MILLIMETER - WAVE RADAR
SCATTERING FROM TERRAIN:
DATA HANDBOOK, Version 2

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Contract DAAL03-89-K-0056
Millimeter-wave Radar Scattering From Terrain: Data Handbook, Version 2.0

This report provides a summary of experimental observations of the radar backscatter from terrain, as reported in the literature. The data is at 35, 94, 140 and 225 GHz, primarily at HH, VV, and HV polarizations. The terrain types observed include dry and wet snow, in-covered ground, trees, grasses, asphalt, gravel, and others.

Keywords: Radar signals; Backscattering (RH)
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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 wave 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.
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.

TERMNOLOGY

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°.

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

Fig. I-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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequencies</strong></td>
<td>35, 94, 140 GHz</td>
</tr>
<tr>
<td><strong>IF Bandwidth</strong></td>
<td>0 to 2.0 GHz</td>
</tr>
<tr>
<td><strong>Transmit Power</strong></td>
<td>35 GHz: +3 dBm 94 GHz: 0 dBm 140 GHz: -4 dBm</td>
</tr>
<tr>
<td><strong>Sweep Rate</strong></td>
<td>1 m-sec/freq., 51, 101, 201, 401 freq./sweep</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>HH, HV, VV, VH</td>
</tr>
<tr>
<td><strong>Incidence Angles</strong></td>
<td>0 to 70 degrees</td>
</tr>
<tr>
<td><strong>Platform Height</strong></td>
<td>3 meters minimum, to 18 meters maximum</td>
</tr>
<tr>
<td><strong>Noise Equivalent a</strong></td>
<td>35 GHz: -22 dB 94 GHz: -28 dB 140 GHz: -21 dB</td>
</tr>
<tr>
<td><strong>Crosspol Isolation</strong></td>
<td>35 GHz: 23 dB 94 GHz: 20 dB 140 GHz: 10 dB</td>
</tr>
<tr>
<td><strong>Phase Stability</strong></td>
<td>35 GHz: -1 degree/hour 94 GHz: -1 degree/minute 140 GHz: -10 to 50 degrees/second</td>
</tr>
<tr>
<td><strong>Near Field Dist</strong></td>
<td>35 GHz: 2.7 m 94 GHz: 7.3 m 140 GHz: 2.7 m</td>
</tr>
<tr>
<td><strong>Beamwidth</strong></td>
<td>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</td>
</tr>
<tr>
<td><strong>Antenna Diameter</strong></td>
<td>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</td>
</tr>
<tr>
<td><strong>Signal Processing</strong></td>
<td>HP 8510A/8511A based</td>
</tr>
<tr>
<td><strong>Output Products</strong></td>
<td>- received power verses range - received power verses frequency (at fixed R)</td>
</tr>
<tr>
<td></td>
<td>- phase and amplitude for each frequency</td>
</tr>
</tbody>
</table>
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:

<table>
<thead>
<tr>
<th>Data Set Code</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>880329 (S)</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>880329 (SR)</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>880329 (VR)</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>890210</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>890223</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>890302 (SM)</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>890302 (LG)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>890307 (RO)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>890307 (SM)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
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/cm³
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)

Data Set Code: 880329 35
Date and Time: March 29, 1988, 5:15 PM
Target: Dry Snow
Frequency: 35 GHz

Backscatter Coefficient \( \sigma^0 \) (dB)

Incidence Angle \( \theta \) (Degrees)
Smooth Snow at Houghton

Data Set Code: 880329 94
Date and Time: March 29, 1988, 5:15 PM
Target: Dry Snow
Frequency: 94 GHz

Backscatter Coefficient \( \sigma^0 \) (dB)

Incidence Angle \( \theta \) (Degrees)
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/cm³
Ice crystal diameter: 1 to 4 mm
Surface temperature: 0 °C
Description: snowpack of highly metamorphosed snow with a slightly rough surface
MMW DATA FOR DRY SNOW

880329(SR)

Data Set Code: 880329 35
Date and Time: March 29, 1988, 5:15 PM
Target: Dry Snow
Frequency: 35 GHz

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

---

88032994

Data Set Code: 880329 94
Date and Time: March 29, 1988, 5:15 PM
Target: Dry Snow
Frequency: 94 GHz

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$^3$
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)

Data Set Code: 88032935
Date and Time: March 29, 1988, 5:15 PM
Target: Dry Snow
Frequency: 35 GHz

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

Data Set Code: 88032994
Date and Time: March 29, 1988, 5:15 PM
Target: Dry Snow
Frequency: 94 GHz

Incidence Angle $\theta$ (Degrees)
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/cm³
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

<table>
<thead>
<tr>
<th>depth (cm)</th>
<th>temp. (deg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>20</td>
<td>-4.8</td>
</tr>
<tr>
<td>19</td>
<td>-4.8</td>
</tr>
<tr>
<td>18</td>
<td>-4.0</td>
</tr>
<tr>
<td>17</td>
<td>-4.0</td>
</tr>
<tr>
<td>16</td>
<td>-3.3</td>
</tr>
<tr>
<td>15</td>
<td>-3.3</td>
</tr>
<tr>
<td>14</td>
<td>-2.1</td>
</tr>
<tr>
<td>13</td>
<td>-2.1</td>
</tr>
<tr>
<td>12</td>
<td>-0.8</td>
</tr>
<tr>
<td>11</td>
<td>-0.8</td>
</tr>
<tr>
<td>10</td>
<td>-0.8</td>
</tr>
<tr>
<td>9</td>
<td>-0.8</td>
</tr>
<tr>
<td>8</td>
<td>-0.8</td>
</tr>
<tr>
<td>7</td>
<td>-0.8</td>
</tr>
<tr>
<td>6</td>
<td>-0.8</td>
</tr>
<tr>
<td>5</td>
<td>-0.8</td>
</tr>
<tr>
<td>4</td>
<td>-0.8</td>
</tr>
<tr>
<td>3</td>
<td>-0.8</td>
</tr>
<tr>
<td>2</td>
<td>-0.8</td>
</tr>
<tr>
<td>1</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

air temperature: -4.4 C
MMW DATA FOR DRY SNOW

890210

Data Set Code: 890210 140
Date and Time: February 10, 1989, 1:40 PM
Target: Dry Snow
Frequency: 140 GHz

Backscatter Coefficient $\sigma^2$ (dB)

Incidence Angle $\theta$ (Degrees)

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
MMW DATA FOR DRY SNOW

890223

Snow pit

Data collection scene
MMW DATA FOR DRY SNOW

890223

- Data Set Code: 890223 35
- Date and Time: February 23, 1989, 11:35 AM
- Target: Dry Snow
- Frequency: 35 GHz

Dry snow at Brighton

- Data Set Code: 890223 94
- Date and Time: February 23, 1989, 11:35 AM
- Target: Dry Snow
- Frequency: 94 GHz

Dry snow at Brighton
MMW DATA FOR DRY SNOW

890223

Data Set Code: 890223 140
Date and Time: February 23, 1989, 11:35 AM
Target: Dry Snow
Frequency: 140 GHz

Backscatter Coefficient $\sigma^0$ (dB)

Incidence Angle $\theta$ (Degrees)

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)

Data Set Code: 890302-sm 35
Date and Time: March 2, 1989, 9:55 PM
Target: Dry Snow
Frequency: 35 GHz

Incidence Angle \( \theta \) (Degrees)
Small snow crystals at Brighton

Data Set Code: 890302-sm 94
Date and Time: March 2, 1989, 9:55 PM
Target: Dry Snow
Frequency: 94 GHz

Incidence Angle \( \theta \) (Degrees)
Small snow crystals at Brighton
Data Set Code: 890302-sm 140
Date and Time: March 2, 1989, 9:55 PM
Target: Dry Snow
Frequency: 140 GHz

