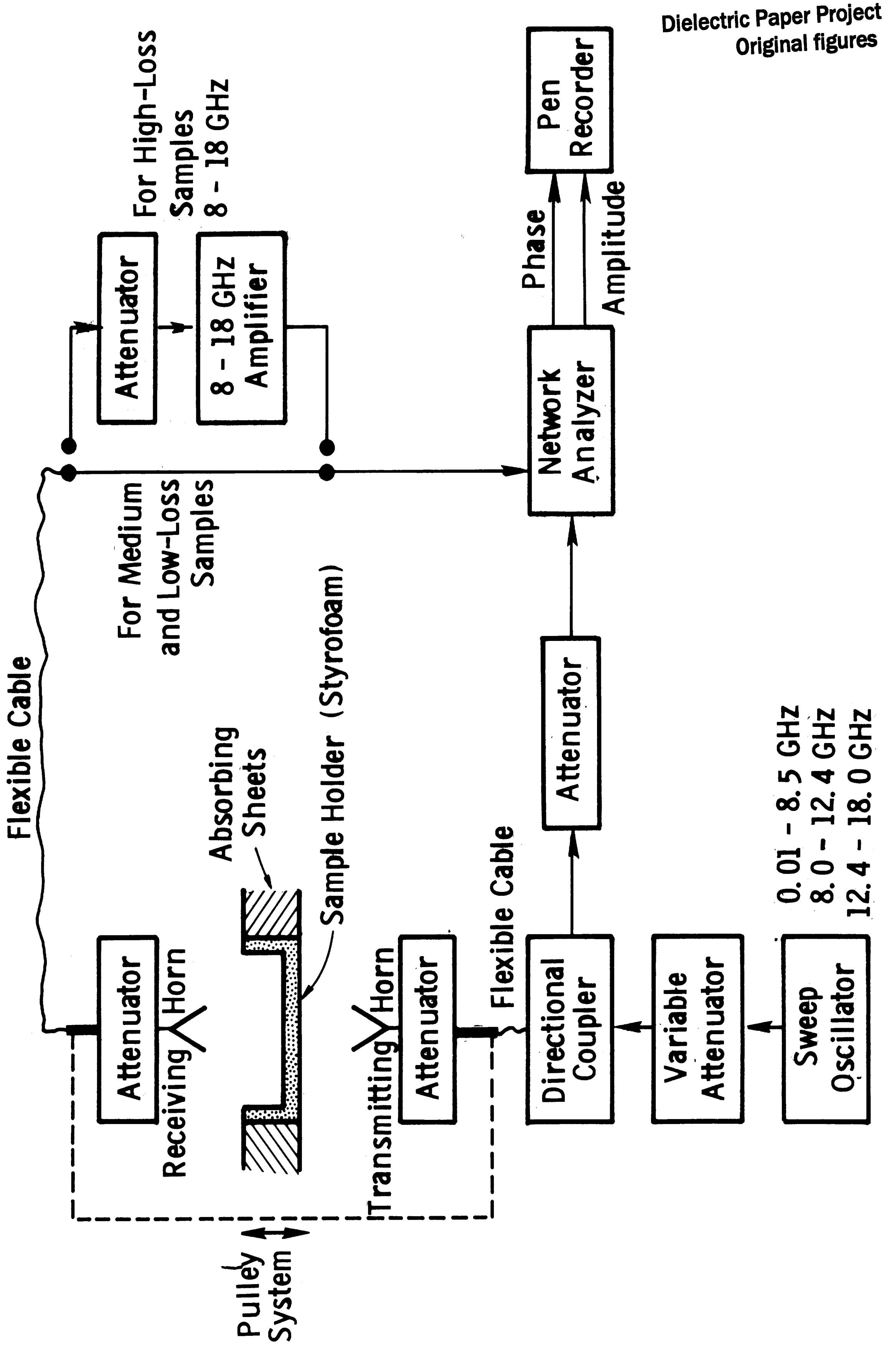
(None) = RL-2007

Dielectric Paper Project 5450 -
Original figures



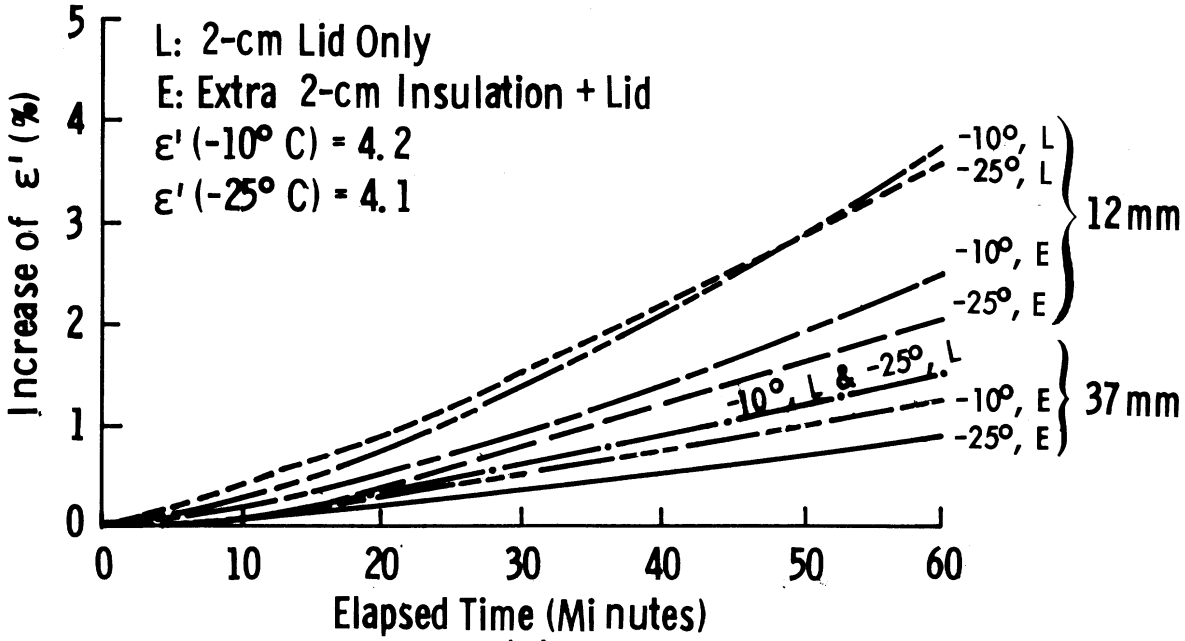
Field 2

Temperatures: -10° C and -25° C

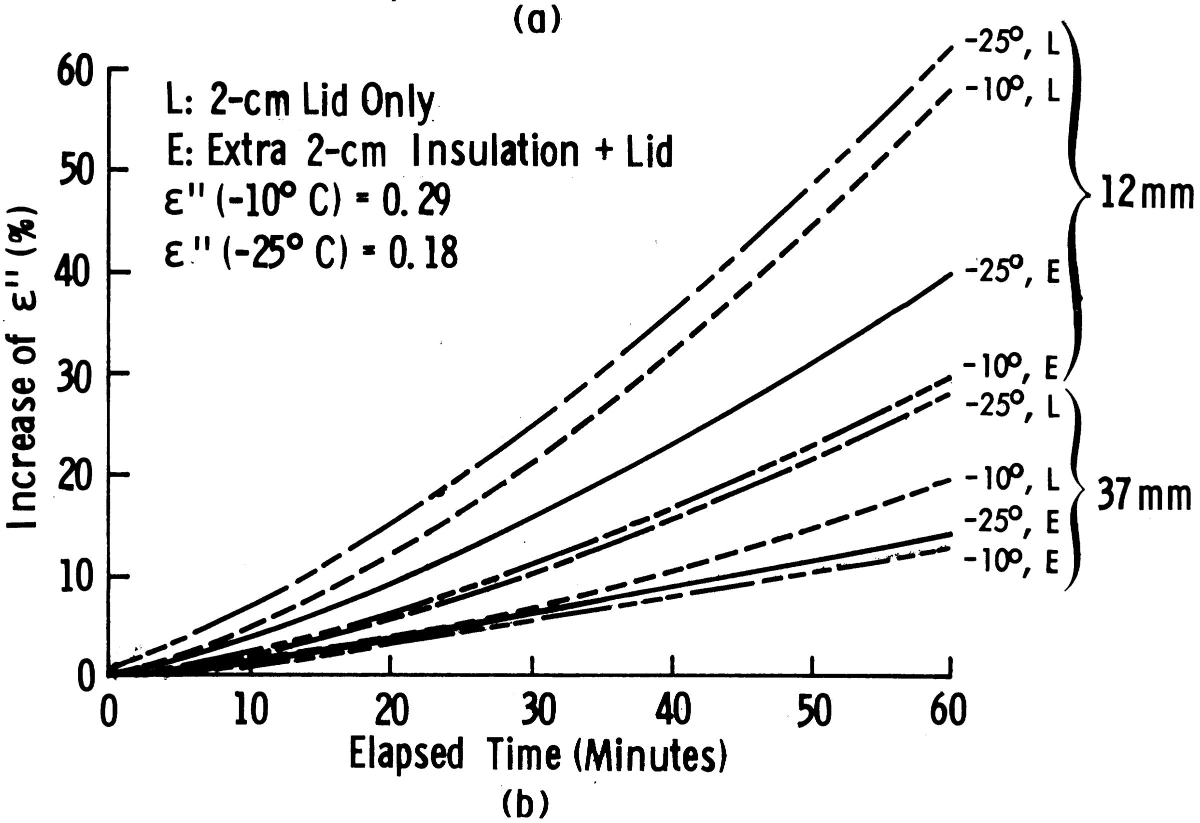
Sample Thicknesses: 12 mm and 37 mm

Volumetric Wetness: 0.22 cm³/cm⁻³

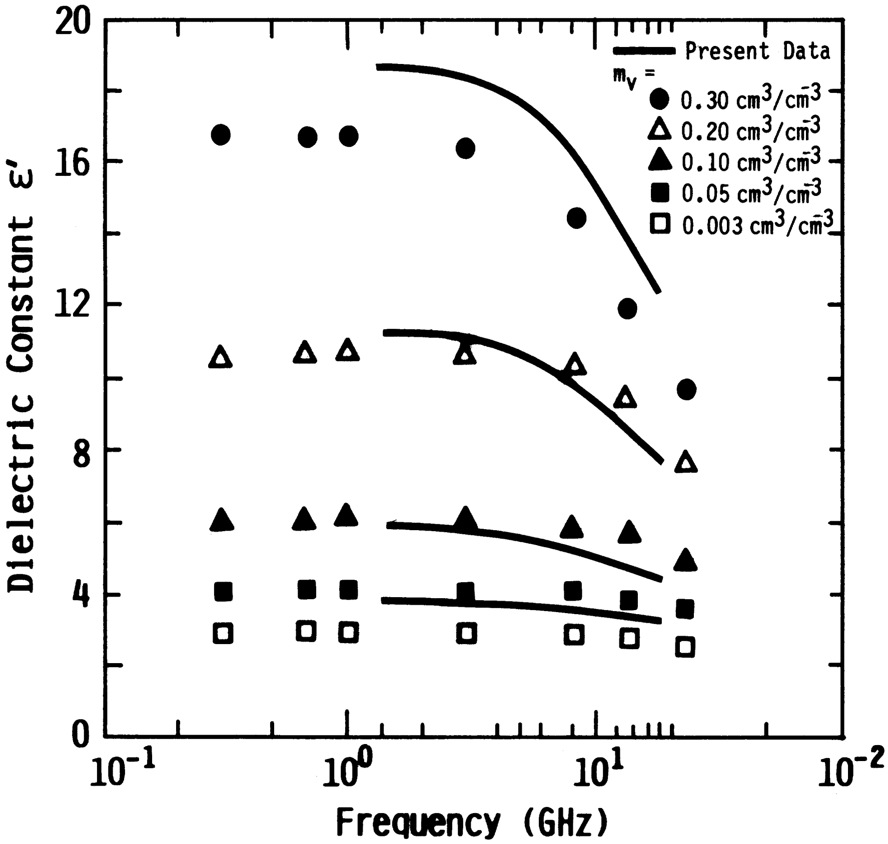
Frequency: 18 GHz



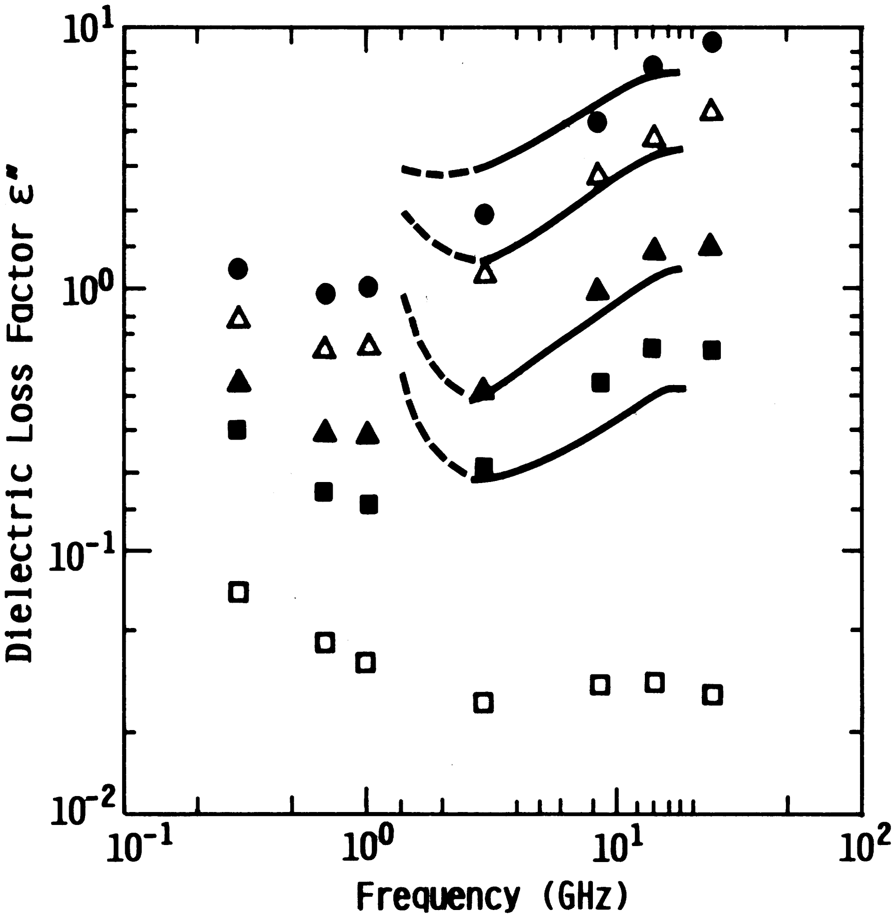
(a)



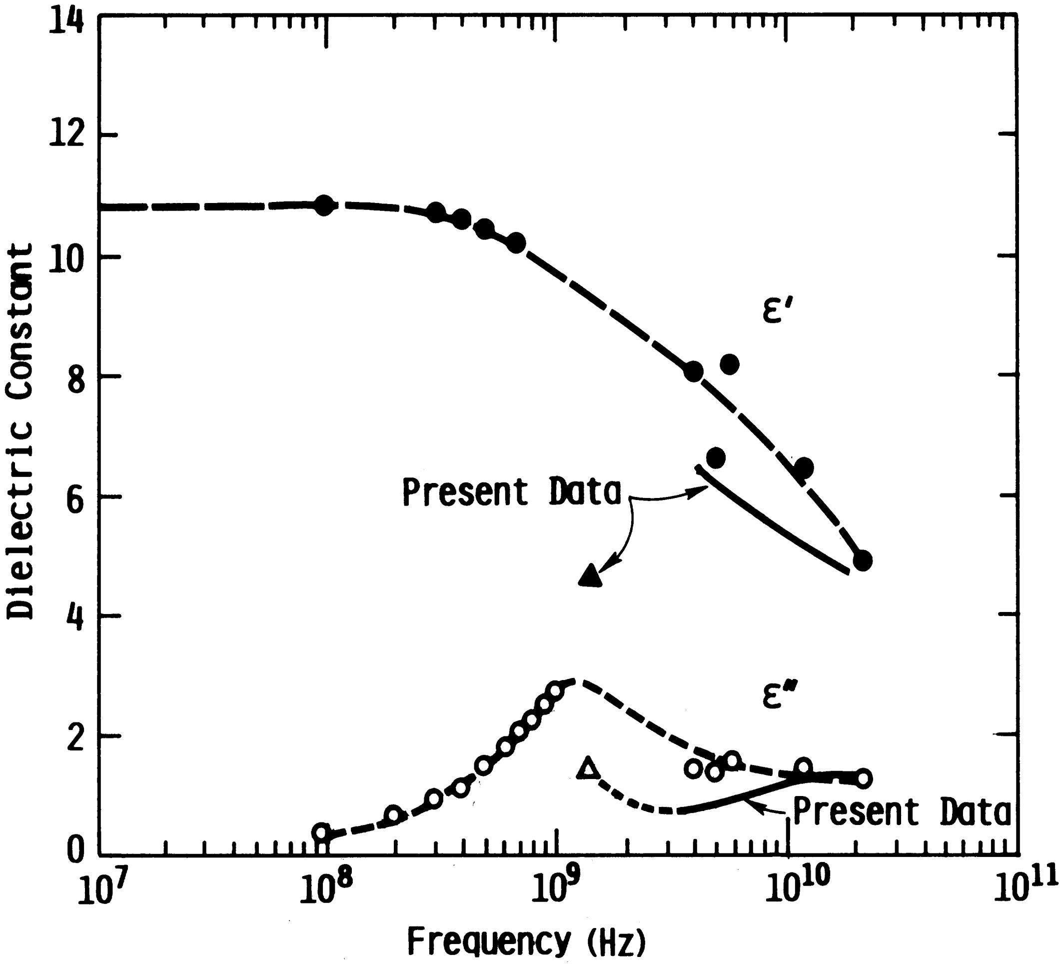
(b)



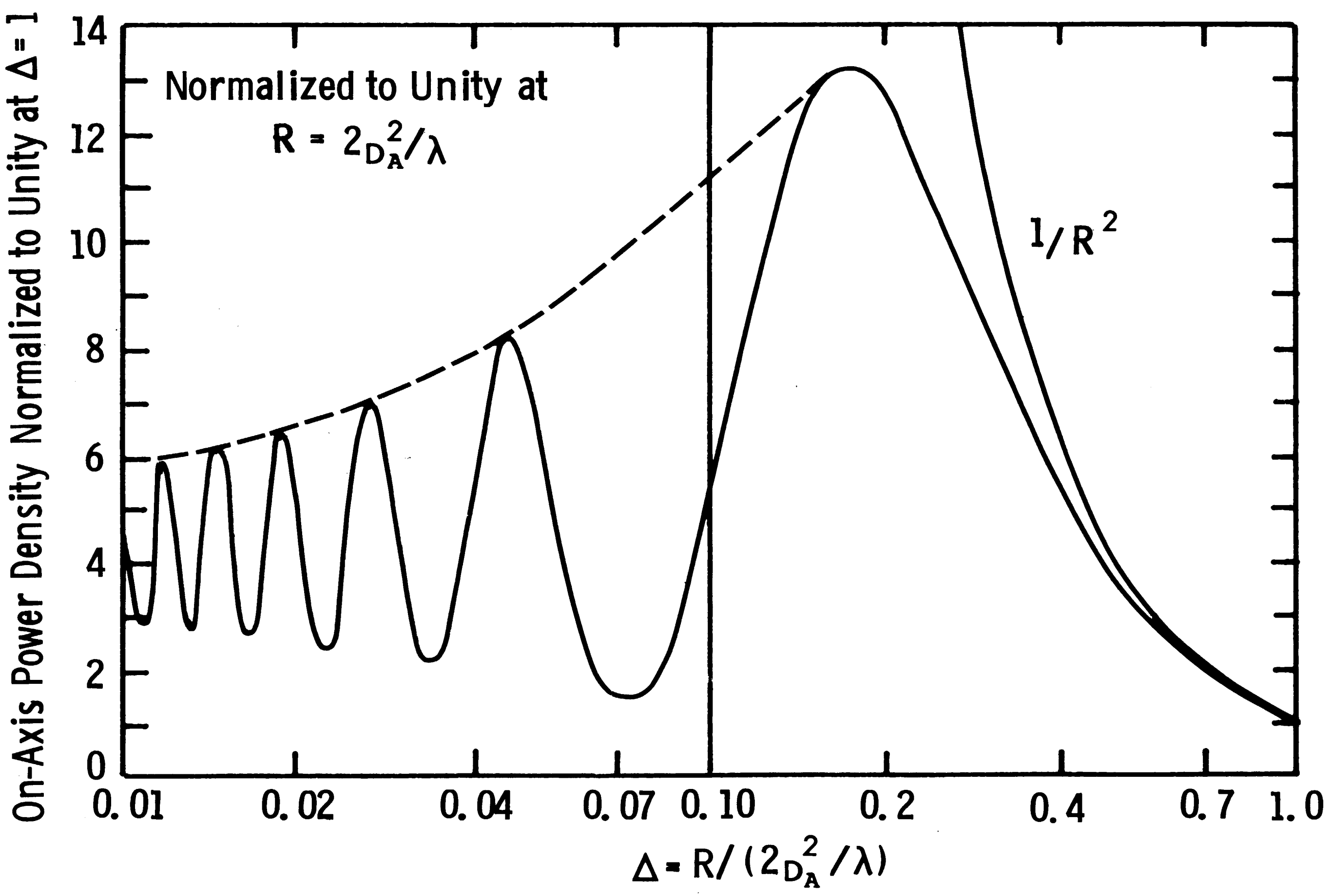
Present Data
m_v =
0.30 cm³/cm³
0.20 cm³/cm³
0.10 cm³/cm³
0.05 cm³/cm³
0.003 cm³/cm³
Dielectric Constant ε′
Frequency (GHz)



