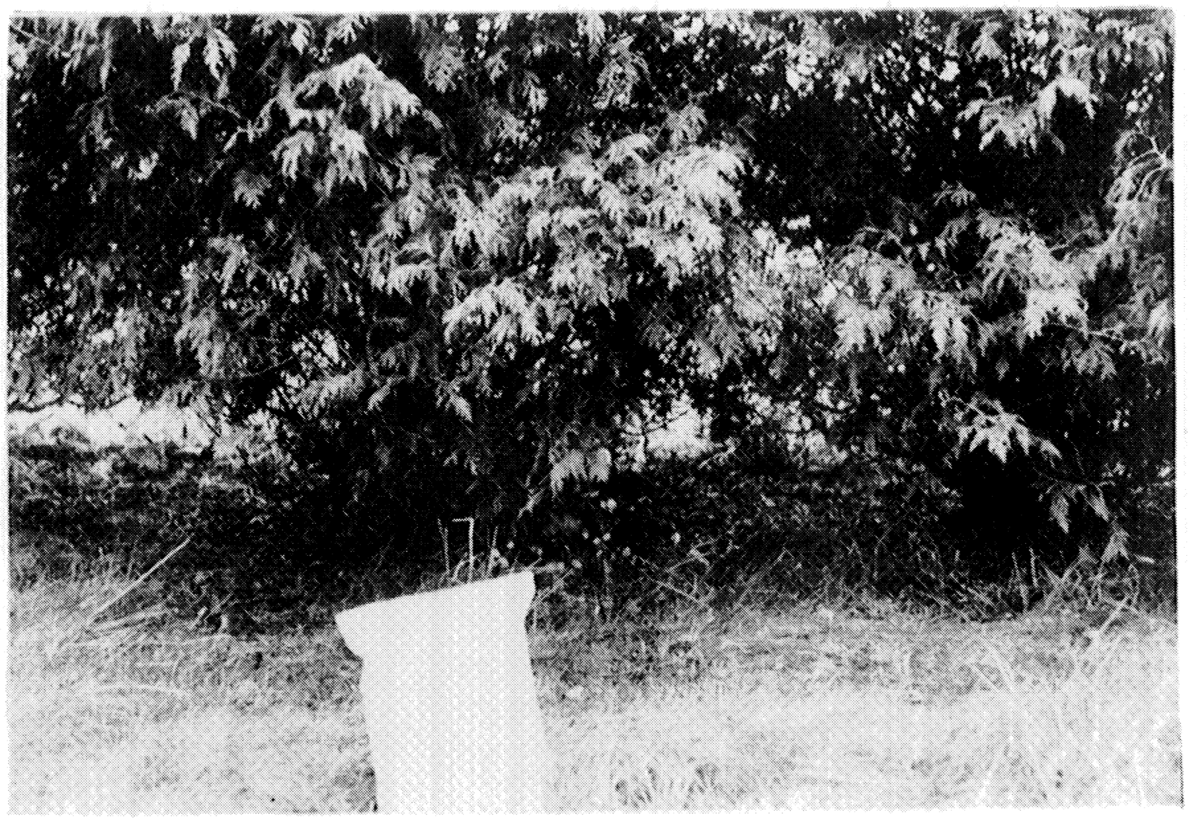
Blue Spruce & Norway Spruce (Picea Puryens & Picea Abies)



Blue Spruce & Norway Spruce (Picea Puryens & Picea Abies)

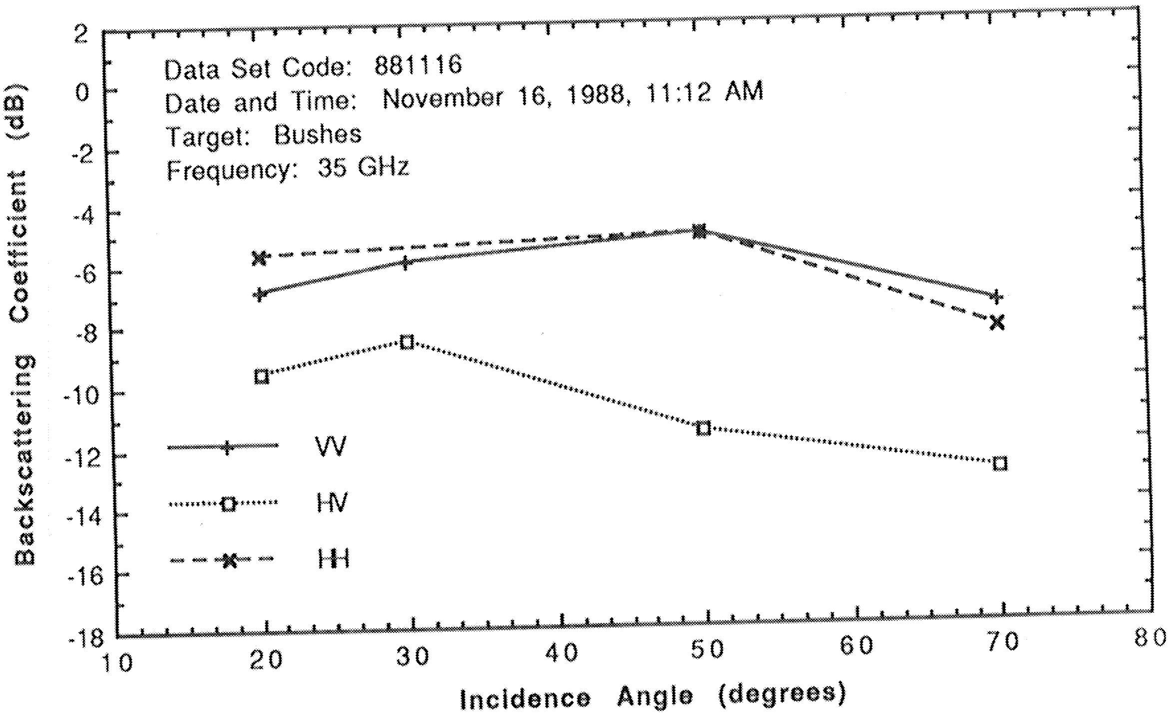
F. White Cedar Bushes

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

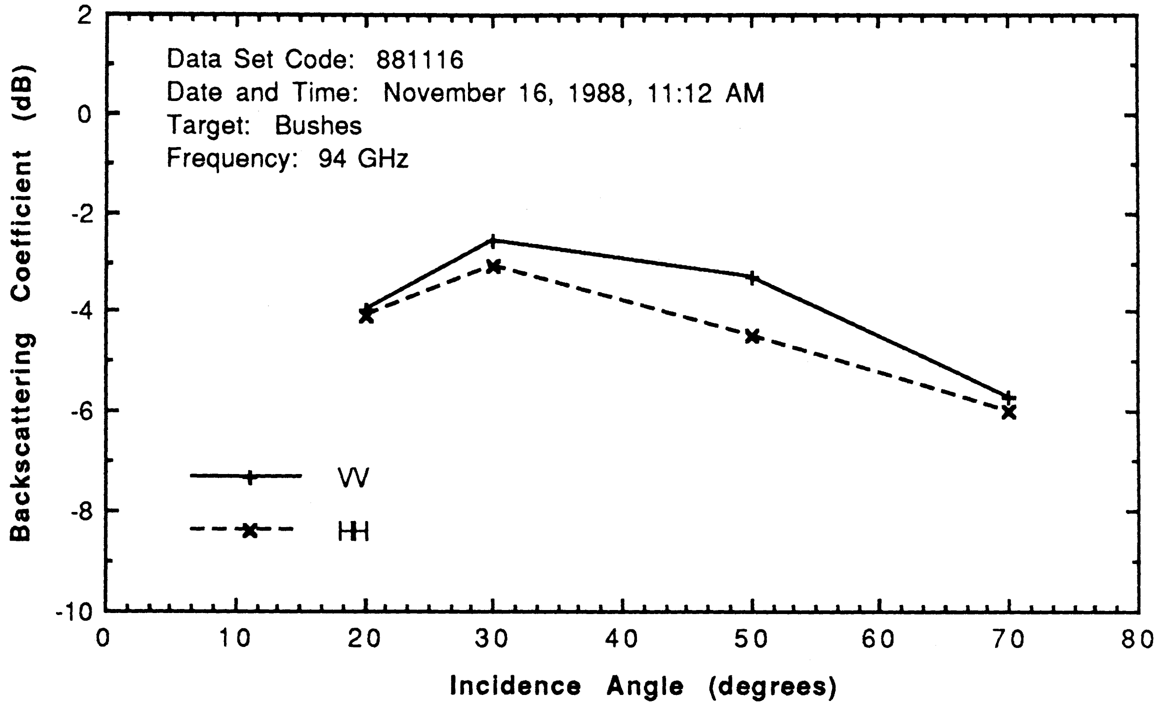


White Cedar bush

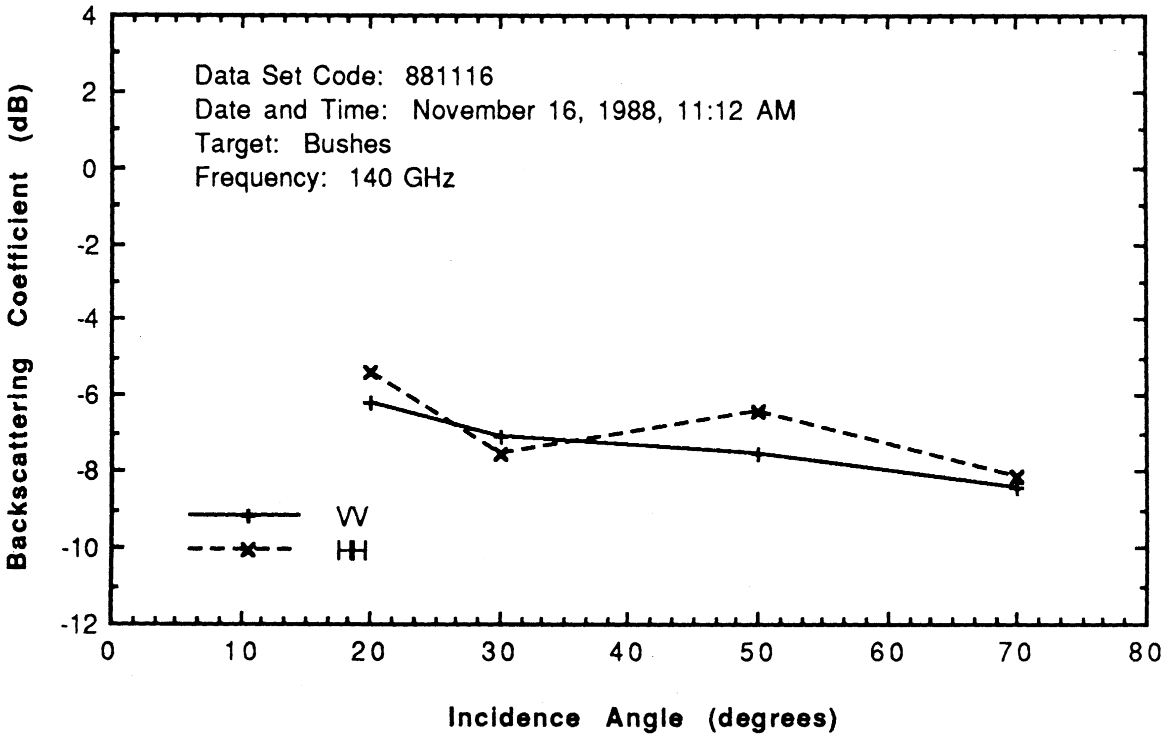
Close-up view of branches of White Cedar bush



White Cedar at Botanical Gardens (Thuja Occidentalis)



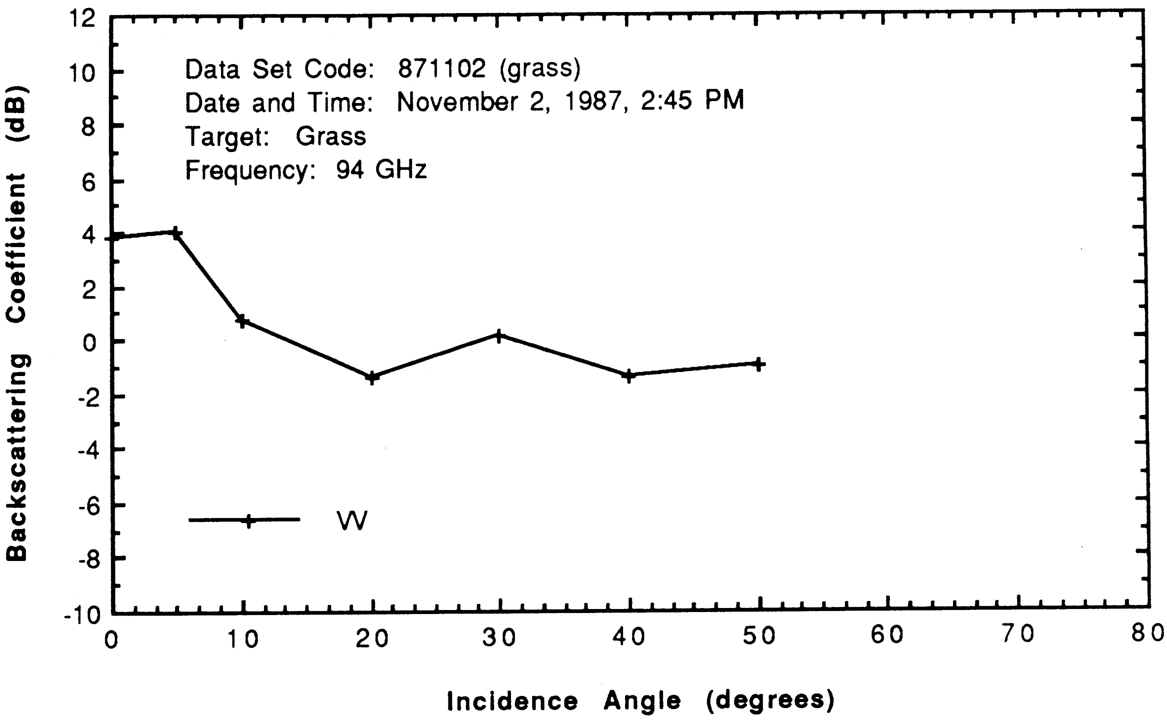
White Cedar at Botanical Gardens (Thuja Occidentalis)



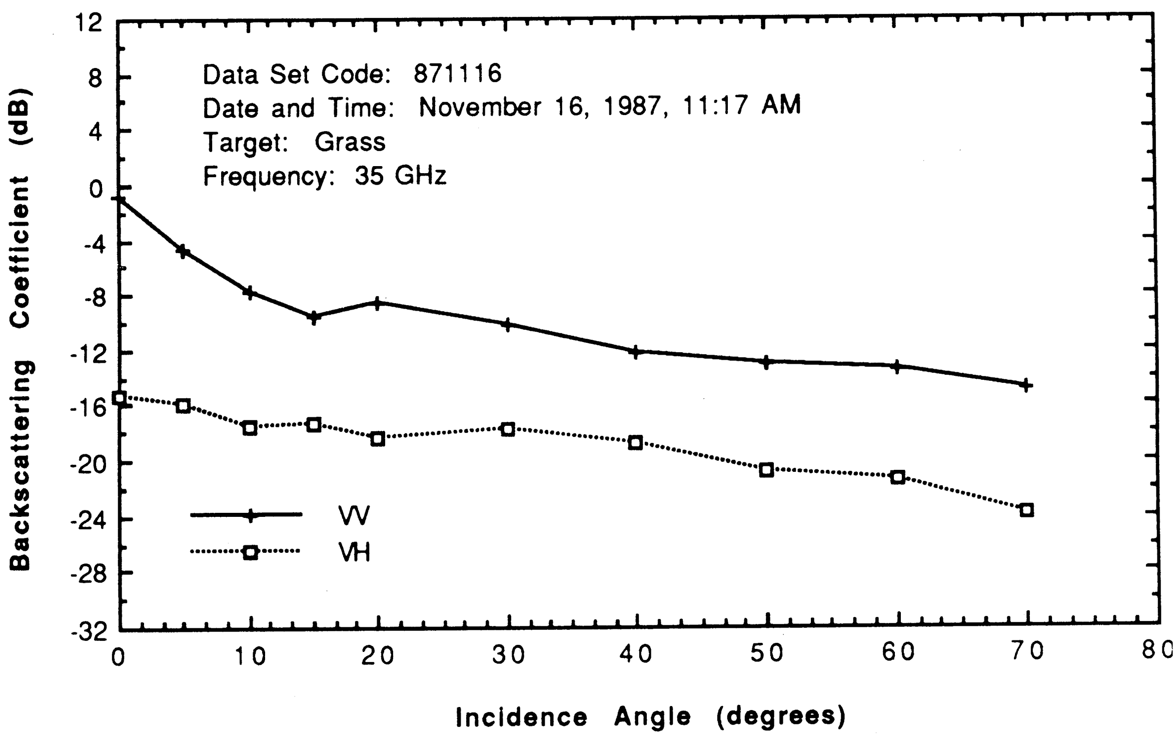
White Cedar (Thuja Occidentalis)