Incidence Angle \( \theta \) (Degrees)
Small snow crystals at Brighton
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/cm³
Ice crystal diameter: 2 to 2.5 mm
Surface Temperature: -5 C
Description: fresh smooth snow surface

890302(LG)

Data Set Code: 890302-lg 35
Date and Time: March 2, 1989, 6:45 PM
Target: Dry Snow
Frequency: 35 GHz
MMW DATA FOR DRY SNOW

890302(LG)

Data Set Code: 890302-lg 94
Date and Time: March 2, 1989, 6:45 PM
Target: Dry Snow
Frequency: 94 GHz

Incidence Angle $\theta$ (Degrees)
Large snow crystals at Brighton

Data Set Code: 890302-lg 140
Date and Time: March 2, 1989, 6:45 PM
Target: Dry Snow
Frequency: 140 GHz

Incidence Angle $\theta$ (Degrees)
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

1 mm
MMW DATA FOR DRY SNOW

890307(RO)

Data Set Code: 890307-ro 35
Date and Time: March 7, 1989, 6:00 PM
Target: Dry Snow
Frequency: 35 GHz

Incidence Angle $\theta$ (Degrees)

Dry rough metamorphosed snow at Brighton

Data Set Code: 890307-ro 94
Date and Time: March 7, 1989, 6:00 PM
Target: Dry Snow
Frequency: 94 GHz

Incidence Angle $\theta$ (Degrees)

Dry rough metamorphosed snow at Brighton
Data Set Code: 890307-ro 140
Date and Time: March 7, 1989, 6:00 PM
Target: Dry Snow
Frequency: 140 GHz

Incidence Angle $\theta$ (Degrees)
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/cm³
Surface temperature: -10 to -12 C
Description: dry slightly metamorphosed snow
MMW DATA FOR DRY SNOW

890307(SM)

Data Set Code: 890307-sm 35
Date and Time: March 7, 1989, 6:00 PM
Target: Dry Snow
Frequency: 35 GHz

Incidence Angle $\theta$ (Degrees)
Dry smooth metamorphosed snow at Brighton

---

Data Set Code: 890307-sm 94
Date and Time: March 7, 1989, 6:00 PM
Target: Dry Snow
Frequency: 94 GHz

Incidence Angle $\theta$ (Degrees)
Dry smooth metamorphosed snow at Brighton
MMW DATA FOR DRY SNOW

890307(SM)

Data Set Code: 890307-sm 140
Date and Time: March 7, 1989, 6:00 PM
Target: Dry Snow
Frequency: 140 GHz

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:

<table>
<thead>
<tr>
<th>Data Set Code</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>890220</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>890309 (vw w/ rs)</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>890221</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>890309 (vw w/ ss)</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>890215</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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/cm³
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

Data Set Code: 890215 35
Date and Time: February 15, 1989, 11:30 AM
Target: Wet Snow
Frequency: 35 GHz

Wet Snow at Brighton

Data Set Code: 890215 94
Date and Time: February 15, 1989, 11:30 AM
Target: Wet Snow
Frequency: 94 GHz

Wet Snow at Brighton
MMW DATA FOR WET SNOW

890215

Data Set Code: 890215 140
Date and Time: February 15, 1989, 11:30 AM
Target: Wet Snow
Frequency: 140 GHz

Backscatter Coefficient $\sigma^0$ (dB)

Angle of Incidence $\theta$ (Degrees)
Wet Snow at Brighton
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$^3$
Ice crystal diameter: 1 to 2 mm
Surface temperature: 0.0 C
Description: smooth, wet natural snow

<table>
<thead>
<tr>
<th>top (cm)</th>
<th>temp. (deg C)</th>
<th>density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
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air temperature: 1.1 C
MMW DATA FOR WET SNOW

Data collection scene

Snow crystals from surface
Data Set Code: 890220 35
Date and Time: February 20, 1989, 12:45 PM
Target: Wet Snow
Frequency: 35 GHz

Backscatter Coefficient $\sigma^0$ (dB)

Angle of Incidence $\theta$ (Degrees)

Wet Snow at Brighton

Data Set Code: 890220 94
Date and Time: February 20, 1989, 12:45 PM
Target: Wet Snow
Frequency: 94 GHz

Backscatter Coefficient $\sigma^0$ (dB)

Angle of Incidence $\theta$ (Degrees)

Wet Snow at Brighton
MWW DATA FOR WET SNOW

Data Set Code: 890220 140
Date and Time: February 20, 1989, 12:45 PM
Target: Wet Snow
Frequency: 140 GHz

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/cm³
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

DataSet Code: 890221 35
Date and Time: February 21, 1989, 11:40 AM
Target: Wet Snow
Frequency: 35 GHz

Data Set Code: 890221 94
Date and Time: February 21, 1989, 11:40 AM
Target: Wet Snow
Frequency: 94 GHz
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$^3$
Ice crystal diameter: 2 to 4 mm
Surface temperature: 4 to 6 C
Description: rough, wet snow

890309(RO)

Data Set Code: 890309-ro 35
Date and Time: March 9, 1989, 12:15 PM
Target: Wet Snow
Frequency: 35 GHz

Wet rough metamorphosed snow at Brighton
MMW DATA FOR WET SNOW

890309(RO)

Data Set Code: 890309-ro 94
Date and Time: March 9, 1989, 12:15 PM
Target: Wet Snow
Frequency: 94 GHz

Angle of Incidence $\theta$ (Degrees)
Wet rough metamorphosed snow at Brighton

Data Set Code: 890309-ro 140
Date and Time: March 9, 1989, 12:15 PM
Target: Wet Snow
Frequency: 140 GHz

Angle of Incidence $\theta$ (Degrees)
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)
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$^3$
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 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.

![Graph](image-url)
MMW DIURNAL DATA FOR SNOW

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

Data Set Code: 880331 35
Data: March 31, 1988
Target: Snow
Frequency: 35 GHz
Incidence Angle: 40°

Houghton snow with smooth surface

Time (Hours)

Backscatter Coefficient $\sigma^0$ (dB)

VV

Houghton snow with slightly rough surface

Time (Hours)
MMW DIURNAL DATA FOR SNOW

880331

Data Set Code: 880331 35
Data: March 31, 1988
Target: Snow
Frequency: 35 GHz
Incidence Angle: 40°

Time (Hours)
Houghton snow with very rough surface

Data Set Code: 880331 94
Data: March 31, 1988
Target: Snow
Frequency: 94 GHz
Incidence Angle: 40°

Time (Hours)
Houghton snow with smooth surface

- VV
- VH
- HH
MMW DIURNAL DATA FOR SNOW

880331

Data Set Code: 880331 94
Data: March 31, 1988
Target: Snow
Frequency: 94 GHz
Incidence Angle: 40°

Time (Hours)
Houghton snow with slightly rough surface

Time (Hours)
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/cm³
Ice crystal diameter: 1 mm
Surface temperature: 0.0 C to -9.0 C
Description: partially metamorphosed snow

890227/28

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55
MMW DIURNAL DATA FOR SNOW

890227/28

Data Set Code: 890227/28
Data: February 27-28, 1989
Target: Snow

Liquid water content during snow diurnal at Brighton

Surface roughness profile with 1 cm grid
MMW DIURNAL DATA FOR SNOW

890227/28

Data Set Code: 890227/28 35
Data: February 27-28, 1989
Target: Snow
Frequency: 35 GHz
Incidence Angle: 40°

Data Set Code: 890227/28 94
Data: February 27-28, 1989
Target: Snow
Frequency: 94 GHz
Incidence Angle: 40°

Time (Hours)
Snow diurnal at Brighton
MMW DIURNAL DATA FOR SNOW

890227/28

Data Set Code: 890227/28 140
Data: February 27-28, 1989
Target: Snow
Frequency: 140 GHz
Incidence Angle: 40°