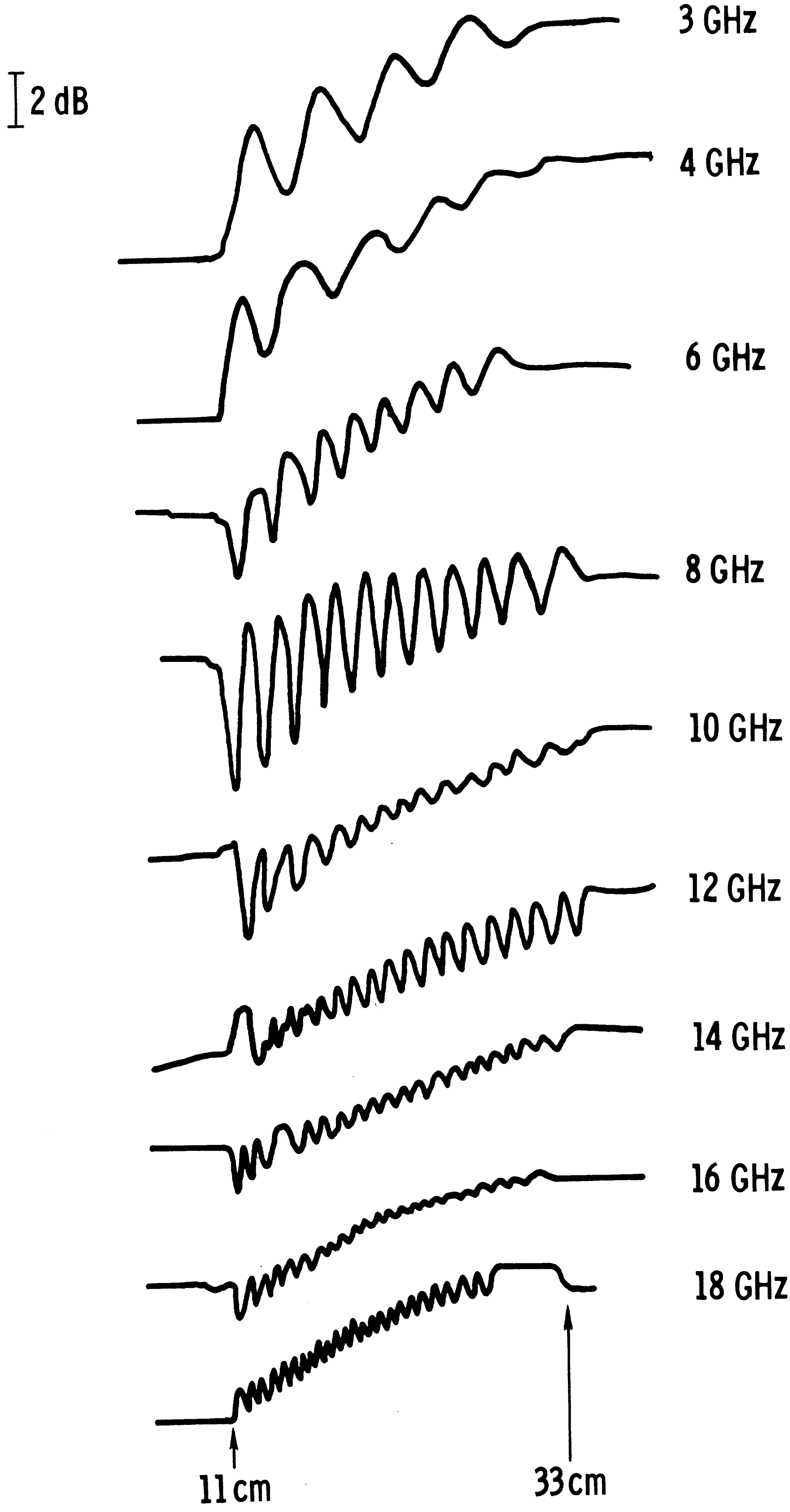
Dielectric Loss Factor ε″
Frequency (GHz)



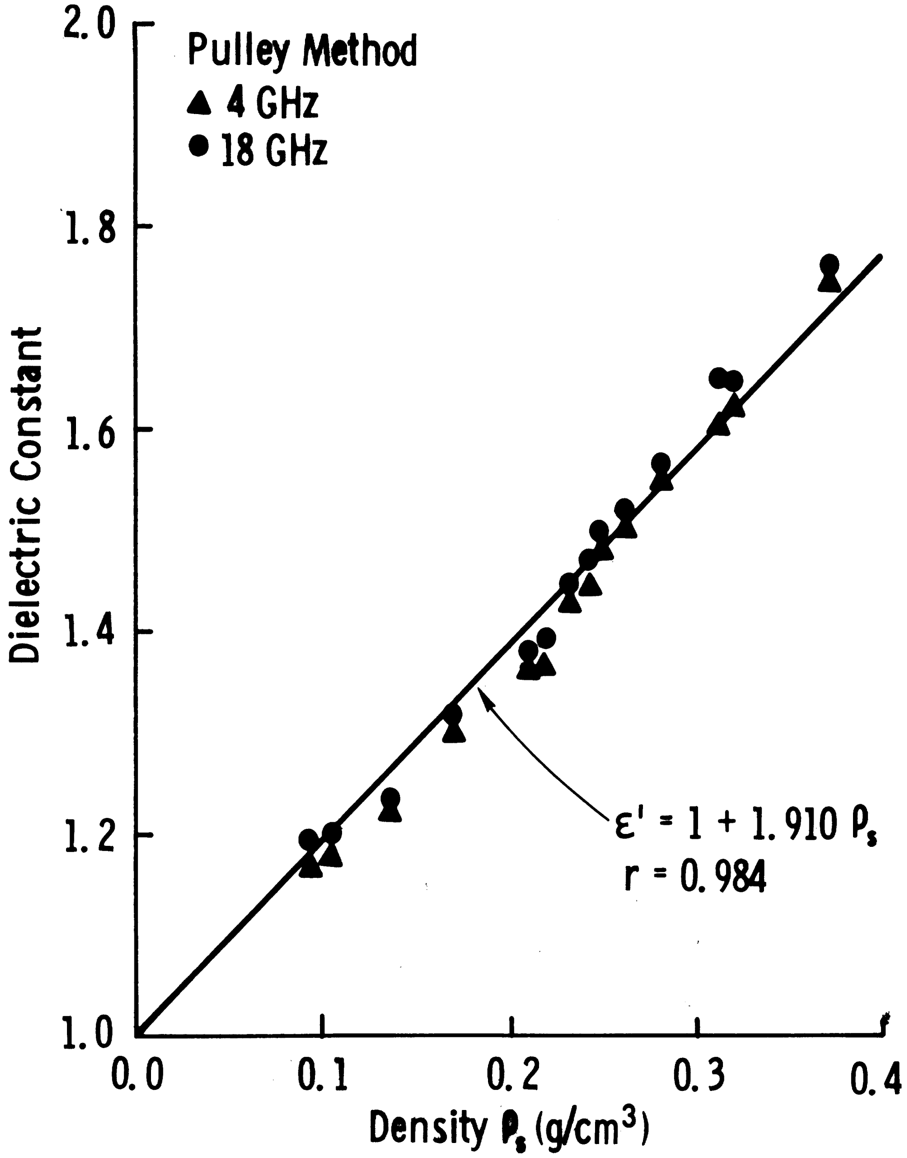
14
12
10
8
6
4
2
0
Dielectric Constant
ε′
Present Data
ε″
Present Data
10^7
10^8
10^9
10^{10}
10^{11}
Frequency (Hz)



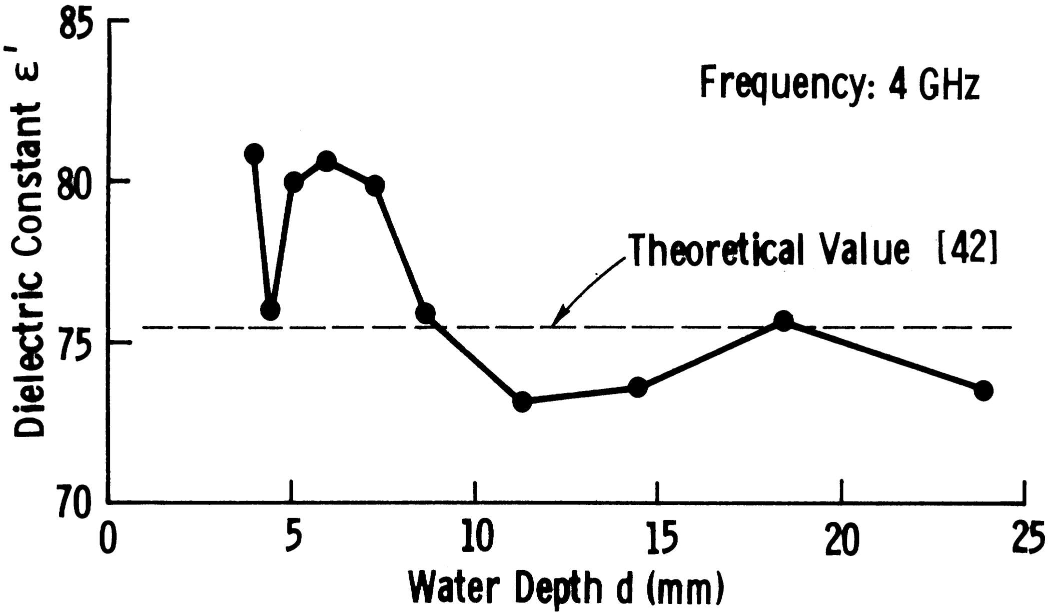
Normalized to Unity at
R = 2D_A^2/λ
1/R^2
On-Axis Power Density Normalized to Unity at Δ = 1
14
12
10
8
6
4
2
0
0.01
0.02
0.04
0.07
0.10
0.2
0.4
0.7
1.0
Δ = R/(2D_A^2/λ)

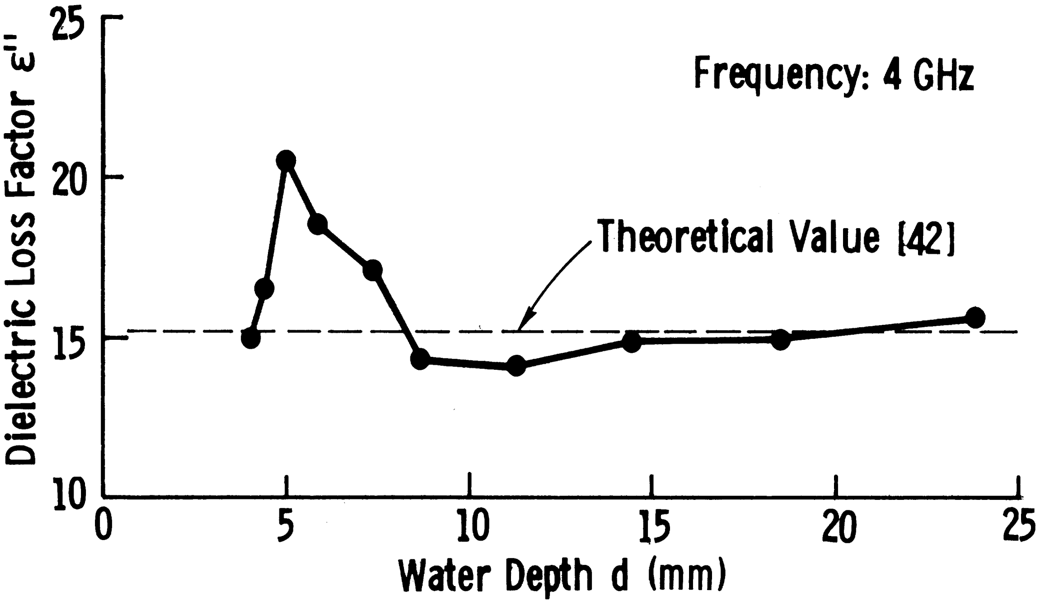


2 dB
3 GHz
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
11cm
33cm

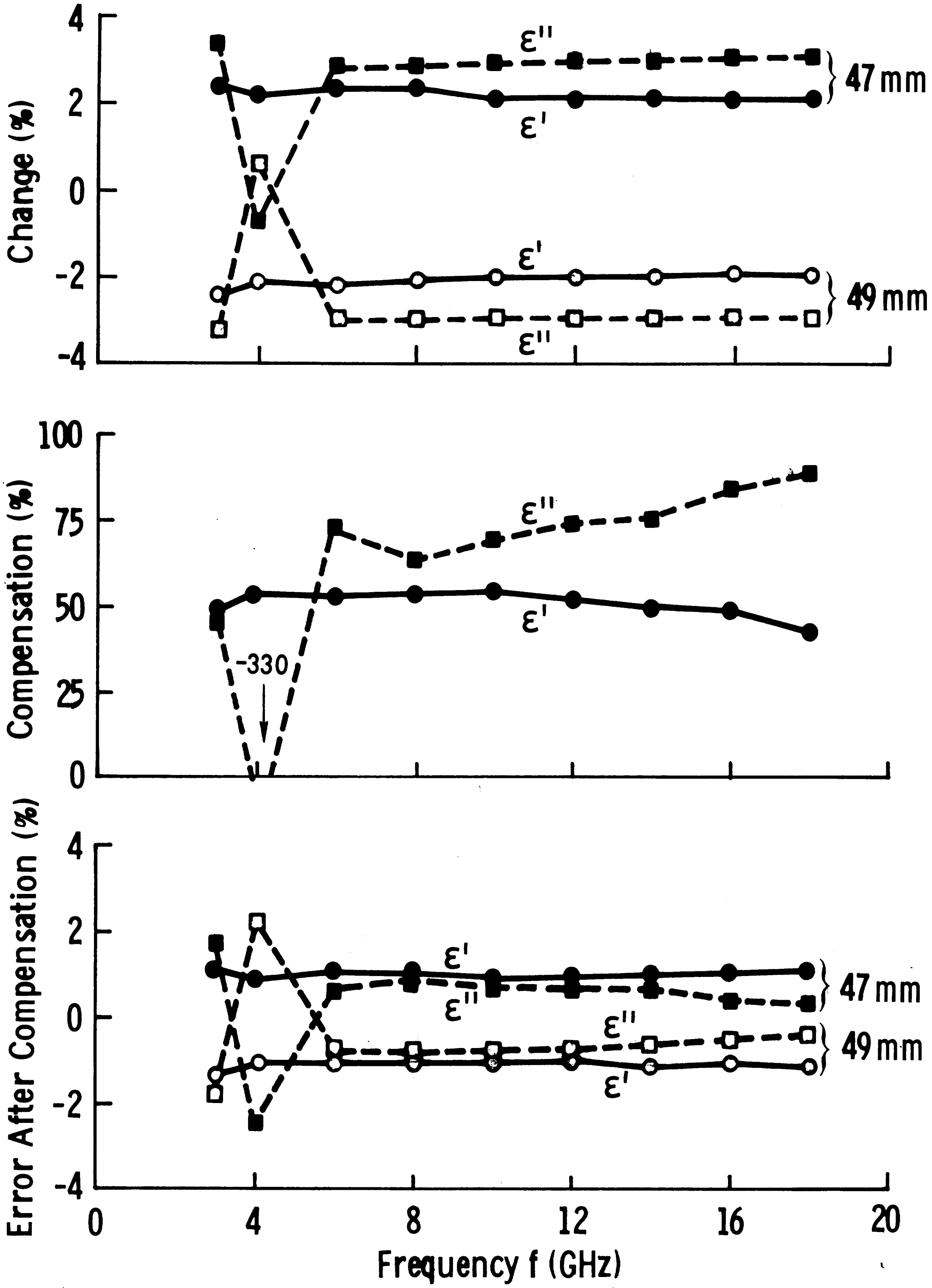


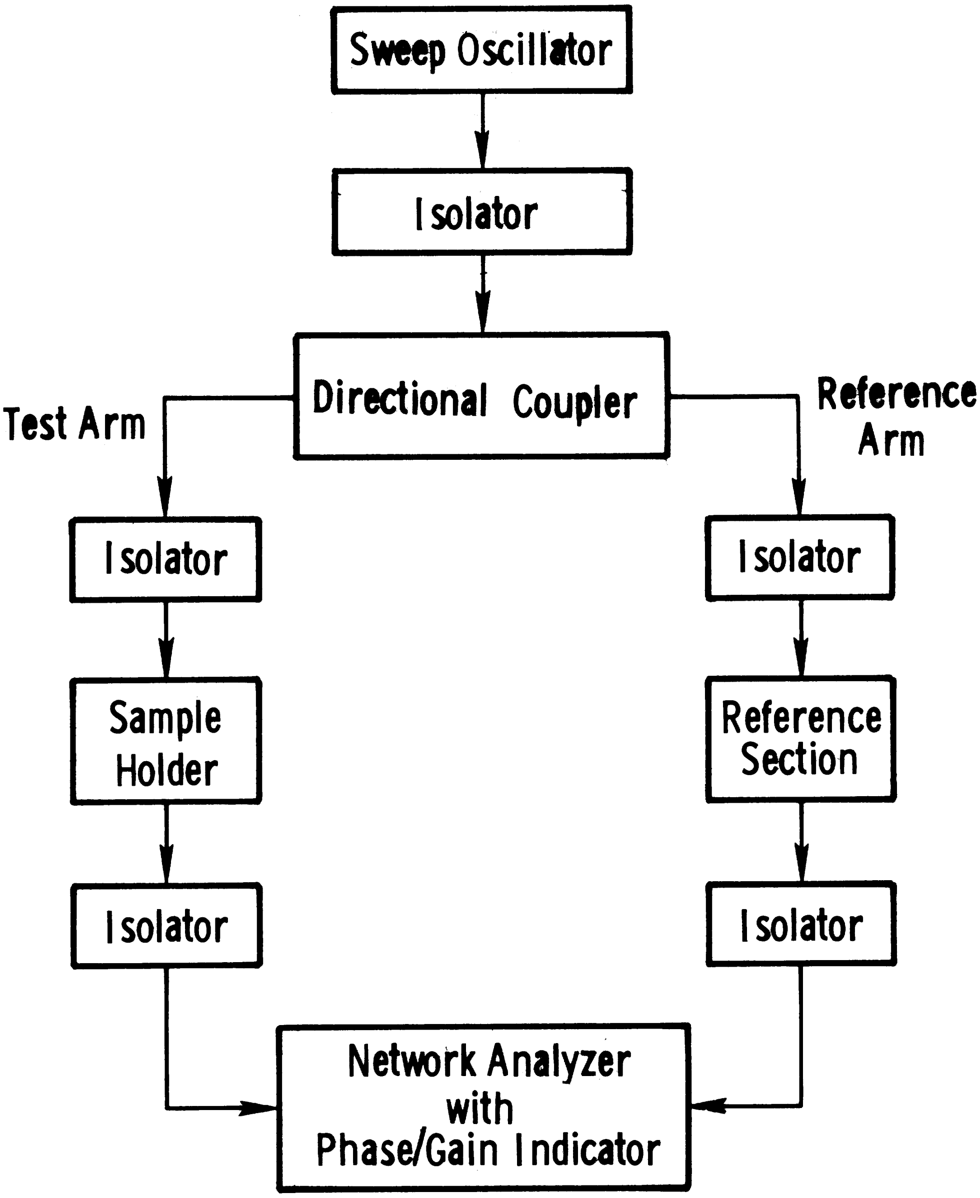
Pulley Method
4 GHz
18 GHz
ε' = 1 + 1.910 ρ_s
r = 0.984
Dielectric Constant
Density ρ_s (g/cm³)
2.0
1.8
1.6
1.4
1.2
1.0
0.0
0.1
0.2
0.3
0.4

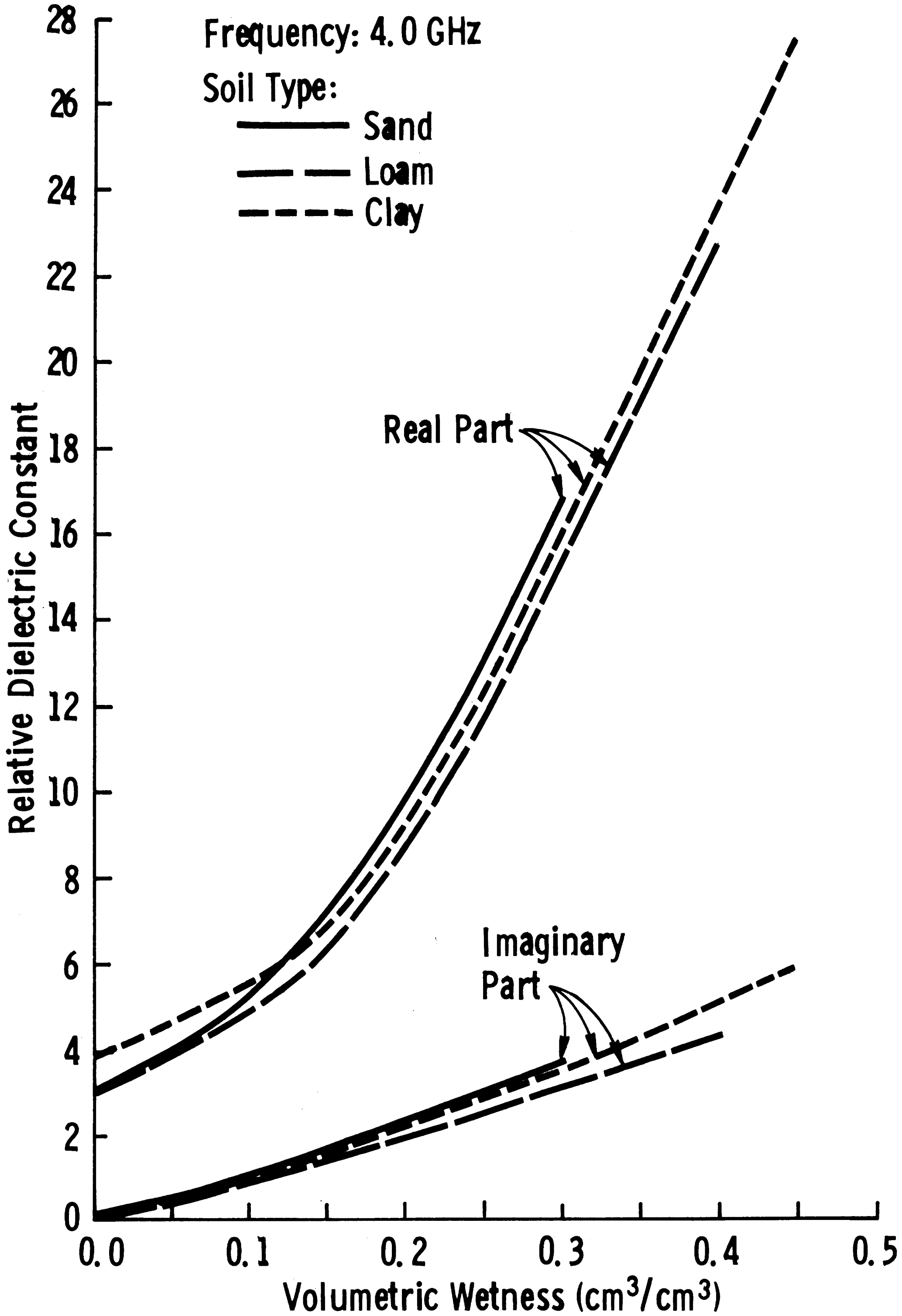

Frequency: 4 GHz
Theoretical Value [42]
Dielectric Constant ε'
85
80
75
70
0
5
10
15
20
25
Water Depth d (mm)

