MILLIMETER - WAVE RADAR SCATTERING FROM TERRAIN: DATA HANDBOOK

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U.S. Army Research Office
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<td>Smooth Surface</td>
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<td>B</td>
<td>Slightly Rough Surface</td>
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<tr>
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<td>Red Pine</td>
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<td>C</td>
<td>Apple Trees</td>
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<td>D</td>
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<tr>
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<td>Short Grass</td>
<td>94</td>
</tr>
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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 $\sigma^0$ 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 $\sigma^0$ versus the incidence angle $\theta$ 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° (nadir) 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 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.

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

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

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

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

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

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.
11. 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>x</td>
<td>x</td>
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<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>880329 (VR)</td>
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<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>890210</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>890302 (SM)</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></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>
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<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>890307 (SM)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></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)

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

Surface roughness profile with 1 cm grid
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

Slightly rough snow at Houghton

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

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/cm³
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: 880329 35  
Date and Time: March 29, 1988, 5:15 PM  
Target: Dry Snow  
Frequency: 35 GHz

Very rough snow at Houghton

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

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>
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<tbody>
<tr>
<td>22</td>
<td>-4.8</td>
</tr>
<tr>
<td>21</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
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</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

air temperature: -4.4 C
Data Set Code: 890210
Date and Time: February 10, 1989, 1:40 PM
Target: Dry Snow
Frequency: 140 GHz

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/cm³
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

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

Backscattering Coefficient (dB)

Incidence Angle (degrees)

Dry snow at Brighton

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

Backscattering Coefficient (dB)

Incidence Angle (degrees)

Dry snow at Brighton
MMW DATA FOR DRY SNOW

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

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/cm³
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
Date and Time: March 2, 1989, 9:55 PM
Target: Dry Snow
Frequency: 35 GHz

Small snow crystals at Brighton

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

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

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/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
Date and Time: March 2, 1989, 6:45 AM
Target: Dry Snow
Frequency: 35 GHz

Large snow crystals at Brighton
Large snow crystals at Brighton

890302(LG)
H. Large Crystal Size with Rough Surface

Dry snow
Data set code: 890307(ro)
Depth: 10 cm
LWC: 0 %
Surface RMS height: 1.17 cm
Density: 0.4 gm/cm³
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
Data collection scene

Snow crystals from surface
MMW DATA FOR DRY SNOW

890307(RO)

Dry rough metamorphosed snow at Brighton

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

Dry rough metamorphosed snow at Brighton

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

890307(RO)

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

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)

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

Dry smooth metamorphosed snow at Brighton

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

Dry smooth metamorphosed snow at Brighton
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:

<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>x</td>
<td></td>
<td></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></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>890309 (vw w/ ss)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>890215</td>
<td>x</td>
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</tbody>
</table>
MMW DATA FOR WET SNOW

A. Manmade Wet Snow

Wet snow
Data set code: 890215
Depth: 27 cm
LWC: (at 3:25 PM): 8.82 %
Surface RMS height: 1.6 cm
Density: 0.48 gm/cm³
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

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

Wet snow at Brighton

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

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

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/cm³
Ice crystal diameter: 1 to 2 mm
Surface temperature: 0.0 C
Description: smooth, wet natural snow

**SNOW PIT PROFILE FOR 890220**

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MMW DATA FOR WET SNOW

Data collection scene

Snow crystals from surface
MMW DATA FOR WET SNOW

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

Backscattering Coefficient (dB)

Incidence Angle (degrees)

Wet snow at Brighton

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

Backscattering Coefficient (dB)

Incidence Angle (degrees)

Wet snow at Brighton
MMW DATA FOR WET SNOW

Data Set Code: 890220
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
MMW DATA FOR WET SNOW

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

Wet snow at Brighton

Data Set Code: 890221
Date and Time: February 21, 1989, 11:40 AM
Target: Wet Snow
Frequency: 94 GHz