VII. MMW DATA FOR GRASSES

Grass
Data set code: 871102
Description: cut grass with wet surface

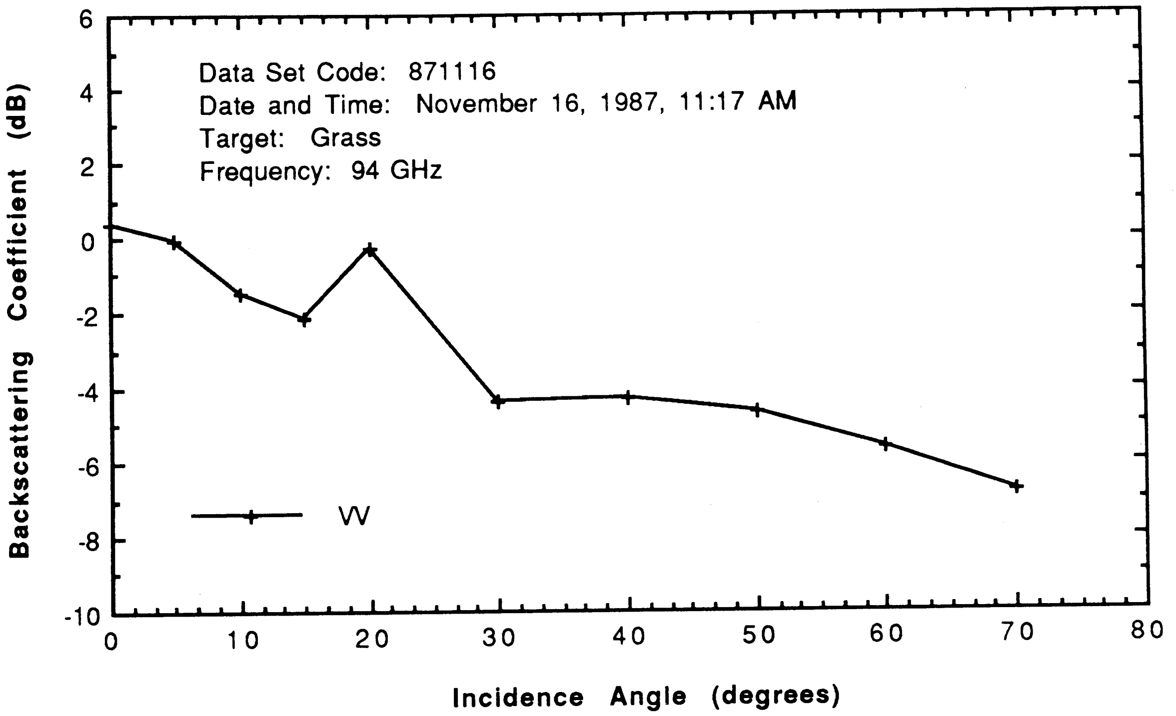


Grass Height = 10 cm

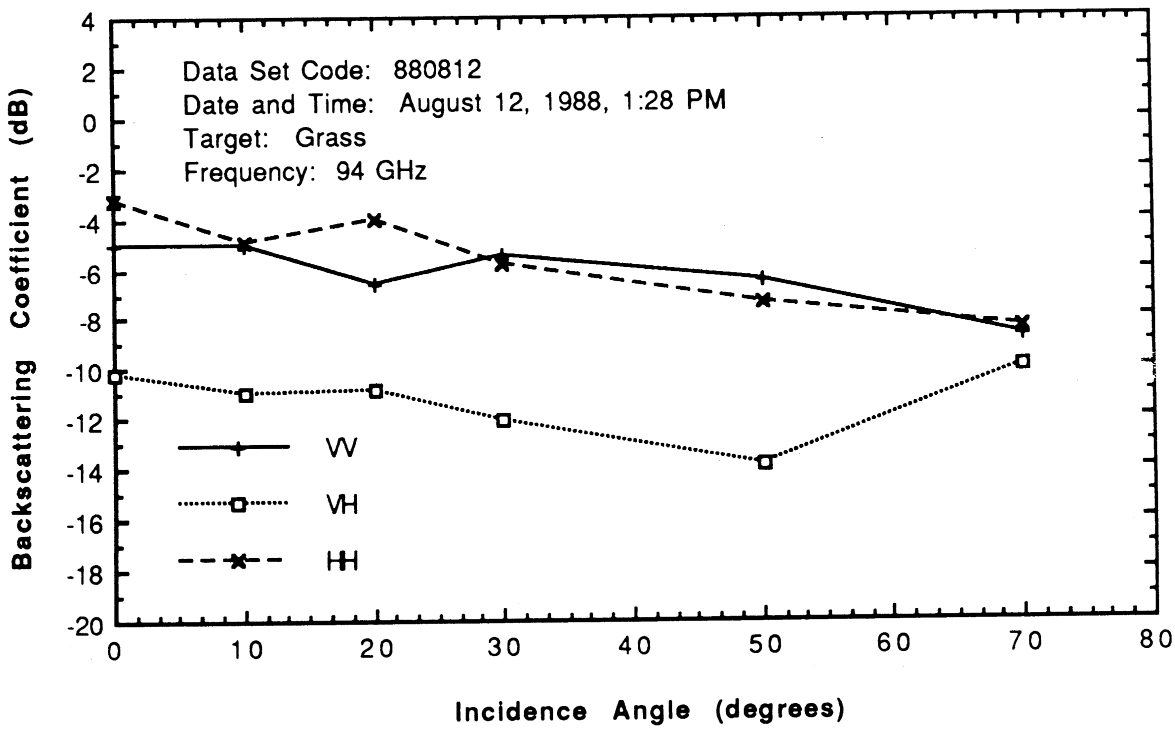


Cut grass at North Campus (Height = 5 cm)

871116



Cut grass at North Campus (Height = 5 cm)



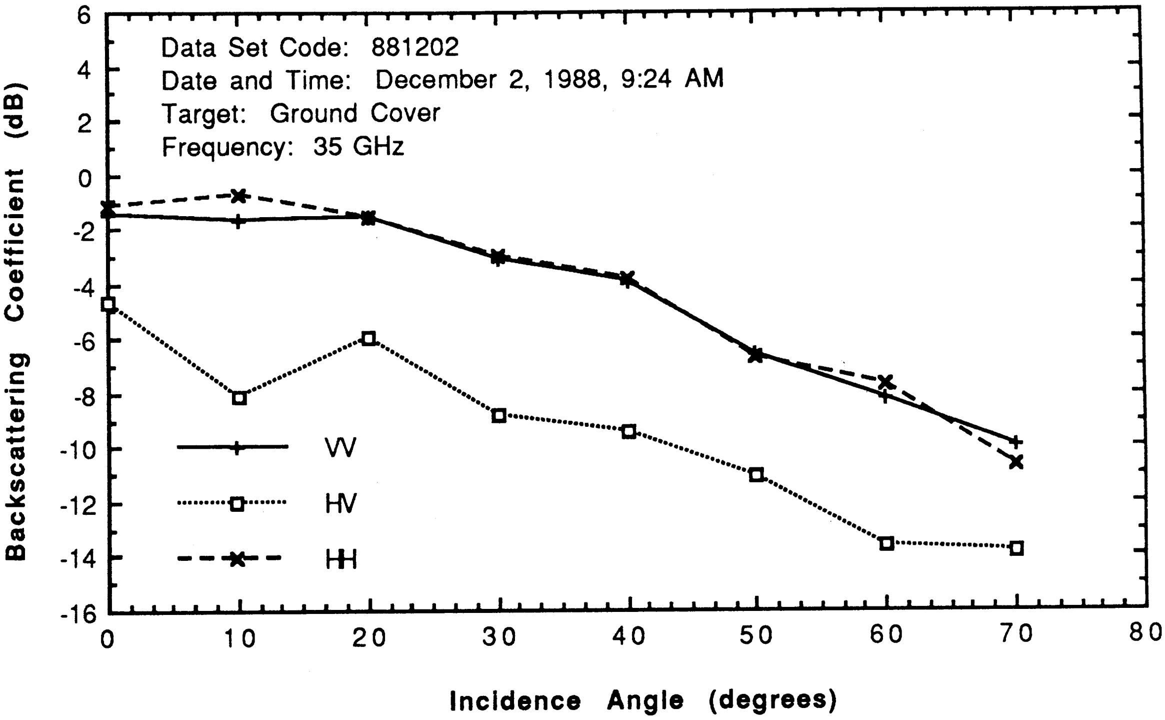
Cut Grass (Height = 6 cm)