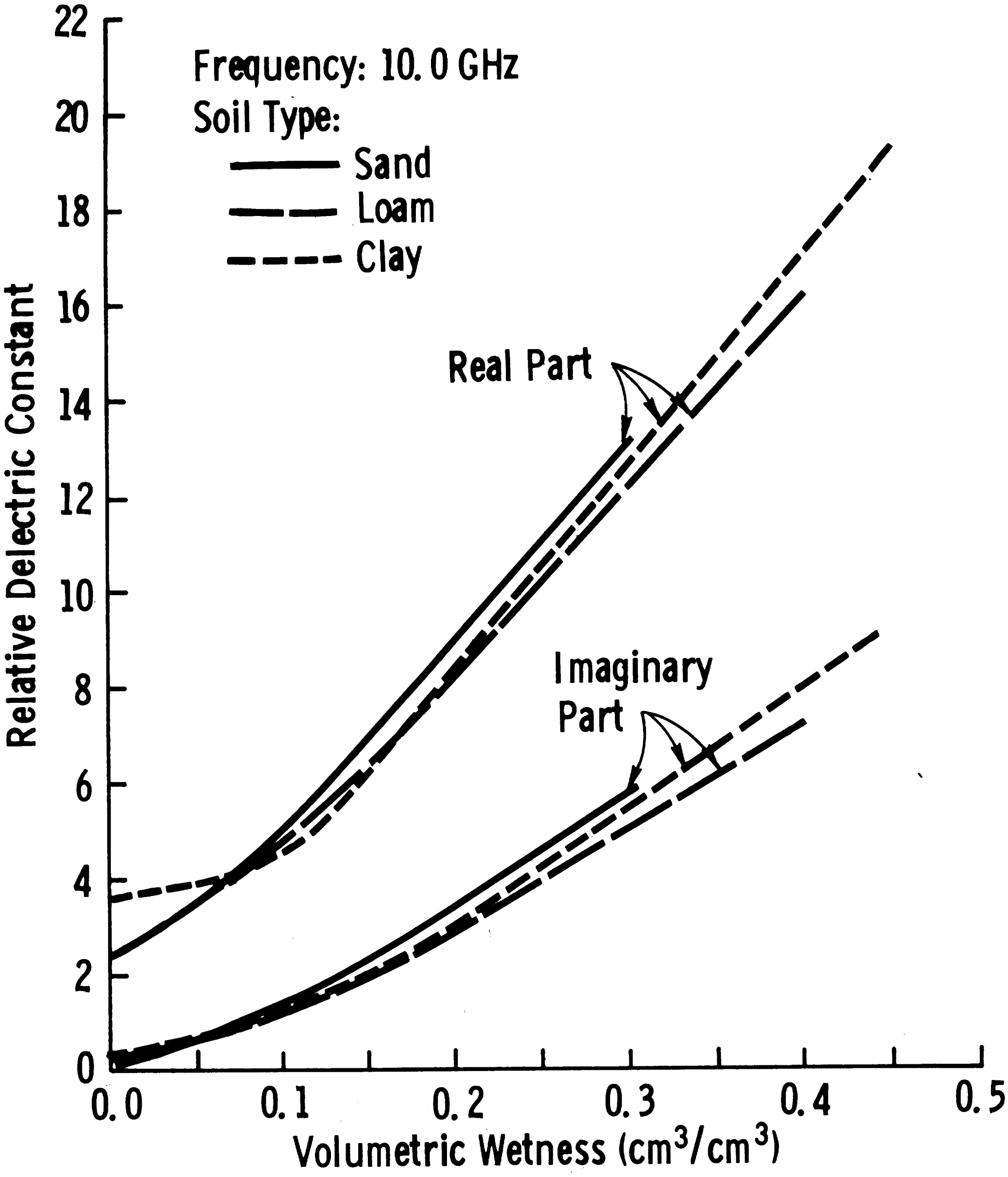

Frequency: 4 GHz
Theoretical Value [42]
Dielectric Loss Factor ε''
25
20
15
10
0
5
10
15
20
25
Water Depth d (mm)

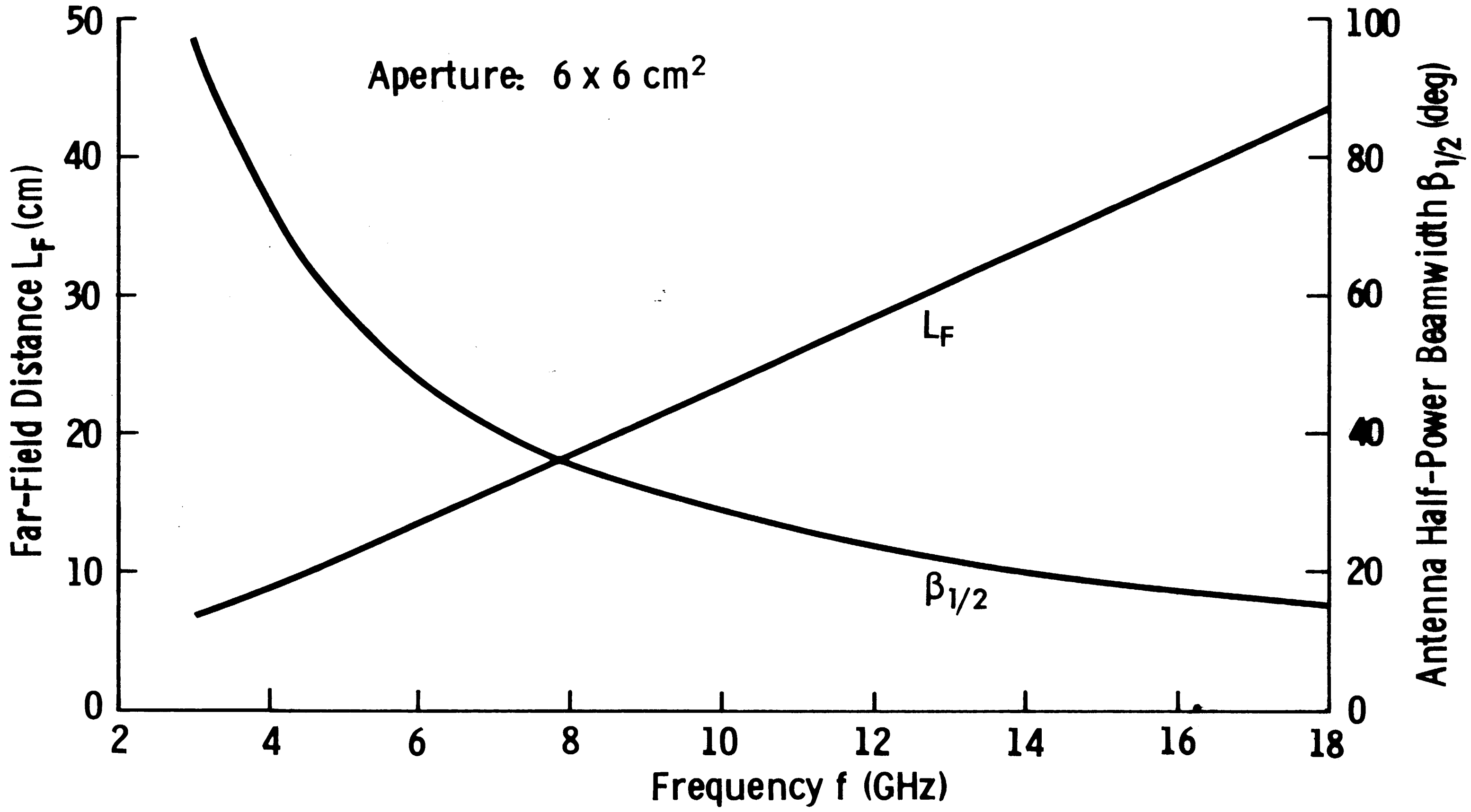
Field #2
Temperature: 23° C
Volumetric Wetness: 0.08 cm³/cm³
Nominal Sample Thickness: 48 mm



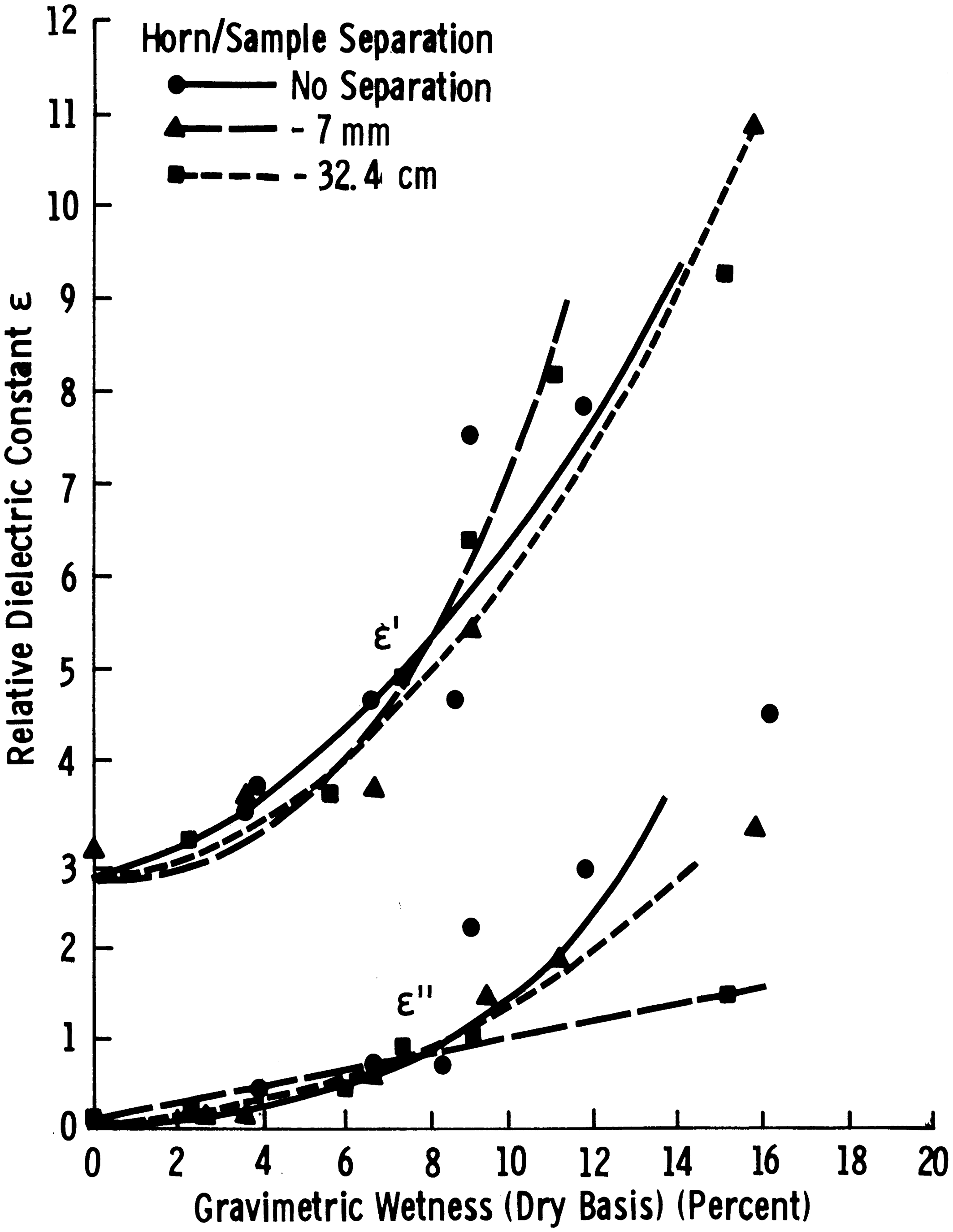

Sweep Oscillator
Isolator
Directional Coupler
Test Arm
Reference Arm
Isolator
Isolator
Sample Holder
Reference Section
Isolator
Isolator
Network Analyzer with Phase/Gain Indicator

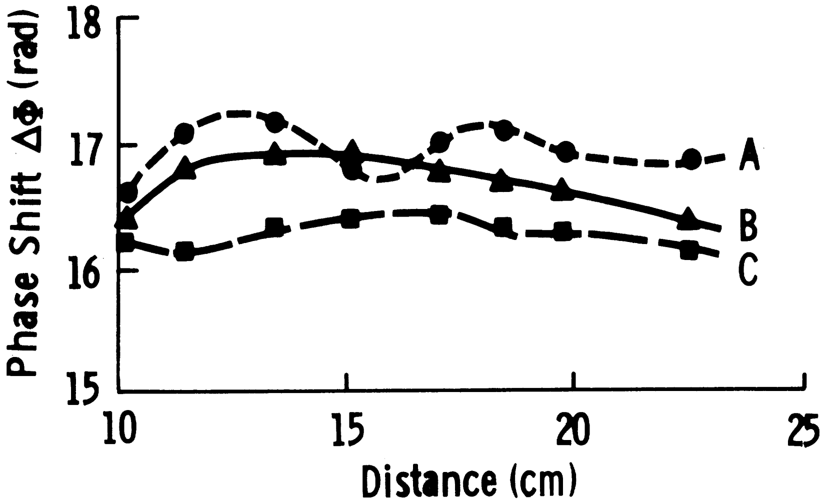

Frequency: 4.0 GHz
Soil Type:
Sand
Loam
Clay
Real Part
Imaginary Part
Relative Dielectric Constant
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0.0
0.1
0.2
0.3
0.4
0.5
Volumetric Wetness (cm3/cm3)

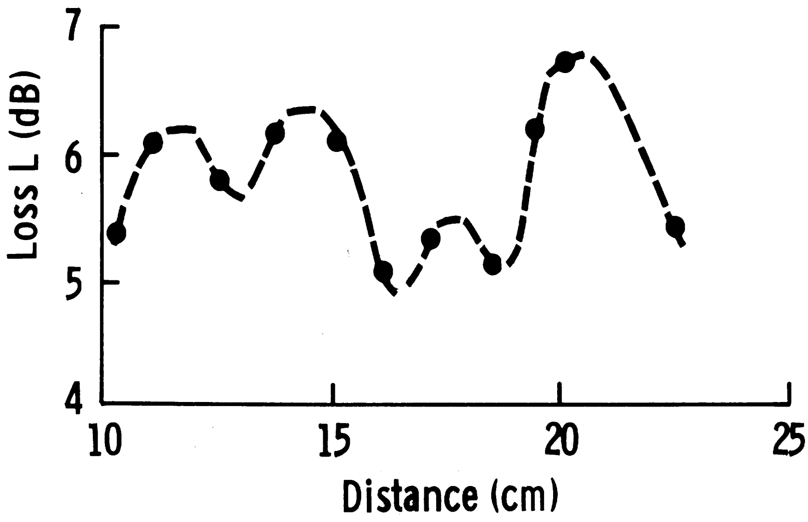

Frequency: 10.0 GHz
Soil Type:
Sand
Loam
Clay
Real Part
Imaginary Part
Relative Delectric Constant
Volumetric Wetness (cm3/cm3)
0
2
4
6
8
10
12
14
16
18
20
22
0.0
0.1
0.2
0.3
0.4
0.5

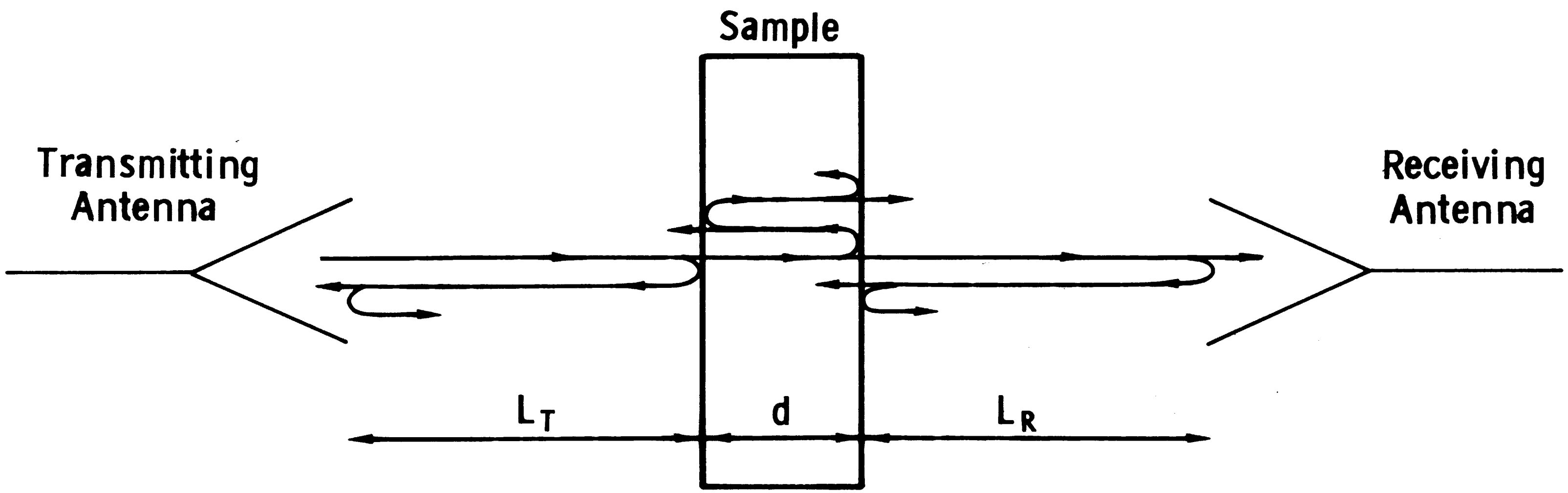


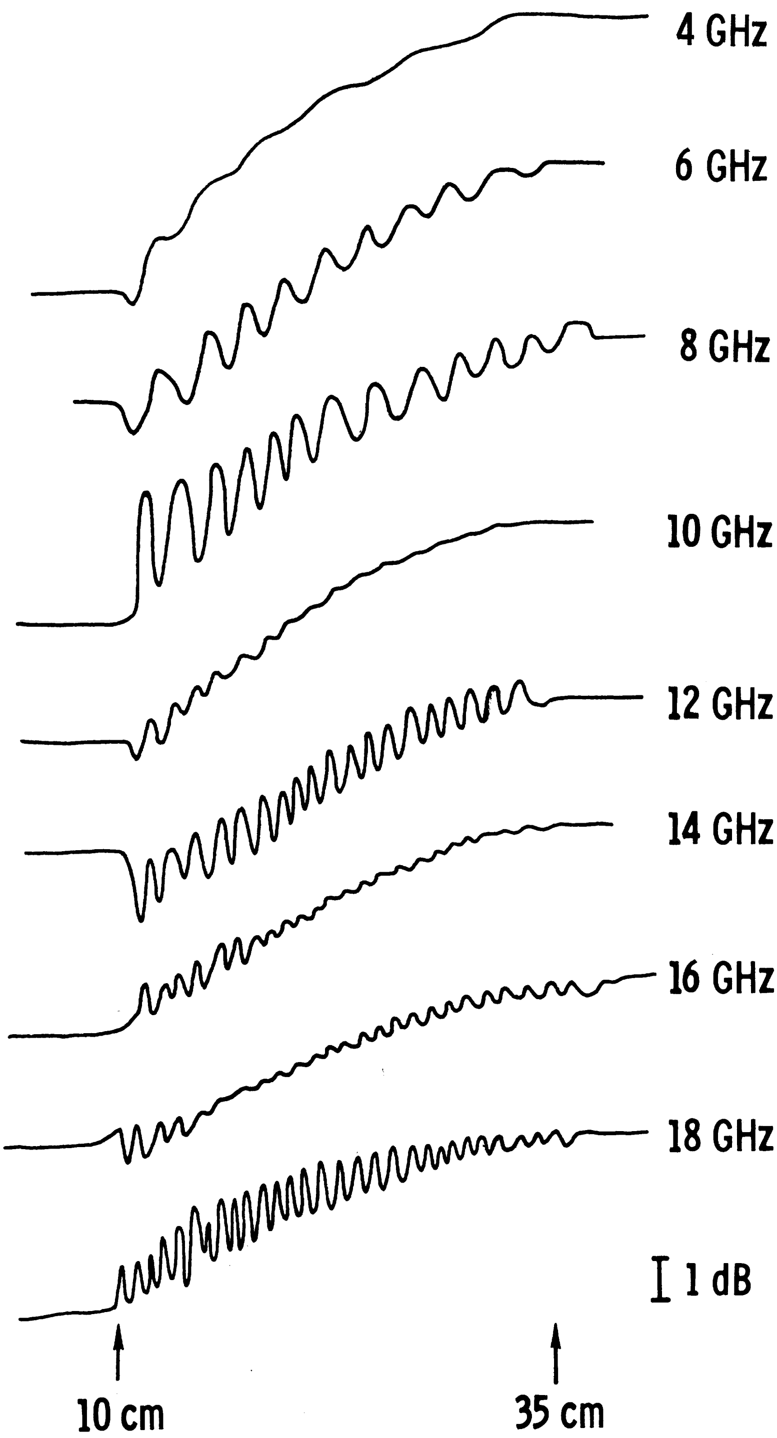
Aperture: 6 x 6 cm²
Far-Field Distance L_F (cm)
Antenna Half-Power Beamwidth $\beta_{1/2}$ (deg)
Frequency f (GHz)
L_F
$\beta_{1/2}$

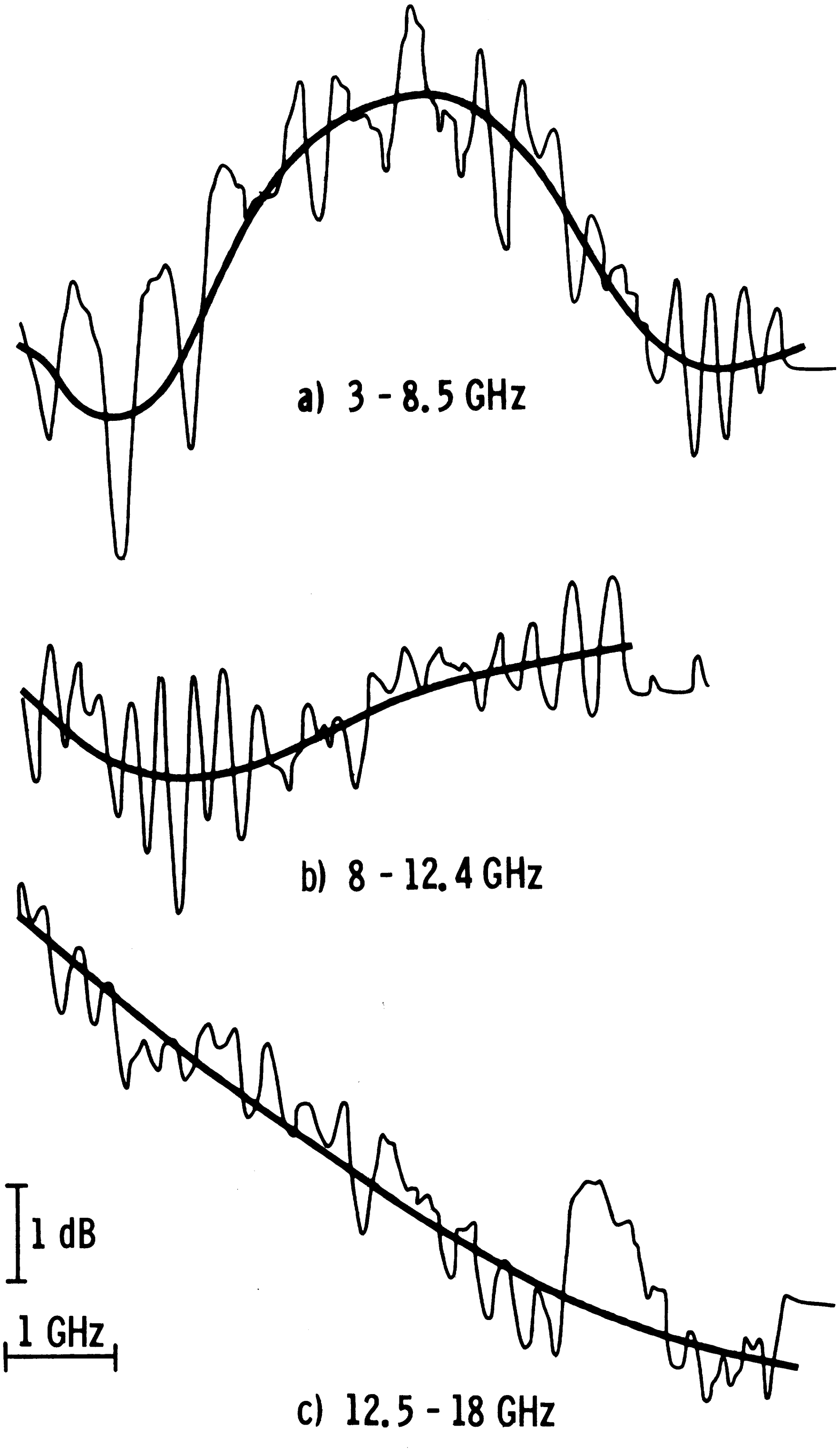

Horn/Sample Separation
No Separation
- 7 mm
- 32.4 cm
Relative Dielectric Constant ε
ε'
ε''
0
1
2
3
4
5
6
7
8
9
10
11
12
0
2
4
6
8
10
12
14
16
18
20
Gravimetric Wetness (Dry Basis) (Percent)