Snow diurnal at Brighton
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/cm³
Ice crystal diameter: 2 to 2.5 mm
Surface temperature: -4 C to -5 C
Description: partially metamorphosed snow

<table>
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<tr>
<th>SNOW PIT TEMPERATURE PROFILE (°C)</th>
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<tbody>
<tr>
<td>Time</td>
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<td>Top 10</td>
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<tr>
<td>depth (cm)</td>
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<tr>
<td>5</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>bottom</td>
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</table>

| 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 |
| depth (cm) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | -2.3 | -2.7 | -3.1 | -3.5 | -1.0 | -1.8 | -1.7 | -1.7 | -2.7 | -3.1 | -3.5 |
| 4 | -1.8 | -2.0 | -2.2 | -2.5 | -0.0 | -1.5 | -1.5 | -1.5 | -2.0 | -2.2 | -2.5 |
| 3 | -1.6 | -1.8 | -2.0 | -2.2 | -2.5 | -1.0 | -1.5 | -1.5 | -2.0 | -2.2 | -2.5 |
| 2 | -1.5 | -1.7 | -1.9 | -2.2 | -2.5 | -1.0 | -1.5 | -1.5 | -2.0 | -2.2 | -2.5 |
| 1 | -1.4 | -1.6 | -1.8 | -2.1 | -2.4 | -1.0 | -1.5 | -1.5 | -2.0 | -2.2 | -2.5 |
| bottom | -1.3 | -1.5 | -1.7 | -2.0 | -2.3 | -1.0 | -1.5 | -1.5 | -2.0 | -2.2 | -2.5 |

air temp

| Time | 1700 | 1800 | 1900 | 2100 | 1400 | 1500 | 1600 | 1700 | 1800 | 1900 | 2100 |
| Top 10 | -5.5 | -6.0 | -6.5 | -7.5 | -4.0 | -4.5 | -5.0 | -5.0 | -6.0 | -6.5 | -7.5 |
| depth (cm) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | -3.6 | -4.1 | -4.6 | -5.1 | -3.0 | -3.5 | -4.0 | -4.0 | -4.5 | -5.0 | -5.5 |
| 4 | -3.4 | -3.9 | -4.4 | -4.9 | -2.9 | -3.4 | -3.9 | -4.0 | -4.5 | -5.0 | -5.5 |
| 3 | -3.2 | -3.7 | -4.2 | -4.7 | -2.7 | -3.2 | -3.7 | -3.8 | -4.3 | -4.8 | -5.3 |
| 2 | -3.0 | -3.5 | -4.0 | -4.5 | -2.5 | -3.0 | -3.5 | -3.6 | -4.1 | -4.6 | -5.1 |
| 1 | -2.8 | -3.3 | -3.8 | -4.3 | -2.8 | -3.3 | -3.8 | -4.0 | -4.5 | -5.0 | -5.5 |
| bottom | -2.6 | -3.1 | -3.6 | -4.1 | -2.6 | -3.1 | -3.6 | -3.7 | -4.2 | -4.7 | -5.2 |
MMW DIURNAL DATA FOR SNOW

890302

Data Set Code: 890302-dium 35
Data: March 2, 1989
Target: Snow
Frequency: 35 GHz
Incidence Angle: 40°

VV
VH
HH

Time (Hours)
Snow diurnal at Brighton

Data Set Code: 890302-dium 94
Data: March 2, 1989
Target: Snow
Frequency: 94 GHz
Incidence Angle: 40°

VV
HV
HH

Time (Hours)
Snow diurnal at Brighton
MMW DATA FOR SNOW

Data Set Code: 890302-diurn 140
Data: March 2, 1989
Target: Snow
Frequency: 140 GHz
Incidence Angle: 40°

Snow diurnal at Brighton
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

Data Set Code: 880308 35
Data and Time: March 8, 1988, 2:32 PM
Target: Ice Covered Ground
Frequency: 35 GHz

Backscatter Coefficient $\sigma^0$ (dB)

Angle of Incidence $\theta$ (Degrees)

- VV
- VH
- HH

Data Set Code: 880308 94
Data and Time: March 8, 1988, 2:32 PM
Target: Ice Covered Ground
Frequency: 94 GHz

Backscatter Coefficient $\sigma^0$ (dB)

Angle of Incidence $\theta$ (Degrees)
6. 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

   ~ 2 M
   ~ 0.3 M
   87111111
Needles of Cedar trees

Ground cover beneath Cedar trees
MMW DATA FOR TREE CANOPIES

Data Set Code: 87111135
Date and Time: November 11, 1987, 9:18 AM
Target: Cedar Trees
Frequency: 35 GHz

Data Set Code: 87111194
Date and Time: November 11, 1987, 9:18 AM
Target: Cedar Trees
Frequency: 94 GHz
B. Red Pine

5-11 November, 1987
Data set code: 871105
Tree density: 0.14 trees/m²
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
Needles of Red Pines

Ground cover beneath Red Pines
MWW WAVE DATA FOR TREE CANOPIES

871105

Data Set Code: 871105 35
Date and Time: November 5, 1987, 12:01 PM
Target: Pine Trees
Frequency: 35 GHz

Angle of Incidence $\theta$ (Degrees)
Red Pines at Arboretum (5 November, 1987)

871107

Data Set Code: 871107 35
Date and Time: November 7, 1987, 10:59 AM
Target: Pine Trees
Frequency: 35 GHz

Angle of Incidence $\theta$ (Degrees)
Red Pines at Arboretum (7 November, 1987)
**MMW DATA FOR TREE CANOPIES**

871107

- **Data Set Code:** 871107 94
- **Date and Time:** November 7, 1987, 10:59 AM
- **Target:** Pine Trees
- **Frequency:** 94 GHz

![Graph of Backscatter Coefficient vs Angle of Incidence]

**Angle of Incidence \( \theta \) (Degrees)**

Red Pines at Arboretum (7 November, 1987)

871109

- **Data Set Code:** 871109 94
- **Date and Time:** November 9, 1987, 2:20 PM
- **Target:** Pine Trees
- **Frequency:** 94 GHz

![Graph of Backscatter Coefficient vs Angle of Incidence]

**Angle of Incidence \( \theta \) (Degrees)**

Red Pines at Arboretum (9 November, 1987)
MMW DATA FOR TREE CANOPIES

871110

Data Set Code: 871110 35
Date and Time: November 10, 1987, 9:24 AM
Target: Pine Trees
Frequency: 35 GHz

Angle of Incidence $\theta$ (Degrees)
Red Pines at Arboretum (10 November, 1987)

871111

Data Set Code: 871111 RP
Date and Time: November 11, 1987, 1:43 PM
Target: Pine Trees
Frequency: 35 GHz

Angle of Incidence $\theta$ (Degrees)
Red Pines at Arboretum (11 November, 1987)
C. Apple Trees

Data set code: 880811
Tree density: 0.1 trees/m²
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

Data Set Code: 880811 94
Date and Time: August 12, 1988, 9:45 AM
Target: Apple Tree
Frequency: 94 GHz

Backscatter Coefficient $\sigma^\circ$ (dB)

Angle of Incidence $\theta$ (Degrees)
D. Bur Oak

Bur Oak (Quercus macrocarpa)
Data set code: 880930-1027
Tree density: 0.09 trees/m²
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
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
MMW DATA FOR TREE CANOPIES

880930-1027

Data Set Code: 880930-1027
Dates: September 30 - October 27, 1988
Target: Oak Trees
Frequency: 35 GHz
Incidence Angle: 20°

Day
Bur Oaks (Quercus Macrocarpa)

---

Data Set Code: 880930-1027
Dates: September 30 - October 27, 1988
Target: Oak Trees
Frequency: 35 GHz
Incidence Angle: 30°

