Field 2
Temperatures: -10° C and -25° C
Sample Thicknesses: 12 mm and 37 mm
Volumetric Wetness: 0.22 cm³/cm³
Frequency: 18 GHz

L: 2-cm Lid Only
E: Extra 2-cm Insulation + Lid
ε'(-10° C) = 4.2
ε'(-25° C) = 4.1

(a)

L: 2-cm Lid Only
E: Extra 2-cm Insulation + Lid
ε''(-10° C) = 0.29
ε''(-25° C) = 0.18

(b)
Pulley Method

\[
\varepsilon' = 1 + 1.910 \rho_s,
\]

\[r = 0.984\]
Frequency: 4 GHz

Dielectric Constant $\varepsilon'$

Theoretical Value [42]

Water Depth $d$ (mm)

Dielectric Loss Factor $\varepsilon''$

Theoretical Value [42]

Water Depth $d$ (mm)
Field #2
Temperature: 23° C
Volumetric Wetness: 0.08 cm³/cm³
Nominal Sample Thickness: 48 mm

![Graph showing change, compensation, and error after compensation with frequency (GHz)]
Frequency: 4.0 GHz

Soil Type:
- Sand
- Loam
- Clay

Relative Dielectric Constant

Volumetric Wetness (cm$^3$/cm$^3$)

Real Part

Imaginary Part
a) 3 - 8.5 GHz

b) 8 - 12.4 GHz

c) 12.5 - 18 GHz
\[ \epsilon' = 25 \]
\[ \tan \delta \ll 1 \]

**Top Diagram:**
- \( \theta_1 = 0^\circ \)
- \( \theta_1 = 45^\circ \)

**Bottom Diagram:**
- \( \theta_1 = 0^\circ \)
- \( \theta_1 = 45^\circ \)
Frequency f (GHz)

Coating: 4.0 mil plastic
Thickness: 2.0 cm
Sample holder

Phase Shift \( \Delta \phi \) (deg)
Phase Shift $\Delta \varphi$ (deg)

- 18 GHz
- 16 GHz
- 14 GHz
- 12 GHz
- 10 GHz
- 8 GHz
- 6 GHz
- 4 GHz

Distilled Water

$T = 23 \, ^\circ C$

Antennas 13.5 cm Apart
Perpendicular Incidence

Measured:
- ▼ 4 GHz
- ● 6 GHz
- ■ 8 GHz
- ○ 10 GHz
- ▲ 12 GHz
- △ 14 GHz
- □ 16 GHz
- ◆ 18 GHz

Theory

Water Depth $d$ (mm)
Phase Shift $\Delta \phi$ (deg)

Water Depth $d$ (mm)

Measured:
- ▼ 4 GHz
- ● 6 GHz
- ■ 8 GHz
- ○ 10 GHz
- □ 12 GHz
- △ 14 GHz
- □ 16 GHz
- ◇ 18 GHz
- - Theory

Distilled Water
$T = 23 \, ^\circ C$
Antennas 16.7 cm Apart
Perpendicular Incidence
Phase Shift $\Delta \phi$ (deg)

Water Depth $d$ (mm)

Measured:
- ▼ 4 GHz
- ○ 6 GHz
- □ 8 GHz
- ○ 10 GHz
- □ 12 GHz
- △ 14 GHz
- □ 16 GHz
- ◊ 18 GHz

Distilled Water
$T = 23 \, ^\circ C$
Antennas 23 cm Apart
Perpendicular Incidence

Theory
Distilled Water
T = 23 °C
Antennas 16.7 cm Apart
Perpendicular Incidence

Measured:
- ▼ 4 GHz
- ● 6 GHz
- ■ 8 GHz
- ○ 10 GHz
- ■ 12 GHz
- △ 14 GHz
- □ 16 GHz
- ◇ 18 GHz

Theory
Distilled Water
T = 23 °C
Antennas 23 cm Apart
Perpendicular Incidence

Measured:
- ▼ 4 GHz
- ● 6 GHz
- ■ 8 GHz
- ○ 10 GHz
- □ 12 GHz
- △ 14 GHz
- □ 16 GHz
- ◇ 18 GHz
- — Theory
Phase Shift $\Delta \phi$ (deg)

8 GHz

6 GHz

4 GHz

Measured:
- ▼ 4 GHz
- • 6 GHz
- ■ 8 GHz
- --- Theory

Distilled Water

$T = 23 \, ^\circ C$

Antennas 13 cm Apart

Perpendicular Incidence

Water Depth $d$ (mm)
Distilled Water

T = 23 °C

Antennas 16 cm Apart
Perpendicular Incidence

Measured:
- ▼ 4 GHz
- ● 6 GHz
- □ 8 GHz
- ○ 10 GHz
- ■ 12 GHz
- △ 14 GHz
- □ 16 GHz
- ◇ 18 GHz