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

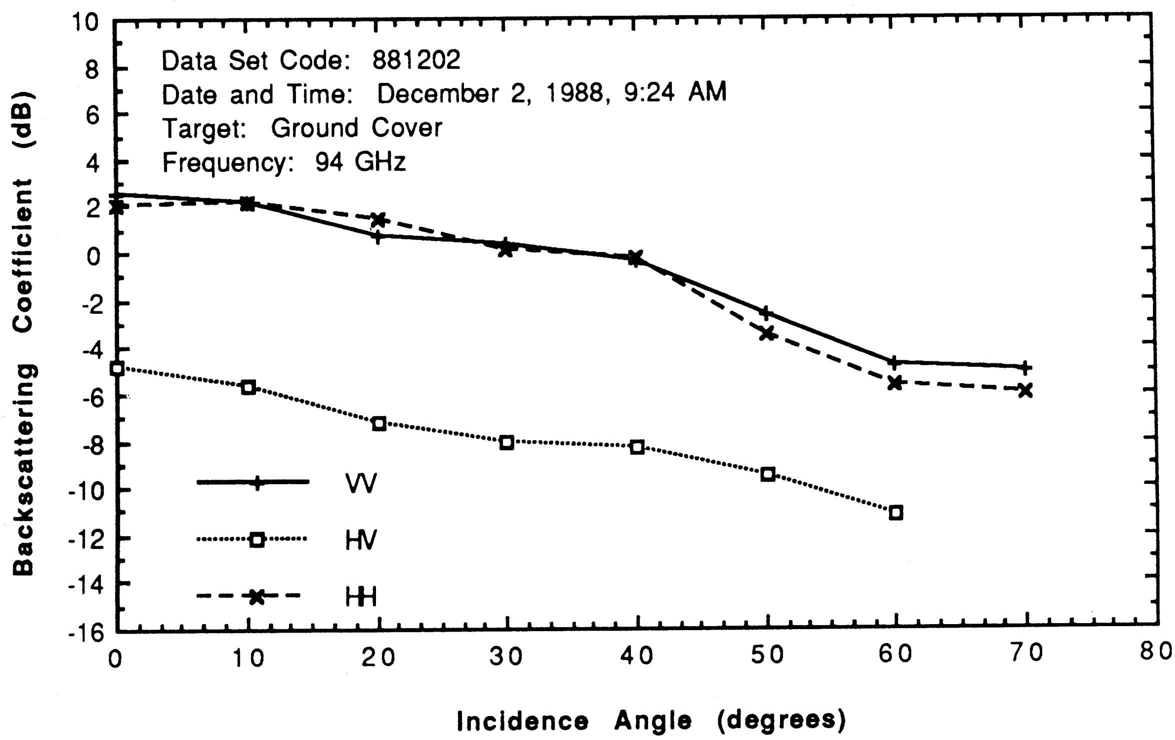
Amaranthus over chickweed

MMW DATA FOR GRASSES

881202

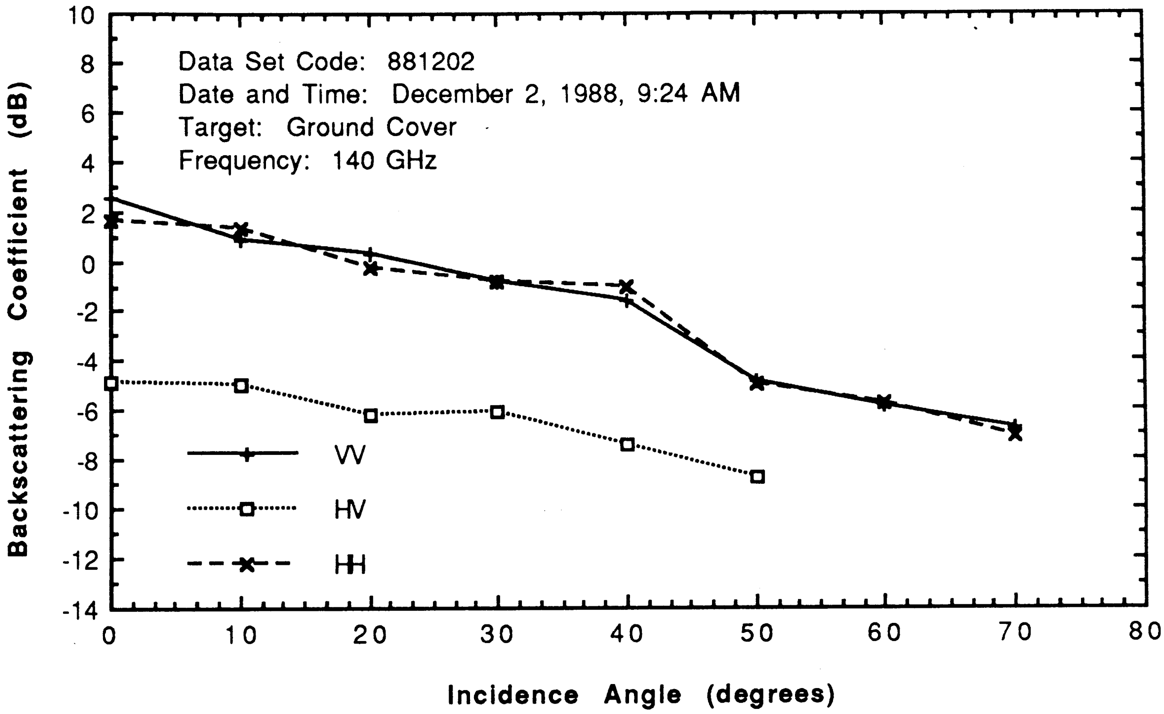


Amaranthus over chick weed



Amaranthus over chick weed

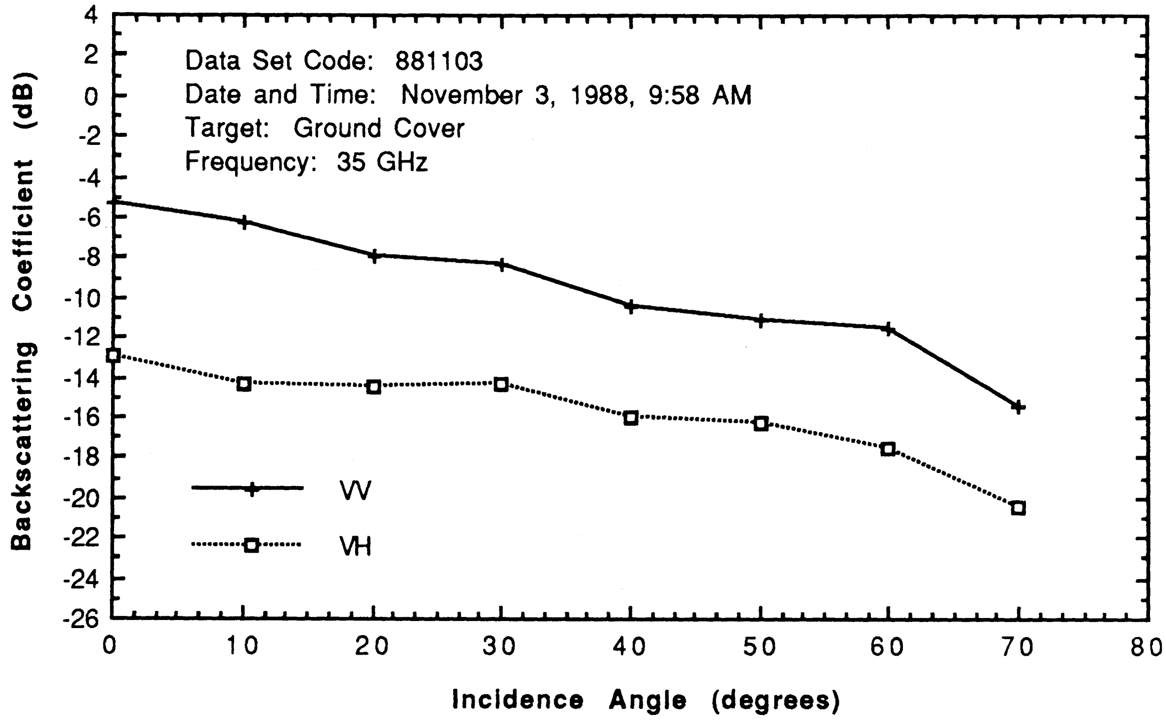
881202

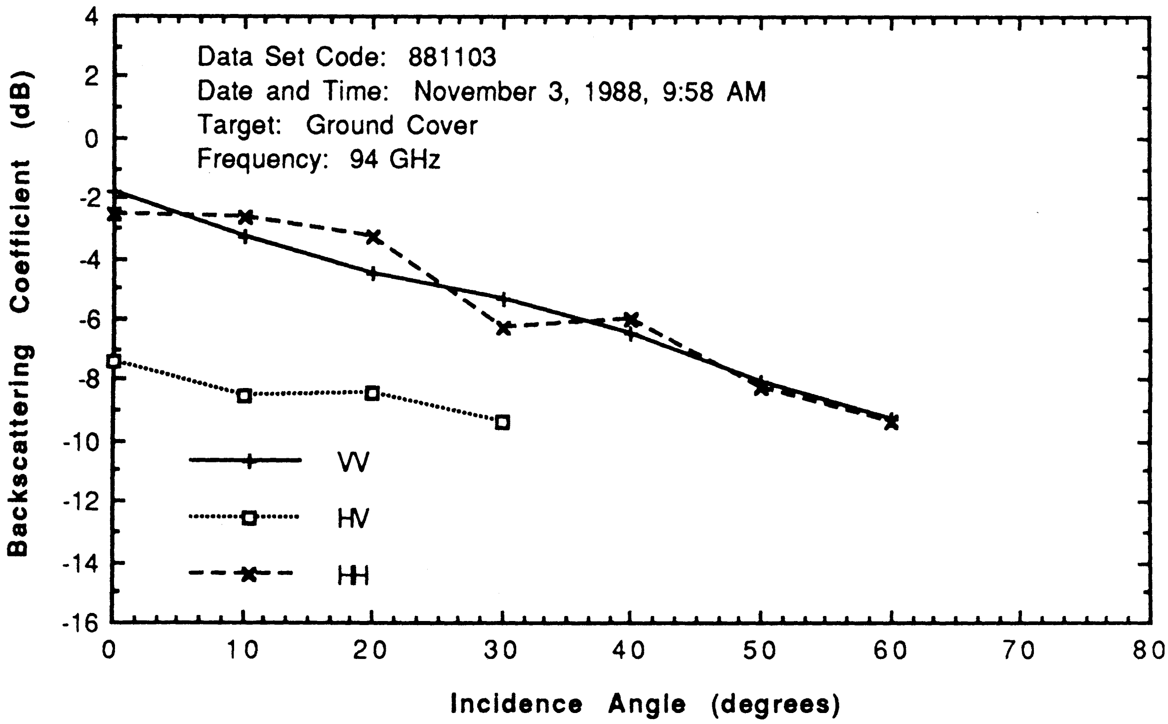


Amaranthus over chick weed

881103

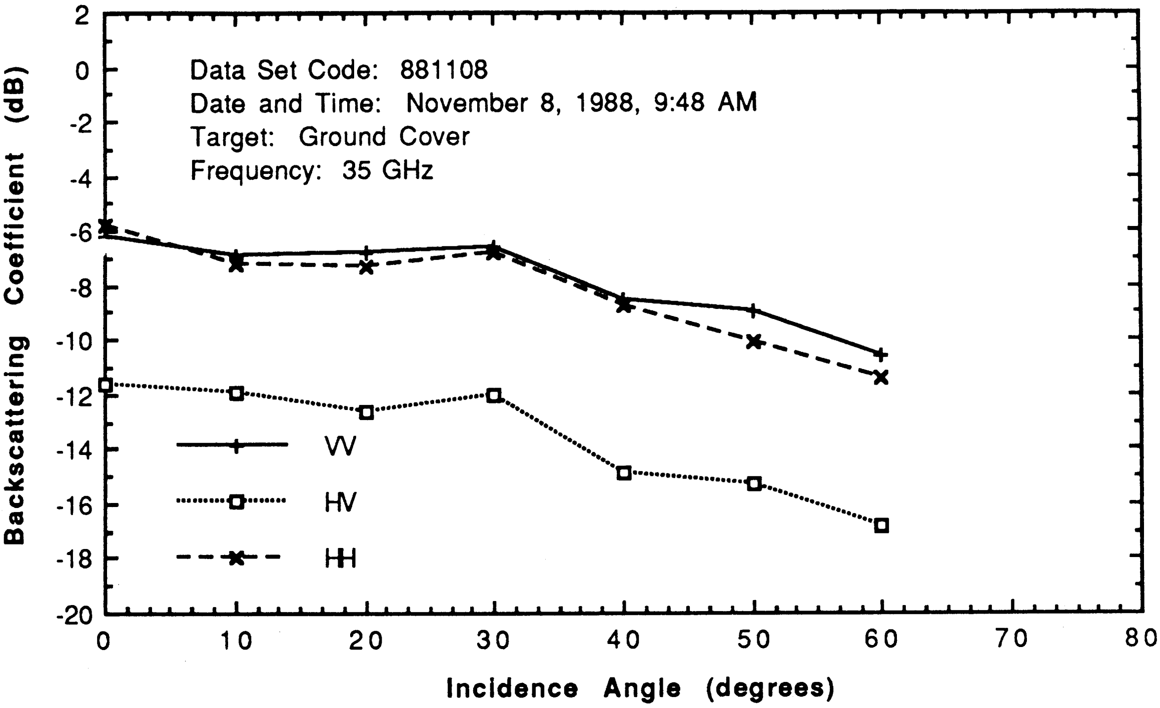
Tall Grass (Andropogon gerardi)
Data set code: 881103
Leaf Moisture Content = 33%
Height: 80 cm
Description: dry, uncut





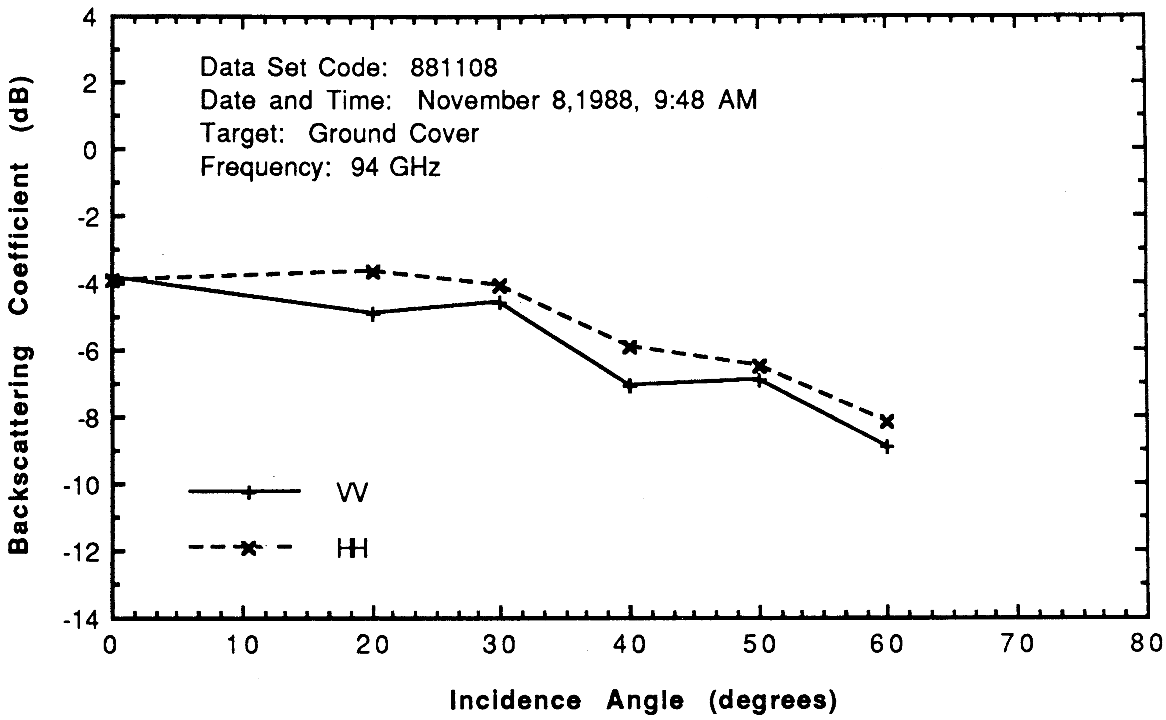
881108

Grass (Andropogon gerardi)
Data set code: 881108
Leaf Moisture Content = 44.5%
Height: 80 cm
Description: moist, uncut

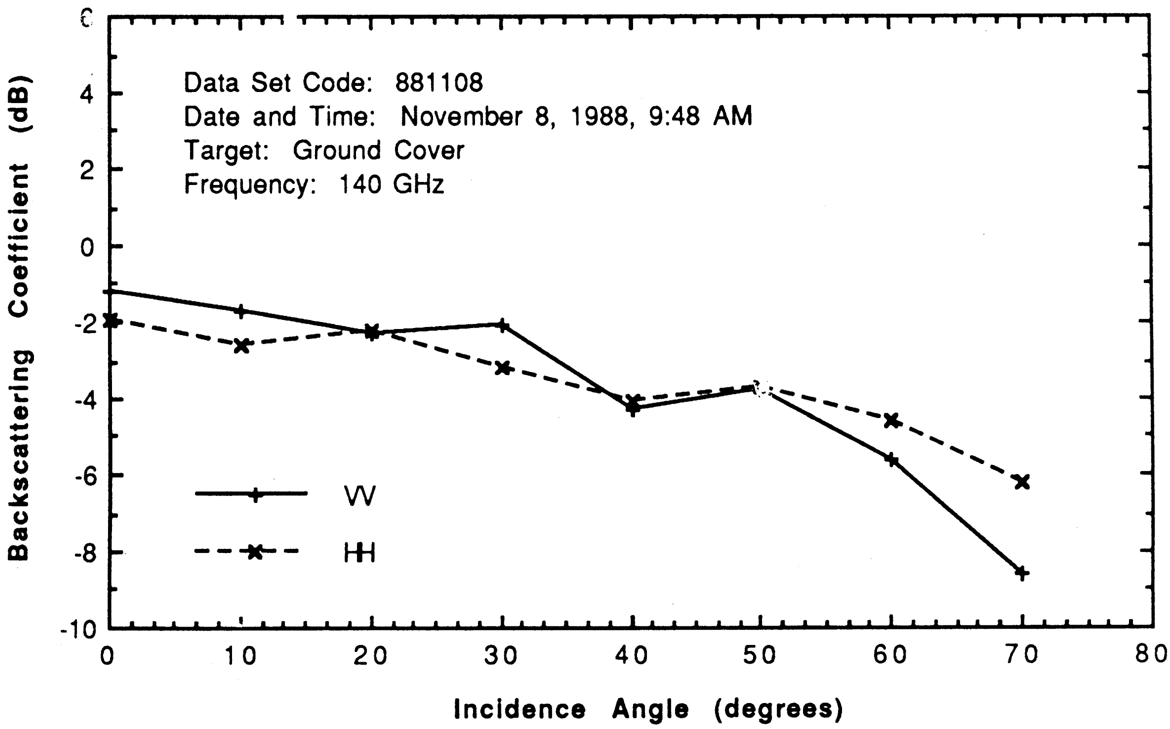


Turkey Foot or Big Bluestem (Andropogon gerardi)

881108



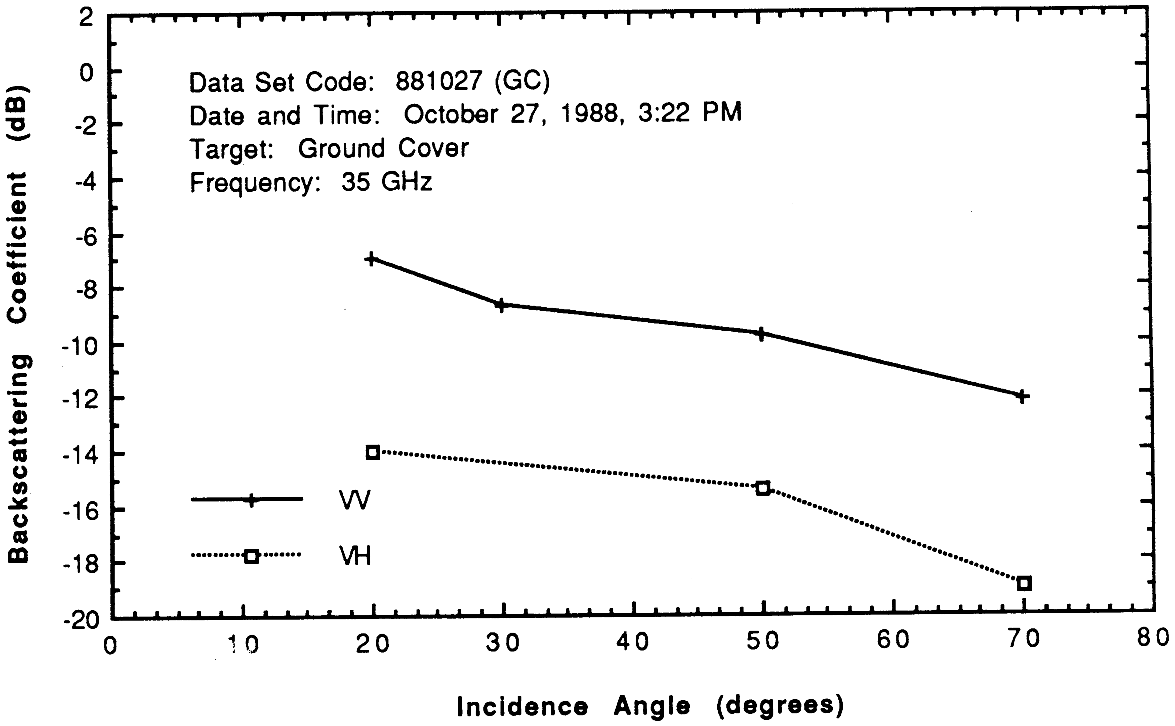
Turkey Foot or Big Bluestem (Andropogon gerardi)

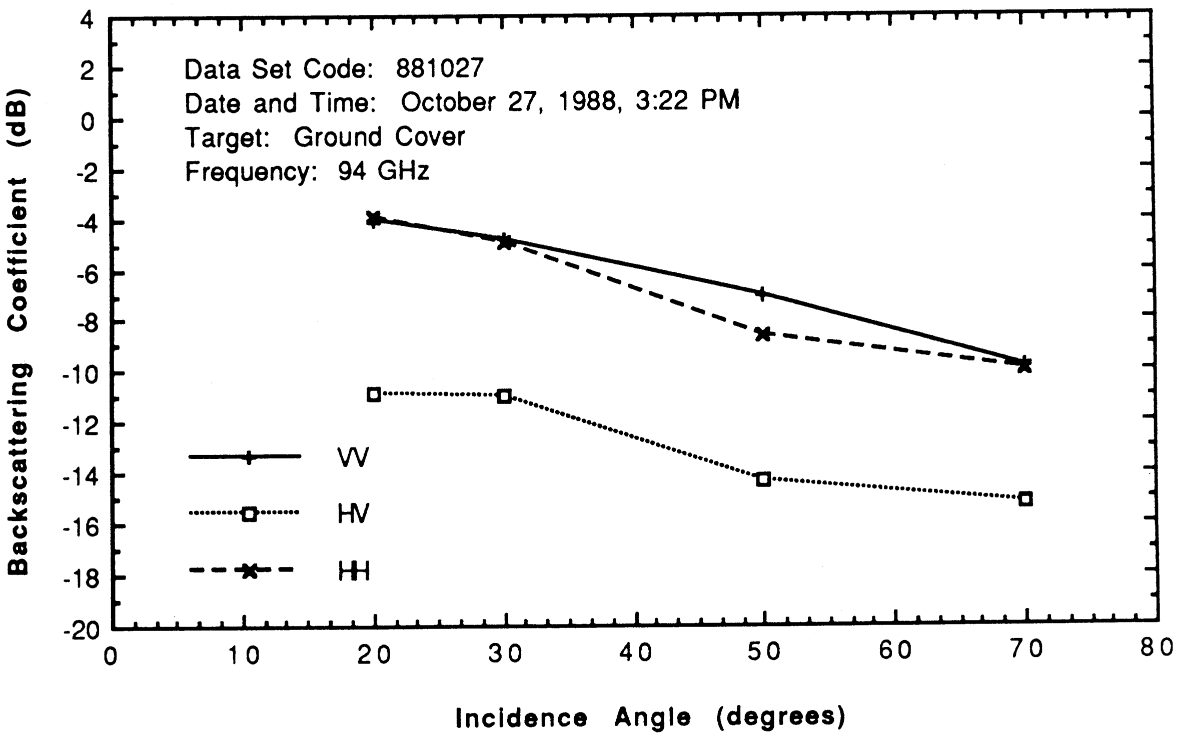


Turkey Foot or Big Bluestem (Andropogon gerardi)

881027

Tall Grass (Bromus inermis)
Data set code: 881027
Leaf Moisture Content = 70 %
Height: 80 cm
Description: uncut



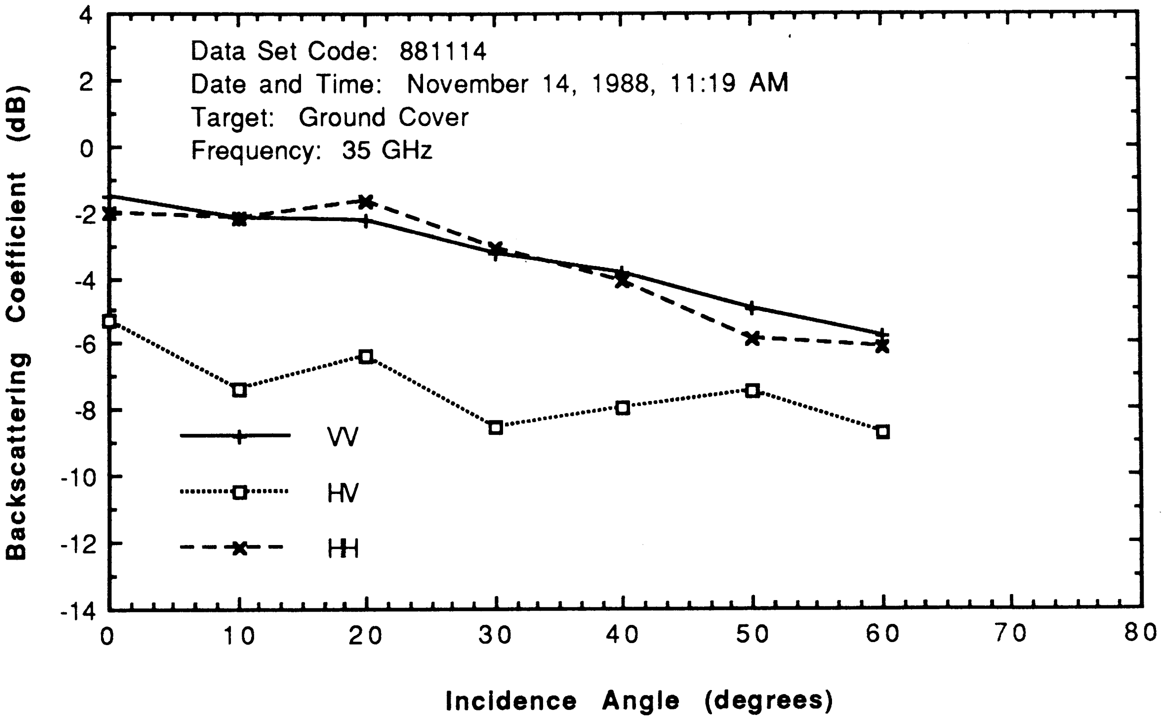


881114

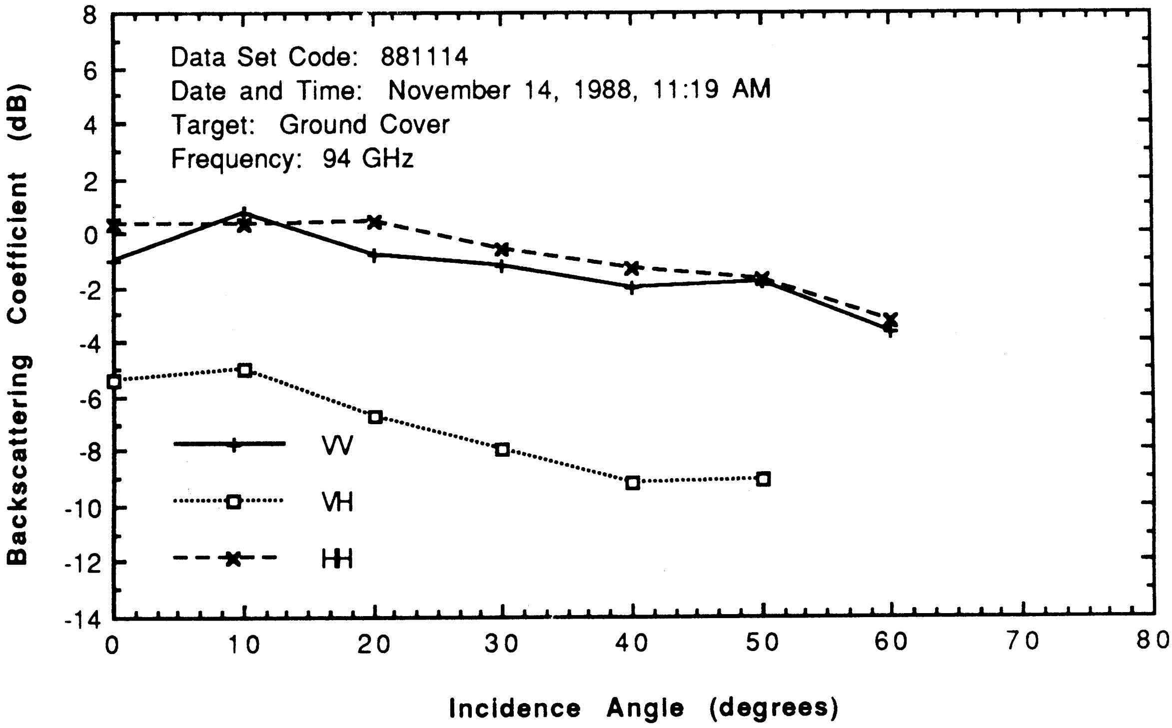
Grass (Bromus inermis)
Data set code: 881114
Leaf Water Content = 43.1%
Height: 10 cm
Description: cut