Day
Bur Oaks (Quercus Macrocarpa)
MMW DATA FOR TREE CANOPIES

880930-1027

Data Set Code: 880930-1027
Dates: September 30 - October 27, 1988
Target: Oak Trees
Frequency: 35 GHz
Incidence Angle: 70°

Backscatter Coefficient $\sigma^0$ (dB)

Day
Bur Oaks (Quercus Macrocarpa)

Data Set Code: 880930-1027
Dates: September 30 - October 27, 1988
Target: Oak Trees
Frequency: 94 GHz
Incidence Angle: 50°

Backscatter Coefficient $\sigma^0$ (dB)

Day
Bur Oaks (Quercus Macrocarpa)
MMW WAVE DATA FOR TREE CANOPIES

880930-1027

Data Set Code: 880930-1027
Dates: September 30 - October 27, 1988
Target: Oak Trees
Frequency: 94 GHz
Incidence Angle: 70°

Day
Bur Oaks (Quercus Macrocarpa)

880930

Data Set Code: 880930 35
Date and Time: September 30, 1988, 11:53 AM
Target: Oak Trees
Frequency: 35 GHz

Bur Oaks (Quercus Macrocarpa) Leaf Moisture Content = 59.7%
MMW WAVE DATA FOR TREE CANOPIES

881004

Data Set Code: 880930 35
Date and Time: October 4, 1988, 12:05 PM
Target: Oak Trees
Frequency: 35 GHz

Angle of Incidence $\theta$ (Degrees)
Bur Oaks (Quercus Macrocarpa)

Data Set Code: 881004 94
Date and Time: October 4, 1988, 12:05 PM
Target: Oak Trees
Frequency: 94 GHz

Leaf Moisture Content = 54.2 %
**MMW DATA FOR TREE CANOPIES**

### 881013

- **Data Set Code:** 881013 94
- **Date and Time:** October 13, 1988, 12:14 PM
- **Target:** Oak Trees
- **Frequency:** 94 GHz

![Graph](image)

**Angle of Incidence θ (Degrees)**

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

### 881014

- **Data Set Code:** 881014
- **Date and Time:** October 14, 1988, 1:40 PM
- **Target:** Oak Trees
- **Frequency:** 35 GHz

![Graph](image)

**Angle of Incidence θ (Degrees)**

Bur Oaks (Quercus Macrocarpa)  Leaf Moisture Content = 50.1%
MMW DATA FOR TREE CANOPIES

881015

- Data Set Code: 881015 35
- Date and Time: October 15, 1988, 12:30 PM
- Target: Oak Trees
- Frequency: 35 GHz

Angle of Incidence $\theta$ (Degrees)
Bur Oaks (Quercus Macrocarpa)

- VV
- HV
- HH

Backscatter Coefficient $\sigma^0$ (dB)

88101594

- Data Set Code: 881015 94
- Date and Time: October 15, 1988, 12:30 PM
- Target: Oak Trees
- Frequency: 94 GHz

Angle of Incidence $\theta$ (Degrees)
Bur Oaks (Quercus Macrocarpa) Leaf Moisture Content = 55.2%
MMW WAVE DATA FOR TREE CANOPIES

881027

Data Set Code: 881027 35
Date and Time: October 27, 1988, 1:00 PM
Target: Oak Trees
Frequency: 35 GHz

Angle of Incidence $\theta$ (Degrees)
Bur Oaks (Quercus Macrocarpa)

Data Set Code: 881027 94
Date and Time: October 27, 1988, 1:00 PM
Target: Oak Trees
Frequency: 94 GHz

Leaf Moisture Content = 42%
MMW WAVE DATA FOR TREE CANOPIES

**881118**

- **Data Set Code:** 881118 35
- **Date and Time:** November 18, 1988, 11:42 AM
- **Target:** Oak Trees
- **Frequency:** 35 GHz

![Graph showing backscatter coefficient vs angle of incidence for Bur Oaks (Quercus Macrocarpa) at 35 GHz.](image)

**Angle of Incidence θ (Degrees)**

Bur Oaks (Quercus Macrocarpa)

---

**881118**

- **Data Set Code:** 881118 94
- **Date and Time:** November 18, 1988, 11:43 AM
- **Target:** Oak Trees
- **Frequency:** 94 GHz

![Graph showing backscatter coefficient vs angle of incidence for Bur Oaks (Quercus Macrocarpa) at 94 GHz.](image)

**Angle of Incidence θ (Degrees)**

Bur Oaks (Quercus Macrocarpa) Leaf Moisture Content = 27%
Data Set Code: 881118 140
Date and Time: November 18, 1988, 11:43 PM
Target: Oak Trees
Frequency: 140 GHz

Angle of Incidence θ (Degrees)
Bur Oaks (Quercus Macrocarpa) Leaf Moisture Content = 27%
E. Spruce Trees

Spruce (Picea abies)
Data set code: 881031/881122
Tree density: 0.03 trees/m²
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
MMW DATA FOR TREE CANOPIES

881031

Data Set Code: 881031 35
Date and Time: October 31, 1988, 1:23 PM
Target: Evergreen Trees
Frequency: 35 GHz

Data Set Code: 881031 94
Date and Time: October 31, 1988, 1:23 PM
Target: Evergreen Trees
Frequency: 94 GHz
MMW DATA FOR TREE CANOPIES

881122

Data Set Code: 881122 35
Date and Time: November 22, 1988, 10:21 AM
Target: Evergreen Trees
Frequency: 35 GHz

Angle of Incidence \( \theta \) (Degrees)
Blue Spruce & Norway Spruce (Picea Puryens & Picea Abies)

Data Set Code: 881122 94
Date and Time: October 31, 1988, 10:21 AM
Target: Evergreen Trees
Frequency: 94 GHz

Angle of Incidence \( \theta \) (Degrees)
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
MMW DATA FOR TREE CANOPIES

Close-up view of branches of White Cedar Bush

881116

Data Set Code: 881116 35
Date and Time: November 16, 1988, 11:12 AM
Target: Bushes
Frequency: 35 GHz

White Cedar at Botanical Gardens (Thuja Occidentalis)
MMW WAVE DATA FOR TREE CANOPIES

881116

Data Set Code: 881116 94
Date and Time: November 16, 1988, 11:12 AM
Target: Bushes
Frequency: 94 GHz

Angle of Incidence θ (Degrees)
White Cedar at Botanical Gardens (Thuja Occidentalis)

Data Set Code: 881116 140
Date and Time: November 16, 1988, 11:12 AM
Target: Bushes
Frequency: 140 GHz

Angle of Incidence θ (Degrees)
White Cedar (Thuja Occidentalis)
VII. MMW DATA FOR GRASSES

871102

Data Set Code: 871102 (grass) 94
Date and Time: November 2, 1987, 2:45 PM
Target: Grass
Frequency: 94 GHz

Angle of Incidence θ (Degrees)
Cut grass with wet surface (Height = 10 cm)

871116

Data Set Code: 871116 (grass) 35
Date and Time: November 16, 1987, 11:17 AM
Target: Grass
Frequency: 35 GHz

Angle of Incidence θ (Degrees)
Cut grass at North Campus (Height = 5cm)
MMW WAVE DATA FOR GRASSES

871116

Data Set Code: 871116 (grass) 94
Date and Time: November 16, 1987, 11:17 AM
Target: Grass
Frequency: 94 GHz

880812

Data Set Code: 880812 (grass) 94
Date and Time: August 12, 1988, 1:28 PM
Target: Grass
Frequency: 94 GHz
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

Data Set Code: 881202 35
Date and Time: December 2, 1988, 9:24 AM
Target: Ground Cover
Frequency: 35 GHz

Backscatter Coefficient $\sigma^0$ (dB)