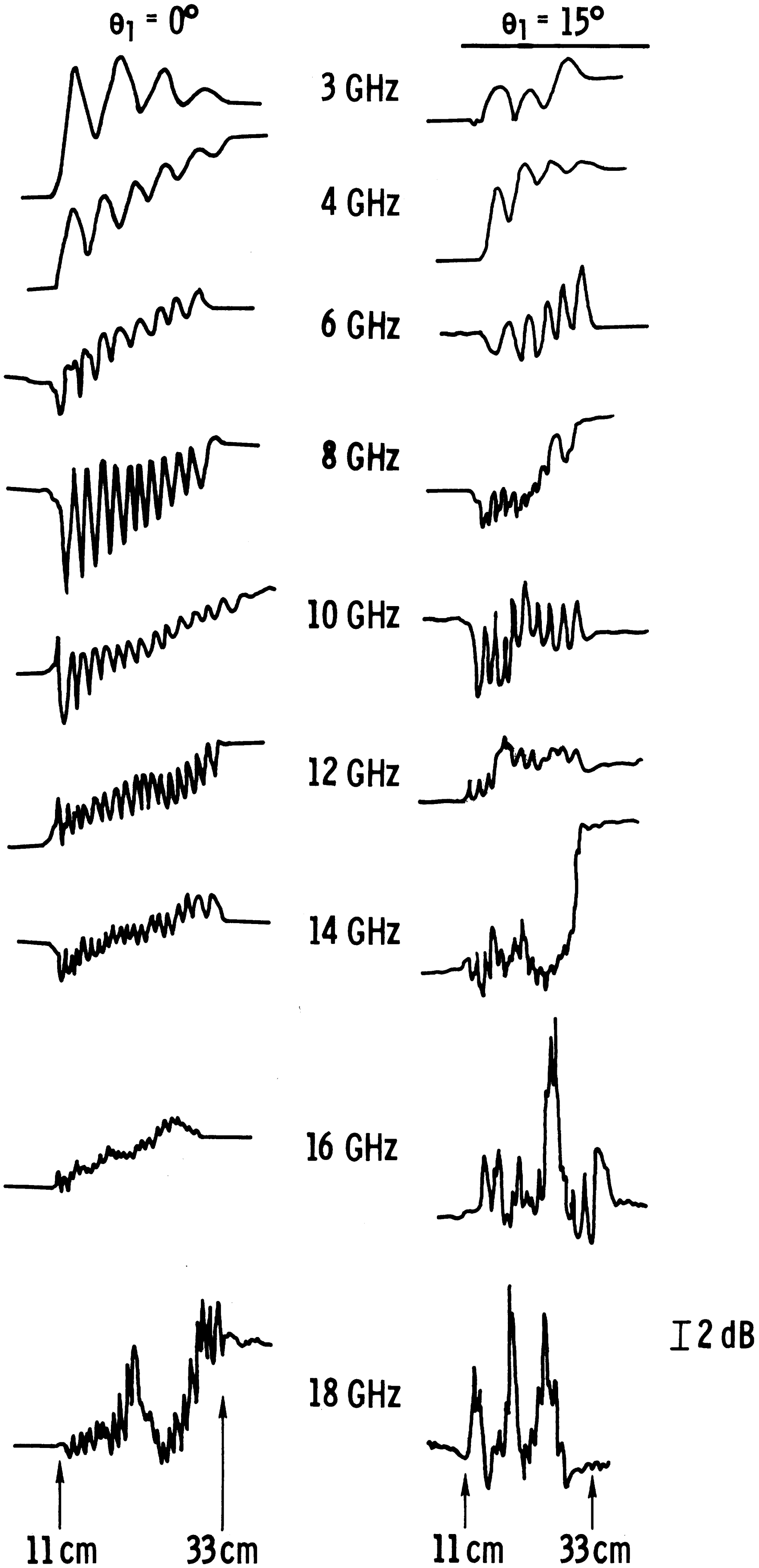

18
17
16
15
Phase Shift ΔΦ (rad)
10
15
20
25
Distance (cm)
A
B
C

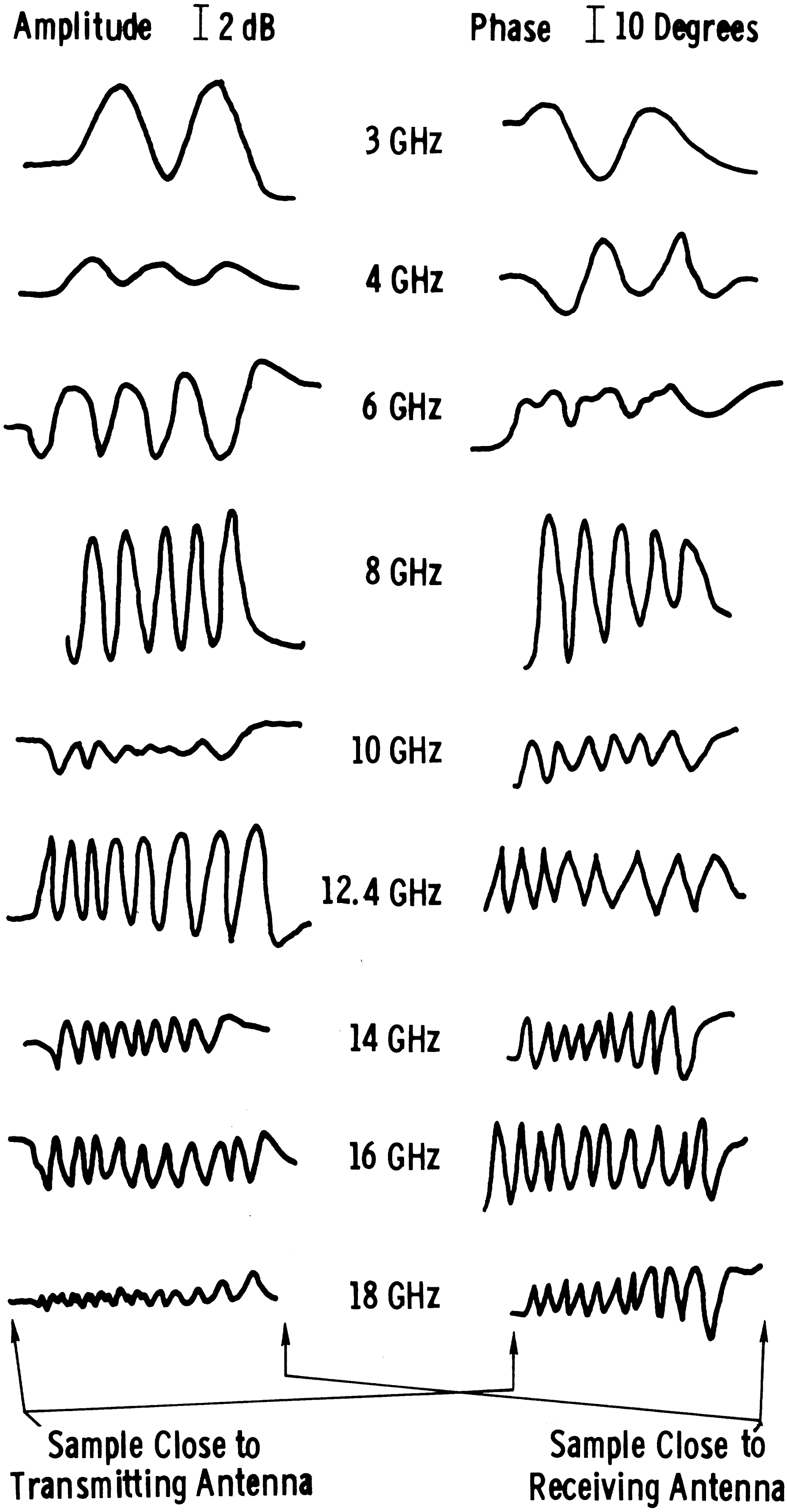

7
6
5
4
Loss L (dB)
10
15
20
25
Distance (cm)


Sample
Transmitting Antenna
Receiving Antenna
L_T
d
L_R

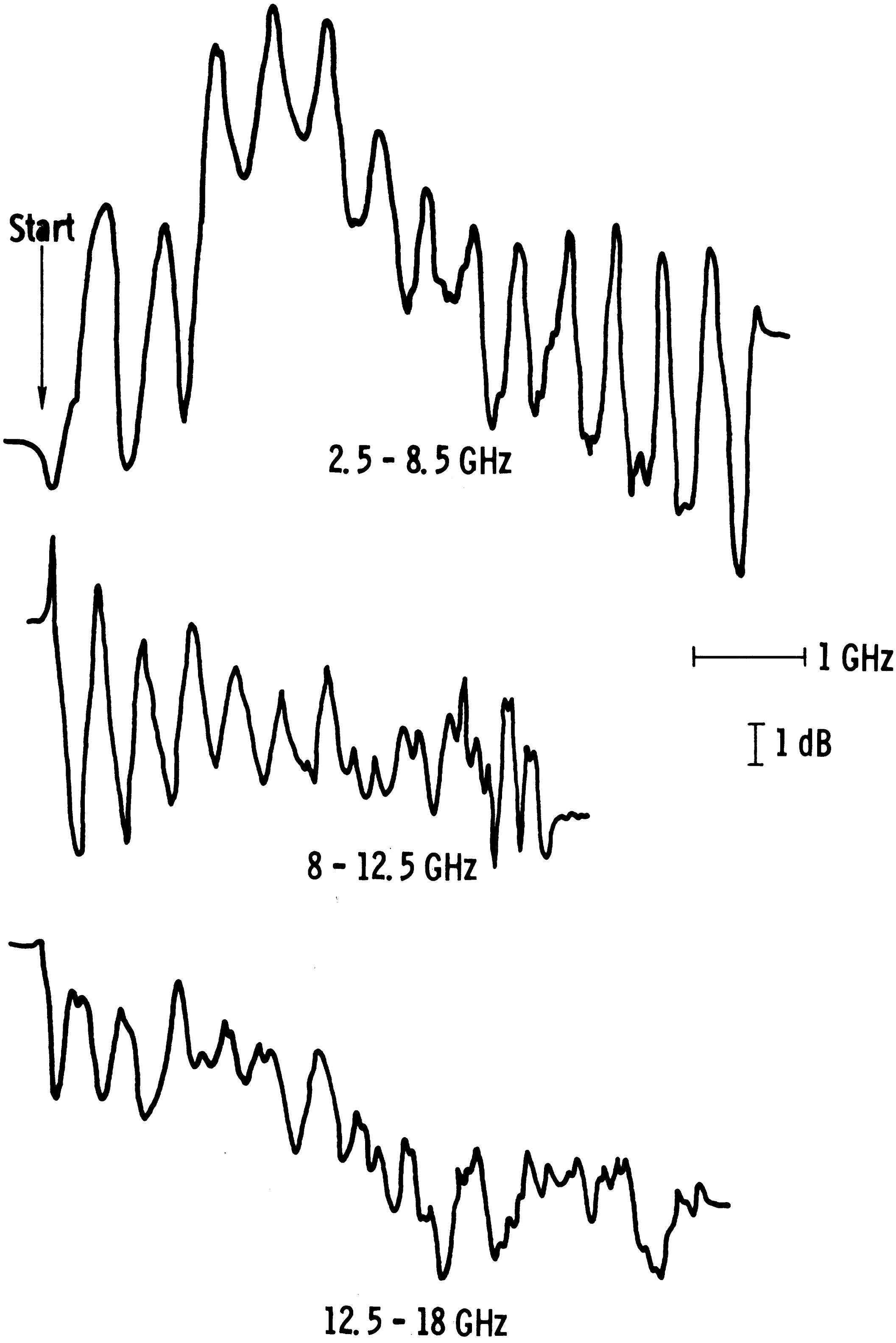

4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
1 dB
10 cm
35 cm

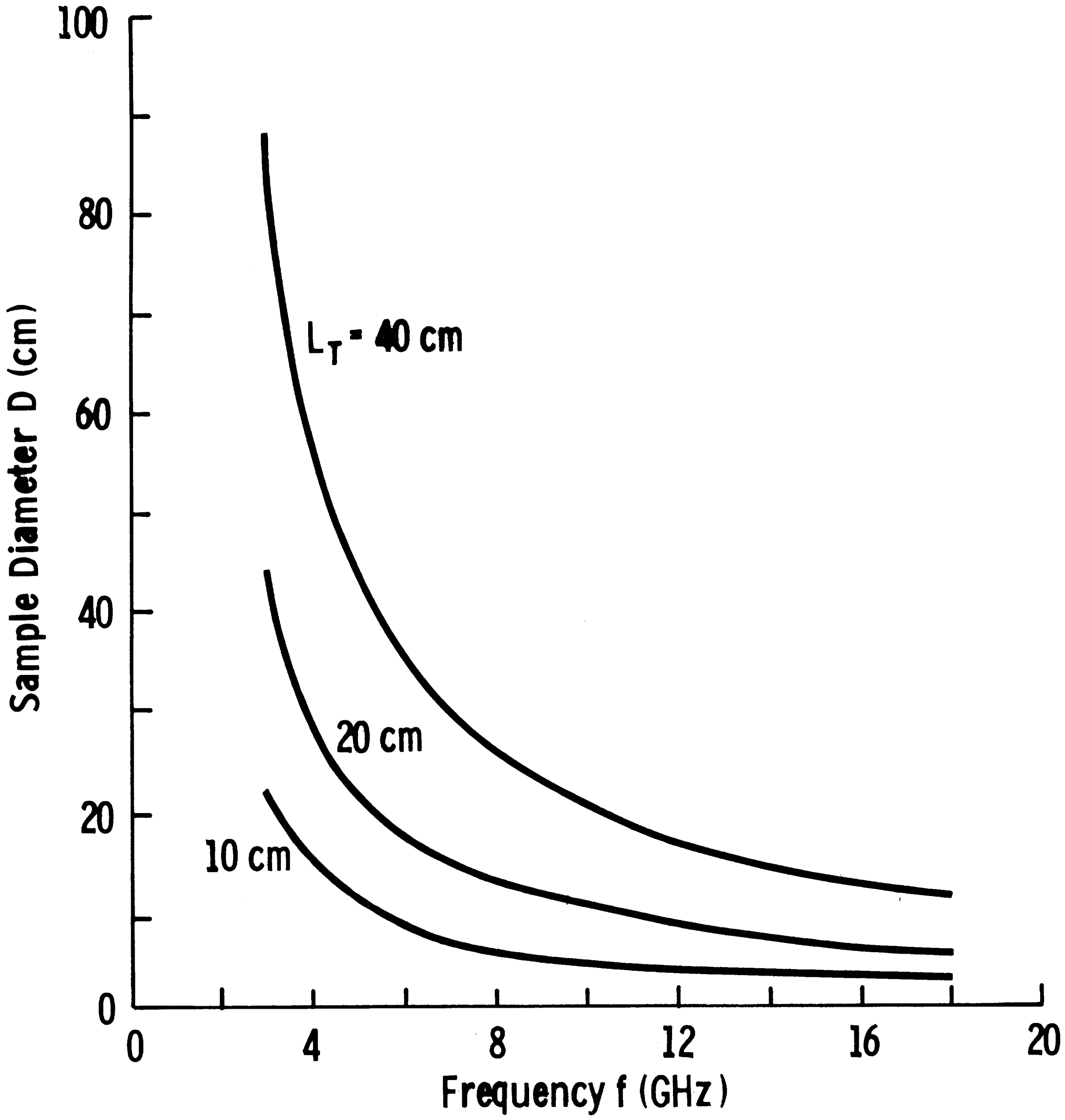

a) 3 - 8.5 GHz
b) 8 - 12.4 GHz
1 dB
1 GHz
c) 12.5 - 18 GHz

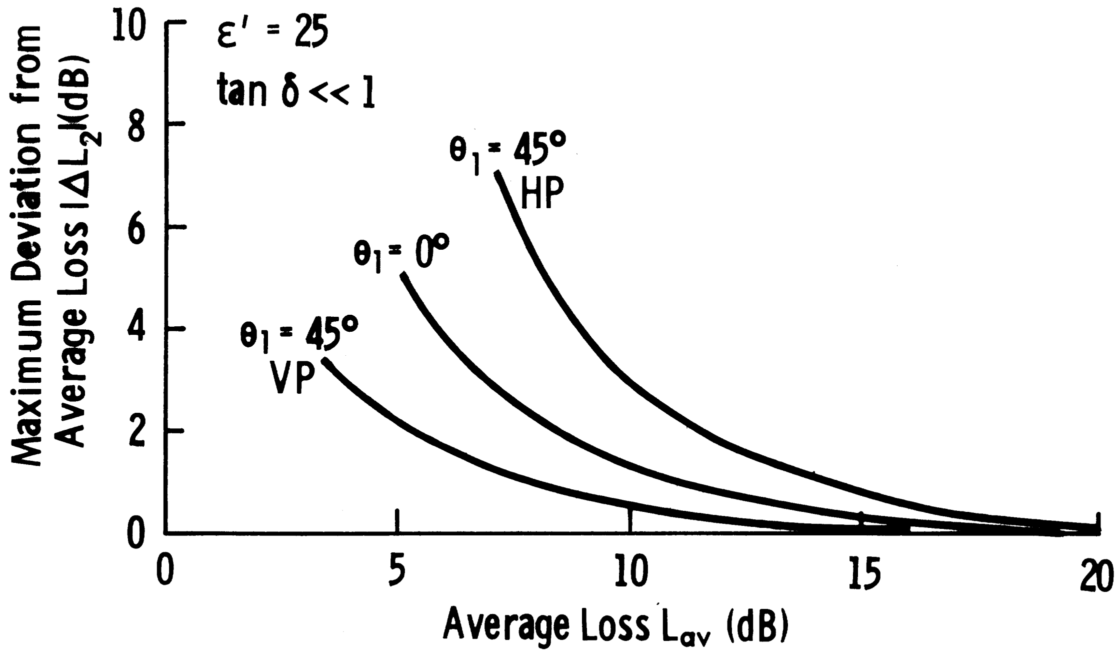

θ1 = 0°
θ1 = 15°
3 GHz
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
2 dB
11 cm
33 cm
11 cm
33 cm

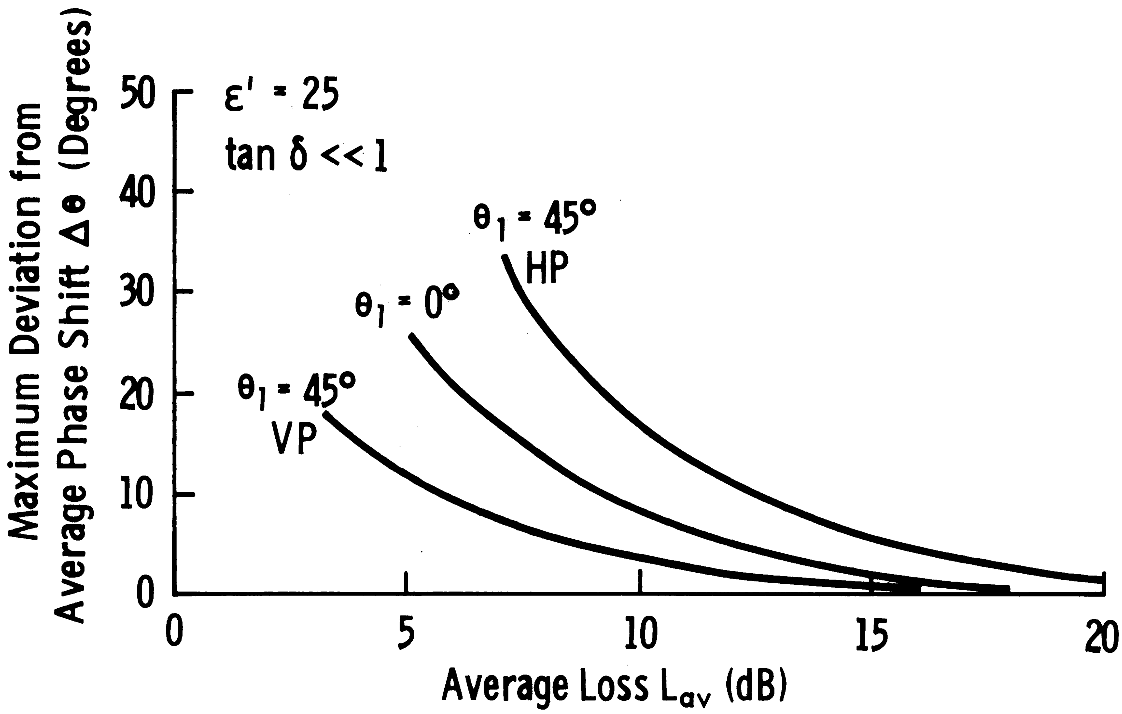


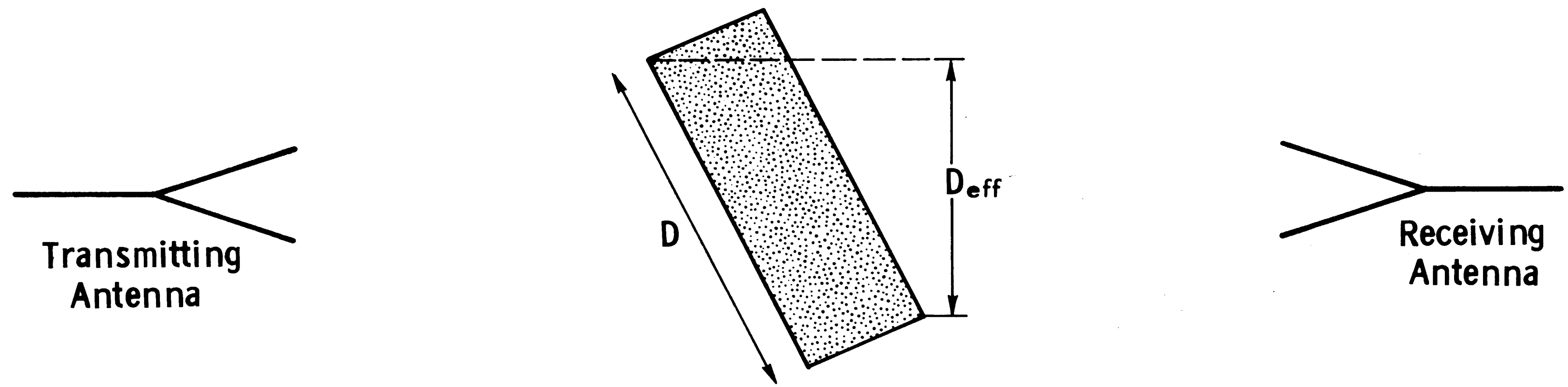
Amplitude
2 dB
Phase
10 Degrees
3 GHz
4 GHz
6 GHz
8 GHz
10 GHz
12.4 GHz
14 GHz
16 GHz
18 GHz
Sample Close to Transmitting Antenna
Sample Close to Receiving Antenna