Broom grass (Bromus inermis)

881114

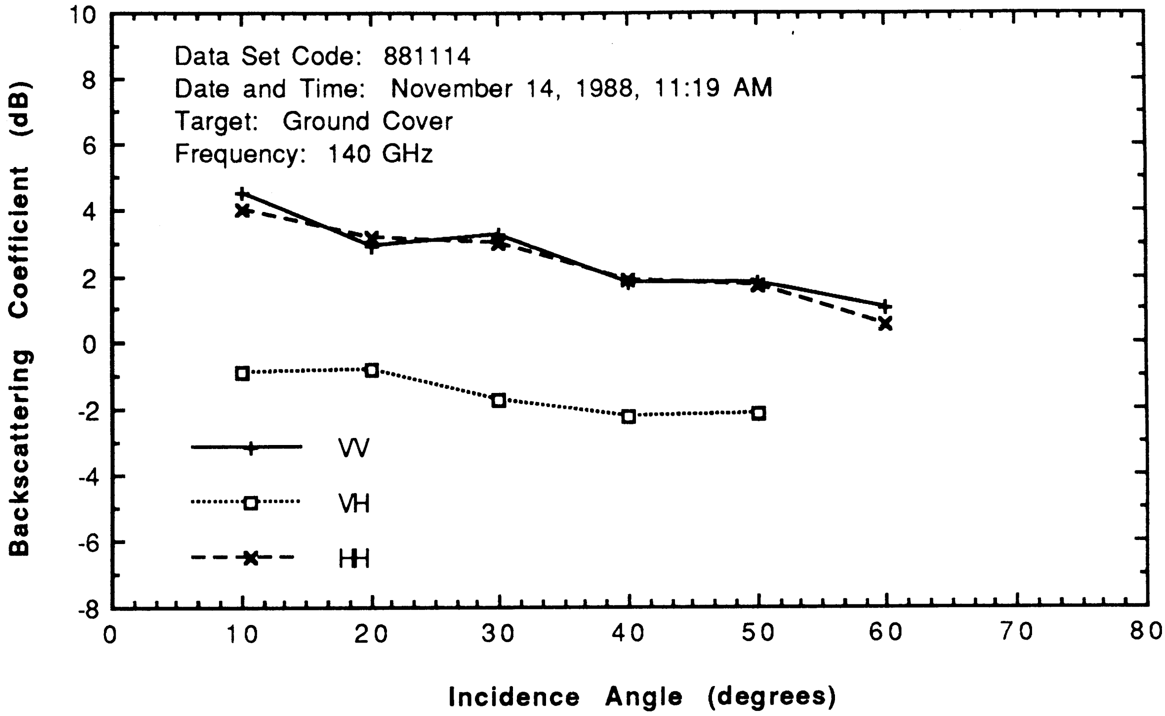


Broom Grass (Bromus inermis)



Broom Grass (Bromus inermis)

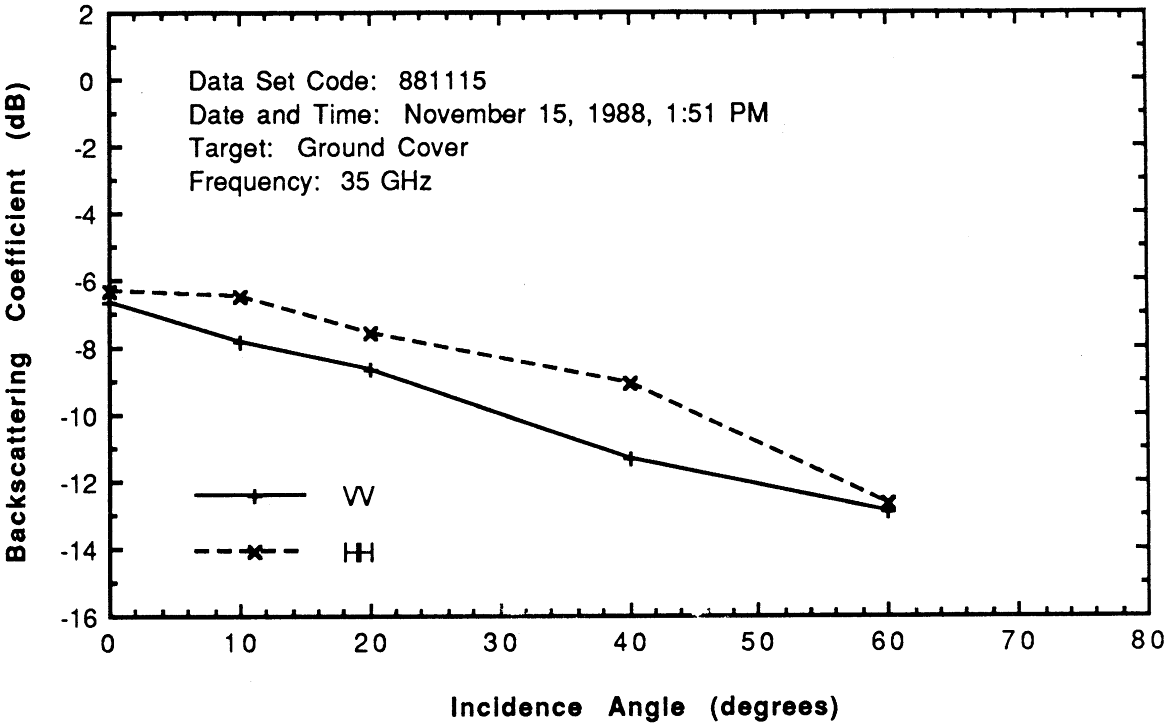
881114



Broom Grass (Bromus Inermis)

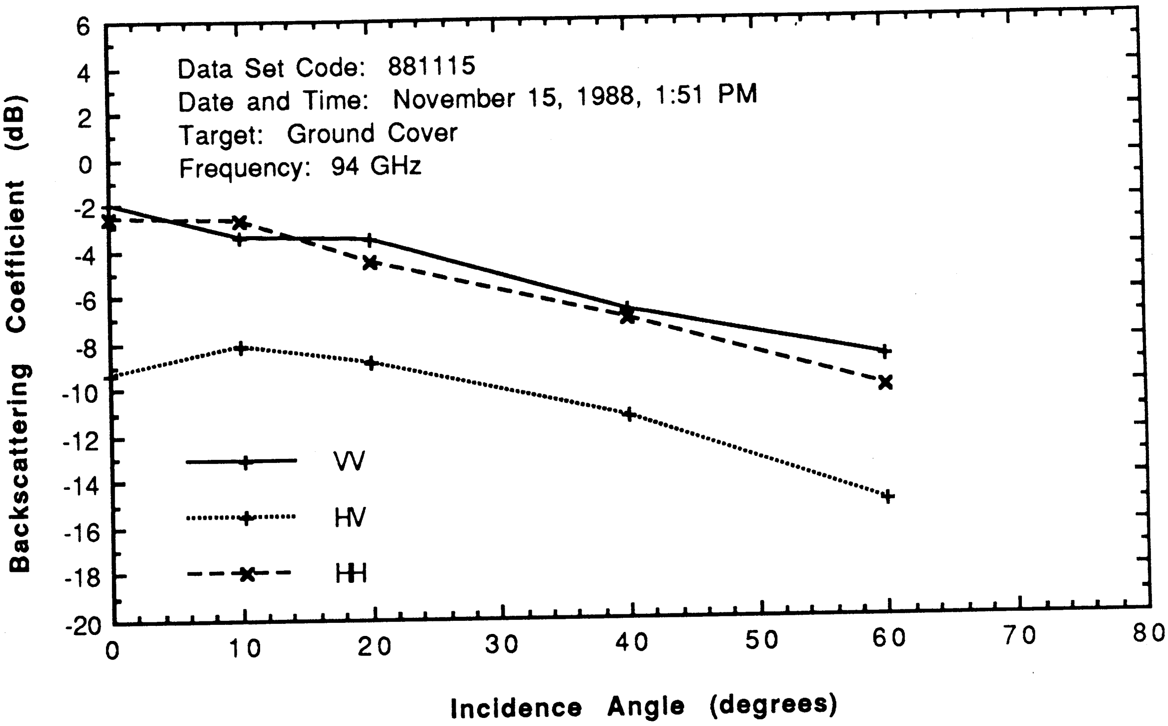
881115

Grass (Bromus inermis)
Data set code: 881115
Leaf Water Content = 50%
Height: 25 cm
Description: uncut

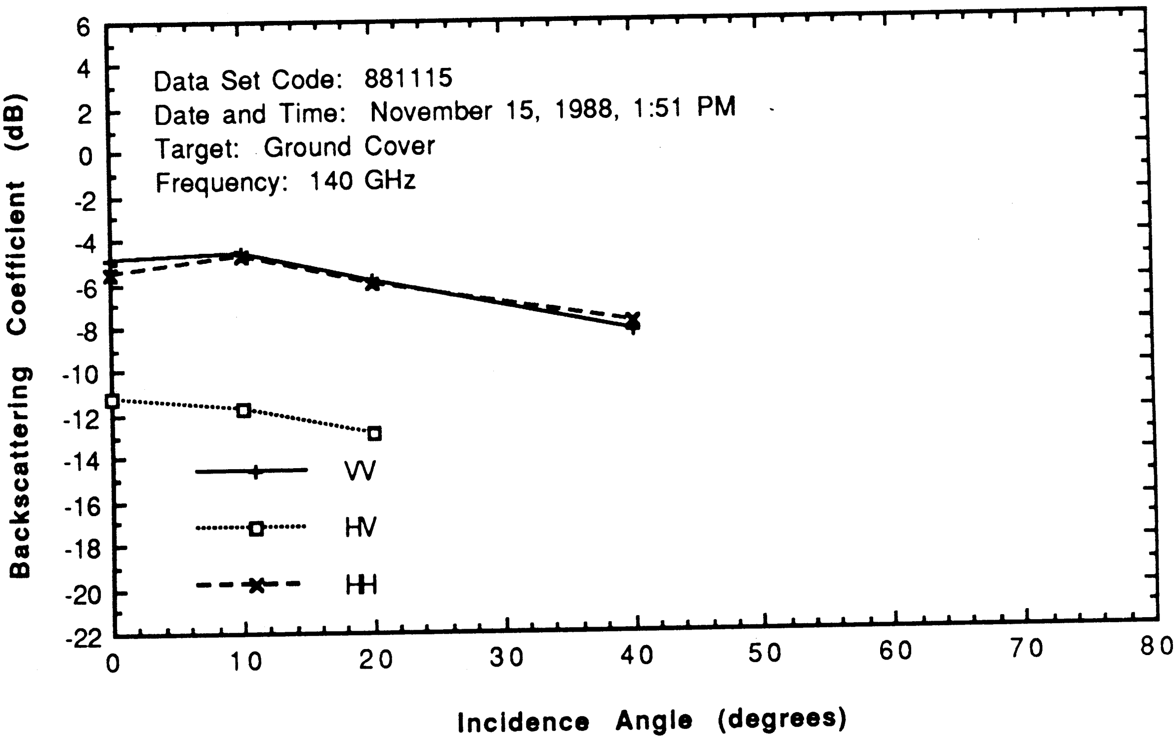


Broom Grass (Bromus inermis)

881115



Broom Grass (Bromus inermis)



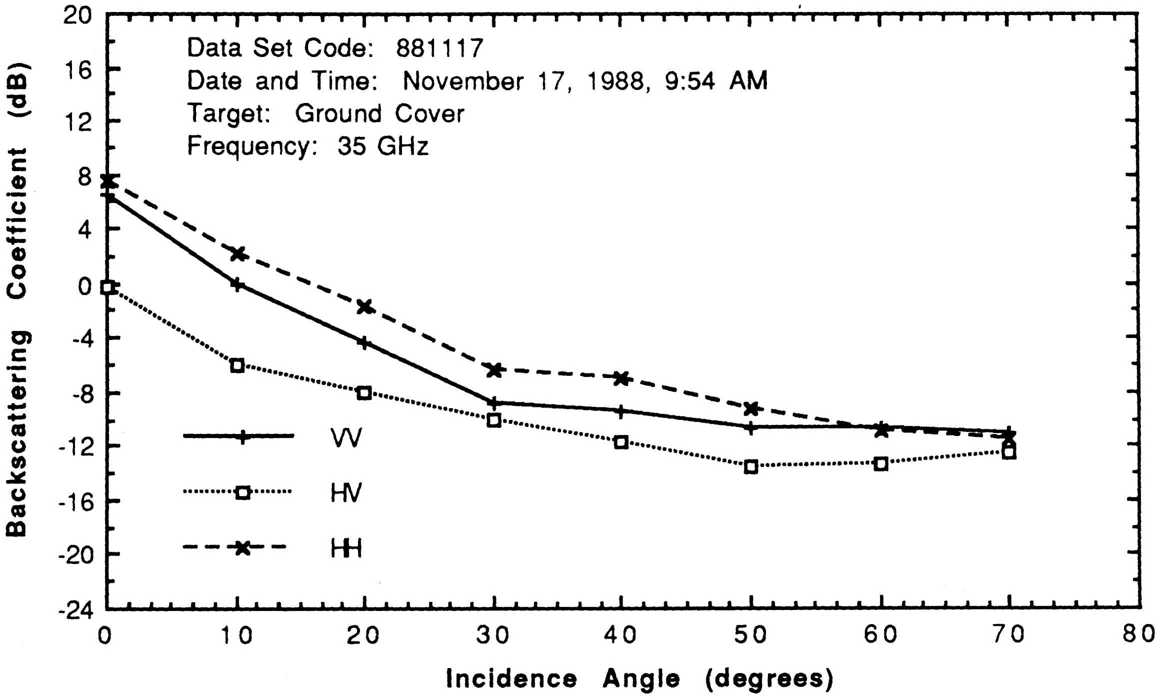
Broom Grass (Bromus inermis)

881117

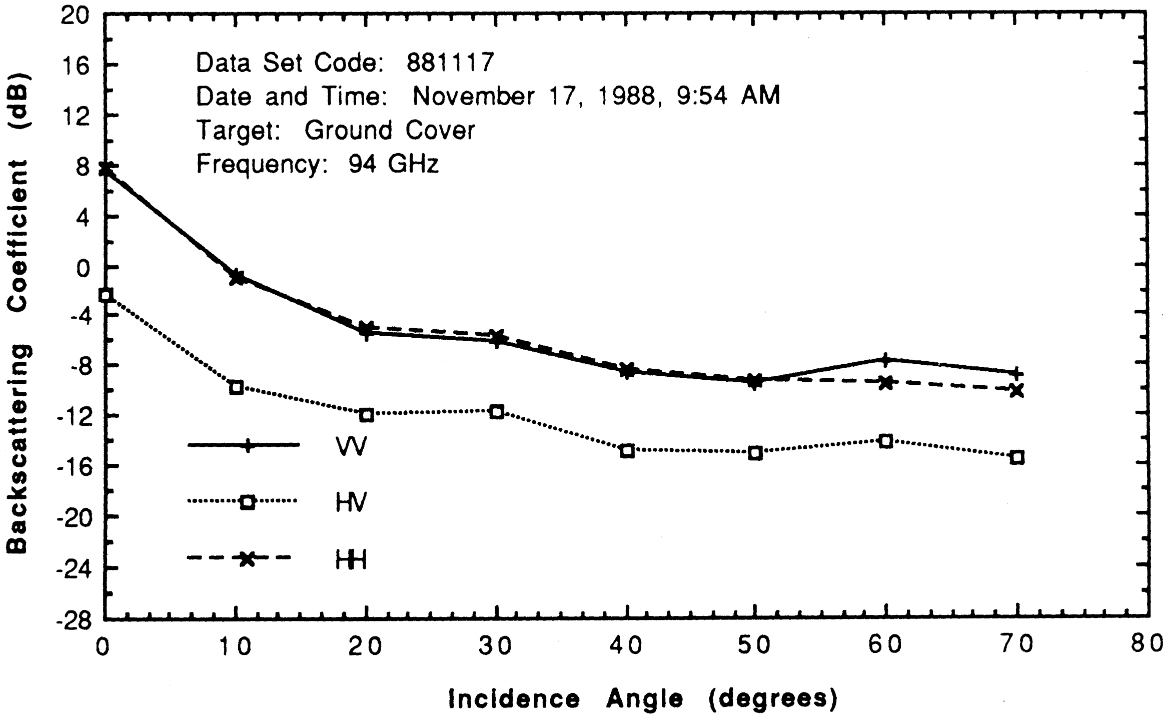
Grass (Lythrum salicaria)
Data set code: 881117
Leaf Moisture Content = 24.8%
Height: 1 m
Description: uncut