Angle of Incidence $\theta$ (Degrees)

Amaranthus over chick weed

---

Data Set Code: 881202 94
Date and Time: December 2, 1988, 9:24 AM
Target: Ground Cover
Frequency: 35 GHz

Backscatter Coefficient $\sigma^0$ (dB)

Angle of Incidence $\theta$ (Degrees)

Amaranthus over chick weed
Data Set Code: 881202 140
Date and Time: December 2, 1988, 9:24 AM
Target: Ground Cover
Frequency: 140 GHz

Amaranthus over chick weed
MMW WAVE DATA FOR GRASSES

Data Set Code: 881103 35
Date and Time: November 3, 1988, 9:58 AM
Target: Ground Cover
Frequency: 35 GHz

Data Set Code: 881103 94
Date and Time: November 3, 1988, 9:58 AM
Target: Ground Cover
Frequency: 94 GHz

Tall Grass (Andropogon gerardi)
Leaf Moisture Content = 33%
Description: dry, uncut
MMW WAVE DATA FOR GRASSES

Data Set Code: 881108 35
Date and Time: November 8, 1988, 9:48 AM
Target: Ground Cover
Frequency: 35 GHz

Data Set Code: 881108 94
Date and Time: November 8, 1988, 9:48 AM
Target: Ground Cover
Frequency: 94 GHz

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

881108

Data Set Code: 881108 140
Date and Time: November 8, 1988, 9:48 AM
Target: Ground Cover
Frequency: 140 GHz

Turkey Foot or Big Bluestem (Andropogon gerardi)
Grass (Andropogon gerardi)

Angle of Incidence $\theta$ (Degrees)

Backscatter Coefficient $\sigma^0$ (dB)

- $\text{VV}$
- $\text{HH}$
MMW WAVE DATA FOR GRASSES

881027

Data Set Code: 881027 35
Date and Time: October 27, 1988, 3:22 PM
Target: Ground Cover
Frequency: 35 GHz

[Graph showing backscatter coefficient vs. angle of incidence for two polarizations (VV and VH) with data points for different angles of incidence.]

881027 94

Data Set Code: 881027 94
Date and Time: October 27, 1988, 3:22 PM
Target: Ground Cover
Frequency: 94 GHz

[Graph showing backscatter coefficient vs. angle of incidence for four polarizations (VV, VH, HH) with data points for different angles of incidence.]

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

Data Set Code: 88111435
Date and Time: November 14, 1988, 11:19 AM
Target: Ground Cover
Frequency: 35 GHz

---

881114

Data Set Code: 88111494
Date and Time: November 14, 1988, 11:19 AM
Target: Ground Cover
Frequency: 94 GHz

---
Data Set Code: 881114 140
Date and Time: November 14, 1988, 11:19 AM
Target: Ground Cover
Frequency: 140 GHz

Broom Grass (Bromus inermis)
MMW WAVE DATA FOR GRASSES

881115

Data Set Code: 881115 35
Date and Time: November 15, 1988, 1:51 PM
Target: Ground Cover
Frequency: 35 GHz

Angle of Incidence $\theta$ (Degrees)
Broom Grass (Bromus inermis)

Data Set Code: 881115 94
Date and Time: November 15, 1988, 1:51 PM
Target: Ground Cover
Frequency: 94 GHz

Leaf Water Content = 50%
Height: 25 cm
Description: uncut
Data Set Code: 881115 140
Date and Time: November 15, 1988, 1:51 PM
Target: Ground Cover
Frequency: 140 GHz

Backscatter Coefficient $\sigma^o$ (dB)

Angle of Incidence $\theta$ (Degrees)

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)
MMW WAVE DATA FOR GRASSES

881117

Data Set Code: 881117 35
Date and Time: November 17, 1988, 9:54 AM
Target: Ground Cover
Frequency: 35 GHz

- VV
- HV
- HH

Angle of Incidence $\theta$ (Degrees)
Purple Loose Strife over water (Lythrum salicaria)

Data Set Code: 881117 94
Date and Time: November 17, 1988, 9:54 AM
Target: Ground Cover
Frequency: 94 GHz

- VV
- HV
- HH

Angle of Incidence $\theta$ (Degrees)
Purple Loose Strife over water (Lythrum salicaria)
MMW WAVE DATA FOR GRASSES

Data Set Code: 890406 35
Date and Time: April 6, 1989, 2:51 PM
Target: Grass
Frequency: 35 GHz

Data Set Code: 890406 94
Date and Time: April 6, 1989, 2:51 PM
Target: Grass
Frequency: 94 GHz

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

Data Set Code: 890406 140
Date and Time: April 6, 1989, 2:51 PM
Target: Grass
Frequency: 140 GHz

Backscatter Coefficient \( \sigma^0 \) (dB)

Angle of Incidence \( \theta \) (Degrees)

Brighton grass substrate

- VV
- HV
- HH
Data Set code: 860918 35
Date and Time: September 18, 1986, 12:40 PM
Target: Asphalt
Frequency: 35 GHz

Dry Asphalt at Willow Run
Surface RMS height: 0.7 mm
Description: smooth, dry asphalt
MMW WAVE DATA FOR ROAD SURFACES

871113

Data Set code: 871113
Date and Time: November 13, 1987, 1:00 PM
Target: Asphalt
Frequency: 35 GHz

Backscatter Coefficient \( \sigma^0 \) (dB)

Angle of Incidence \( \theta \) (Degrees)

880928

Data Set code: 880928 94
Date: September 28, 1988
Target: Asphalt
Frequency: 94 GHz

Asphalt Surface RMS height: 0.42 mm
Condition: Dry, smooth asphalt
MMW WAVE DATA FOR ROAD SURFACES

880923 (1)

Data Set code: 880923 94
Date: September 23, 1988
Target: Asphalt
Frequency: 94 GHz

Damp Asphalt at Dow Parking Lot

880923 (2)

Data Set code: 880923 94
Date: September 23, 1988
Target: Asphalt
Frequency: 94 GHz

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
MMW WAVE DATA FOR ROAD SURFACES

881109

Data Set code: 881109 35
Date and Time: November 9, 1988, 10:17 AM
Target: Asphalt
Frequency: 35 GHz

Note: Overall Calibration Uncertain -- Values are Relative Only!

Angle of Incidence $\theta$ (Degrees)
Rough Asphalt at Botanical Gardens

881109

Data Set code: 881109 140
Date and Time: November 9, 1988, 10:17 AM
Target: Asphalt
Frequency: 140 GHz

Note: Overall Calibration Uncertain -- Values are Relative Only!

Angle of Incidence $\theta$ (Degrees)
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
MMW WAVE DATA FOR ROAD SURFACES

871113

- Data Set code: 871113 35
- Date: November 13, 1987
- Target: Gravel
- Frequency: 35 GHz

Gravel in North Campus Parking Lot

880815 (2)

- Data Set code: 880815 94
- Date and Time: August 15, 1988
- Target: Gravel
- Frequency: 94 GHz

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°, and the receiver antenna was a horn with a wide beam width of 23°.
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**