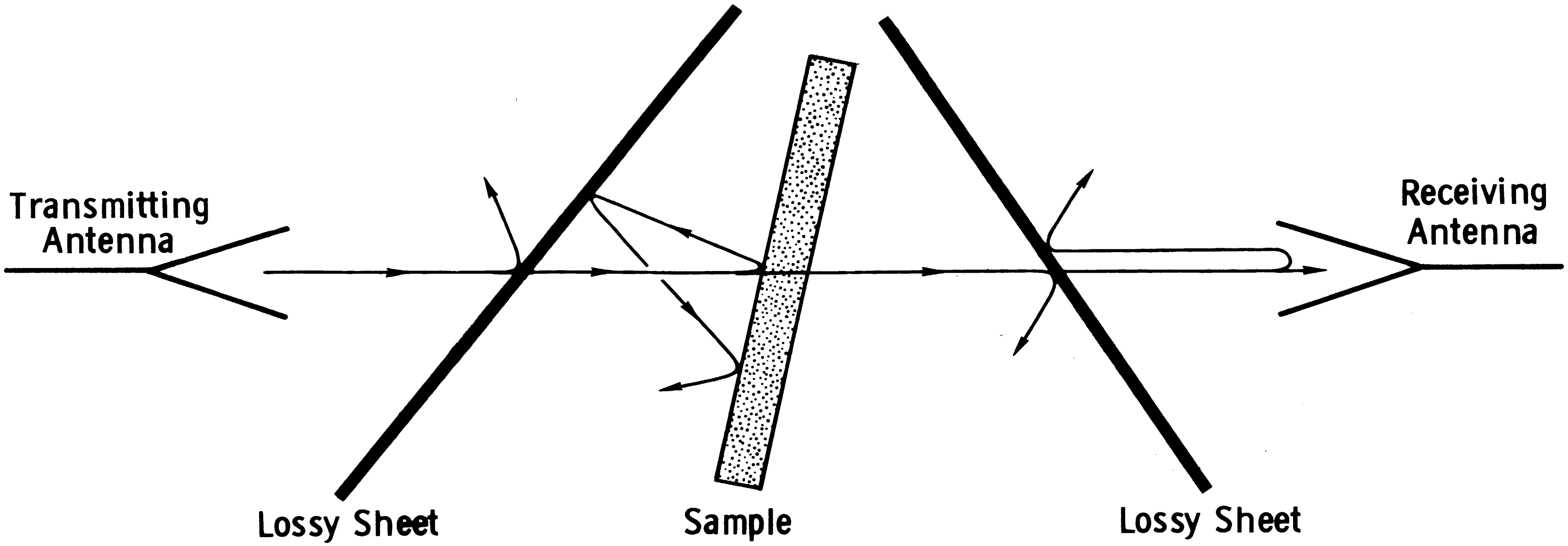

Start
2.5 - 8.5 GHz
8 - 12.5 GHz
12.5 - 18 GHz
1 GHz
1 dB

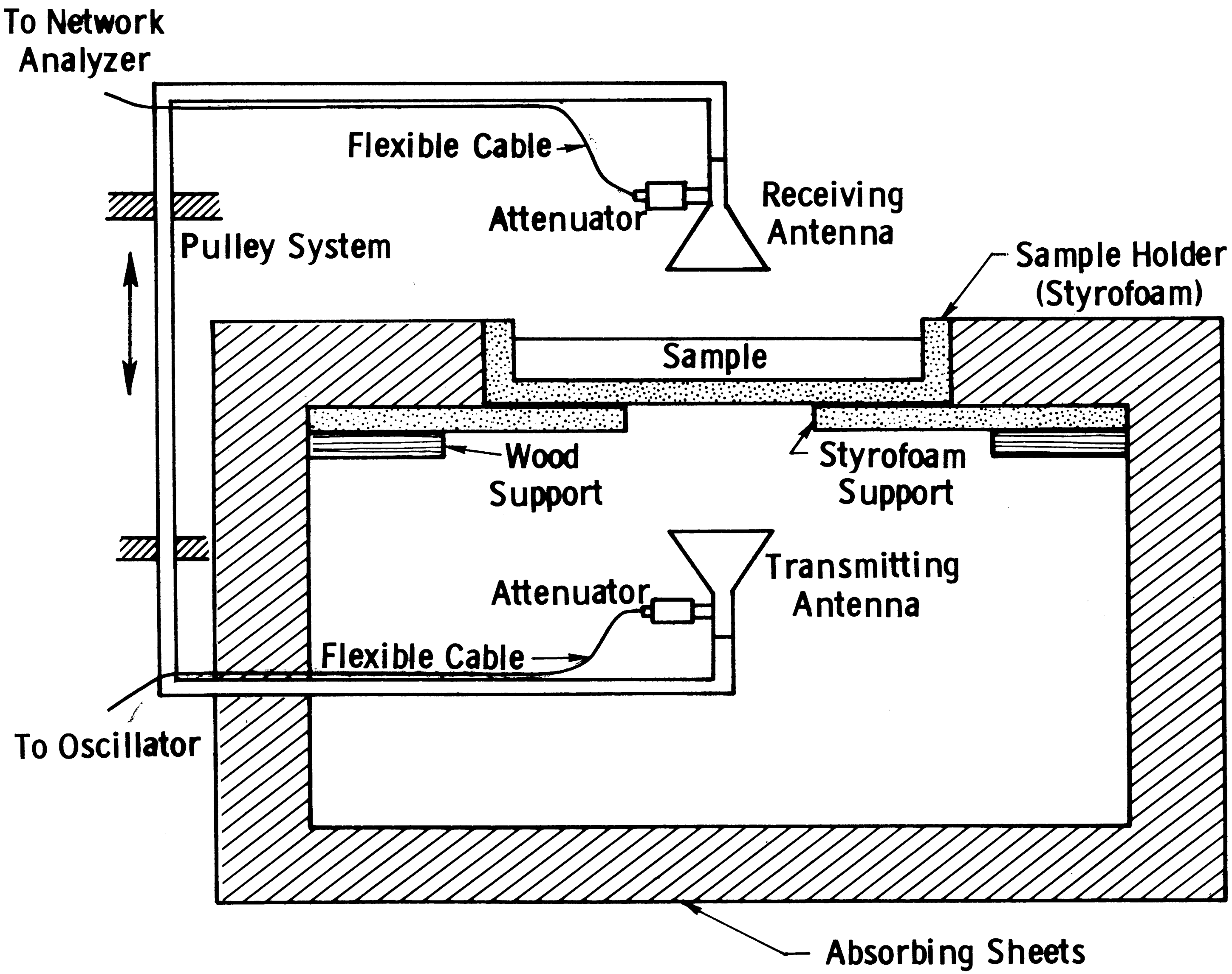

100
80
60
40
20
0
Sample Diameter D (cm)
L_T = 40 cm
20 cm
10 cm
0
4
8
12
16
20
Frequency f (GHz)

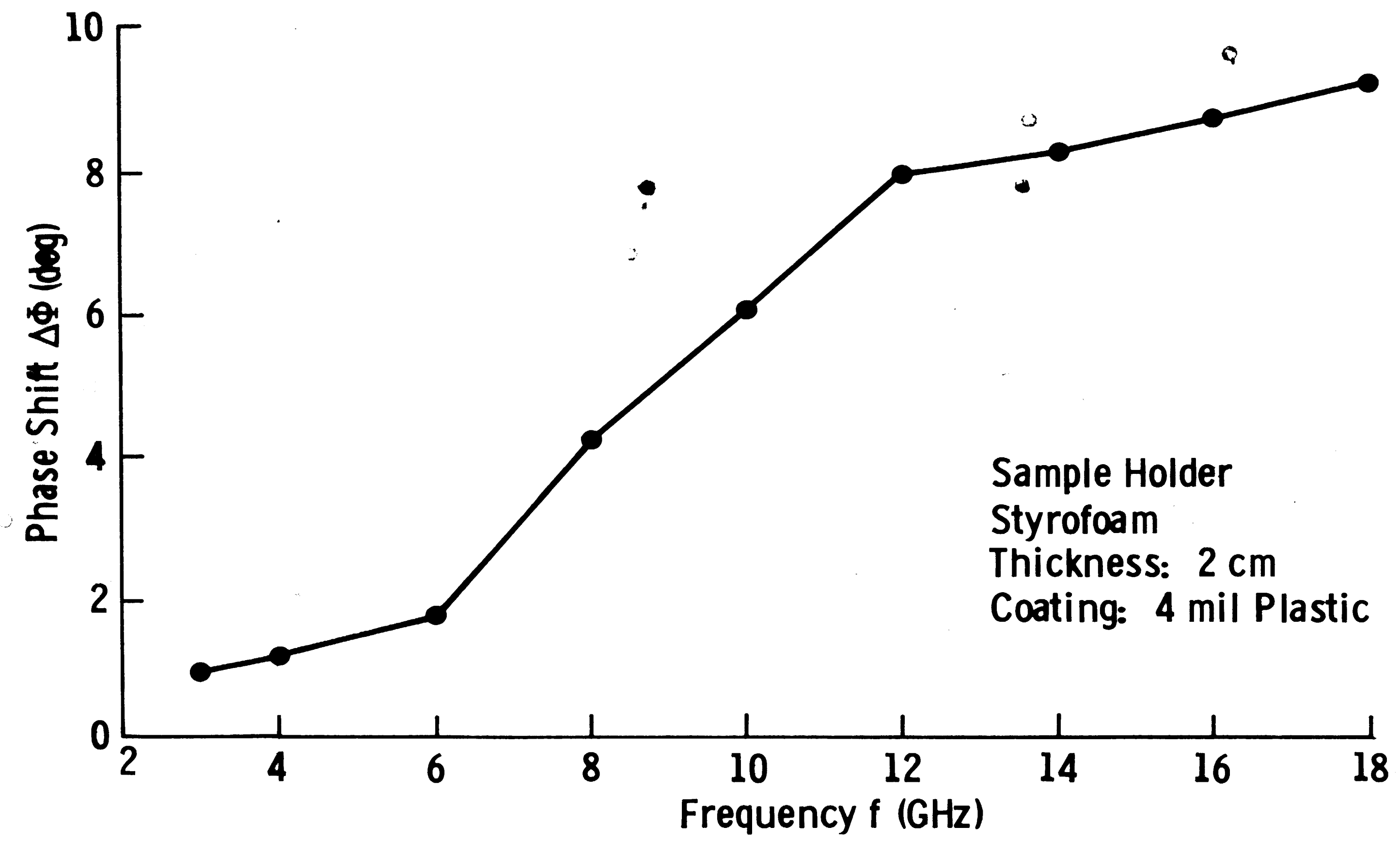

ε' = 25
tan δ << 1
θ1 = 45° HP
θ1 = 0°
θ1 = 45° VP
Maximum Deviation from Average Loss |ΔL2| (dB)
0
2
4
6
8
10
0
5
10
15
20
Average Loss Lav (dB)

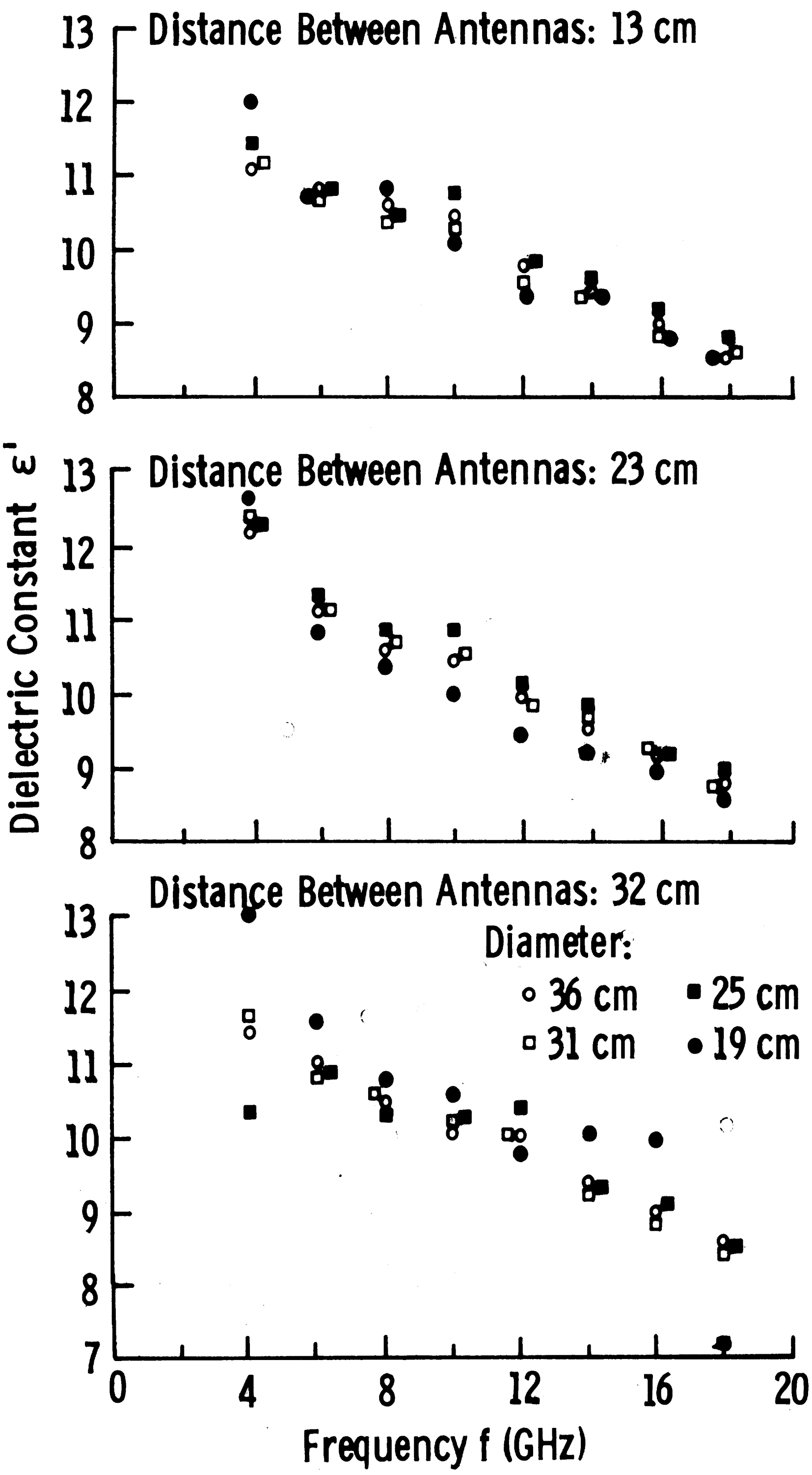

ε' = 25
tan δ << 1
θ1 = 45° HP
θ1 = 0°
θ1 = 45° VP
Maximum Deviation from Average Phase Shift Δθ (Degrees)
0
10
20
30
40
50
0
5
10
15
20
Average Loss Lav (dB)

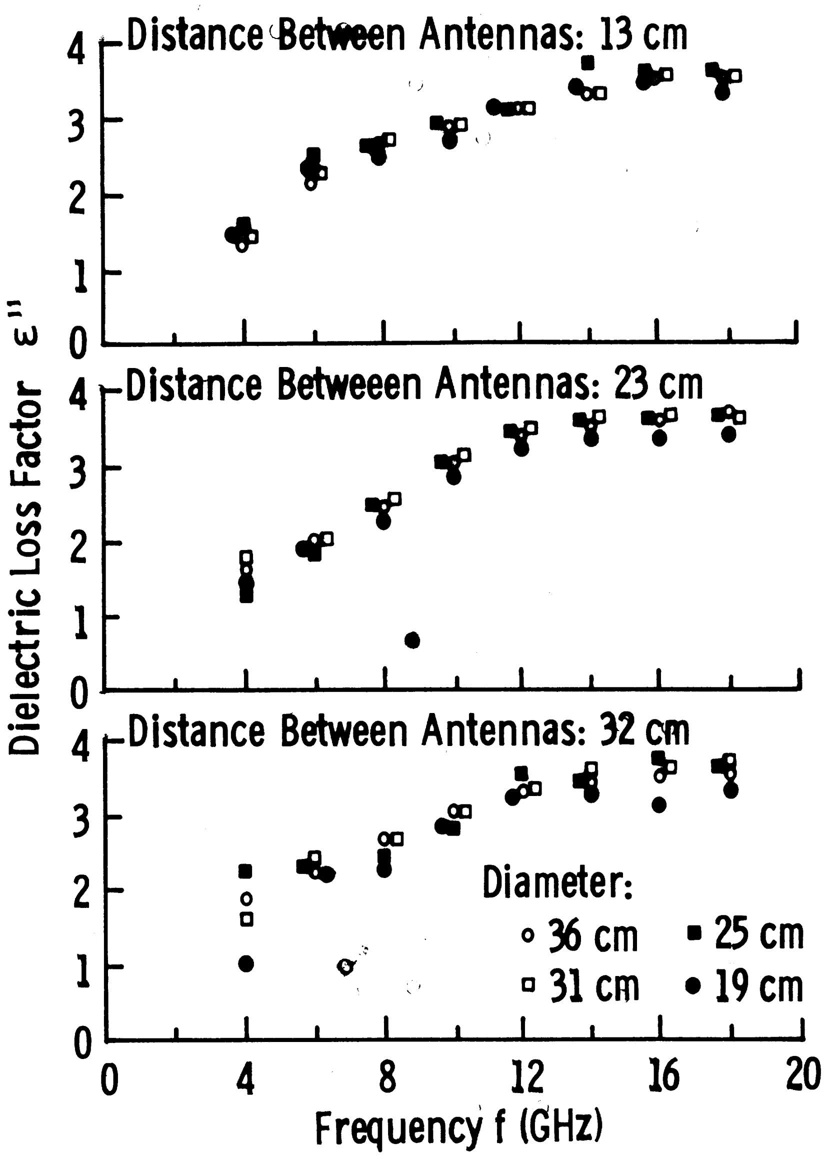

Transmitting
Antenna
D
D_{eff}
Receiving
Antenna


Transmitting
Antenna
Lossy Sheet
Sample
Lossy Sheet
Receiving
Antenna

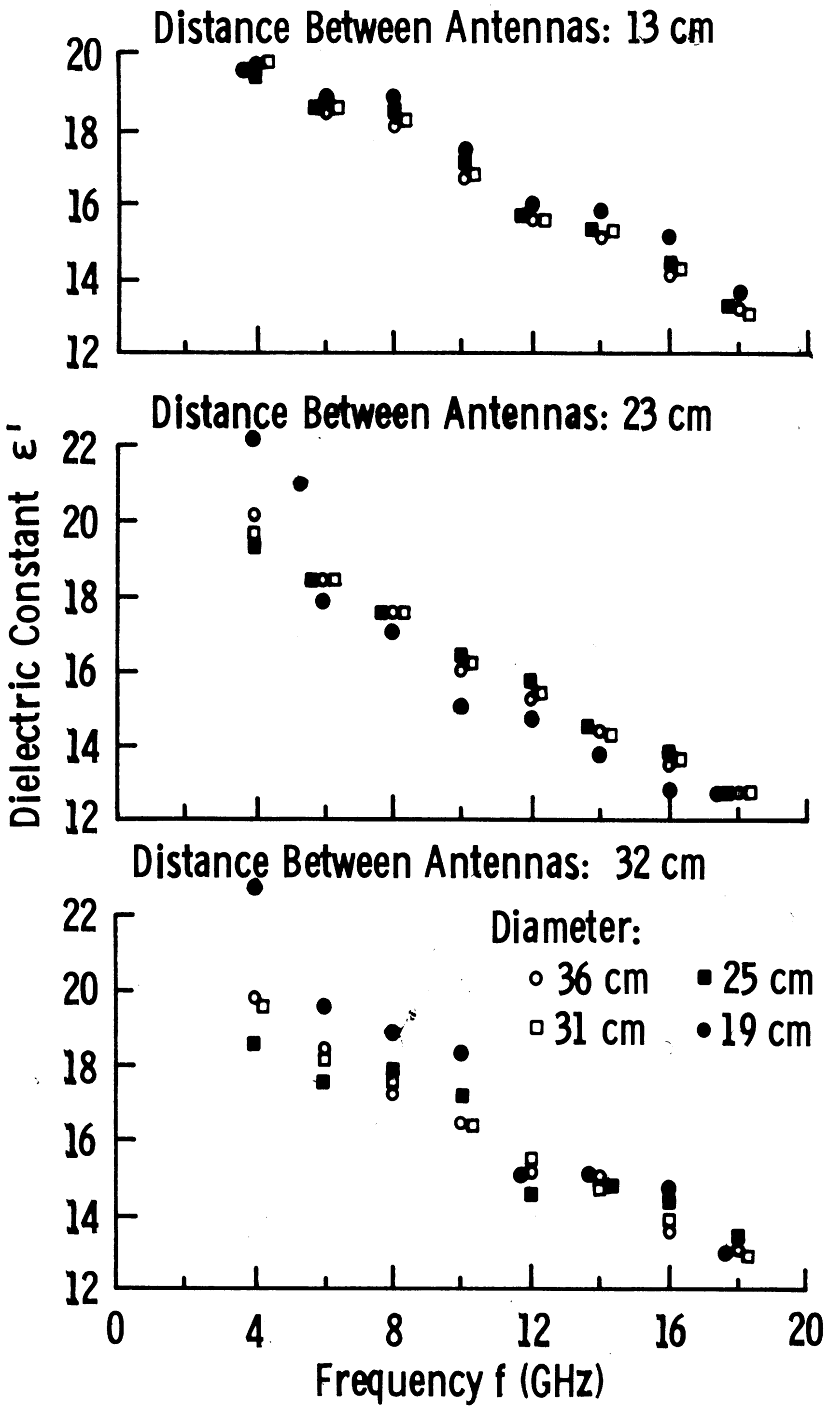

To Network Analyzer
Flexible Cable
Attenuator
Receiving Antenna
Pulley System
Sample Holder (Styrofoam)
Sample
Wood Support
Styrofoam Support
Transmitting Antenna
Attenuator
Flexible Cable
To Oscillator
Absorbing Sheets