Purple loose strife (Lythrum salicaria)

881117



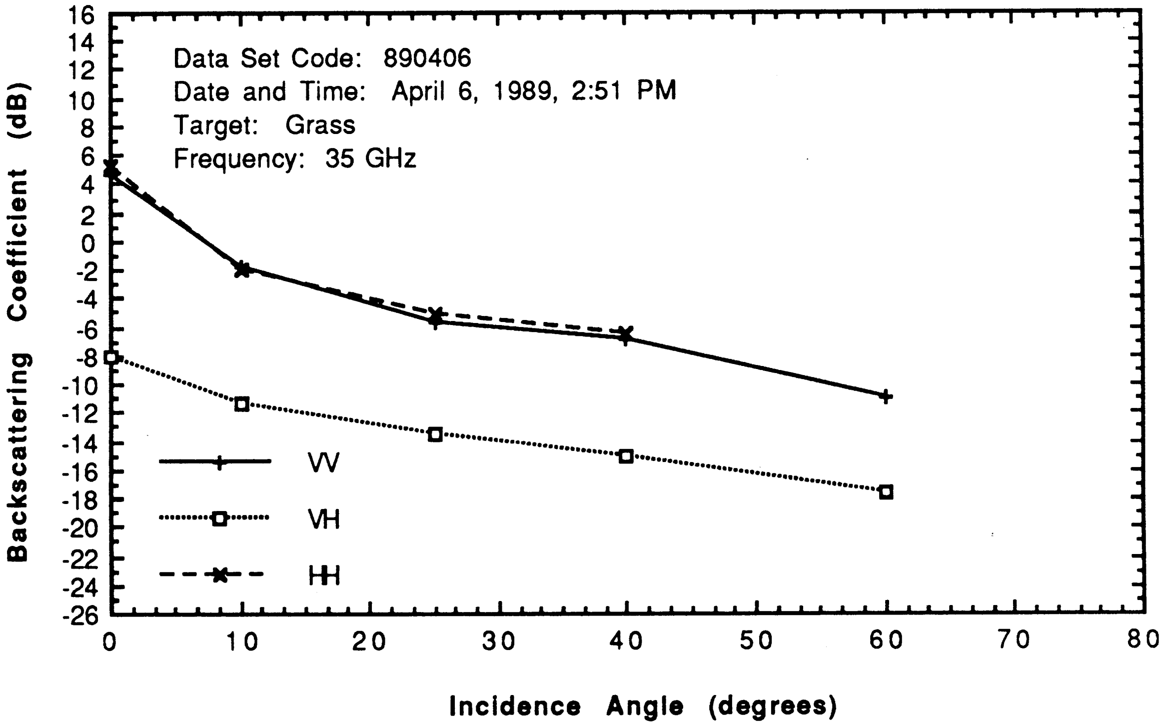
Purple Loose Strife over water (Lythrum salicaria)



Purple Loose Strife over water (Lythrum salicaria)

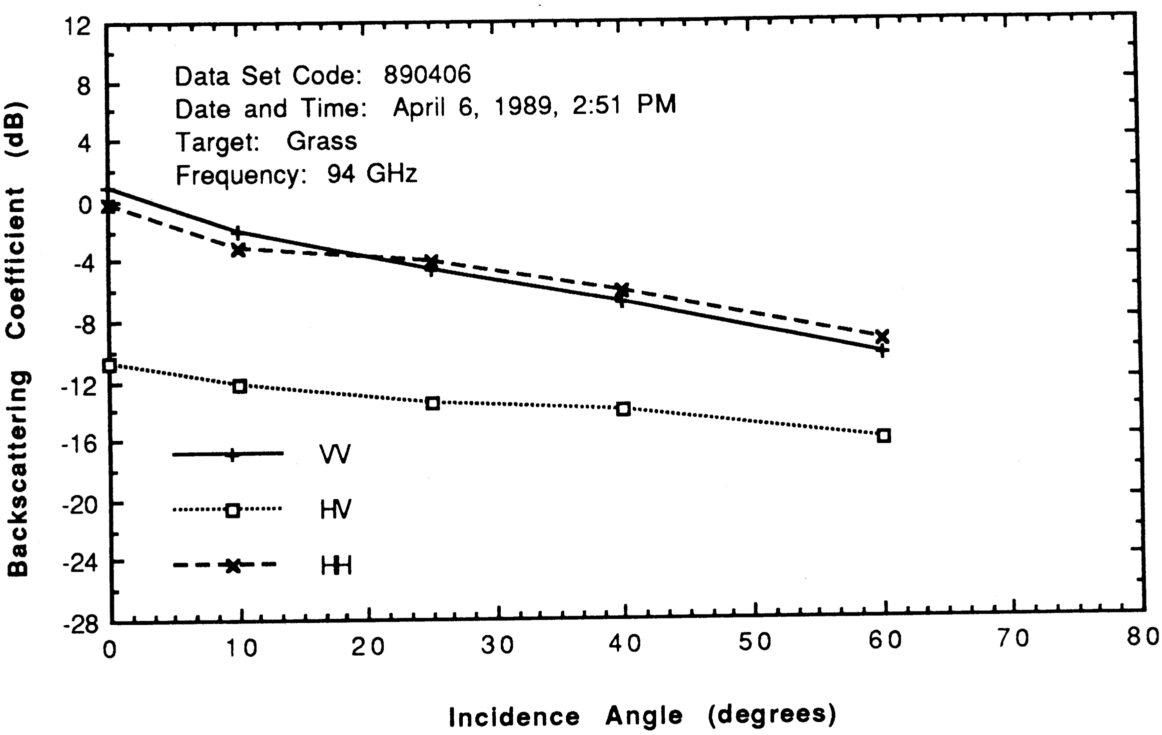
890406

Grass
Data set code: 890406
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.

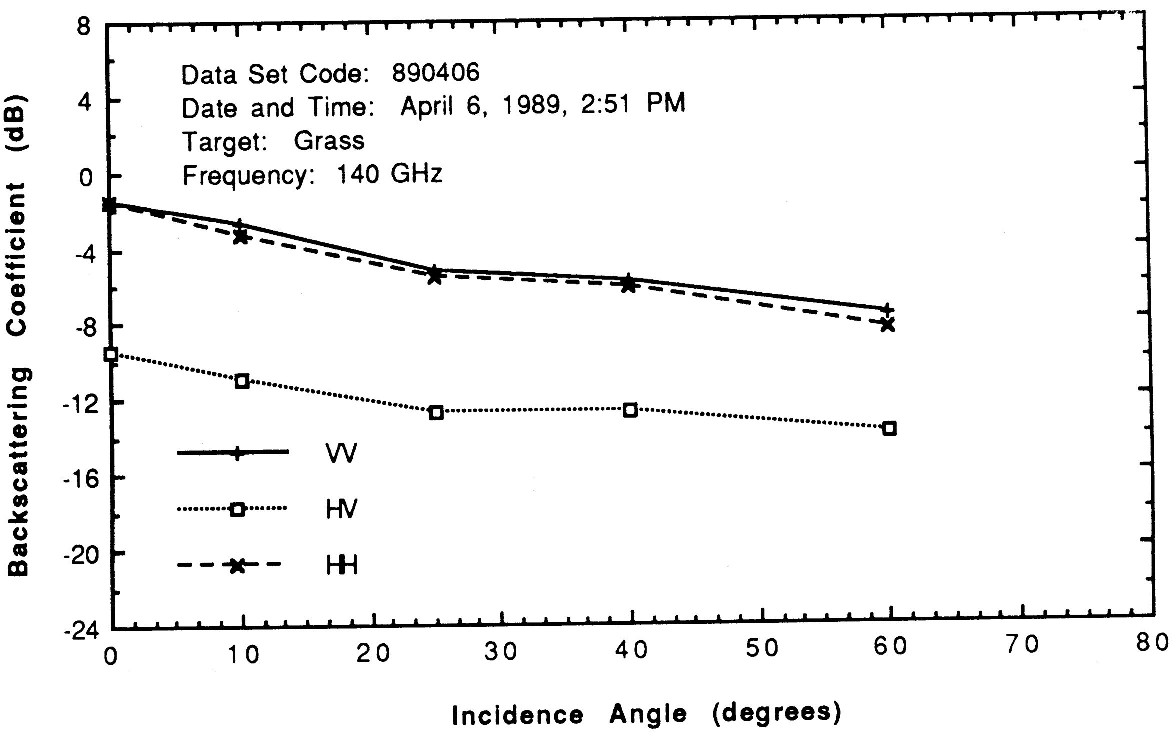


Brighton grass substrate

890406



Brighton grass substrate



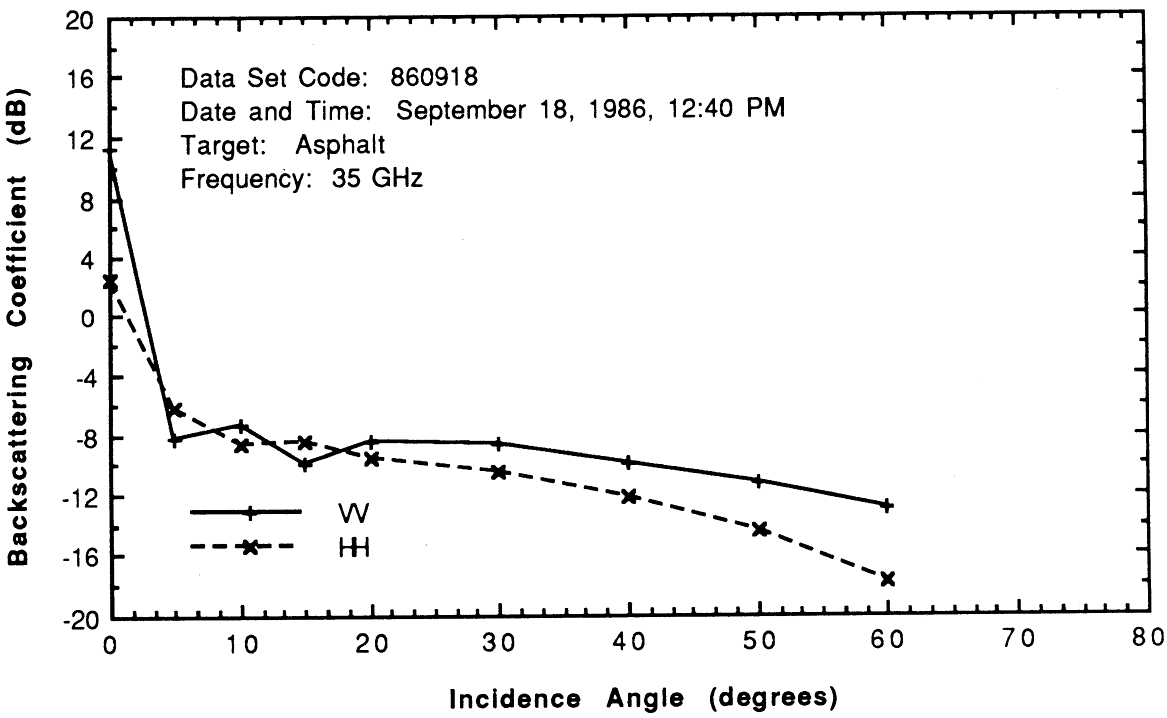
Brighton grass substrate

VIII. MMW DATA FOR ROAD SURFACES

A. Asphalt

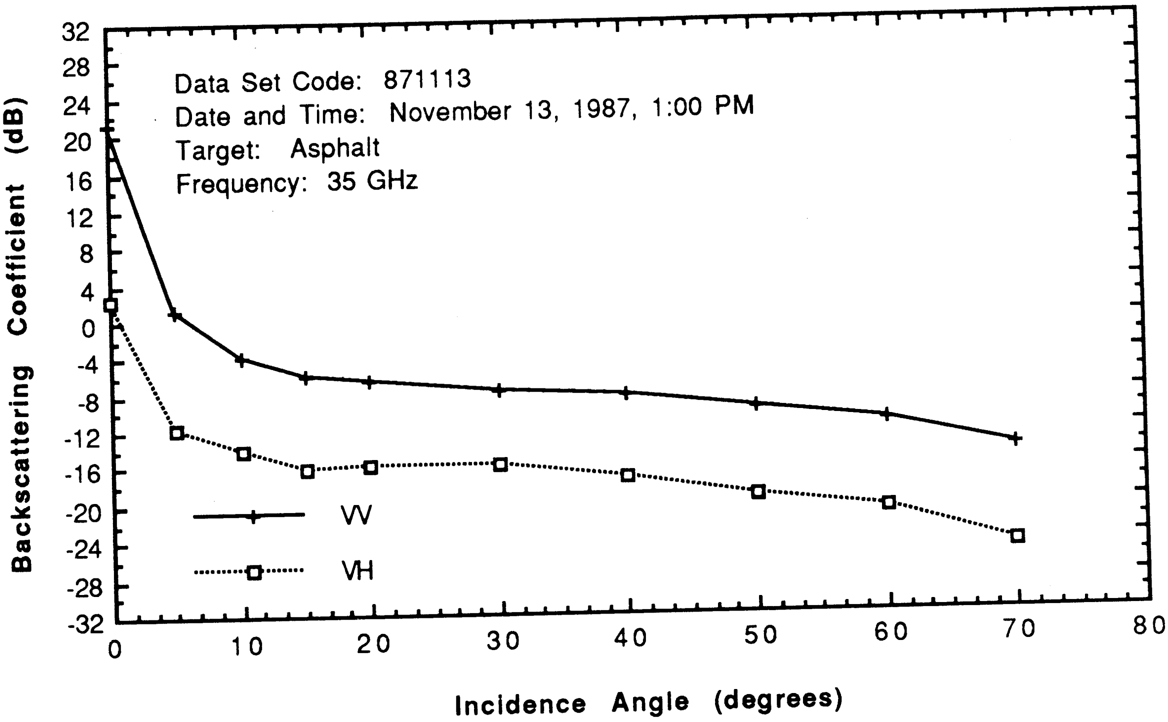
Asphalt
Data set code: 860918
Surface RMS height: 0.7 mm
Description: smooth, dry asphalt

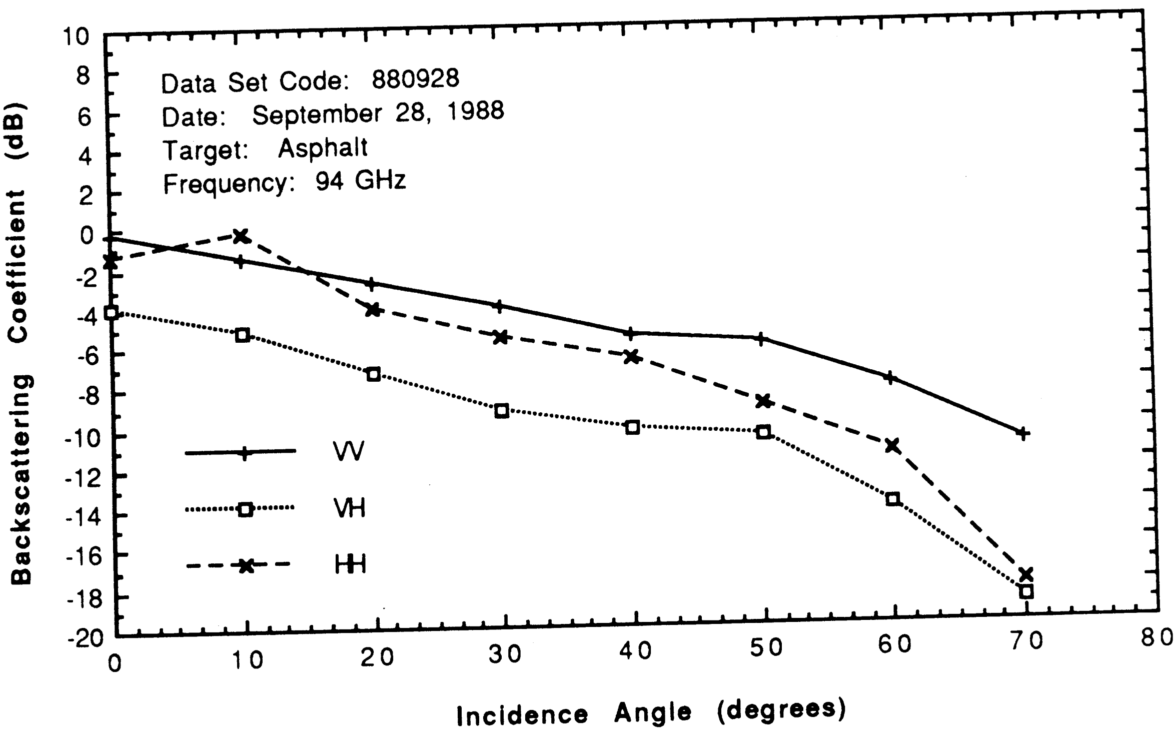
860918



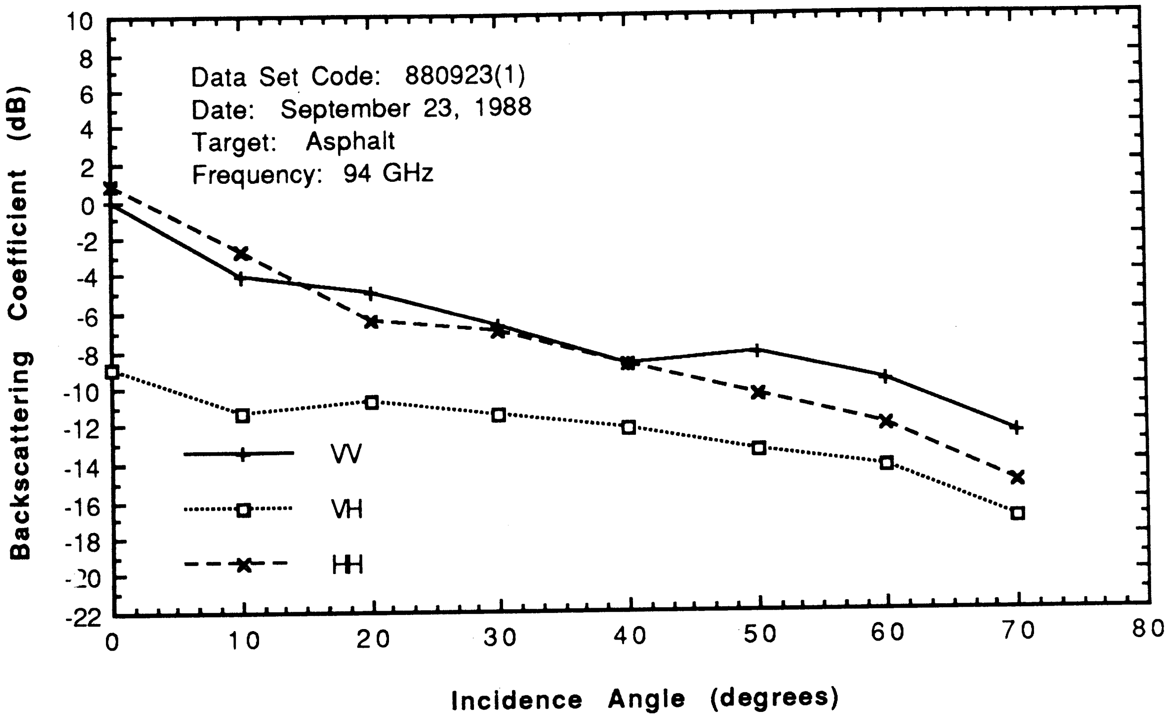
Dry Asphalt at Willow Run

Asphalt
Data set code: 871113
Surface RMS height: 0.42 mm
Condition: dry, smooth asphalt