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/cm³
Ice crystal diameter: 2 to 4 mm
Surface temperature: 4 to 6 C
Description: rough, wet snow

---

890309(RO)

Data Set Code: 890309-ro
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

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

Wet rough metamorphosed snow at Brighton
890309(RO)

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

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)

![Graph showing backscattering coefficient vs. incidence angle](image)

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/cm³
- 15 cm depth: 0.50 gm/cm³
- 30 cm depth: 0.54 gm/cm³
- 45 cm depth: 0.53 gm/cm³
- 60 cm depth: 0.58 gm/cm³
- 71 cm depth (ground): 0.65 gm/cm³
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

![Graph showing data for snow temperature, air temperature, and LWC over 24 hours on March 31, 1988.](image-url)
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
Date: March 31, 1988
Target: Dry Snow
Frequency: 35 GHz
Incidence Angle: 40°

Houghton snow with smooth surface

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

Houghton snow with slightly rough surface
MMW DIURNAL DATA FOR SNOW

880331

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

Houghton snow with very rough surface

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

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

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MMW DIURNAL DATA FOR SNOW

890227/28

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

![Graph showing liquid water content (LWC) over time](image)

Liquid water content during snow diurnal at Brighton

![Image of surface roughness profile with 1 cm grid](image)

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

890227/28

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

Backscattering Coefficient (dB)

Time (hours)

Snow diurnal at Brighton

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

Backscattering Coefficient (dB)

Time (hours)

Snow diurnal at Brighton
MMW DIURNAL DATA FOR SNOW

890227/28

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

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

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MMW DIURNAL DATA FOR SNOW

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

Snow diurnal at Brighton

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

Snow diurnal at Brighton

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MMW DIURNAL DATA FOR SNOW

890302

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

Snow diurnal at Brighton
V. MMW DATA FOR ICE-COVERED GROUND

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

Ice covered ground
MMW DATA FOR ICE-COVERED GROUND

**880308**

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

**Graph 1:**
- Backscattering Coefficient (dB) vs. Incidence Angle (degrees)
- Lines: WW, VH, HH

**Graph 2:**
- Backscattering Coefficient (dB) vs. Incidence Angle (degrees)
- Lines: WW

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VI. MMW DATA FOR TREE CANOPIES

A. Cedar Trees

Cedar trees
Data set code: 871111
Tree density: 0.07 trees/m²
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
MMW DATA FOR TREE CANOPIES

871111

Data Set Code: 871111
Date and Time: November 11, 1987, 9:18 AM
Target: Cedar Trees
Frequency: 35 GHz

Cedars at Arboretum

Data Set Code: 871111
Date and Time: November 11, 1987, 9:18 AM
Target: Cedar Trees
Frequency: 94 GHz

Cedars at Arboretum
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

Red pines
Needles of Red Pines

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

Backscattering Coefficient (dB)

Incidence Angle (degrees)

Red Pines at Arboretum
(5 November, 1987)

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

Backscattering Coefficient (dB)

Incidence Angle (degrees)

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)

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%
Leaves of apple tree

880811

Data Set Code: 880811
Date and Time: August 12, 1988, 9:45 AM
Target: Apple Tree
Frequency: 94 GHz
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
Leaves of Bur oaks at Botanical Gardens -- 881027

Ground cover beneath Bur oaks at Botanical Gardens -- 881027
Data Set Code: 880930-1027
Dates: September 30 -- October 27, 1988
Target: Oak Trees
Frequency: 35 GHz
Incidence Angle: 20°

[Graph showing backscattering coefficient over days for different polarization angles.]