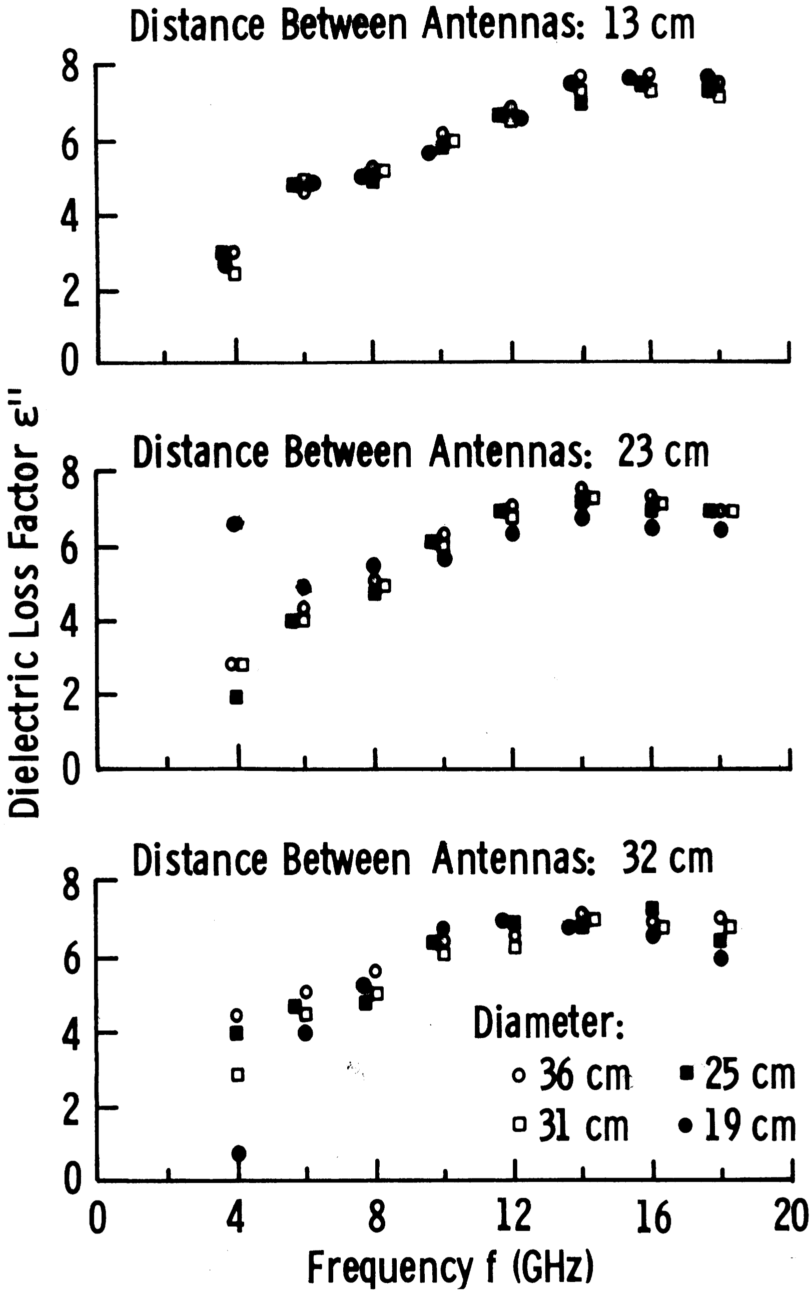

Phase Shift ΔΦ (deg)
10
8
6
4
2
0
2
4
6
8
10
12
14
16
18
Frequency f (GHz)
Sample Holder
Styrofoam
Thickness: 2 cm
Coating: 4 mil Plastic


Distance Between Antennas: 13 cm
Distance Between Antennas: 23 cm
Distance Between Antennas: 32 cm
Diameter:
36 cm
25 cm
31 cm
19 cm
Dielectric Constant ε'
Frequency f (GHz)
13
12
11
10
9
8
7
0
4
8
12
16
20

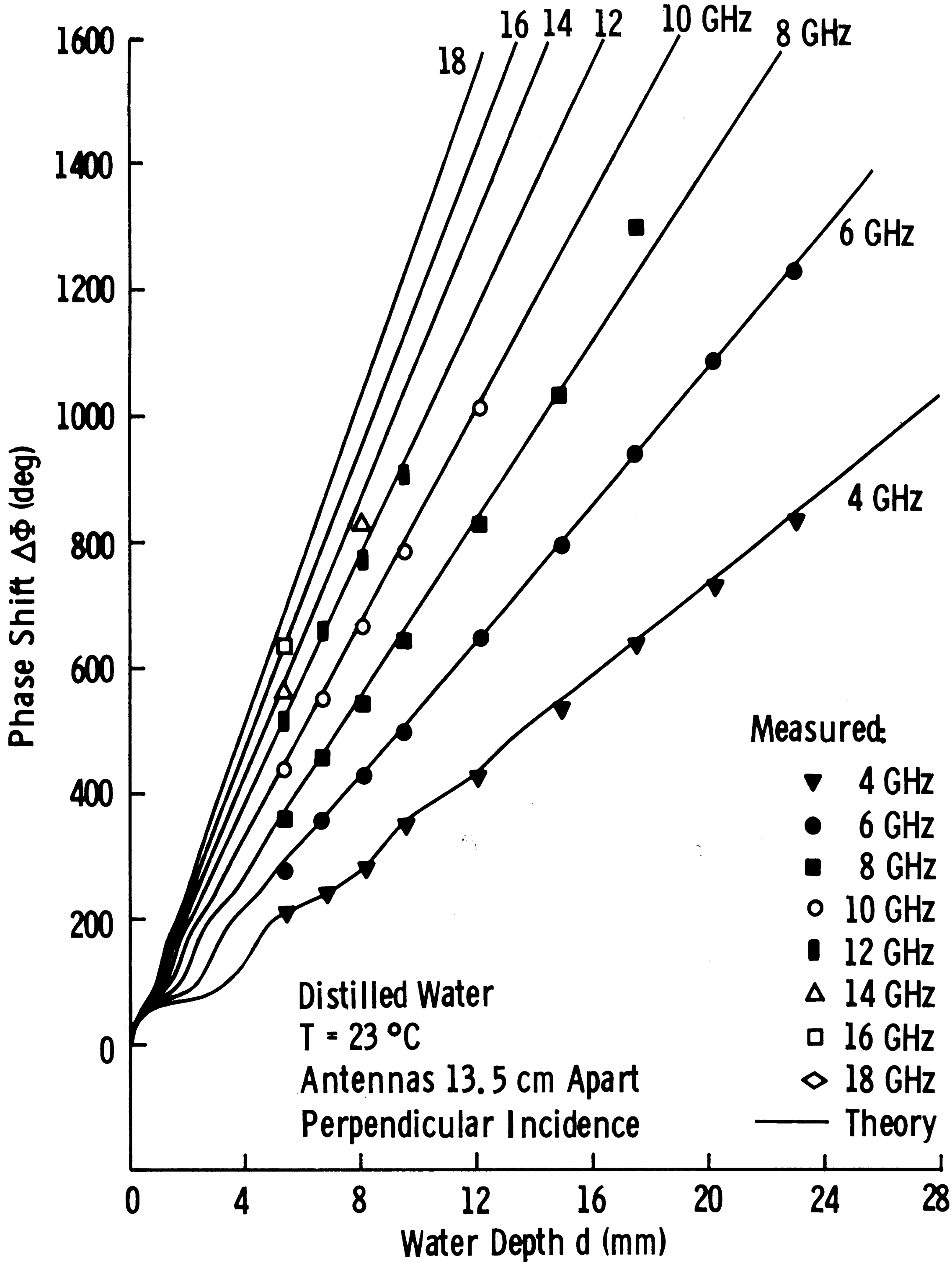


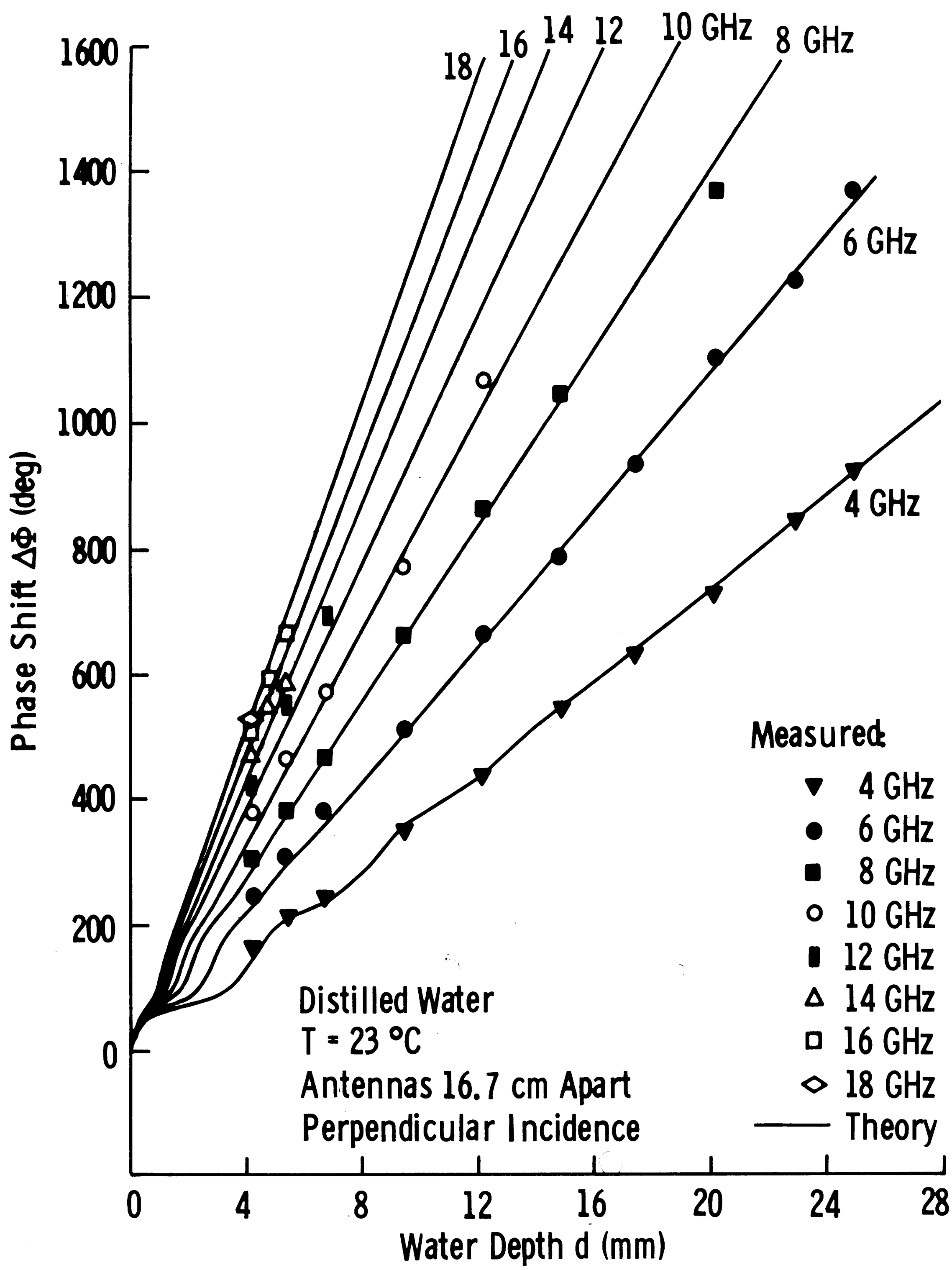
Distance Between Antennas: 13 cm
Distance Betweeen Antennas: 23 cm
Distance Between Antennas: 32 cm
Dielectric Loss Factor ε''
Frequency f (GHz)
0
4
8
12
16
20
0
1
2
3
4
Diameter:
36 cm
25 cm
31 cm
19 cm


Distance Between Antennas: 13 cm
Distance Between Antennas: 23 cm
Distance Between Antennas: 32 cm
Dielectric Constant ε'
Diameter:
36 cm
25 cm
31 cm
19 cm
Frequency f (GHz)

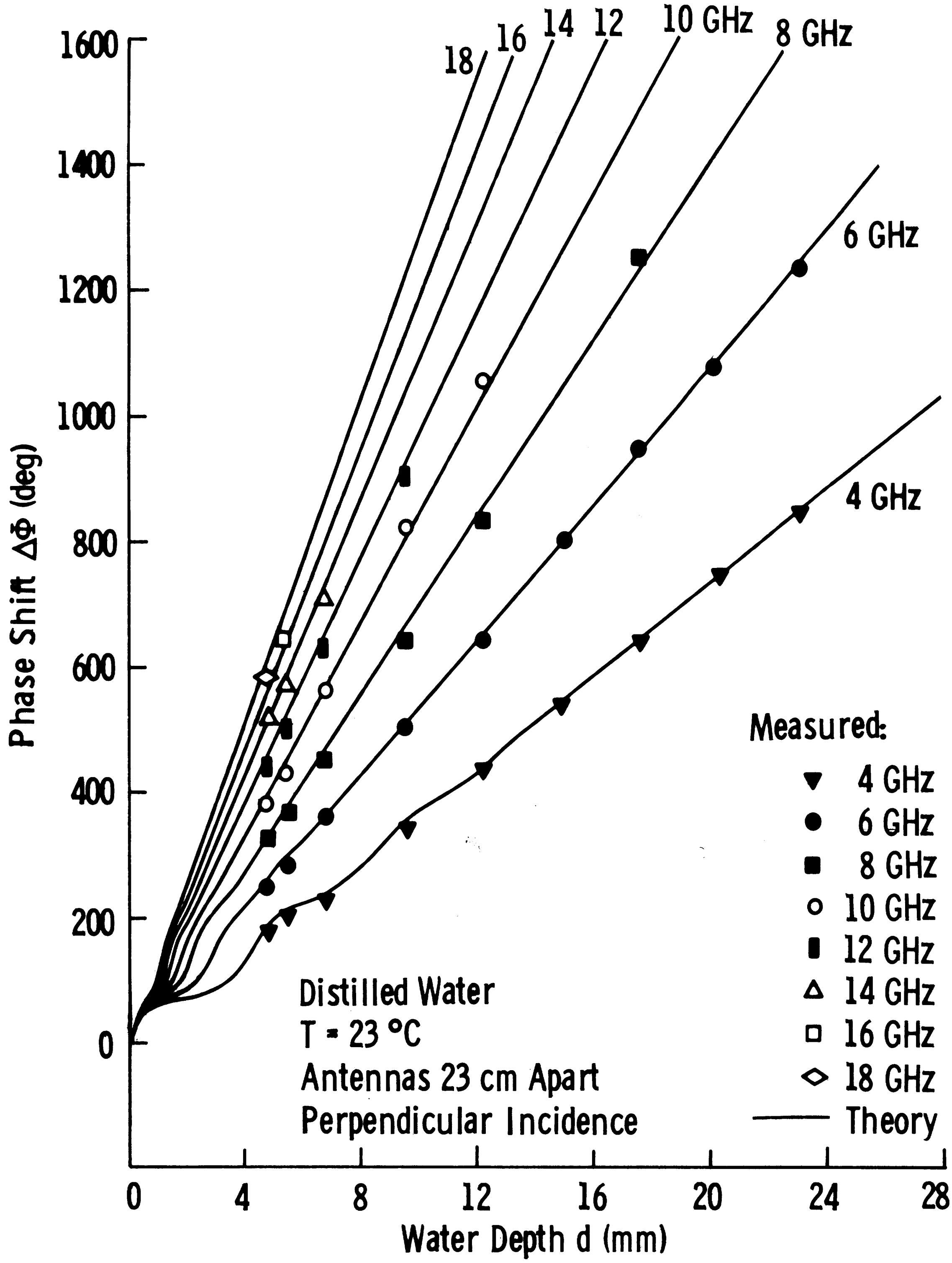


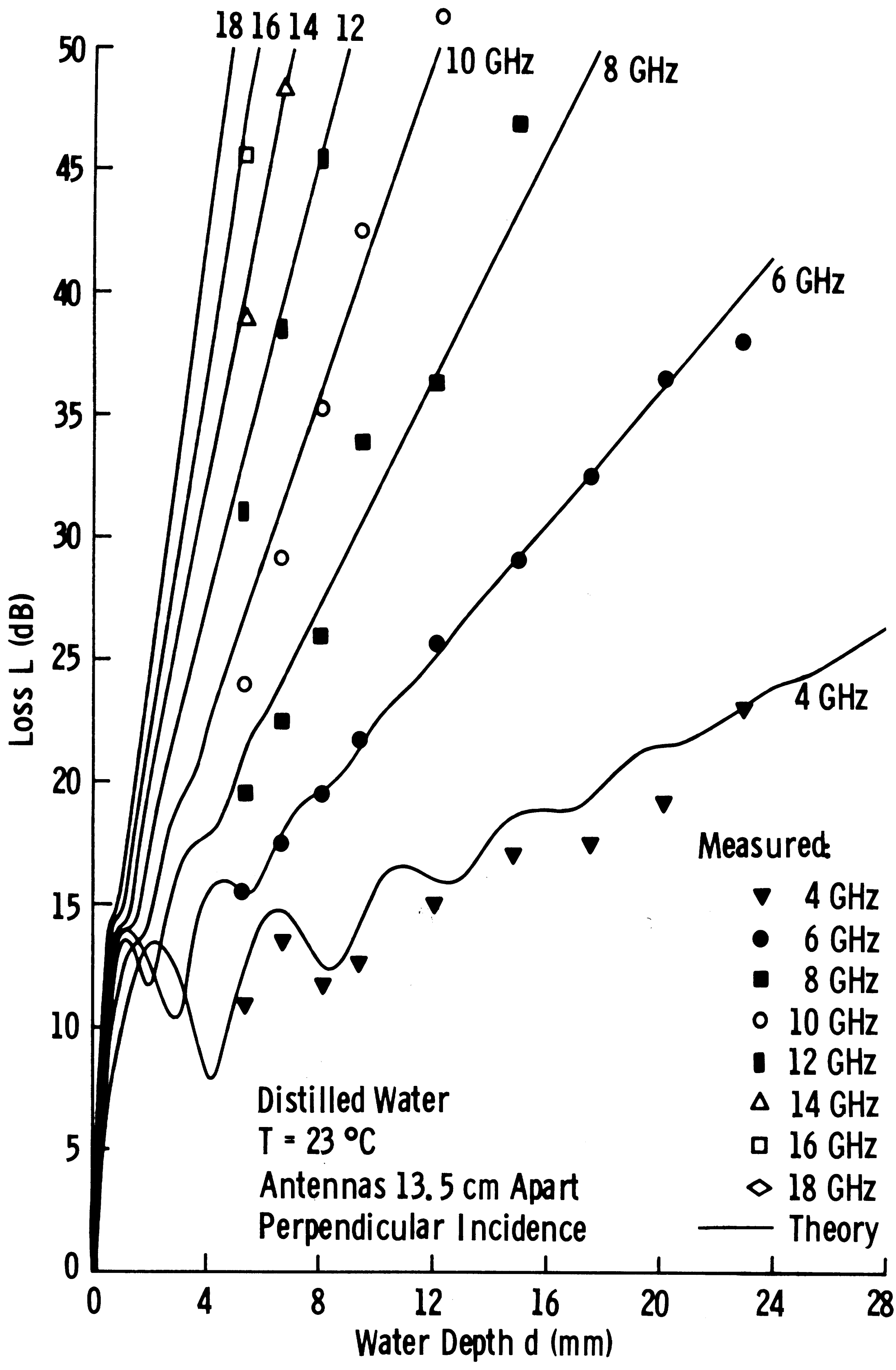
Distance Between Antennas: 13 cm
Distance Between Antennas: 23 cm
Distance Between Antennas: 32 cm
Dielectric Loss Factor ε''
Diameter:
○ 36 cm
■ 25 cm
□ 31 cm
● 19 cm
0
2
4
6
8
0
4
8
12
16
20
Frequency f (GHz)

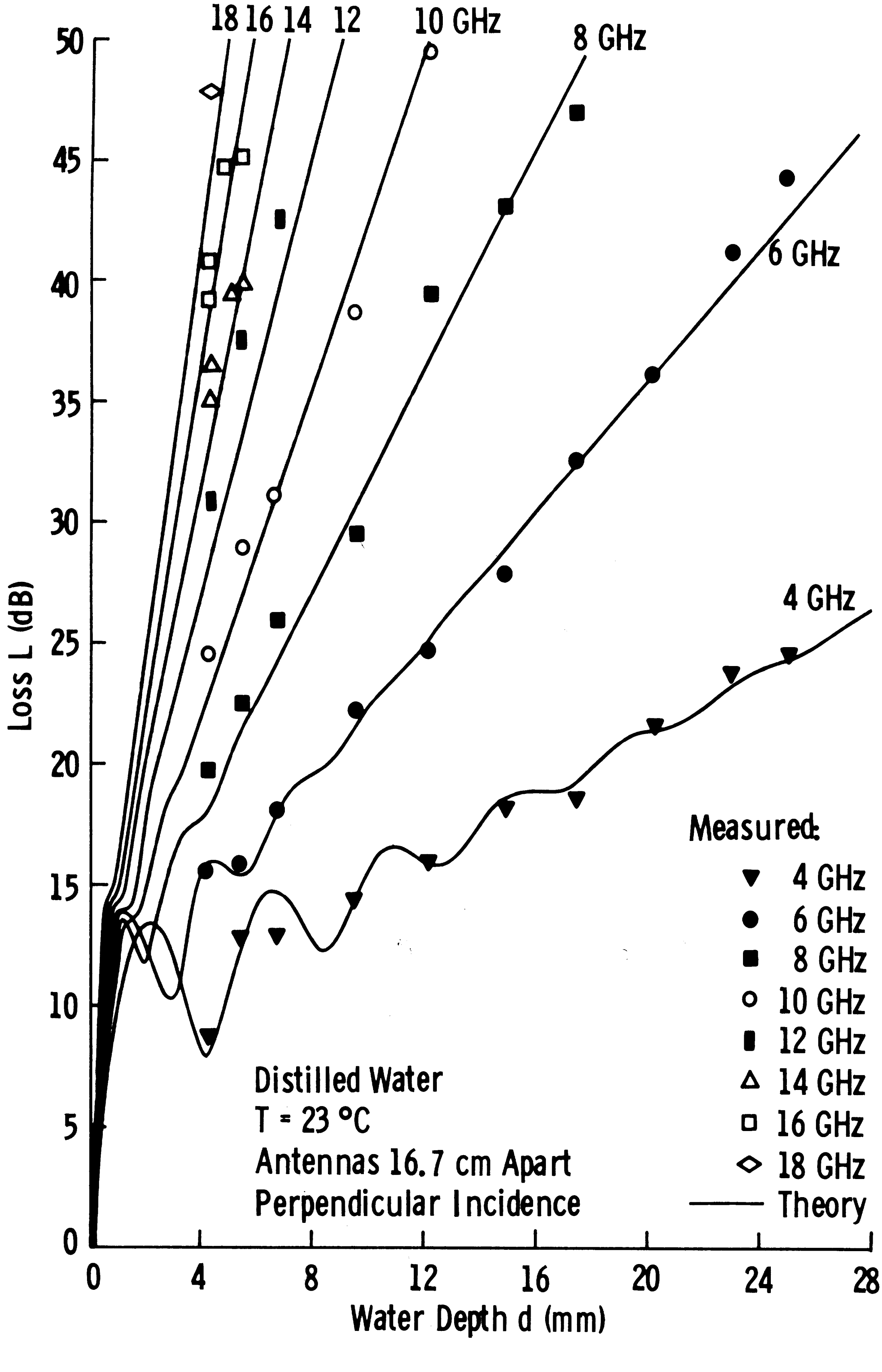

1600
1400
1200
1000
800
600
400
200
0
Phase Shift ΔΦ (deg)
0
4
8
12
16
20
24
28
Water Depth d (mm)
18
16
14
12
10 GHz
8 GHz
6 GHz
4 GHz
Distilled Water
T = 23 °C
Antennas 13.5 cm Apart
Perpendicular Incidence
Measured:
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
Theory