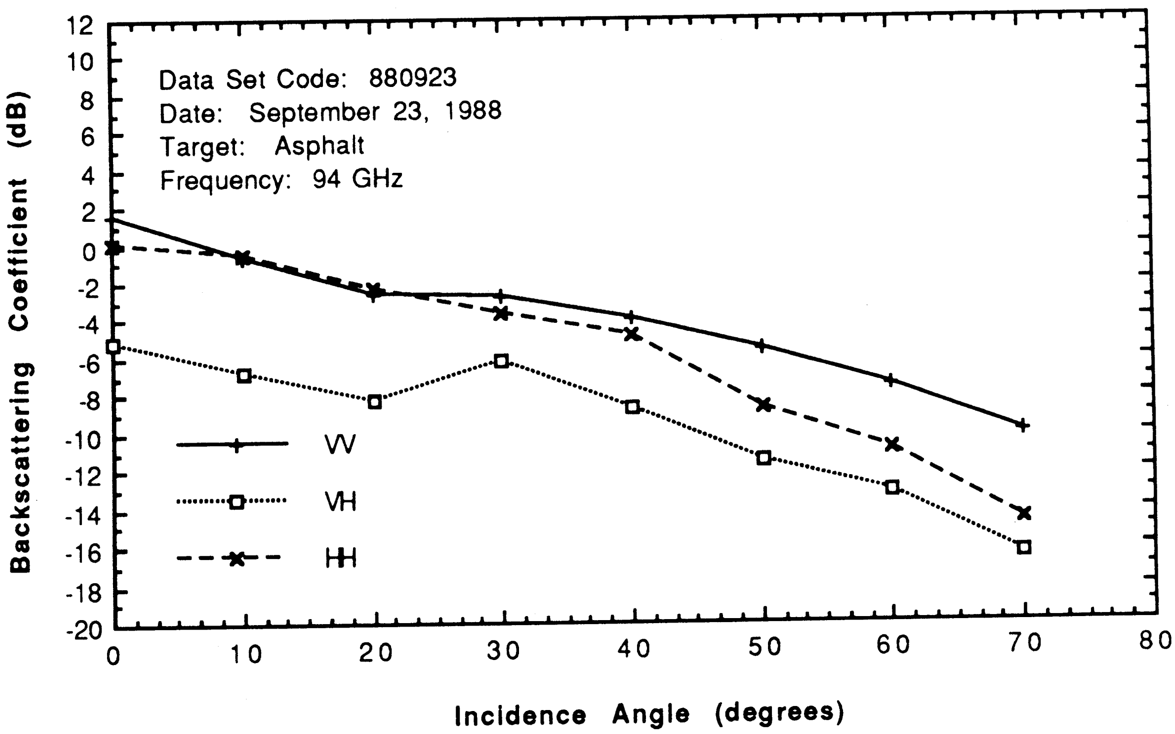


Asphalt
Data set code: 880923(1)
Surface RMS height: 0.42 mm
Condition: smooth, damp asphalt



Damp Asphalt at Dow Parking Lot

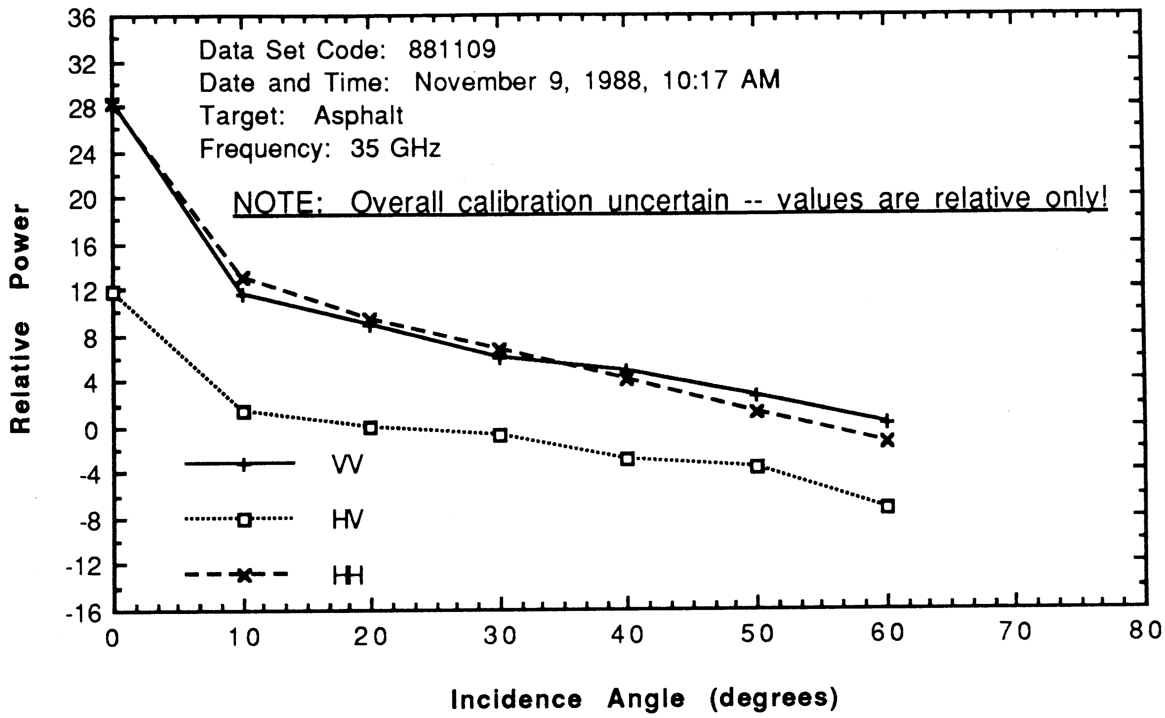
880923(2)



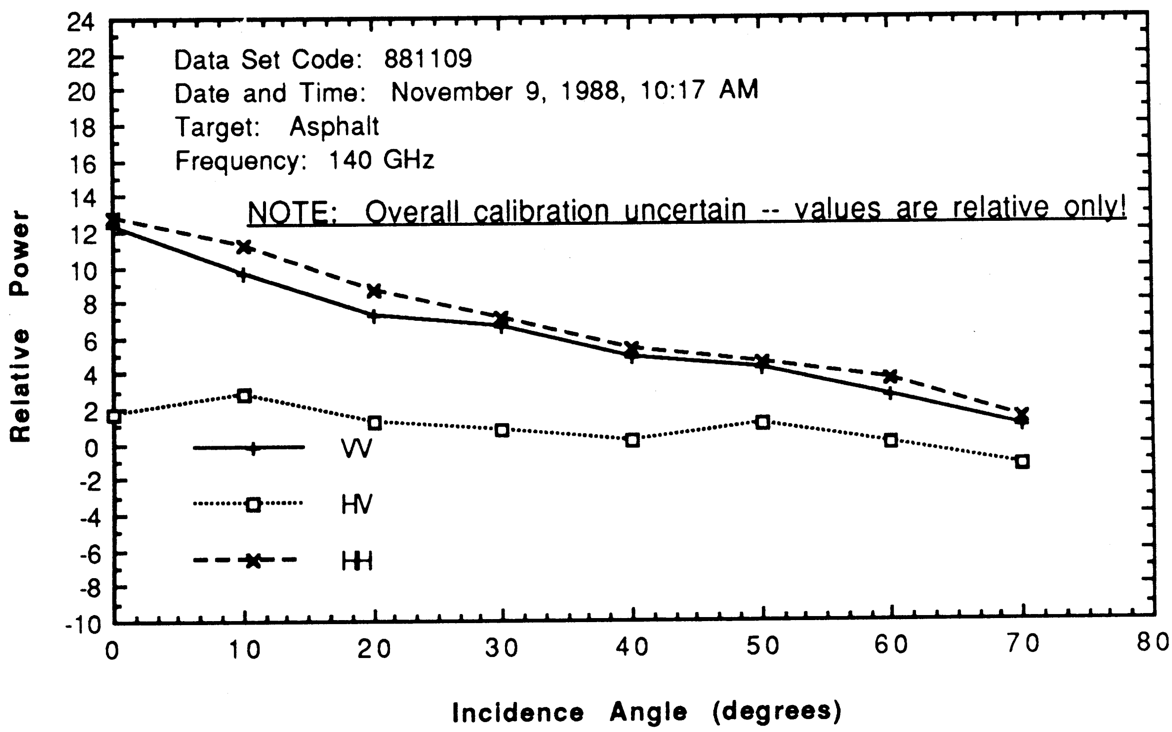
Dry Asphalt at Dow Parking Lot

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

Asphalt at Botanical Gardens



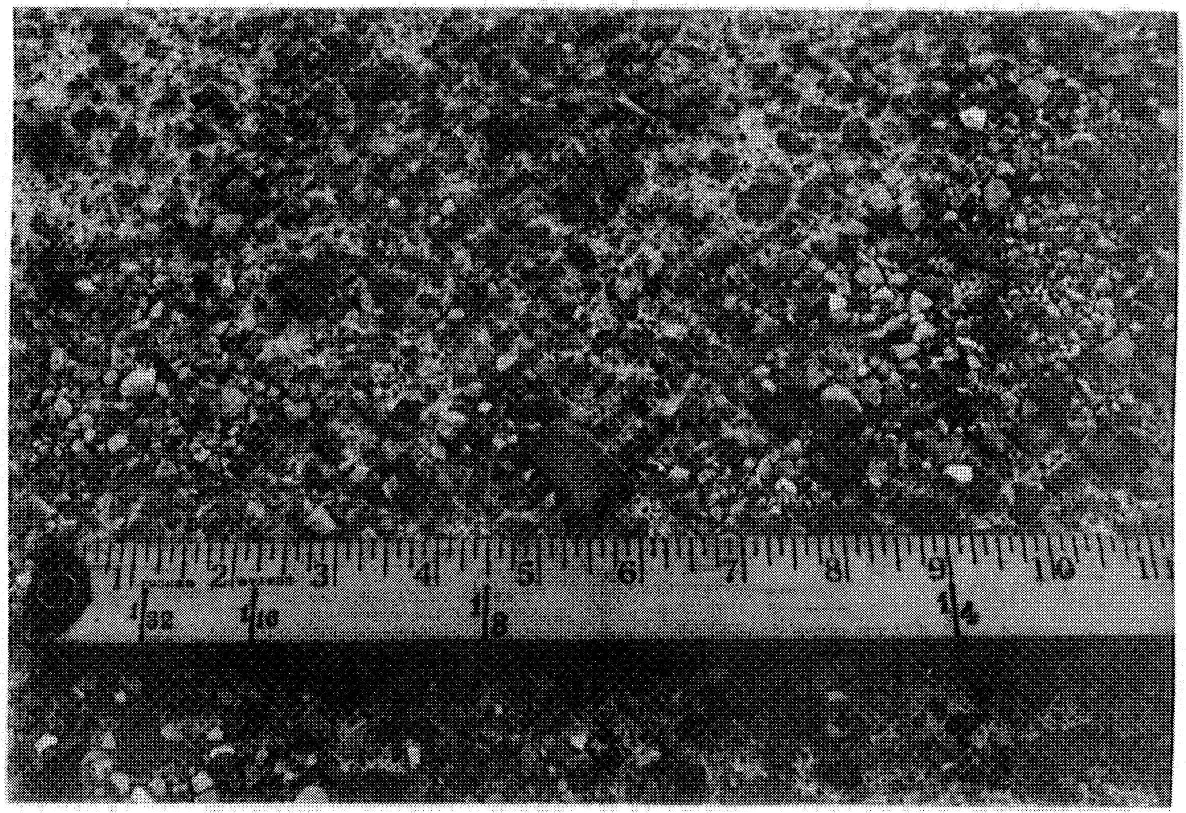
Rough Asphalt at Botanical Gardens



Rough Asphalt at Botanical Gardens

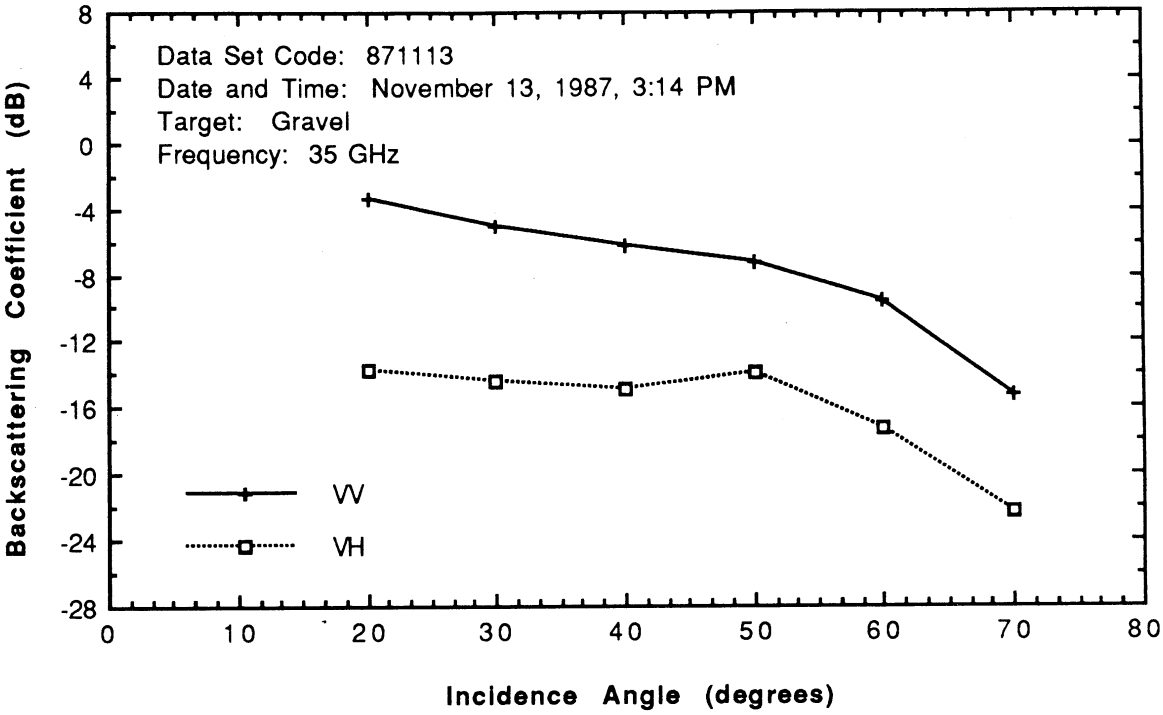
B. Gravel

Gravel
Data set code: 871113 and 880815
Surface RMS height: ~ 2 mm
Typical stone size: ~ 6 mm
Description: dry gravel