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

Bur Oaks (Quercus Macrocarpa)

79
Bur Oaks (Quercus Macrocarpa)

Bur Oaks (Quercus Macrocarpa)

880930-1027
Bur Oaks (Quercus Macrocarpa)
880930

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

Bur Oaks (Quercus Macrocarpa)
Leaf Moisture Content = 59.7%
Data Set Code: 881004
Date and Time: October 4, 1988, 12:05 PM
Target: Oak Trees
Frequency: 35 GHz

Bur Oaks (Quercus Macrocarpa)

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

Bur Oaks (Quercus Macrocarpa)
Leaf Moisture Content = 54.2%
Data Set Code: 881013
Date and Time: October 13, 1988, 12:14 PM
Target: Oak Trees
Frequency: 94 GHz

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

Data Set Code: 881014
Date and Time: October 14, 1989, 1:40 PM
Target: Oak Trees
Frequency: 35 GHz

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

Incidence Angle (degrees)

Bur Oaks (Quercus Macrocarpa)

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

Leaf Moisture Content = 42%
Bur Oaks (Quercus Macrocarpa)

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

Backscattering Coefficient (dB)

Incidence Angle (degrees)

Bur Oaks (Quercus Macrocarpa)

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

Backscattering Coefficient (dB)

Incidence Angle (degrees)

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

Incidence Angle (degrees)

Backscattering Coefficient (dB)

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

Spruce trees
MMW DATA FOR TREE CANOPIES

881031

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

[Graph showing backscattering coefficient vs. incidence angle]

Norway Spruce (Picea Abies)

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

[Graph showing backscattering coefficient vs. incidence angle]

Norway Spruce (Picea Abies)
MMW DATA FOR TREE CANOPIES

881122

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

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

Data Set Code: 881122
Date and Time: November 22, 1988, 10:21 AM
Target: Evergreen Trees
Frequency: 94 GHz

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
Close-up view of branches of White Cedar bush

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

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

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

Cut grass at North Campus (Height = 5 cm)

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

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

Incidence Angle (degrees)
Amaranthus over chick weed

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

Incidence Angle (degrees)
Amaranthus over chick weed
Amaranthus over chick weed
Tall Grass (Andropogon gerardi)
Data set code: 881103
Leaf Moisture Content = 33%
Height: 80 cm
Description: dry, uncut

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

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Data Set Code: 881103
Date and Time: November 3, 1988, 9:58 AM
Target: Ground Cover
Frequency: 94 GHz
Grass (Andropogon gerardi)
Data set code: 881108
Leaf Moisture Content = 44.5%
Height: 80 cm
Description: moist, uncut

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

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

Turkey Foot or Big Bluestem (Andropogon gerardi)
Tall Grass (Bromus inermis)
Data set code: 881027
Leaf Moisture Content = 70 %
Height: 80 cm
Description: uncut

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

Data Set Code: 881027
Date and Time: October 27, 1988, 3:22 PM
Target: Ground Cover
Frequency: 94 GHz
881114

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

Broom grass (Bromus inermis)
Data Set Code: 881114
Date and Time: November 14, 1988, 11:19 AM
Target: Ground Cover
Frequency: 35 GHz

Backscattering Coefficient (dB)

Incidence Angle (degrees)

Broom Grass (Bromus inermis)

Data Set Code: 881114
Date and Time: November 14, 1988, 11:19 AM
Target: Ground Cover
Frequency: 94 GHz

Backscattering Coefficient (dB)

Incidence Angle (degrees)

Broom Grass (Bromus inermis)
Data Set Code: 881114
Date and Time: November 14, 1988, 11:19 AM
Target: Ground Cover
Frequency: 140 GHz

Backscattering Coefficient (dB)

Incidence Angle (degrees)

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

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

Broom Grass (Bromus inermis)
Data Set Code: 881115
Date and Time: November 15, 1988, 1:51 PM
Target: Ground Cover
Frequency: 94 GHz

Broom Grass (Bromus inermis)

Data Set Code: 881115
Date and Time: November 15, 1988, 1:51 PM
Target: Ground Cover
Frequency: 140 GHz

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

Purple loose strife (Lythrum salicaria)
Purple Loose Strife over water (Lythrum salicaria)
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
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