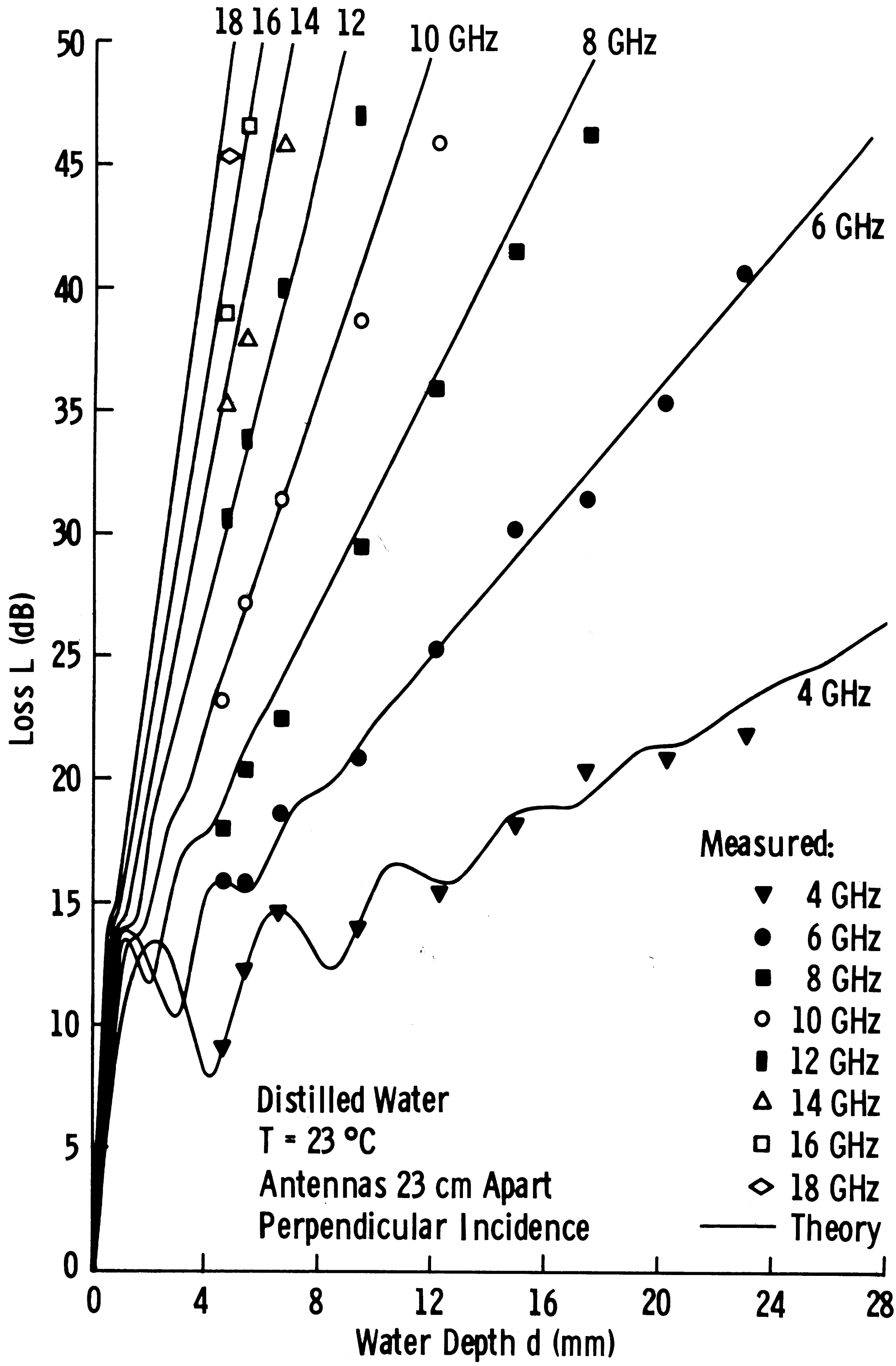
18
16
14
12
10 GHz
8 GHz
6 GHz
4 GHz
1600
1400
1200
1000
800
600
400
200
0
Phase Shift ΔΦ (deg)
Measured:
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
Theory
Distilled Water
T = 23 °C
Antennas 16.7 cm Apart
Perpendicular Incidence
0
4
8
12
16
20
24
28
Water Depth d (mm)

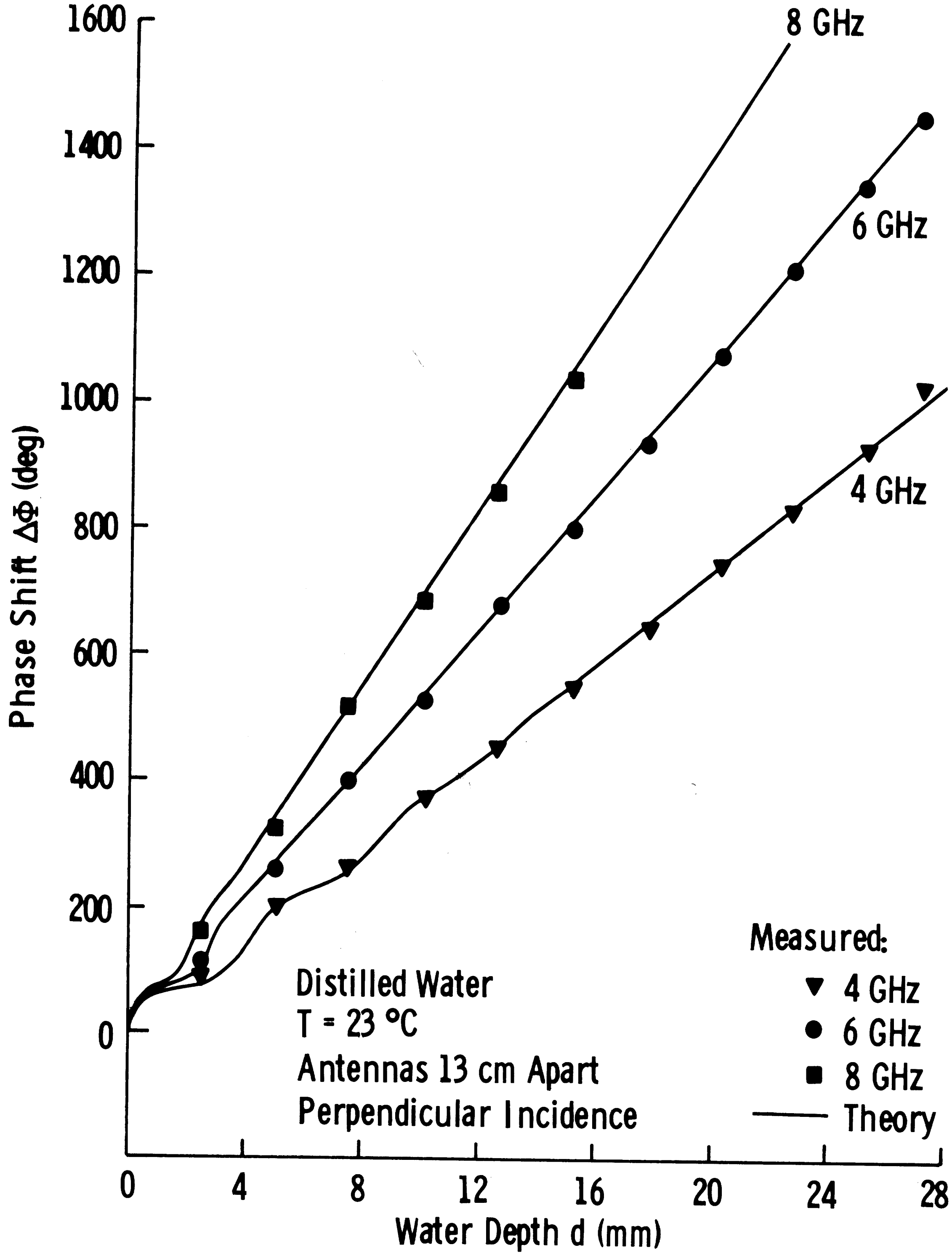

18
16
14
12
10 GHz
8 GHz
6 GHz
4 GHz
1600
1400
1200
1000
800
600
400
200
0
Phase Shift ΔΦ (deg)
0
4
8
12
16
20
24
28
Water Depth d (mm)
Distilled Water
T = 23 °C
Antennas 23 cm Apart
Perpendicular Incidence
Measured:
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
Theory

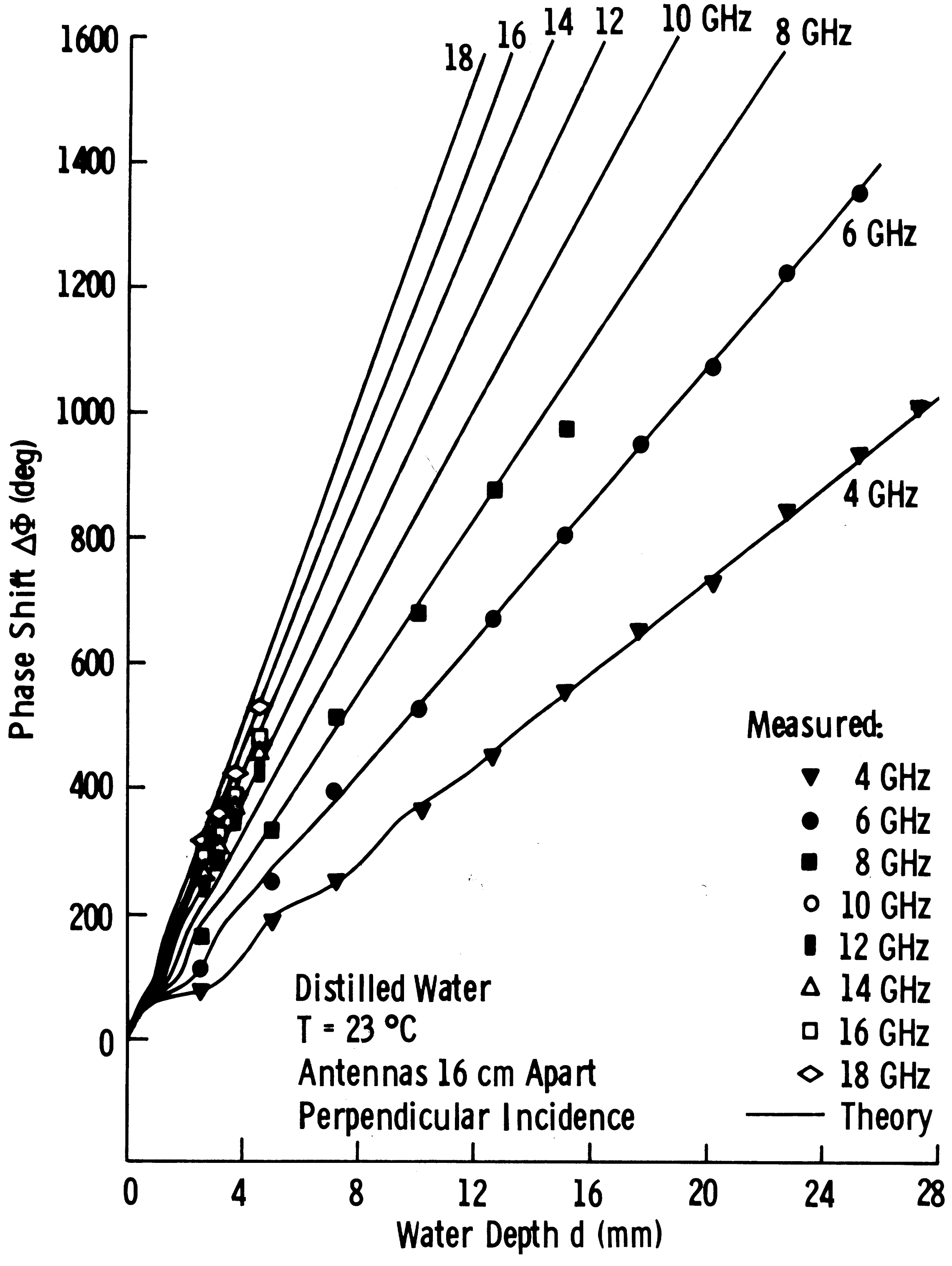

18 16 14 12
10 GHz
8 GHz
6 GHz
4 GHz
Loss L (dB)
50
45
40
35
30
25
20
15
10
5
0
0
4
8
12
16
20
24
28
Water Depth d (mm)
Distilled Water
T = 23 °C
Antennas 13.5 cm Apart
Perpendicular Incidence
Measured:
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
Theory

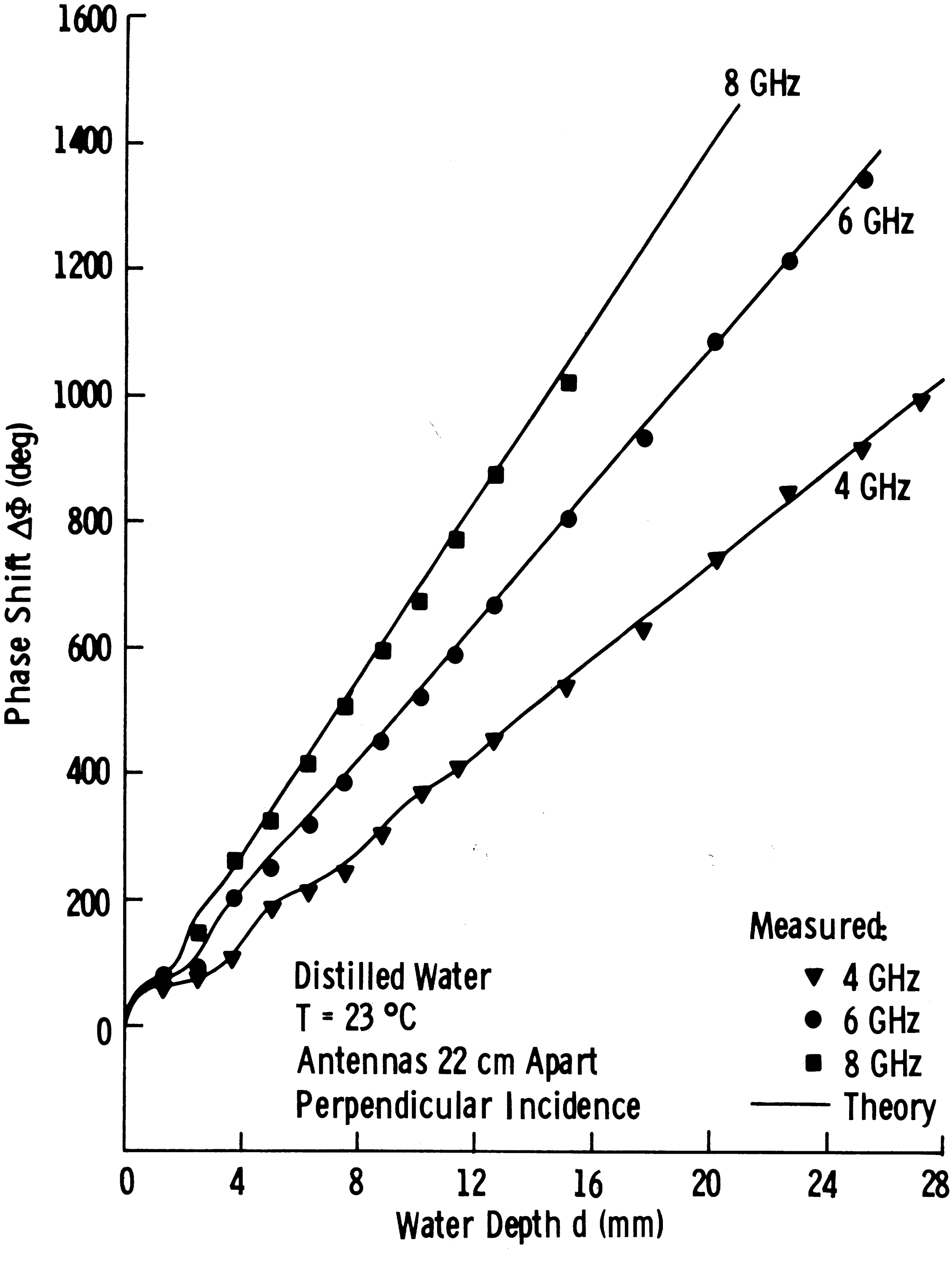


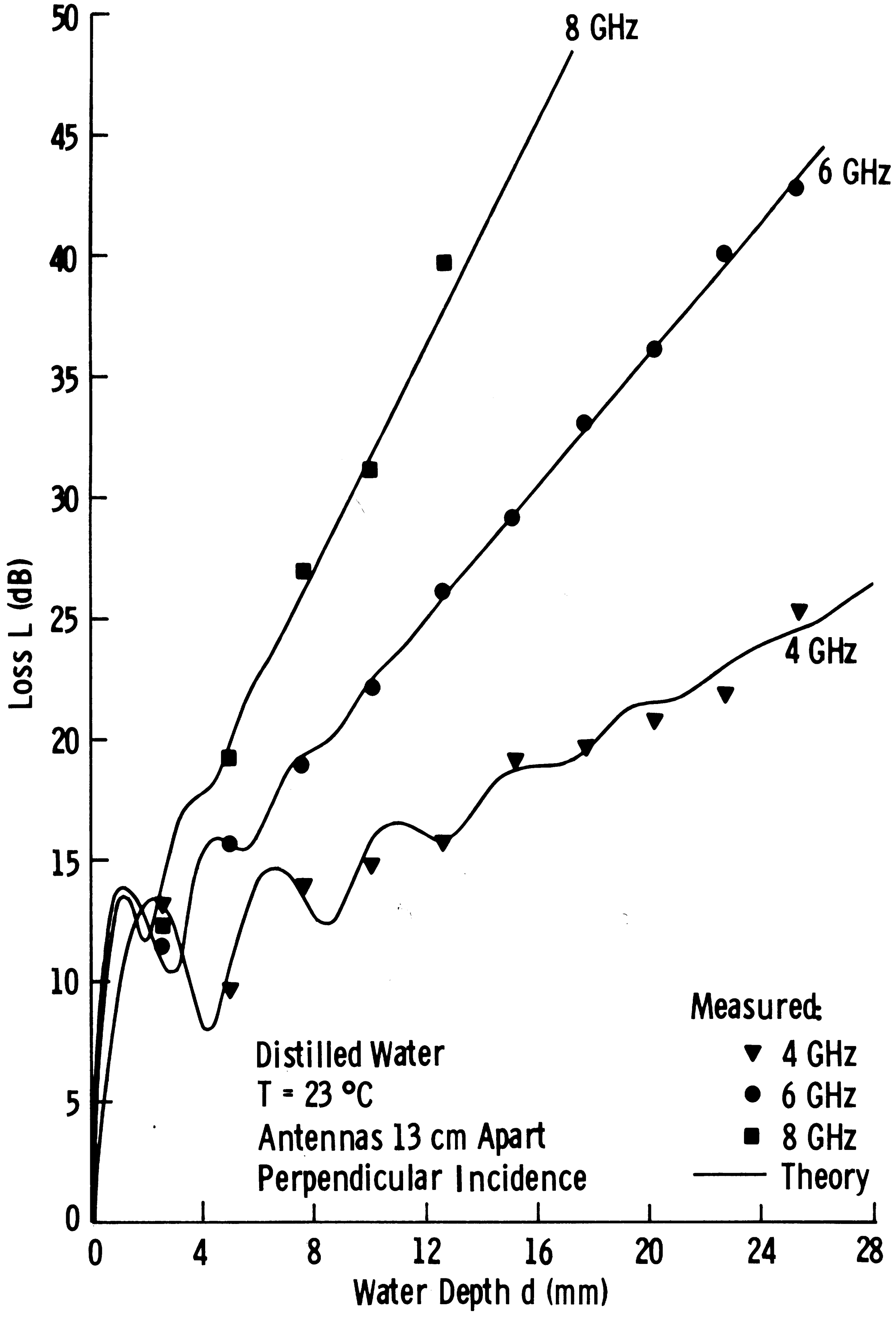
18 16 14 12 10 GHz
8 GHz
6 GHz
4 GHz
Loss L (dB)
50
45
40
35
30
25
20
15
10
5
0
Water Depth d (mm)
0
4
8
12
16
20
24
28
Measured:
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
Theory
Distilled Water
T = 23 °C
Antennas 16.7 cm Apart
Perpendicular Incidence


18 16 14 12
10 GHz
8 GHz
6 GHz
4 GHz
Loss L (dB)
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 °C
Antennas 23 cm Apart
Perpendicular Incidence