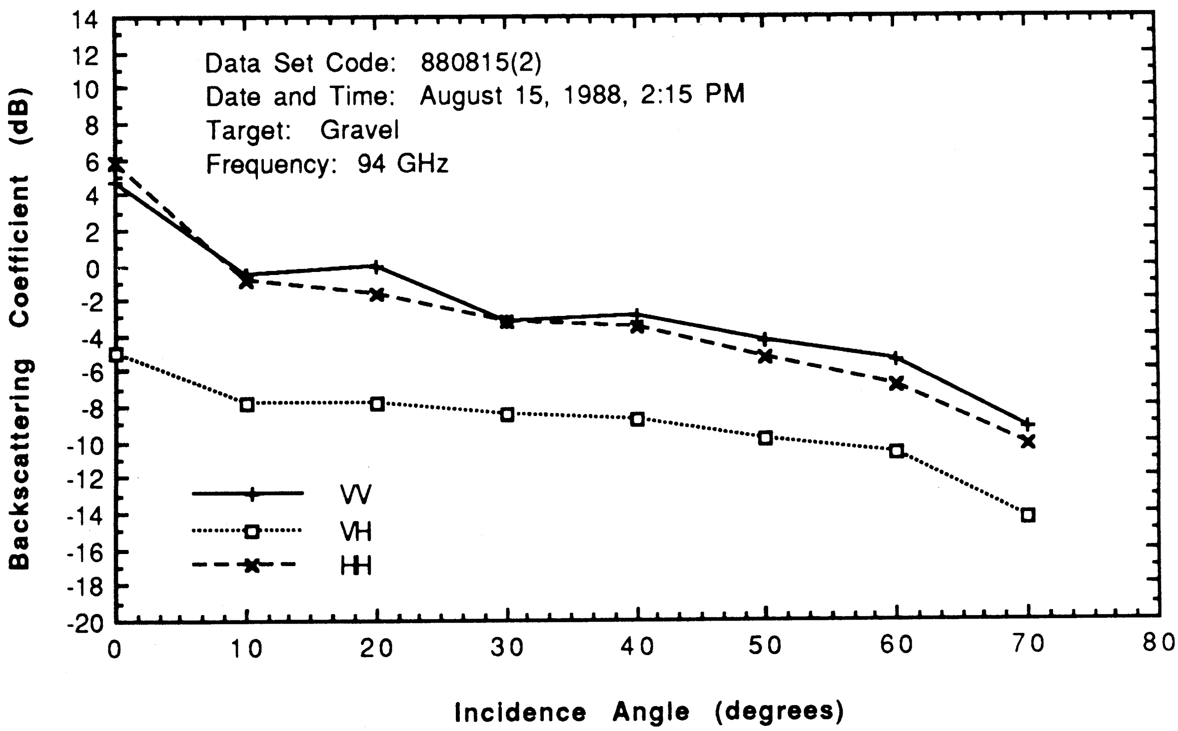
Gravel in North Campus parking lot

871113



Gravel in North Campus Parking Lot

880815(2)



Gravel in North Campus Parking Lot

APPENDIX A

A Millimeterwave Network Analyzer Based Scatterometer

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Thomas F. Haddock
Jack R. East
Michael W. Whitt

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A Millimeterwave Network Analyzer Based Scatterometer

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***Abstract*—The Millimeterwave Polarimeter (MMP) is a network-analyzer based scatterometer and reflectometer system that has been developed in support of a program to characterize radar clutter at 35, 94, and 140 GHz. A HP 8510A network analyzer is employed in the MMP system as a signal conditioner and processor to facilitate real-time data reduction, to reduce the short time-delay leakage noise inherent in traditional FM/CW radar, and to further enhance the signal-to-noise ratio of the system through signal processing techniques. Operation of the system at millimeter wavelengths is achieved with up-conversion and harmonic downconversion. The use of harmonic downconverters permits low-frequency signal connections between components of the system and allows easy reconfiguration in either scatterometer, bistatic, or reflection/transmission modes.**

I. Introduction

The PRIMARY design objectives of the Millimeterwave Polarimeter (MMP) is to achieve a system that can operate at 35, 94, and 140 GHz with full polarization and phase capability. It should operate from a truck platform as a scatterometer for backscatter measurements and in the laboratory for bistatic and transmission measurements, and should have ranging and real-time processing capabilities. The HP 8510A is an automatic vector network analyzer with a computer-control system that allows vector error correction of imperfections through the use of calibration standards. It provides the needed flexibility and signal conditioning and processing for our requirements.

The three configurations of the MMP are illustrated in Fig. 1. Fig. 1(a) illustrates the 94-GHz system in its backscatter mode. In this configuration it operates from a variable-angle mount on the end of an extendable boom mounted on a truck. The front end RF and IF components are mounted on the boom top, while the network analyzer and ancillary data processing and recording equipment are mounted in a control house on the bed of the truck. Fig. 1(b) shows the bistatic measurement configuration in which the transmitter and receiver sections are separated from one another and used to make bistatic measurements. Fig. 1(c) illustrates the transmitter and receiver subsystems, operating without the lens-horn antennas, to make transmission and reflection measurements. In this configuration the two subsystems directly face one another, so the transmitted signal passes directly through the sample.

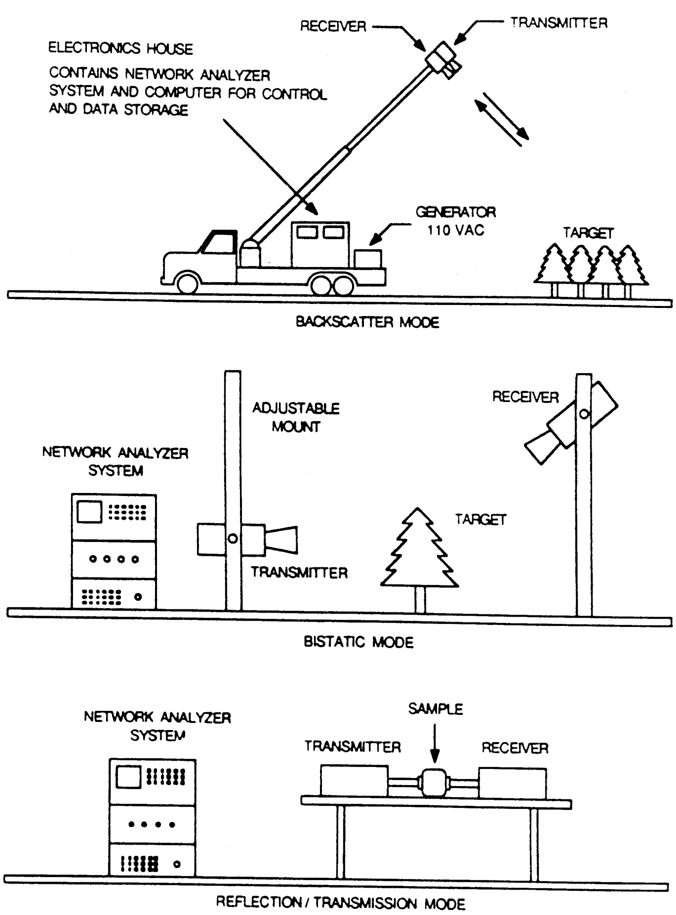

Fig. 1. The three operating configurations of the MMP.

Note that in the bistatic and reflection/transmission modes the receiver and transmitter sections must be positioned independently of each other. Scatterometer usage requires that the entire system be portable, with the front end moving remotely and independently from the HP 8510A back end. The MMP system illustrated in Fig. 2 addresses each of these goals, while providing standard operating procedures and data format for all three types of data acquisition.

II. MMP Design

The design goal was to produce a single versatile instrument with the ability to be configured in the three de-

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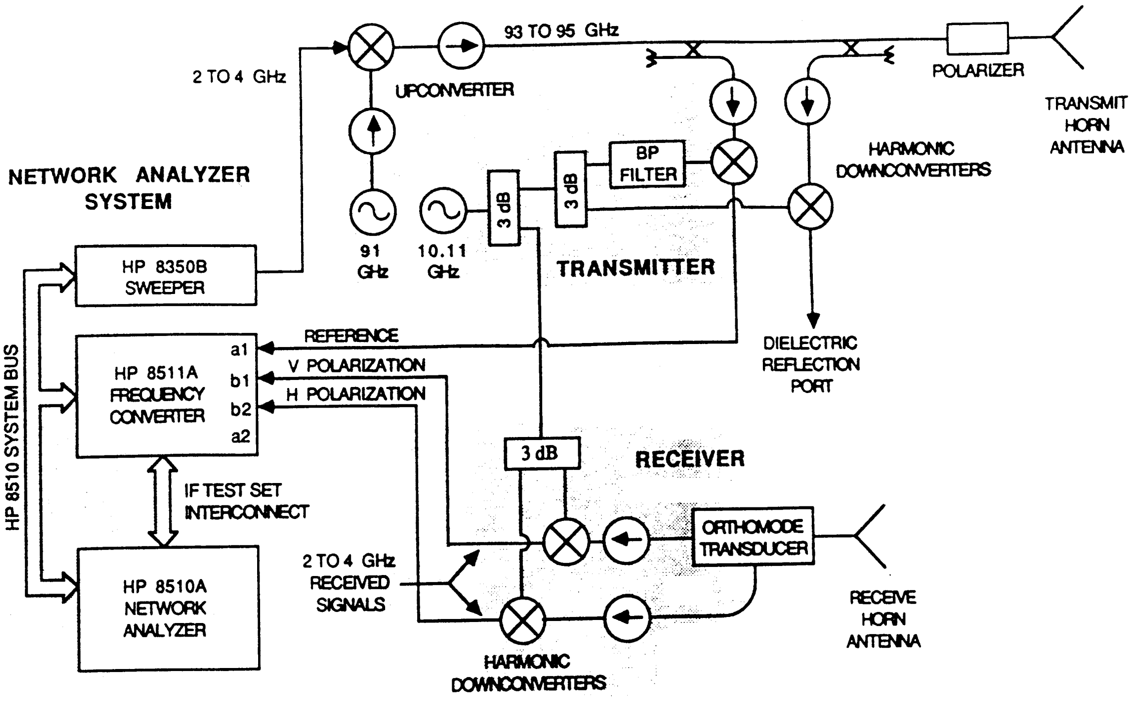
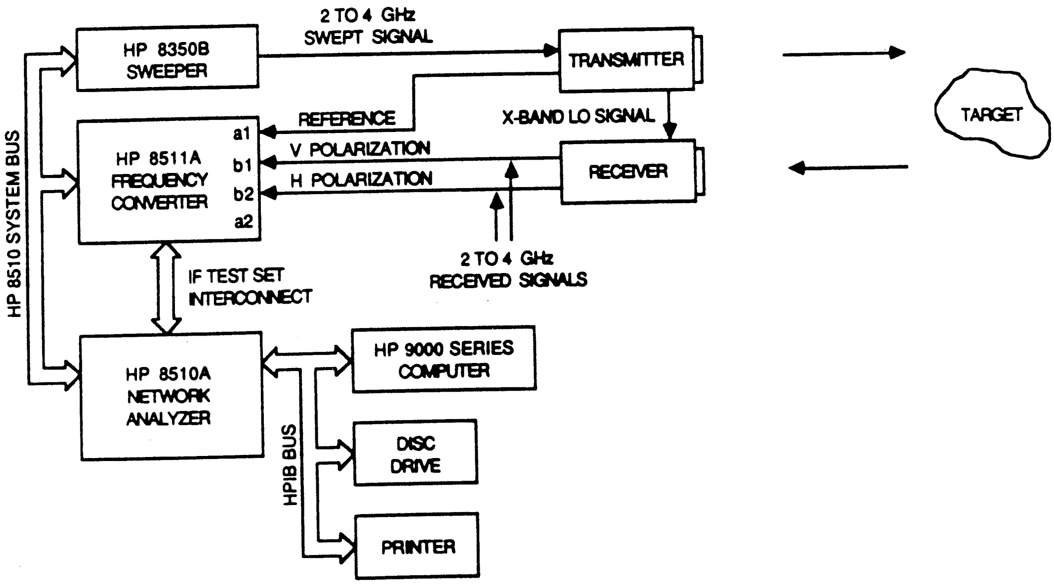


(a)



(b)

Fig. 2. Scattering configuration of the system, detail, and block diagrams. (a) System diagram in scatterometer mode. The 94-GHz system is illustrated, 35- and 140-GHz systems are analogous. (b) Scatterometer configuration of the system.

sired configurations. Discussion of each of the configurations follows.

A. Backscatter Mode

Fig. 2 illustrates the system in its backscatter mode, in detail (part a) and in block diagram form (part b). At each RF frequency a fixed-frequency Gunn source and mixer are used to upconvert a 2–4 GHz swept signal, controlled by the HP 8510A, to a swept 93–95 GHz signal. This signal is transmitted (in vertical or horizontal polarization) through a lens-horn antenna to the target. A sample of the transmitted signal is harmonically downconverted with a low-frequency LO (~ 10 GHz) and transmitted through flexible coaxial cable to the reference signal (a_1) port of the network analyzer. The reflected signal, picked up by a second antenna, is downconverted and fed into the return signal (b_1) port. The polarization switch allows the selection of either the horizontal or the vertical returned signal. Due to the low frequency (2–4 GHz and 10 GHz) coaxial interconnections between the various up and down converters, the transmitter and receiver subsystems are independently mobile.

In a traditional FM/CW radar [1]–[3] the noise floor is set by nonvarying leakages and reflections within the system. For short-range calibrated radars, or scatterometers, this level is typically about 30 to 35 dB above the thermal

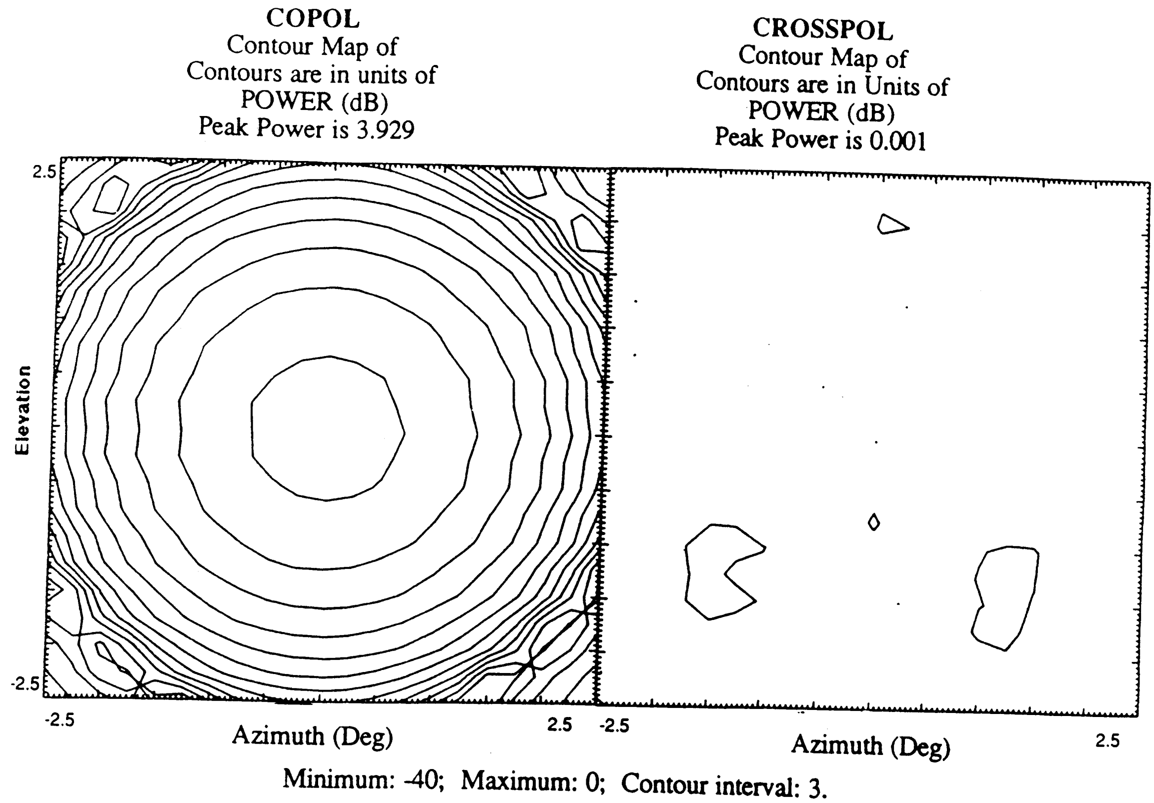


Fig. 3. Like- and cross-polarization traces for a typical MMP antenna.

noise floor of the system. The HP 8510A has error correction routines that correct for imperfections in the test circuitry through measurements of standard calibrators. By using an HP 8510A as a radar back-end, sources of system measurement error can be characterized and partially subtracted from the signal, hence, greatly increasing system sensitivity over that provided by a conventional design.

In addition, since the HP 8510A makes measurements by determining the phase and amplitude of returned signals over a series of stepped frequencies, all phase information is retained. When both horizontal and vertical modes of polarization are measured, complete polarization information can be obtained. This allows the reconstruction of any mode of polarization, linear or circular, thus making the system completely polarization agile. This capacity can be used to completely specify the scattering matrix of an object or target of interest.

The HP 8510A has the capability to perform complex binary math operations on pairs of swept signals. For example, a signal may be memorized and used to operate on subsequent signals to remove or reduce unwanted responses. This can be used to reduce reflection and leakage noise from within the system, as well as to reduce unwanted responses from outside the instrument.

The HP 8510A can perform real-time fast-Fourier transforms from the frequency domain, in which the data is taken, to the time domain. Range-gating capabilities in the time domain allow setting the response of the instrument to a specified time range. This can be used to reject signals reflected from targets outside of the desired range, as well as to measure the backscattered power as a function of range. In studying the scattering from vegetation canopies, for example, it is possible to record the differential scattering as a function of range from the top of the canopy down to the underlying ground surface.