<table>
<thead>
<tr>
<th>Tree Code</th>
<th>Tree Name (Latin Name)</th>
<th>Basal Diameter [m]</th>
<th>Canopy Height [m]</th>
<th>Crown Diameter [m]</th>
<th>Canopy Cover [%]</th>
<th>Day 99 [%]</th>
<th>210 [%]</th>
<th>210 Type</th>
<th>Depression [deg]</th>
<th>Azimuth [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Northern White Cedar</td>
<td>0.15-0.3</td>
<td>13.</td>
<td>5.</td>
<td>90</td>
<td>90</td>
<td>C</td>
<td>28.8</td>
<td>56.5</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>White Pine</td>
<td>0.73</td>
<td>30.</td>
<td>16.</td>
<td>85</td>
<td>90</td>
<td>E</td>
<td>20.8</td>
<td>41.</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Fir</td>
<td>0.48</td>
<td>21.</td>
<td>8.</td>
<td>80</td>
<td>85</td>
<td>D</td>
<td>21.9</td>
<td>38.5</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Sugar Maple</td>
<td>0.32</td>
<td>19.</td>
<td>14.</td>
<td>40</td>
<td>95</td>
<td>A</td>
<td>19.2</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Eastern Cottonwood</td>
<td>0.43</td>
<td>25.</td>
<td>3.</td>
<td>35</td>
<td>65</td>
<td>B</td>
<td>24.3</td>
<td>30.5</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Pin Oak</td>
<td>1.05</td>
<td>38.</td>
<td>24.</td>
<td>45</td>
<td>90</td>
<td>E</td>
<td>14.2</td>
<td>37.</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Black Oak</td>
<td>1.02</td>
<td>20.</td>
<td>24.</td>
<td>50</td>
<td>90</td>
<td>A</td>
<td>11.6</td>
<td>43.</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Silver Maple</td>
<td>0.78</td>
<td>21.</td>
<td>20.</td>
<td>50</td>
<td>75</td>
<td>A</td>
<td>11.8</td>
<td>46.</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Weeping Willow</td>
<td>0.82</td>
<td>22.</td>
<td>15.</td>
<td>50</td>
<td>90</td>
<td>B</td>
<td>10.4</td>
<td>49.5</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>White Pine</td>
<td>1.05</td>
<td>27.</td>
<td>12.</td>
<td>85</td>
<td>95</td>
<td>E</td>
<td>10.4</td>
<td>51.</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>White Pine</td>
<td>0.8</td>
<td>27.</td>
<td>14.</td>
<td>85</td>
<td>90</td>
<td>E</td>
<td>8.2</td>
<td>56.5</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Pin Oak</td>
<td>0.92</td>
<td>20.</td>
<td>14.</td>
<td>35</td>
<td>90</td>
<td>B</td>
<td>9.1</td>
<td>58.</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Red Maple</td>
<td>1.01</td>
<td>14.</td>
<td>15.</td>
<td>35</td>
<td>80</td>
<td>A</td>
<td>9.7</td>
<td>50.</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>Group of White Pines</td>
<td>0.5-0.8</td>
<td>20-30</td>
<td>5-10</td>
<td>85</td>
<td>90</td>
<td>E</td>
<td>9.4</td>
<td>63.5</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>Mixed Forest*</td>
<td>0.3-0.6</td>
<td>15-25</td>
<td>3-8</td>
<td>35</td>
<td>85</td>
<td>AB</td>
<td>8.3</td>
<td>53.</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Mixed Forest**</td>
<td>0.3-0.6</td>
<td>15-25</td>
<td>3-8</td>
<td>35</td>
<td>85</td>
<td>AB</td>
<td>6.6</td>
<td>53.</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>Mixed Forest***</td>
<td>0.2-0.6</td>
<td>15-25</td>
<td>3-8</td>
<td>35</td>
<td>85</td>
<td>AB</td>
<td>7.0</td>
<td>50.5</td>
<td></td>
</tr>
</tbody>
</table>

* Eastern Cottonwood (Populus deltoids), Grape (Vitis spp), Glossy Buckthorn (Rhamnus frangula) and Red Maple (Acer rubrum)

** Eastern Cottonwood (Populus deltoids) and Red Maple (Acer rubrum)

*** Red Maple (Acer rubrum), Pin Oak (Quercus Palustris) and White Pine (Pinus strobus)
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.
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.
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.
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.
Curves showing measured and computed $\sigma^o$ versus Julian date for VV, HH, and VH/HV polarizations for Silver Maple (H). Also shown is the corresponding measured ground truth data.
Curves showing measured and computed $\sigma^o$ versus Julian date for VV, HH, and VH/HV polarizations for Weeping Willow (I). 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 Mixed Forest (X). 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 Mixed Forest (Y). 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 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

<table>
<thead>
<tr>
<th>Day # (Fig. Ref.)</th>
<th>RMS Surface Roughness (mm)</th>
<th>No of Layers</th>
<th>Layer #</th>
<th>Particle Size (mm)</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Temperature (°C)</th>
<th>Density (gm/cc)</th>
<th>Volumetric Moisture (%)</th>
<th>Layer Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 (as figure)</td>
<td>0.00</td>
<td>2</td>
<td>1 (Bottom)</td>
<td>3</td>
<td>6</td>
<td>-3.0</td>
<td>0.190</td>
<td>0.00</td>
<td>0.00</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 (Top)</td>
<td>3</td>
<td>8</td>
<td>-3.5</td>
<td>0.260</td>
<td>0.00</td>
<td>0.00</td>
<td>12.5</td>
</tr>
<tr>
<td>6 (Fig. 1a)</td>
<td>1.33</td>
<td>3</td>
<td>1 (Bottom)</td>
<td>3</td>
<td>10</td>
<td>0.0</td>
<td>0.250</td>
<td>0.00</td>
<td>0.00</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 (Middle)</td>
<td>2</td>
<td>10</td>
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<td>0.00</td>
<td>10.0</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>3 (Top)</td>
<td>2</td>
<td>5</td>
<td>1.0</td>
<td>0.080</td>
<td>0.00</td>
<td>0.00</td>
<td>15.0</td>
</tr>
<tr>
<td>9 (Fig. 3a)</td>
<td>1.03</td>
<td>2</td>
<td>1 (Bottom)</td>
<td>3</td>
<td>16</td>
<td>-1.0</td>
<td>0.245</td>
<td>0.00</td>
<td>0.00</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 (Top)</td>
<td>3</td>
<td>18</td>
<td>-3.3</td>
<td>0.220</td>
<td>0.00</td>
<td>0.00</td>
<td>15.0</td>
</tr>
<tr>
<td>10 (Fig. 3c)</td>
<td>1.35</td>
<td>2</td>
<td>1 (Bottom)</td>
<td>3</td>
<td>15</td>
<td>0.0</td>
<td>0.255</td>
<td>0.00</td>
<td>0.00</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 (Top)</td>
<td>3</td>
<td>8</td>
<td>-3.3</td>
<td>0.180</td>
<td>0.00</td>
<td>0.00</td>
<td>15.0</td>
</tr>
<tr>
<td>11 (Fig. 3a &amp; 1b)</td>
<td>1.18</td>
<td>2</td>
<td>1 (Bottom)</td>
<td>1</td>
<td>10</td>
<td>-0.0</td>
<td>0.240</td>
<td>0.17</td>
<td>0.00</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 (Top)</td>
<td>1</td>
<td>10</td>
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<td>0.390</td>
<td>0.15</td>
<td>0.00</td>
<td>15.0</td>
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<tr>
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<td>1</td>
<td>2</td>
<td>6</td>
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<td>0.260</td>
<td>0.17</td>
<td>0.00</td>
<td>20.0</td>
</tr>
<tr>
<td>13 (Fig. 5a)</td>
<td>1.22</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>-1.5</td>
<td>0.120</td>
<td>0.05</td>
<td>0.00</td>
<td>15.0</td>
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<tr>
<td>14 (Fig. 3d)</td>
<td>1.56</td>
<td>2</td>
<td>1 (Bottom)</td>
<td>1</td>
<td>3</td>
<td>-1.0</td>
<td>0.180</td>
<td>0.10</td>
<td>0.00</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 (Top)</td>
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<td>3</td>
<td>-2.0</td>
<td>0.160</td>
<td>0.00</td>
<td>0.00</td>
<td>15.0</td>
</tr>
</tbody>
</table>
SNOW AT 215 GHz: DAY 09