Theory

Water Depth d (mm)

Phase Shift Δϕ (deg)
Phase Shift $\Delta \phi$ (deg)

Water Depth $d$ (mm)

8 GHz
6 GHz
4 GHz

Distilled Water
$T = 23 \, ^\circ C$
Antennas 22 cm Apart
Perpendicular Incidence

Measured:
- ▼ 4 GHz
- ● 6 GHz
- □ 8 GHz

Theory
**Measured:**
- ▼ 4 GHz
- □ 6 GHz
- □ 8 GHz
- □ 10 GHz
- □ 12 GHz
- △ 14 GHz
- □ 16 GHz
- ◇ 18 GHz

**Distilled Water**

T = 23 °C

Antennas 16 cm Apart

Perpendicular Incidence

---

**Theory**
Loss L (dB) vs. Water Depth d (mm)

- 8 GHz
- 6 GHz
- 4 GHz

**Measured:**
- ▼ 4 GHz
- • 6 GHz
- ■ 8 GHz

- Distilled Water
- T = 23 °C
- Antennas 22 cm Apart
- Perpendicular Incidence

**Theory**
Distilled Water Temperature: 23 °C
Angle of Incidence: 45°
Vertical Polarization
Antennas 36 cm Apart
Distance from Transmitting Antenna to Sample: 12 cm
Transmitting Antenna: 4 - 18 GHz
Aperture: 6 x 6 cm²
Receiving Antenna: 4-6 GHz
Aperture: 16 x 22 cm²
Sample Size: 50 x 50 cm²

Phase Shift $\Delta \phi$ (Degrees)

Water Depth $d$ (mm)

4 GHz
6 GHz

Measured:
- $4 \text{ GHz}$
- $6 \text{ GHz}$

Theory
Distilled Water Temperature: 23 °C
Angle of Incidence: 45°
Vertical Polarization
Antennas 36 cm Apart
Distance from Transmitting Antenna to Sample: 12 cm
Transmitting Antenna: 4 - 18 GHz
Aperture: 6 x 6 cm²
Receiving Antenna: 4-6 GHz
Aperture: 16 x 22 cm²
Sample Size: 50 x 50 cm²

Measured:
- ▼ 4 GHz
- ● 6 GHz

Theory
Distilled Water Temperature: 23 °C
Angle of Incidence: 45°
Vertical Polarization
Antennas 36 cm Apart
Distance from Transmitting Antenna to Sample: 19 cm
Both Antennas: 4 - 18 GHz
Aperture: 6 x 6 cm²
Sample Size: 50 x 50 cm²

Measured:
- ▼ 4 GHz
- • 6 GHz

Theory——
Field #2
Sample Thickness: 13 mm
Volumetric Wetness: 0.33 cm³/cm³
Bulk Density: 1.60 g/cm³

Diameter, Angle of Incidence and Polarization:
- 31 cm, θ₁ = 0°
- 31 cm, θ₁ = 15°, HP
- 31 cm, θ₁ = 15°, VP
- 25 cm, θ₁ = 15°, HP
- 25 cm, θ₁ = 15°, VP

Dielectric Constant $\varepsilon'$ vs. Frequency f (GHz)
Field #2
Sample Thickness: 13 mm
Volumetric Wetness: 0.33 cm³/cm³
Bulk Density: 1.60 g/cm³

Diameter, Angle of Incidence and Polarization:
- • 31 cm, \( \theta_1 = 0^\circ \)
- □ 31 cm, \( \theta_1 = 15^\circ \), HP
- ✭ 31 cm, \( \theta_1 = 15^\circ \), VP
- ■ 25 cm, \( \theta_1 = 15^\circ \), HP
- ▼ 25 cm, \( \theta_1 = 15^\circ \), VP
Density of Snow: 0.39 g/cm³
Temperature: -18 °C
Sample Thickness: 54 mm
Pulley Measurement
Angle of Incidence: 0°

Density of Snow: 0.38 g/cm³
Temperature: -12 °C
Sample Thickness: 56 mm
Sweep Measurement
Angle of Incidence: 15°, VP
Polymethyl Methacrylate Thickness: 15.87 mm

Dielectric Constant $\varepsilon'$

- $L = L_{\text{min}}$ Without Sample,
- $\theta_1 = 15^\circ$, Vertical Polarization (VP)
- $\theta_1 = 15^\circ$, VP
- $\theta_1 = 0^\circ$