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

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

Data Set Code: 871113
Date and Time: November 13, 1987, 3:14 PM
Target: Gravel
Frequency: 35 GHz

Gravel in North Campus Parking Lot

880815(2)

Data Set Code: 880815(2)
Date and Time: August 15, 1988, 2:15 PM
Target: Gravel
Frequency: 94 GHz

Gravel in North Campus Parking Lot
APPENDIX A

A Millimeterwave Network Analyzer Based Scatterometer

Fawwaz T. Ulaby
Thomas F. Haddock
Jack R. East
Michael W. Whitt

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A Millimeterwave Network Analyzer Based Scatterometer

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JACK R. EAST, MEMBER, IEEE, AND MICHAEL W. WHITT, STUDENT MEMBER, IEEE

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.

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-
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 (a₁) port of the network analyzer. The reflected signal, picked up by a second antenna, is downconverted and fed into the return signal (b₁) 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
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 lists projected system performance specifications, based on laboratory tests and specifications of our

| TABLE I |
| TRUCK MOUNTED SCATTEROMETER PARAMETERS |

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequencies</td>
<td>35, 44, 140 GHz</td>
</tr>
<tr>
<td>RF Bandwidth</td>
<td>0 to 2.0 GHz</td>
</tr>
<tr>
<td>Sweep Rate</td>
<td>1, 0.5, 0.25, 1.0, 100 MHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>H, V, VV, HH, magnitude and phase</td>
</tr>
<tr>
<td>Incidence Angles</td>
<td>0 to 70 degrees</td>
</tr>
<tr>
<td>Platform Height</td>
<td>3 meters minimum to 18 meters maximum</td>
</tr>
<tr>
<td>Noise Equivalent dB</td>
<td>94 GHz: -34 dB, 140 GHz: -37 dB</td>
</tr>
</tbody>
</table>

(These values for 4 x 10 meters and 90 x 90 degrees - the actual values will vary with both parameters.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near Field Distance</td>
<td>35 GHz: 5.6 m, 94 GHz: 3.7 m, 140 GHz: 1.8 m</td>
</tr>
<tr>
<td>Footprint</td>
<td>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</td>
</tr>
<tr>
<td>Signal Processing</td>
<td>HP 8510A/8511A based</td>
</tr>
<tr>
<td>Output Products</td>
<td>Received power versus range (MAP &gt; 0.25)</td>
</tr>
<tr>
<td></td>
<td>Received power versus frequency (at fixed range)</td>
</tr>
<tr>
<td></td>
<td>Phase and amplitude for each frequency</td>
</tr>
</tbody>
</table>

Fig. 3. Like- and cross-polarization traces for a typical MMP antenna.
equipment. The values for the noise-equivalent $\sigma^\circ$ 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.
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 \( \sigma_0 = -9.6 \) 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 \( \sigma_0 \) 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 cm², 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
bandwidth, polarization, and configuration of the MMP allow for a flexible system for field as well as laboratory use.

REFERENCES


*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. 1, American Society of Photoengravistry.

Dr. Ulaby is a member of Eta Kappa Nu, Tau Beta Pi, and Sigma Xi. He has been 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 Mentarious service from the American Society of Photoengravistry. 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.

*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. From 1984 to 1985 he was Manager of Development Projects at Applied Intelligent Systems, a machine vision firm involved in real-time optical, infrared, and X-ray vision systems. He is currently with the Radiation Laboratory and the Department of Electrical Engineering and Computer Science, University of Michigan. He has conducted research in the fast flux density variations of quasi-stellar objects at a wavelength of 12.5 mm. Other research has included development of real-time alphanumeric character recognition algo-
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Dr. Haddock is a member of the American Astronomical Society.

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He is now an Associate Research Scientist in the Solid-State Electronics Laboratory of the University of Michigan, working in the area of microwave and millimeter-wave solid-state devices.

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