Measured value of $\sigma^0_W$, $\sigma^0_{HH}$, $\sigma^0_{VH}$, and $\sigma^0_{HV}$ of snow at 215 GHz
SNOW AT 215 GHz: DAY 08

SNOW AT 215 GHz: DAY 11

SNOW AT 215 GHz: DAY 13

Measured (•: σ^0_VV, +: σ^0_HH) and computed (−) values of copolarized 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 $\sigma^0$ for snow-covered ground under both dry and wet conditions, (2) diurnal plots of $\sigma^0$ as a function of time for snow, and (3) angular plots for various types of road surfaces with and without snow cover.
Polarization and angular response of $\sigma^o$ for (a) dry snow condition and (b) wet snow condition.
Angular Response of $\sigma^0$ at 35.6 GHz to Wet and Dry Snow

Polarization: HH
Frequency (GHz): 35.6
Snow Depth (cm): 27
Water Equivalent (cm): 5.9

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>$m_w$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/19</td>
<td>1410</td>
<td>3.3</td>
</tr>
<tr>
<td>2/20</td>
<td>0605</td>
<td>0</td>
</tr>
</tbody>
</table>
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.
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. 
$m_w$ is the volumetric snow wetness of the top 5-cm layer.
Diurnal variation of $\sigma^0$ at 8.6 and 35.6 GHz at $5^\circ$ angle of incidence.
Data: 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

Scattering Coefficient $\sigma^0$ (dB)

Diurnal variation of $\sigma^0$ at 8.6 and 35.6 GHz at 25° angle of incidence.
Diurnal variation snow wetness and $\sigma^o$ at 8.6 and 35.6 GHz. (Note that snow wetness scale has been reversed for ease of comparison with $\sigma^o$.)

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
- Snow Wetness
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):
- 1.2
- 17.0
- 4.6
- 35.6
- 8.6

Diurnal Variation of Snow Wetness and $\sigma^\circ$ 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 $\sigma^o$ Between 1 and 35 GHz at 20° Angle of Incidence.
Diurnal variation of snow wetness and $\sigma^0$ at 8.6, 13.0, 17.0 and 35.6 GHz at 50$^\circ$ angle of incidence.
Diurnal variation of snow wetness and the circular polarized $\sigma^0$ values at 35.6 and the depolarization ratio ($\sigma_{pp}/\sigma_{pp}$) at 50° angle of incidence.

Date: 3/16-3/17/77
Frequency (GHz): 35.6
Angle of Incidence (Degrees): 50
Snow Depth (cm): 45
Water Equivalent (cm): 13.5
D. March 23, 1977 Diurnal

Snow wetness and temperature variation over the measurement period of the diurnal experiment on 3/23/77.
Date: 3/23/77
Angle of Incidence (Degrees): 50
Polarization: HH

0

8.6 GHz
17.0 GHz
35.6 GHz

Time variation of $50^\circ$ backscatter power at 8.6, 17.0, and 35.6 GHz.
Date: 3/23/77
Angle of Incidence (Degrees): 70
Polarization: HH
- 8.6 GHz
- 17.0 GHz
- 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
Snow Depth (cm): 44
Water Equivalent (cm): 12.7

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):
- 8.6
- 17.0
- 35.6

Diurnal variation of $\sigma^o$ at 8.6, 17.0 and 35.6 GHz at 50° angle of incidence.
13. 35 GHz DATA FOR ROAD SURFACES

A. Various Surfaces

Date: 12/18/78
Target: Compacted Dirt
Frequency (GHz): 35.6

Angle of Incidence (Degrees)

Scattering Coefficient (dB)

Date: 12/19/78
Target: Loose Dirt
Frequency (GHz): 35.6

Angle of Incidence (Degrees)

Scattering Coefficient (dB)
Date: 12/13/78  
Target: Rough Asphalt, Dry  
Frequency(GHz): 35.6

Date: 12/15/78  
Target: Smooth Asphalt, Dry  
Frequency(GHz): 35.6
Date: 6/15/78
Target: Dry Asphalt
Frequency (GHz): 35.6

Scattering Coefficient $\sigma^0$ (dB)

Angle of Incidence (Degrees)

Dry Asphalt

Various Surfaces

Target | Date | Soil Moisture (%)
---|---|---
Concrete | 6/6/78 | Dry Surface
Asphalt | 6/15/78 | Dry Surface
Plowed Ground | 12/18/78 | Frozen 0%

Polarization: HH
Frequency: 35.6 GHz
B. Road Surfaces With Snow Cover

**Ground Truth Data**

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Target (Snow)</th>
<th>Soil State</th>
<th>Soil Moisture (% vol.)</th>
<th>Snow Depth (cm)</th>
<th># of Layers</th>
<th>Water Equiv. (L vol.)</th>
<th>Snow Wetness</th>
<th>Air Temp.</th>
<th>Snow Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/10</td>
<td>1315</td>
<td>Dirt</td>
<td>Frozen</td>
<td>---</td>
<td>6-14</td>
<td>1-3</td>
<td>3.0</td>
<td>0</td>
<td>-1.3</td>
<td>-3</td>
</tr>
<tr>
<td>2/11</td>
<td>1030</td>
<td>Dirt</td>
<td>Frozen</td>
<td>---</td>
<td>6-14</td>
<td>1-3</td>
<td>2.0</td>
<td>-10</td>
<td>2.8</td>
<td>-4</td>
</tr>
<tr>
<td>2/13</td>
<td>1037</td>
<td>Grass</td>
<td>Partially Frozen</td>
<td>N.M. (4)</td>
<td>14-20</td>
<td>2-3</td>
<td>5.2</td>
<td>0</td>
<td>-3.0</td>
<td>-5</td>
</tr>
<tr>
<td>2/13</td>
<td>1350</td>
<td>Asphalt(2)</td>
<td>---</td>
<td>---</td>
<td>5-13</td>
<td>2</td>
<td>2.0</td>
<td>7.7</td>
<td>-2.2</td>
<td>-5.5</td>
</tr>
<tr>
<td>2/14</td>
<td>1050</td>
<td>Concrete(3)</td>
<td>---</td>
<td>---</td>
<td>3-4</td>
<td>1</td>
<td>3.0</td>
<td>-10</td>
<td>5.5</td>
<td>---</td>
</tr>
<tr>
<td>2/16</td>
<td>1400</td>
<td>Asphalt</td>
<td>---</td>
<td>---</td>
<td>2-6</td>
<td>2-3</td>
<td>1.5</td>
<td>0</td>
<td>-14.6</td>
<td>-5.5</td>
</tr>
<tr>
<td>2/18</td>
<td>1420</td>
<td>Concrete</td>
<td>---</td>
<td>---</td>
<td>6-13</td>
<td>2-3</td>
<td>3.1</td>
<td>0</td>
<td>-5.2</td>
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</tr>
<tr>
<td>2/19</td>
<td>1100</td>
<td>Grass</td>
<td>Partially Frozen</td>
<td>N.M.</td>
<td>9-14</td>
<td>2</td>
<td>2.8</td>
<td>10.9</td>
<td>4.5</td>
<td>8</td>
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<tr>
<td>2/19</td>
<td>1430</td>
<td>Concrete</td>
<td>---</td>
<td>---</td>
<td>0-3</td>
<td>1</td>
<td>1.5</td>
<td>3.9</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td>2/20</td>
<td>1015</td>
<td>Asphalt</td>
<td>---</td>
<td>---</td>
<td>0-9</td>
<td>0-2</td>
<td>1.1</td>
<td>13.4</td>
<td>2.0</td>
<td>0</td>
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<td>1352</td>
<td>Grass</td>
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<td>N.M.</td>
<td>0-14</td>
<td>0-2</td>
<td>2</td>
<td>12.1</td>
<td>1.9</td>
<td>0</td>
</tr>
</tbody>
</table>