Frequency $f$ (GHz)
Goodrich Clay
Frequency: 10 GHz

Dielectric Constant $\varepsilon$

Temperature, ($^\circ$C)

-20  -10  0   10   20   30

$\varepsilon'$

$\varepsilon''$

0.05  0.10  0.15  0.15 g $\text{H}_2\text{O}/\text{g Soil}$
Dielectric Constant $\varepsilon$

Volumetric Wetness $m_v$

Error After Compensation

$\Delta m_v$

$\Delta \varepsilon_{d_1}$

$\Delta \varepsilon_{d_2}$

$\Delta \varepsilon_m$

$\Delta m_v$

Measured Thickness too Small

Measured Thickness too Large
Field #2
Temperature: 23° C

\[ \text{Slope } \frac{dE}{dm_v} \left( \frac{1}{\text{cm}^3/\text{cm}^3} \right) \]

\[ dE' \quad \text{Volumetric Wetness: } 0.33 \text{ cm}^3/\text{cm}^3 \]

\[ dE'' \quad \text{Volumetric Wetness: } 0.08 \text{ cm}^3/\text{cm}^3 \]

Frequency f (GHz)
Field #2

Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thickness: 13 mm

Field #2

Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thicknesses: 18 mm, 35 mm

Change (%) vs. Frequency f (GHz)
Field #2
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thickness: 33.3 mm and 17.5 mm
Field #2
Temperature: 23°C
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thickness: 13 mm

Compensation (%)

Assumed Sample Thickness:

\[ \varepsilon'' \]

\[ \varepsilon' \]

Frequency f (GHz)

Field #2
Temperature: 23°C
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thicknesses: 18 mm, 35 mm

Compensation (%)

Assumed Sample Thickness:

\[ \varepsilon'' \]

\[ \varepsilon' \]

Frequency f (GHz)
Field #2
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thicknesses: 17.5 mm and 33.3 mm

Compensation (%) vs. Frequency f (GHz)

- 34.3 mm
- 32.3 mm
- 18.5 mm
- 16.5 mm

E'
E''
Field #2
Volumetric Wetness: 0.33 cm$^3$/cm$^3$
Nominal Sample Thickness: 13 mm

Field #2
Volumetric Wetness: 0.33 cm$^3$/cm$^3$
Nominal Sample Thicknesses: 18 mm, 35 mm
Field #2
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thicknesses: 17.5 mm and 33.3 mm

Error After Compensation (%) vs Frequency f (GHz)
Phase Shift $\Delta \Phi$ (Degrees)

Water Depth $d$ (mm)

Measured:
- ▼ 4 GHz
- ● 6 GHz
- ■ 8 GHz
- ○ 10 GHz
- □ 12 GHz
- △ 14 GHz
- □ 16 GHz
- ◇ 18 GHz
- — Theory

Distilled Water
$T = 23 \degree C$
Antennas 23 cm Apart
Angle of Incidence: 15\degree
Vertical Polarization
Pulley Method
The Results Were Obtained by Measuring a Sample at 5 Different Antenna Distances.
The Results were Obtained by Measuring a Sample at 5 Different Antenna Distances.

- Sweep Technique
- Pulley System

<table>
<thead>
<tr>
<th>Measured Loss (dB)</th>
<th>Volumetric Wetness (cm³/cm³)</th>
<th>Sample Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33 cm³/cm³</td>
<td>0.33</td>
<td>18</td>
</tr>
<tr>
<td>15 dB</td>
<td>0.33</td>
<td>13</td>
</tr>
<tr>
<td>10 dB</td>
<td>0.22</td>
<td>12</td>
</tr>
<tr>
<td>8 dB</td>
<td>0.015</td>
<td>46</td>
</tr>
<tr>
<td>1 dB</td>
<td>0.015</td>
<td>39</td>
</tr>
</tbody>
</table>

With 8-18 GHz Amplifier
Field #2
Volumetric Wetness: 0.015 cm³/cm³
Bulk Density: 1.27 g/cm³
Antenna Distance: 23 cm
θ₁ = 15°, Vertical Polarization

- Sample 1
- Sample 2
- Sample 3

Antenna Distance: 29 cm
- Sample 4
- Sample 5
- Sample 6
Field #2
Volumetric Wetness: 0.015 cm$^3$/cm$^3$
Bulk Density: 1.27 g/cm$^3$
Antenna Distance: 23 cm

Dielectric Loss Factor $\varepsilon''$

Frequency $f$ (GHz)

Sample 1
Sample 2
Sample 3

Antenna Distance 29 cm
Sample 4
Sample 5
Sample 6

Frequency $f$ (GHz)
The Results were Obtained by Measuring 3 Identical Samples at 3 Different Antenna Distances Each (Table 13).