TABLE I
TRUCK MOUNTED SCATTEROMETER PARAMETERS

Frequencies:	35 94 140 GHz	
RF Bandwidth:	0 to 2.0 GHz	
Sweep Rate:	1 ms.freq., 51, 101, 201, 401 freq./sweep	
Polarization:	HH, HV, VV, VH, magnitude and phase	
Incidence Angles:	0 to 70 degrees	
Platform Height:	3 meters minimum, to 18 meters maximum	
Noise Equivalent σ°:	35 GHz:	-36 dB *
	94 Ghz:	-34 dB *
	140 GHz:	-37 dB *
(*These values for h=10 meters and Θ = 50 degrees - the actual values will vary with both parameters.)		
Near Field Distance:	35 GHz:	5.53 m
	94 GHz:	3.71 m
	140 GHz:	1.38 m
Footprint:	35 GHz:	0.008 to 16.9 sq.m
	94 GHz:	0.002 to 4.78 sq.m
	140 GHz:	0.004 to 8.22 sq.m
Signal Processing:	HP 8510A/8511A based	
Output Products:	-received power verses range (ΔR = c/2B)	
	-received power verses frequency (at fixed R)	
	-phase and amplitude for each frequency	

Table I lists projected system performance specifications, based on laboratory tests and specifications of our

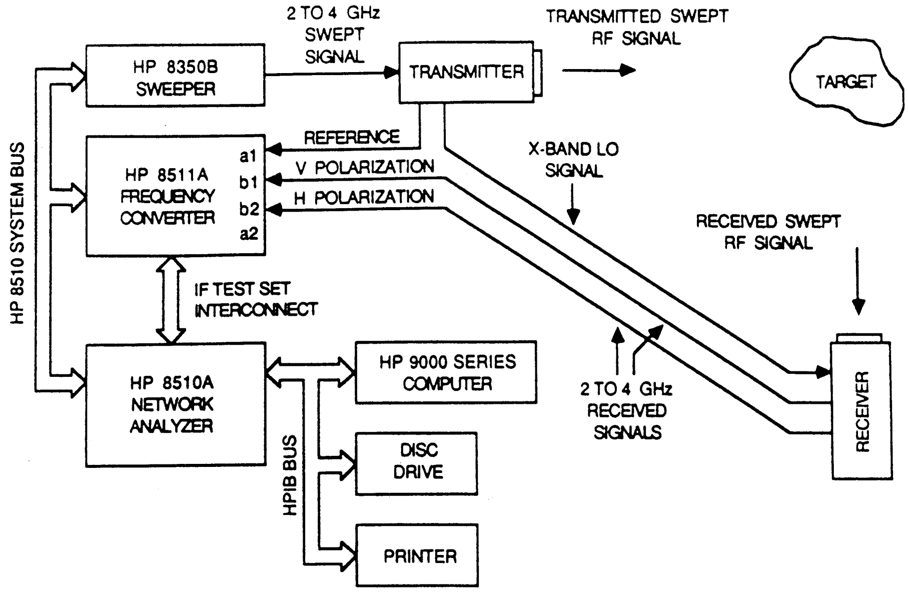


Fig. 4. Bistatic configuration of the system.

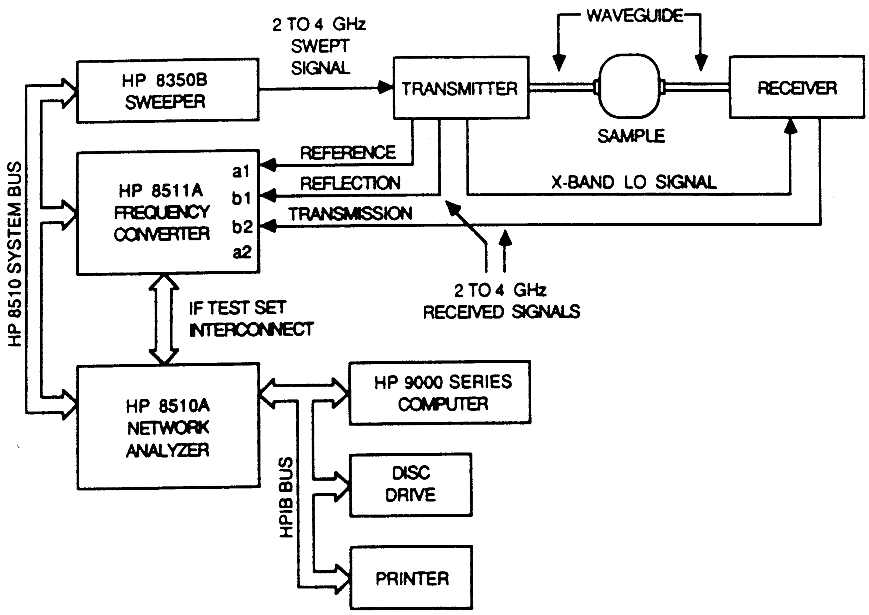


Fig. 5. Reflection/transmission configuration of the system.

equipment. The values for the noise-equivalent $\sigma°$ for the 94- and 140-GHz systems were derived on the basis of tests in the laboratory.

The bandwidth of the MMP can range from 0 to 2 GHz, and can be changed in real-time. Narrow bandwidth allows the system to have high spectral resolution, and hence have good determination of frequency-dependent features of the targets. Wide bandwidth allows good temporal resolution and can be used to reduce and study the effects of fading.

Antenna patterns of a typical MMP antenna are given in Fig. 3. These antennas have corrugated conical feed horns with matched dielectric lenses. Note that the cross-polarization isolation is better than 40 dB.

B. Bistatic Mode

The bistatic configuration diagram is shown in Fig. 4. The operation is similar to that in the backscatter mode, only here the transmitter and receiver sections move independently of each other in making the measurements at various angles. Ease of movement of the two subsystems comes from the low-frequency IF (2 to 4 GHz) and LO (X-band) interconnections. Note that due to range-gating, bistatic measurements can take place anywhere, in the field, where the numerous unwanted reflections can be time-gated out, or in the usual anechoic chamber setting.

C. Transmission Mode

The transmission configuration diagram is shown in Fig. 5. Operation is as in the bistatic case, with the transmitter and receiver units positioned independently, only now the lens-horn antennas are removed and samples are placed directly against the waveguide probes. In this configuration the polarization switch is used to select either the response from the reflected signal or the transmitted signal.

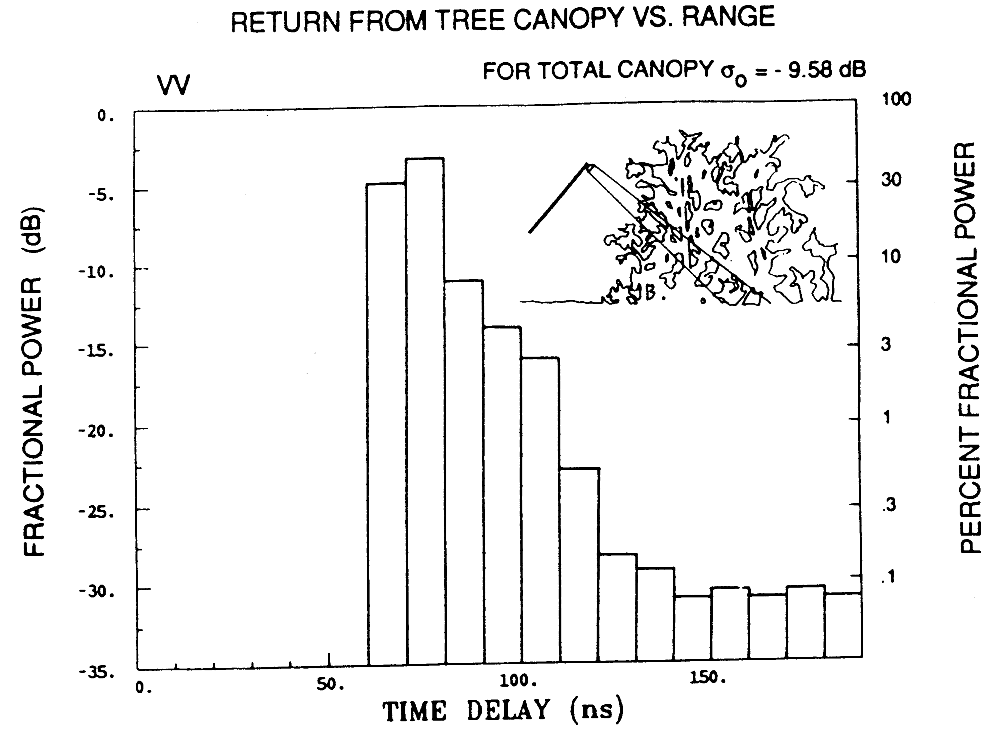


Fig. 6. Histogram of time-domain response of trees at 35 GHz.

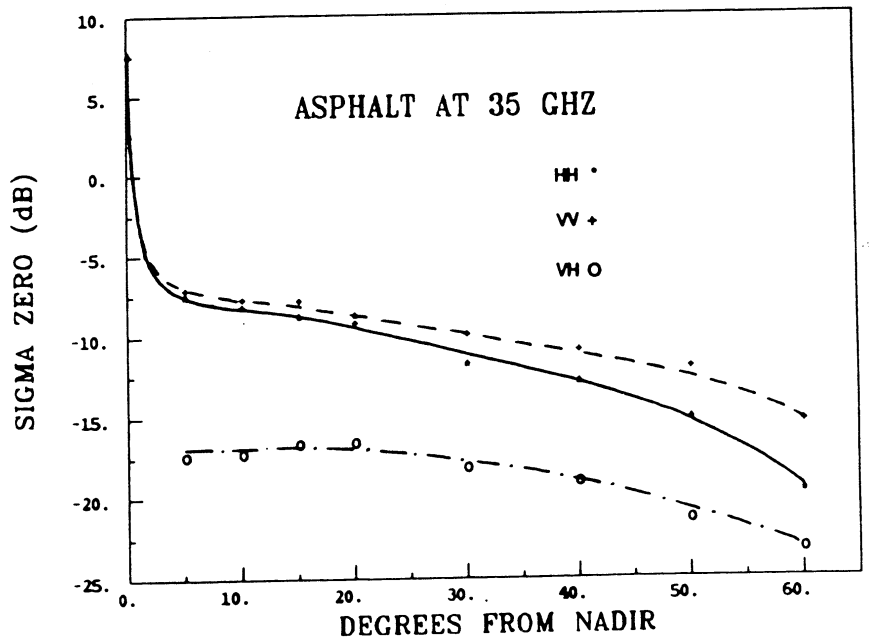


Fig. 7. Backscatter measurements on asphalt at 35 GHz.

III. Preliminary Results

Fig. 6 shows a histogram of the time-domain response of the system operating in the scatterometer mode at 35 GHz. The target was a dense stand of trees, and the data was taken with a full bandwidth of 2 GHz at an angle of approximately 45 degrees. Calibration was performed against a 15-in sphere, and the estimated 1-σ accuracy was 1 dB for the total canopy $\sigma^\circ = -9.6$ dB. The histogram shows the power, given as a percent of the total removed power, through the canopy in 10-ns bins.

Fig. 7 shows σ° measurements of an asphalt surface versus angle for H-H, V-V, and V-H polarizations. This data was taken at 35 GHz with a 2-GHz bandwidth.

Fig. 8 shows a plot of the radar-cross-section versus incidence angle for a leaf of cross section of approximately 40 cm^2, with 63-percent moisture content. This data was taken in an anechoic chamber at 35 GHz with the system operating in the backscatter mode.

IV. Conclusion

The HP 8510A network analyzer shows great promise as the back end of centimeter- and millimeter-wave FM/CW scatterometers and reflectometers. Use of its various error correction and signal processing capabilities should greatly improve signal-to-noise ratio over equivalent conventional systems. Furthermore, the versatility in

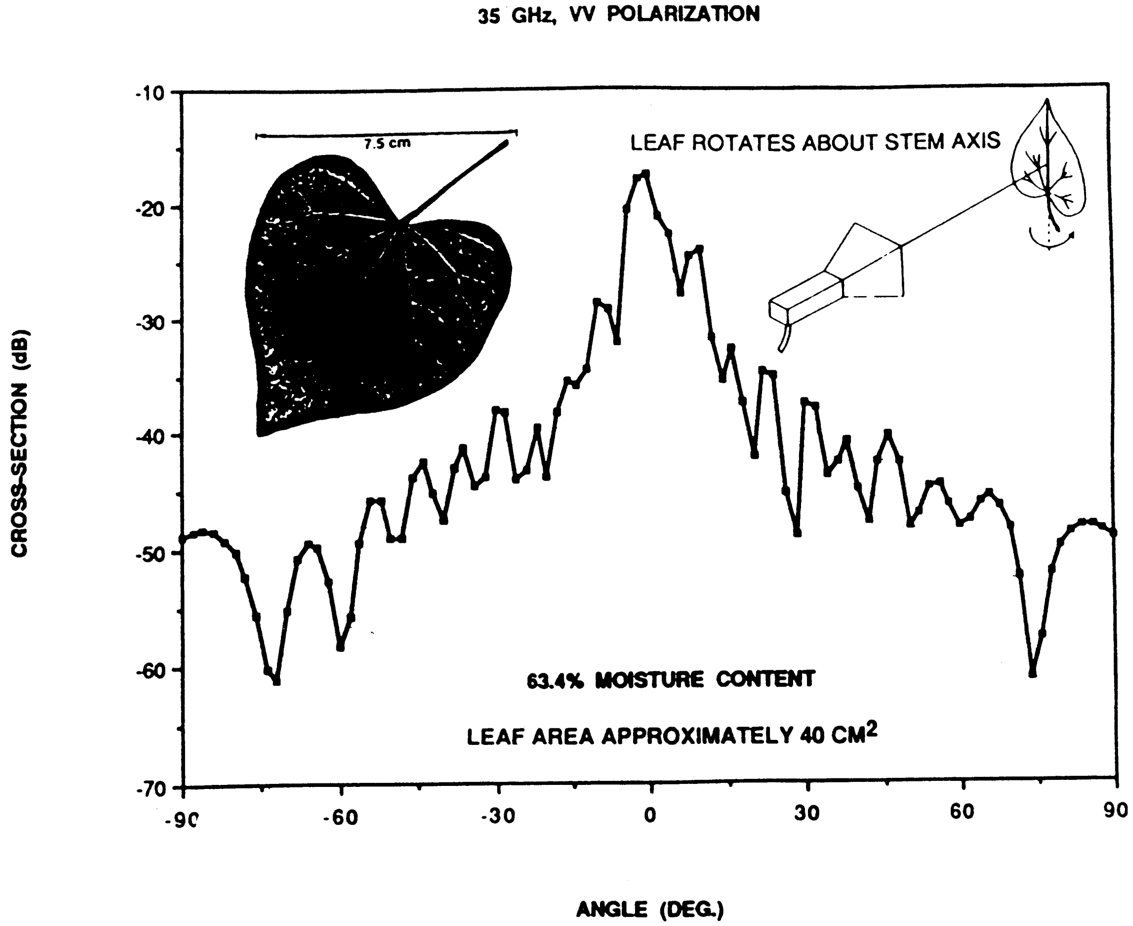


Fig. 8. Leaf backscatter cross section versus angle at 35 GHz for a leaf with 63.4-percent moisture content.

bandwidth, polarization, and configuration of the MMP allow for a flexible system for field as well as laboratory use.

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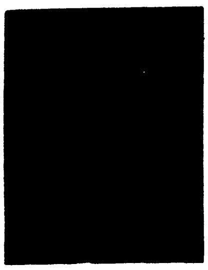

Fawwaz T. Ulaby (M'68–SM'74–F'80) was born in Damascus, Syria, on February 4, 1943. He received the B.S. degree in physics from the American University of Beirut, Lebanon, in 1964 and the M.S.E.E. and Ph.D. degrees in electrical engineering from the University of Texas, Austin, in 1966 and 1968, respectively.

From 1968 to 1984, he was with the Electrical Engineering Department at the University of Kansas, Lawrence, where he was the J. L. Constant Distinguished Professor, and the University of Kansas Center for Research, where he was Director of the Remote Sensing Laboratory. He is currently with the Radiation Laboratory and the Department of Electrical and Computer Engineering, University of Michigan, Ann Arbor. His current research interests involve microwave propagation and active and passive microwave remote sensing. Along with R. K. Moore and A. K. Fung, he is a coauthor of the three-volume series *Microwave Remote Sensing: Active and Passive* (Reading, MA: Addison-Wesley). In addition, he is coeditor of the *Manual of Remote Sensing*, 2nd ed., vol. I, American Society of Photogrammetry.

Dr. Ulaby is a member of Eta Kappa Nu, Tau Beta Pi, and Sigma Xi. He has been named the Executive Editor for IEEE Transactions on Geoscience and Remote Sensing, 1984–1985, and was the Geoscience and Remote Sensing Society's Distinguished Lecturer for 1987. He was named an IEEE Fellow in 1980 "for contributions to the application of radar to remote sensing for agriculture and hydrology," received the GRS Society's Outstanding Service Award in 1982, and its Distinguished Service Award in 1983. In 1984, he also received a Presidential Citation for Meritorious service from the American Service of Photogrammetry. He received the University of Kansas Chancellor's Award for Excellence in Teaching in 1980, the University of Kansas Gould Award for "distinguished service to higher education" in 1973, and the Eta Kappa Nu MacDonald Award as an "outstanding electrical engineering professor in the United States of America" in 1975.

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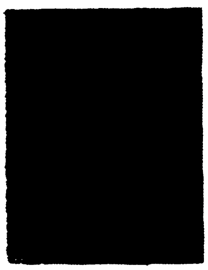

Thomas F. Haddock (M'86) was born in Washington, DC, on November 2, 1949. He received the B.A. degree in mathematics and the M.S. and Ph.D. degrees in physics from the University of Michigan, Ann Arbor, in 1972, 1977, and 1984, respectively.

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Dr. Haddock is a member of the American Astronomical Society.

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Jack R. East (S'70–M'72) received the B.S.E., M.S., and Ph.D. degrees from the University of Michigan, Ann Arbor.

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Michael W. Whitt (S'83) was born in St. Charles, MO, on December 3, 1962. He received the B.S. degree in electrical engineering from the University of Arkansas, Fayetteville, in 1985 and the M.S. degree in electrical engineering from the University of Michigan, Ann Arbor, in 1986. Since September 1985, he has been a Graduate Research Assistant at the University of Michigan Radiation Laboratory, where he is currently working toward the Ph.D. degree.

His research interests include millimeter-wave radar, radar polarimetry, and polarimetric scattering from terrain and vegetation canopies.

APPENDIX B: RELEVANT PUBLICATIONS

[1] F.T. Ulaby, T.F. Haddock, J.R. East AND M.W. Whitt. A Millimeterwave Network Analyzer based Scatterometer. IEEE Transactions on Geoscience and Remote Sensing, Vol. 26(1). Jan.1988.

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[13] Y. Kuga, R.T. Austin, T.F. Haddock and F.T. Ulaby. Millimeter-wave Radar Scattering from Snow Part I--Radiative Transfer Model with Quasi-Crystalline Approximation. To be submitted for publication in IEEE Transactions on Geoscience and Remote Sensing.