(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 Asphalt

Date: 2/13/79
Target: Snow on Asphalt
Snow Wetness (%): 7.7
Polarization: VV

Dry Snow on Asphalt

Date: 2/16/79
Target: Snow on Asphalt
Snow Wetness (%): 0
Polarization: VV, HV

Frequency (GHz): 35.6
Date: 2/20/79
Target: Snow on Grass
Snow Wetness (%): 12.1
Polarization: VV, HV

Date: 2/20/79
Target: Snow on Asphalt
Snow Wetness (%): 13.4
Polarization: VV, HV
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

Three-Foot Alfalfa and Grass (June)

Effects of Mowing Alfalfa
35 GHz
VV Polarization

Effects of Mowing Alfalfa
3' Alfalfa and Grass
- Same After Being Cut
Effects of Mowing Alfalfa
35 GHz
HH Polarization

Effects of Mowing Alfalfa

Angle of Incidence $\theta$ (Degrees)

Effects of Mowing Alfalfa

Rain on Vegetation
35 GHz
VV Polarization

Rain on Vegetation

Effects of Rain on a Vegetation Covered Surface
Seasonal Changes of Alfalfa
35 GHz
VV Polarization

Angle of Incidence $\theta$ (Degrees)
Effects of Seasonal Changes of Alfalfa

Seasonal Changes of Alfalfa
35 GHz
HH Polarization

Angle of Incidence $\theta$ (Degrees)
Effects of Seasonal Changes of Alfalfa
Two-Inch Green Grass

Dew on Two-Inch Grass

Effects of Dew on Two-Inch Grass
Rain on Two-Inch Grass
35 GHz
VV Polarization

Effects of Rain on Two-Inch Grass

Eight-Inch Grass Flattened to 3 Inches

Effects of Rain on Two-Inch Grass

Eight-Inch Grass Flattened to 3 Inches
Effects of Mowing Grass

Fifteen-Inch Green Grass in Head (May)

Backscatter Coefficient $\sigma^0$ (dB)

Angle of Incidence $\theta$ (Degrees)

Fifteen-Inch Green Grass in Head (May)

Effects of Mowing Grass

35 GHz

$\sigma^0$ (dB)

Angle of Incidence $\theta$ (Degrees)

Effects of Mowing Grass
Seasonal Changes of Grass

35 GHz

VV Polarization

Angle of Incidence $\theta$ (Degrees)

Effects of Seasonal Changes of Grass

- 1" March
- 1" April
- 1" May
- 2.75" Sept.
- 2" Nov.

Angle of Incidence $\theta$ (Degrees)

HH Polarization

Effects of Seasonal Changes of Grass
Three-Foot Green Oats (June)

Backscatter Coefficient $\sigma^o$ (dB)

Angle of Incidence $\theta$ (Degrees)

Three-Foot Green Oats (June)

Seasonal Changes of Oats
35 GHz
VV Polarization

Backscatter Coefficient $\sigma^o$ (dB)

Angle of Incidence $\theta$ (Degrees)
Effects of Seasonal Changes of Oats

1/2" Oats
- Plowed Ground
- Disked Ground
- 3' Oats
Seasonal Changes of Soybeans

Effects of Seasonal Changes of Soybeans

Four-Inch Wet Soybean Stubble

35 GHz

V, Polarization

Angle of Incidence $\theta$ (Degrees)

Backscatter Coefficient $\sigma^0$ (dB)
Effects of Seasonal Changes of a Plowed Field

Seasonal Changes of a
Plowed Field

35 GHz
VV Polarization

-100
-150
-200
-250
-300

0 10 20 30 40 50 60 70 80 90
Angle of Incidence \( \theta \) (Degrees)

-100
-150
-200
-250
-300

0 10 20 30 40 50 60 70 80 90
Angle of Incidence \( \theta \) (Degrees)
Effects of Seasonal Changes of a Plowed Field

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15. 35 GHz DATA FOR ROAD SURFACES

A. Various Surfaces

Asphalt Road
rms height: 0.04 cm

Asphalt Road
rms height: 0.05 cm
Asphalt Road
rms height: 0.044 cm

![Graph showing backscatter coefficient \(\sigma^o\) (dB) vs angle of incidence \(\theta\) (degrees) for different frequencies and polarization modes.](image)

- **35 GHz**
  - VV
  - HH

Asphalt Road
Asphalt Road

-10
S-20
0W
S-30
35 GHz
Sm-vv
II
†.HH
-40
I
i,
,, I , ,
1 , , , 1 , ,
,,I
,,I
*ti
*ti
*,
451x510,
493x509
i
0 10 20 30 40 50 60 70 80 90
Angle of Incidence θ (Degrees)
Asphalt Road

Backscatter Coefficient σ° (dB)

35 GHz

Asphalt Road with Thin Cover of Gravel

-25
S......
HH
c a -30
1,
,, I , , i ,
312x188
I , , i ,
390x187
i 1I
408x187
I
503x186
,,
519x186
I
137x168
0 10 20 30 40 50 60 70 80 90
Angle of Incidence θ (Degrees)
Asphalt Road with Thin Cover of Gravel

Backscatter Coefficient σ° (dB)

Asphalt Road

-20

-30

VV

HH

VV

HH

-30

-25

-20

-15

-10

-5

0

35 GHz

-25

-20

-15

-10

-5

0

Asphalt Road with Thin Cover of Gravel

VV

HH

-30

-25

-20

-15

-10

-5

0

Angle of Incidence θ (Degrees)
Asphalt Road with Thin Cover of Gravel

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Effects of Sprayed Water on an Asphalt Road

Effects of Rain on a Smooth Asphalt Road
Effects of Rain on a Rough Asphalt Road

Rain on Rough Asphalt
35 GHz
HH Polarization

Cinder and Gravel Road

35 GHz
VV
HH
Rain on Cinder Road
35 GHz
VV Polarization

Effects of Rain on Cinder Road

Concrete Road
rms height: $1.6 \times 10^{-2}$ cm

Concrete Road
Concrete Road
rms height: $1.5 \times 10^{-2}$ cm

35 GHz

Angle of Incidence $\theta$ (Degrees)

Disked Ground

35 GHz

Angle of Incidence $\theta$ (Degrees)
Various Smooth Surfaces
35 GHz
HH Polarization

Contrast of $\sigma^o$ for Various Smooth Surfaces
B. Various Surfaces With Snow Cover

Effects of Snow Cover
35 GHz
VV Polarization

Angle of Incidence $\theta$ (Degrees)
Effects of Snow Cover

Smooth and Rough Snow Covers on Concrete Road
35 GHz
HH Polarization

Angle of Incidence $\theta$ (Degrees)
Effects of Smooth and Rough Snow Covers on a Concrete Road
Melting Snow on 1 Inch Grass
35 GHz
VV Polarization

Effects of Various Depth of Melting Snow for 1 Inch Grass

Effects of Snow Cover
35 GHz
HH Polarization

Effects of Snow Cover
Effects of Snow Cover
35 GHz
VV Polarization

Backscatter Coefficient $\sigma^0$ (dB)

-20 -15 -10 -5 0

0 10 20 30 40 50 60 70 80 90

Angle of Incidence $\theta$ (Degrees)

- 4" Grass with 2" Snow Cover
- Concrete Road with 2" Snow
- 4" Grass
- Concrete Road

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

Mean $\sigma_0$ for wet and dry asphalt.

Mean $\sigma_0$ for smooth and rippled water.

Mean $\sigma_0$ for wet and dry concrete.

Mean $\sigma_0$ for wet and dry wood.
Mean $\sigma_0$ for wet and dry gravel.

Mean $\sigma_0$ for wet and dry tall weeds.

Mean $\sigma_0$ for wet and dry sod.

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].
REFERENCES