- **Average**
- **Worst Case**

\[
\text{Standard Deviation of } \varepsilon' \quad (\text{%)}
\]

\[
\text{Mean Value of } \varepsilon'
\]

- \( m_\nu = 0.22 \text{ cm}^3/\text{cm}^3 \) and \( m_\nu = 0.33 \text{ cm}^3/\text{cm}^3 \)
  - \( d = 20 \text{ mm} \)
  - \( d = 13 \text{ mm} \)

- \( m_\nu = 0.32 \text{ cm}^3/\text{cm}^3 \)
  - \( d = 18 \text{ mm} \)
  - with 8-18 GHz Amplifier

- \( m_\nu = 0.33 \text{ cm}^3/\text{cm}^3 \)
  - \( d = 35 \text{ mm} \)

- \( m_\nu = 0.015 \text{ cm}^3/\text{cm}^3 \)
  - \( d = 49 \text{ mm} \)

Frequency \( f \) (GHz)
The Results were Obtained by Measuring 3 Identical Samples at 3 Different Antenna Distances Each (Table 13).

- Average
- Worst Case

- $m_v = 0.015 \text{ cm}^3/\text{cm}^3$
  - $d = 49 \text{ mm}$
  - Sweep Technique

- $m_v = 0.22 \text{ cm}^3/\text{cm}^3$
  - $d = 20 \text{ mm}$
  - Sweep and Pulley Methods
  - $m_v = 0.33 \text{ cm}^3/\text{cm}^3$
  - $d = 12 \text{ mm}$
  - Pulley Method

- $m_v = 0.33 \text{ cm}^3/\text{cm}^3$
  - $d = 35 \text{ mm}$
  - Sweep Technique

- $m_v = 0.32 \text{ cm}^3/\text{cm}^3$
  - $d = 18 \text{ mm}$
  - Sweep Technique with 8-18GHz Amplifier

Frequency $f$ (GHz)
Waveguide Technique
Free-Space Technique
Frequency: 6 GHz
Field 2: Loam

Dielectric Constant \( \varepsilon \)

Volumetric Wetness \( m_v(\%) \)
Field 1
51.5% Sand, 35.1% Silt, 13.4% Clay
Volumetric Wetness 0.24 cm³/cm³
Bulk Density: 1.54 g cm³

Dielectric Constant $\varepsilon$

Frequency $f$ (GHz)

$\varepsilon'$

Temperature:
- $23^\circ C$
- $-11^\circ C$
- $23^\circ C$
- $-18^\circ C$
- $23^\circ C$
- $-24^\circ C$

$\varepsilon''$

Temperature:
- $-11^\circ C$
- $-18^\circ C$
- $-24^\circ C$
Field 5
5% Sand, 47.6% Silt, 47.4% Clay
Volumetric Wetness: 0.36 cm³/cm³
Bulk Density: 1.42 g cm³
Field 2: Loam
Temperature: 23°C
Free-Space Method:
- 3 GHz
- 4
- 6
- 8
- 10
- 12.4
- 14
- 16
- 18
- Waveguide Method at 4 GHz [18]
Field 2: Loam
Temperature: 23°C
Free-Space Method:
- ▲ 3 GHz
- ★ 4
- ○ 6
- ★ 8
- △ 10
- ★ 12.4
- △ 14
- ★ 16
- × 18
- ▲ Waveguide Method at 4 GHz

Dielectric Constant $\varepsilon$

$\varepsilon'$
- $\rho_b = 1.46$
- $\rho_b = 1.47$
- $\rho_b = 1.58$
- $\rho_b = 1.60$
- $\rho_b = 1.56$
- $\rho_b = 1.53$
- $\rho_b = 1.42$
- $\rho_b = 1.39$
- $\rho_b = 1.31$
- $\rho_b = 1.32$

$\varepsilon''$

Volumetric Wetness $m_v$ (cm$^3$/cm$^3$)
Field 2: Loam
Temperature: 23°C
Free-Space Method:
- ▲ 3 GHz
- ● 4
- ○ 6
- △ 8
- □ 10
- ● 12.4
- △ 14
- ● 16
- × 18

Waveguide Method at 4 GHz [18]

Dielectric Constant $\varepsilon$

Volumetric Wetness $m_v$ (cm$^3$/cm$^3$)

$\varepsilon'$

$\varepsilon''$

$\rho_b = 1.32$
$\rho_b = 1.31$
$\rho_b = 1.42$
$\rho_b = 1.50$
$\rho_b = 1.53$
$\rho_b = 1.56$
$\rho_b = 1.46$
$\rho_b = 1.47$
$\rho_b = 1.60$
$\rho_b = 1.58$
$3$ GHz