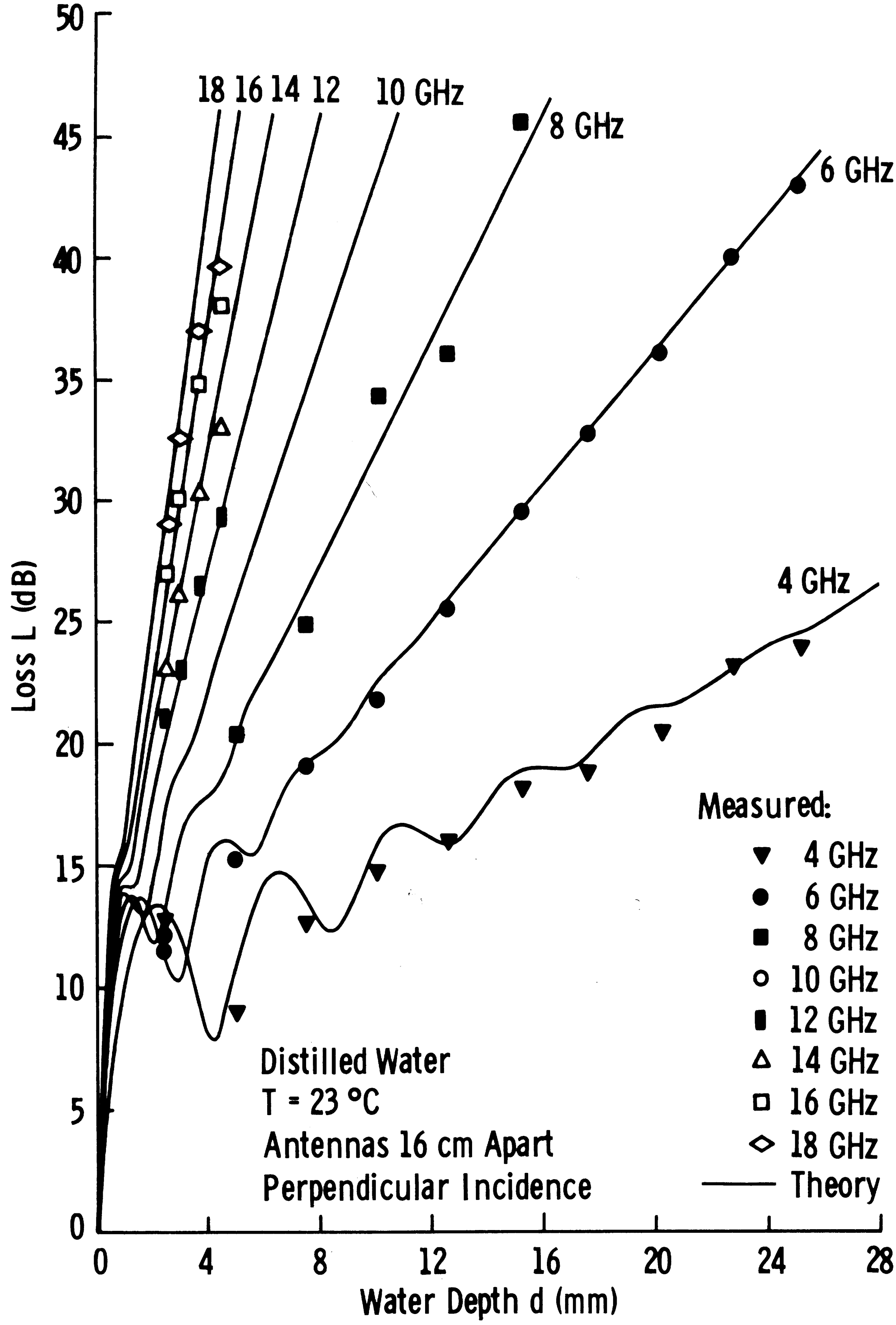

1600
1400
1200
1000
800
600
400
200
0
Phase Shift ΔΦ (deg)
8 GHz
6 GHz
4 GHz
Distilled Water
T = 23 °C
Antennas 13 cm Apart
Perpendicular Incidence
Measured:
4 GHz
6 GHz
8 GHz
Theory
0
4
8
12
16
20
24
28
Water Depth d (mm)


18
16
14
12
10 GHz
8 GHz
6 GHz
4 GHz
Phase Shift ΔΦ (deg)
1600
1400
1200
1000
800
600
400
200
0
Measured:
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
Theory
Distilled Water
T = 23 °C
Antennas 16 cm Apart
Perpendicular Incidence
0
4
8
12
16
20
24
28
Water Depth d (mm)

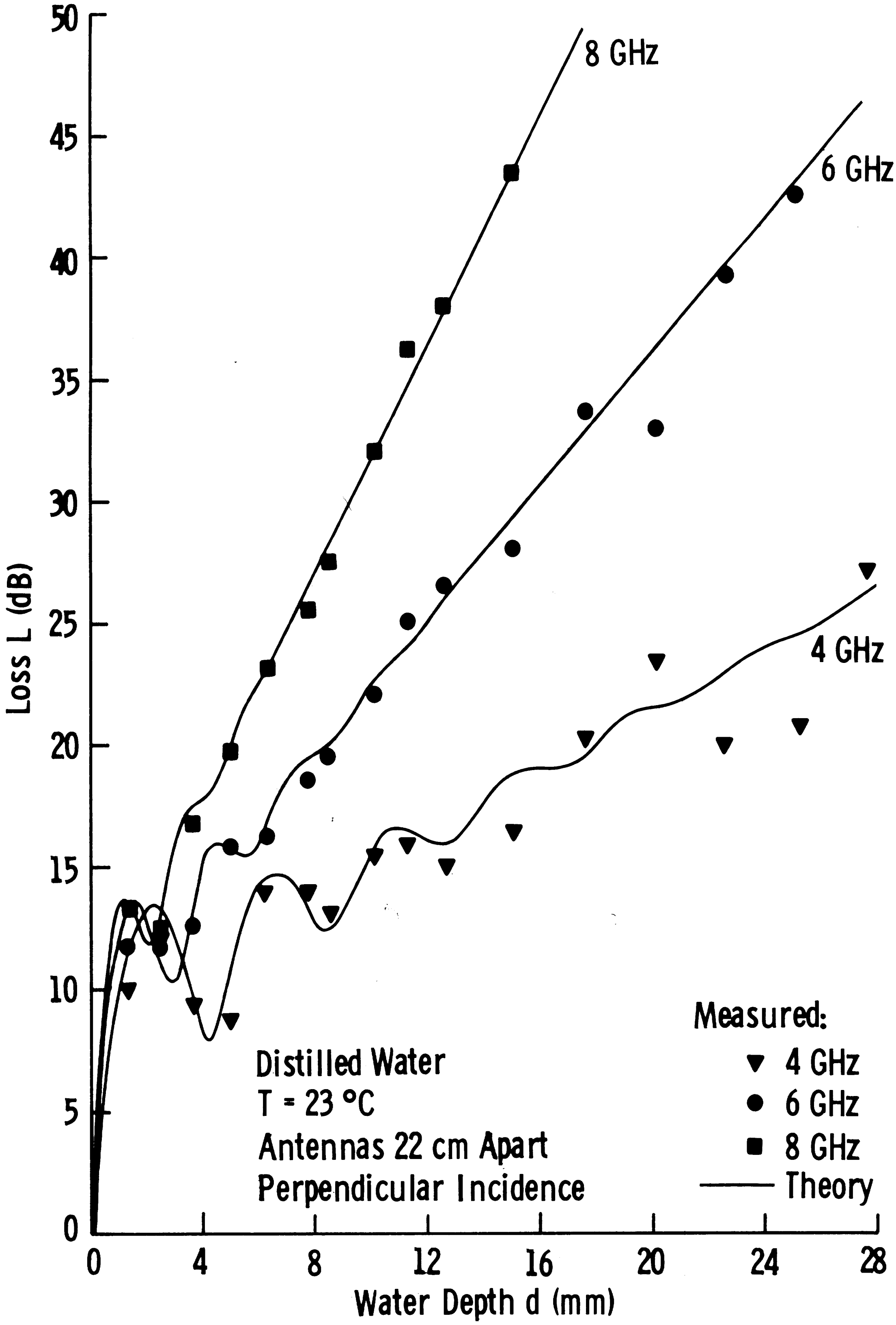

1600
1400
1200
1000
800
600
400
200
0
Phase Shift ΔΦ (deg)
8 GHz
6 GHz
4 GHz
Distilled Water
T = 23 °C
Antennas 22 cm Apart
Perpendicular Incidence
Measured:
4 GHz
6 GHz
8 GHz
Theory
0
4
8
12
16
20
24
28
Water Depth d (mm)

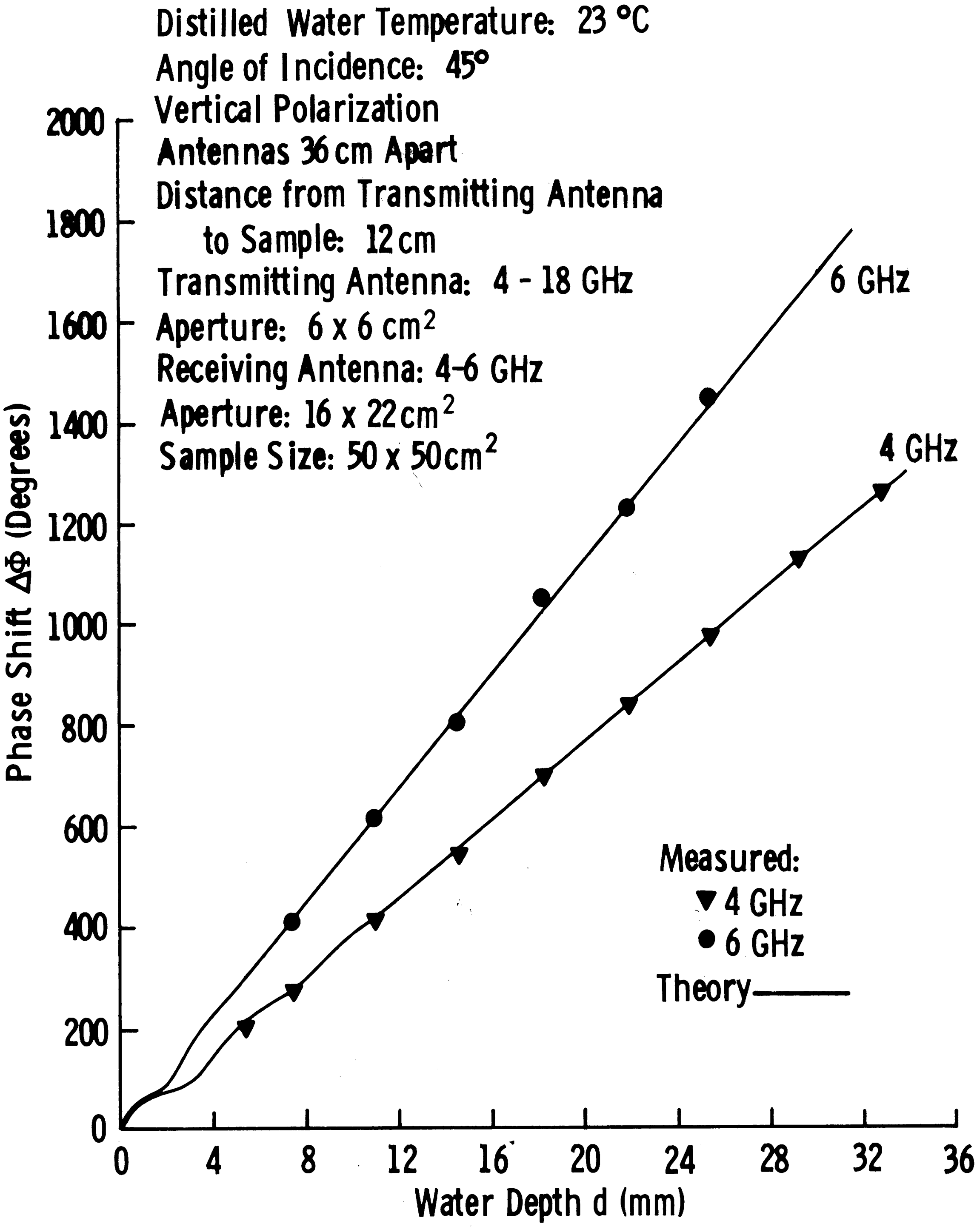


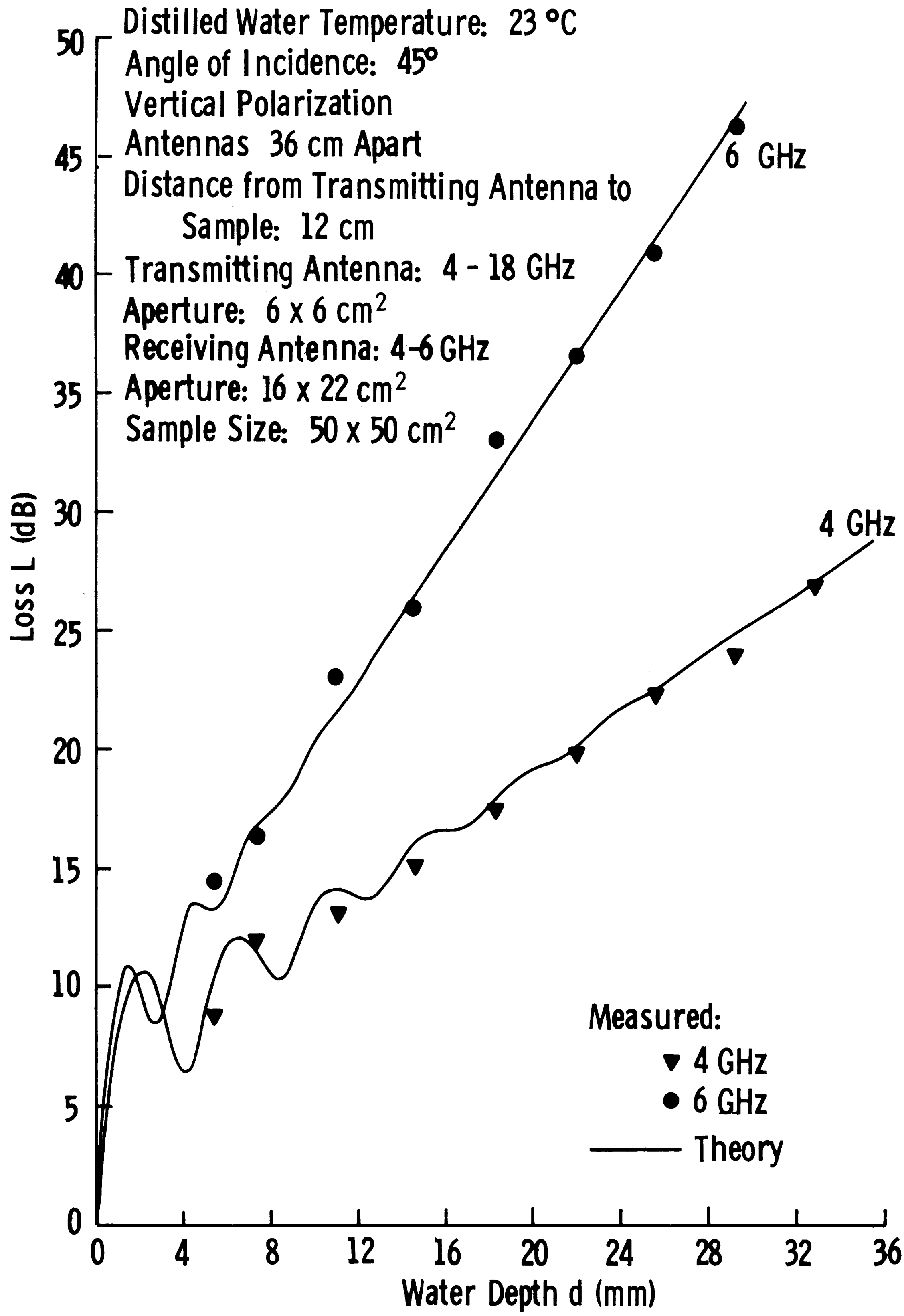
8 GHz
6 GHz
4 GHz
Loss L (dB)
50
45
40
35
30
25
20
15
10
5
0
0
4
8
12
16
20
24
28
Water Depth d (mm)
Distilled Water
T = 23 °C
Antennas 13 cm Apart
Perpendicular Incidence
Measured:
4 GHz
6 GHz
8 GHz
Theory

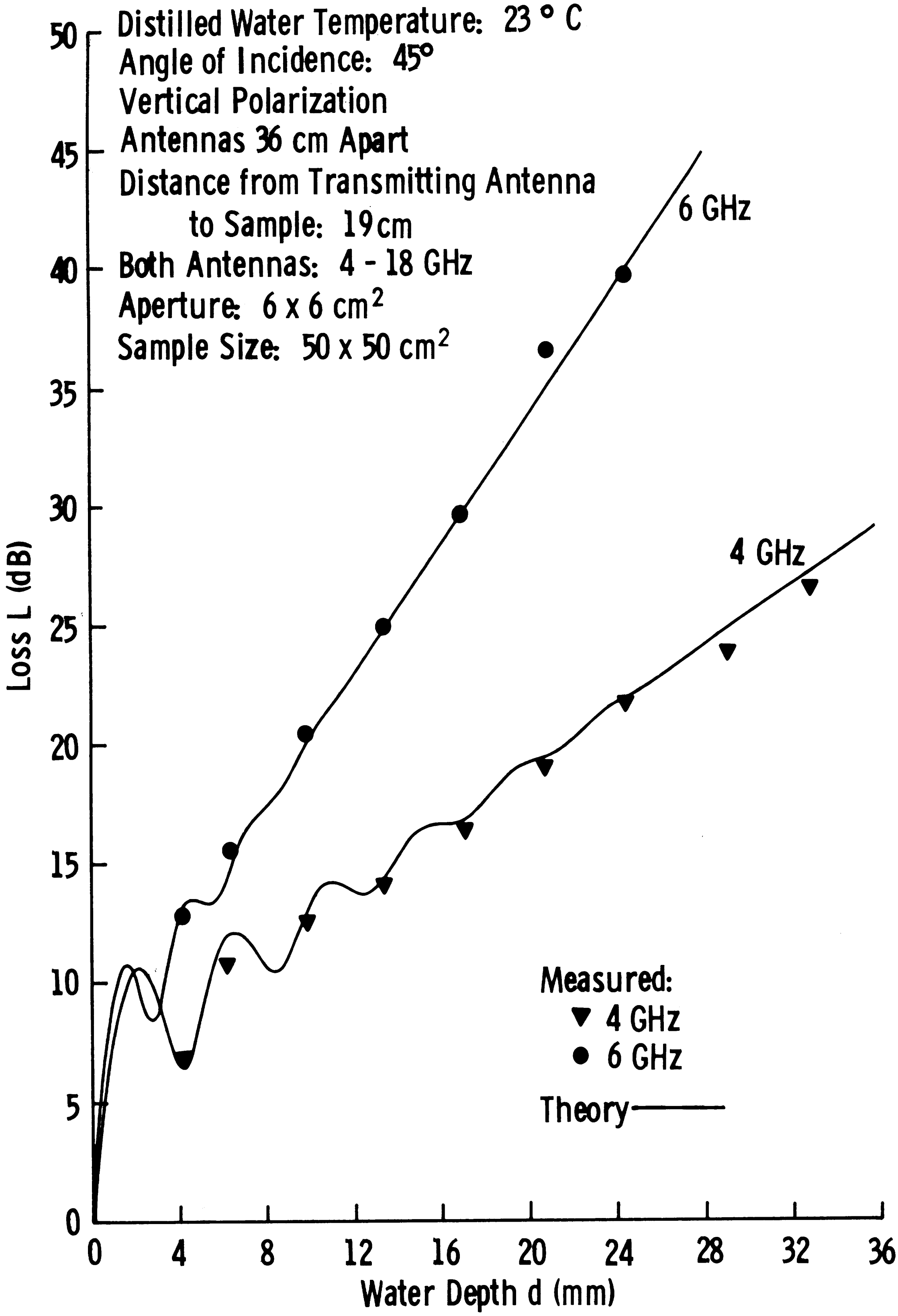


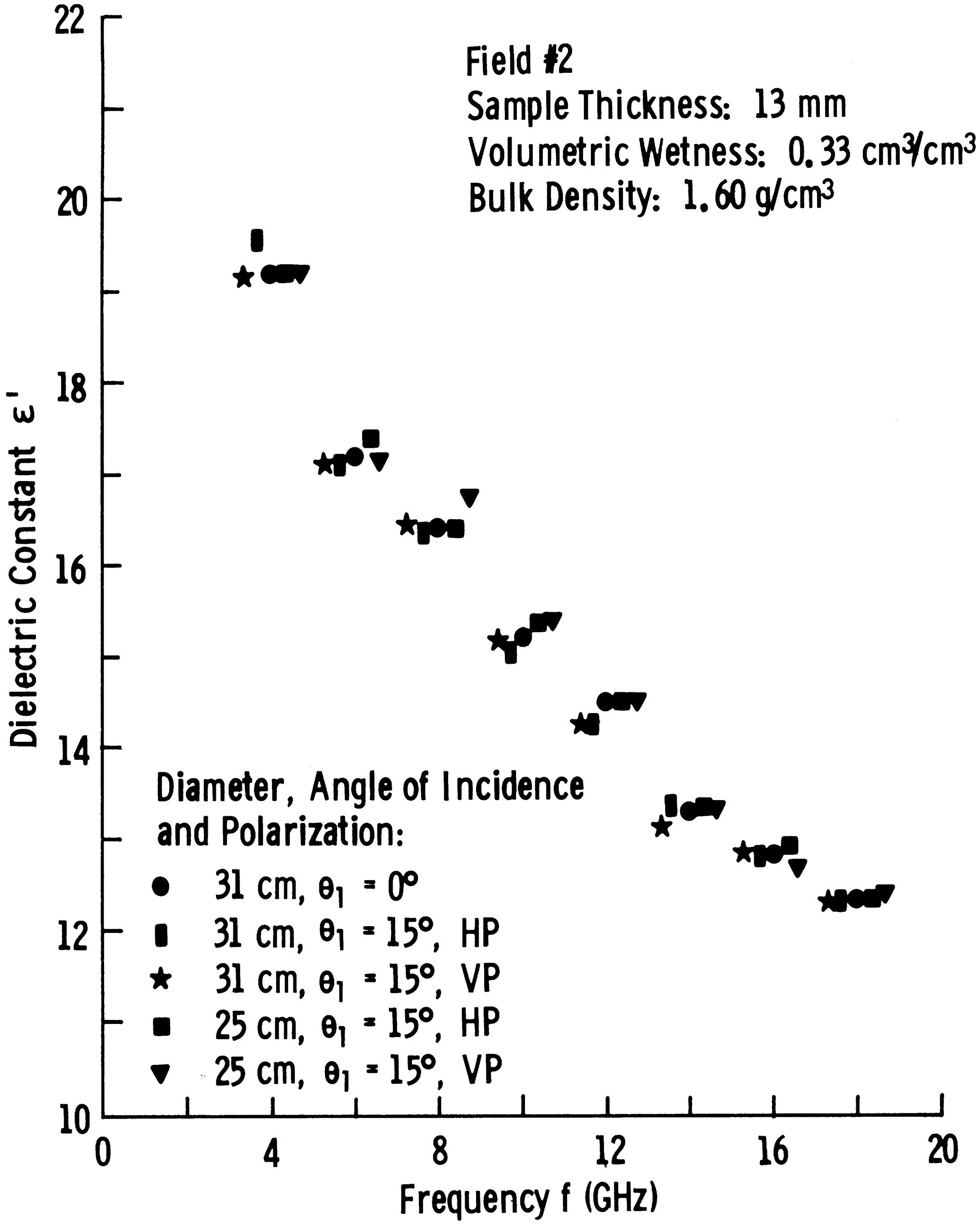
18 16 14 12 10 GHz
8 GHz
6 GHz
4 GHz
Loss L (dB)
Water Depth d (mm)
Measured:
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
Theory
Distilled Water
T = 23 °C
Antennas 16 cm Apart
Perpendicular Incidence

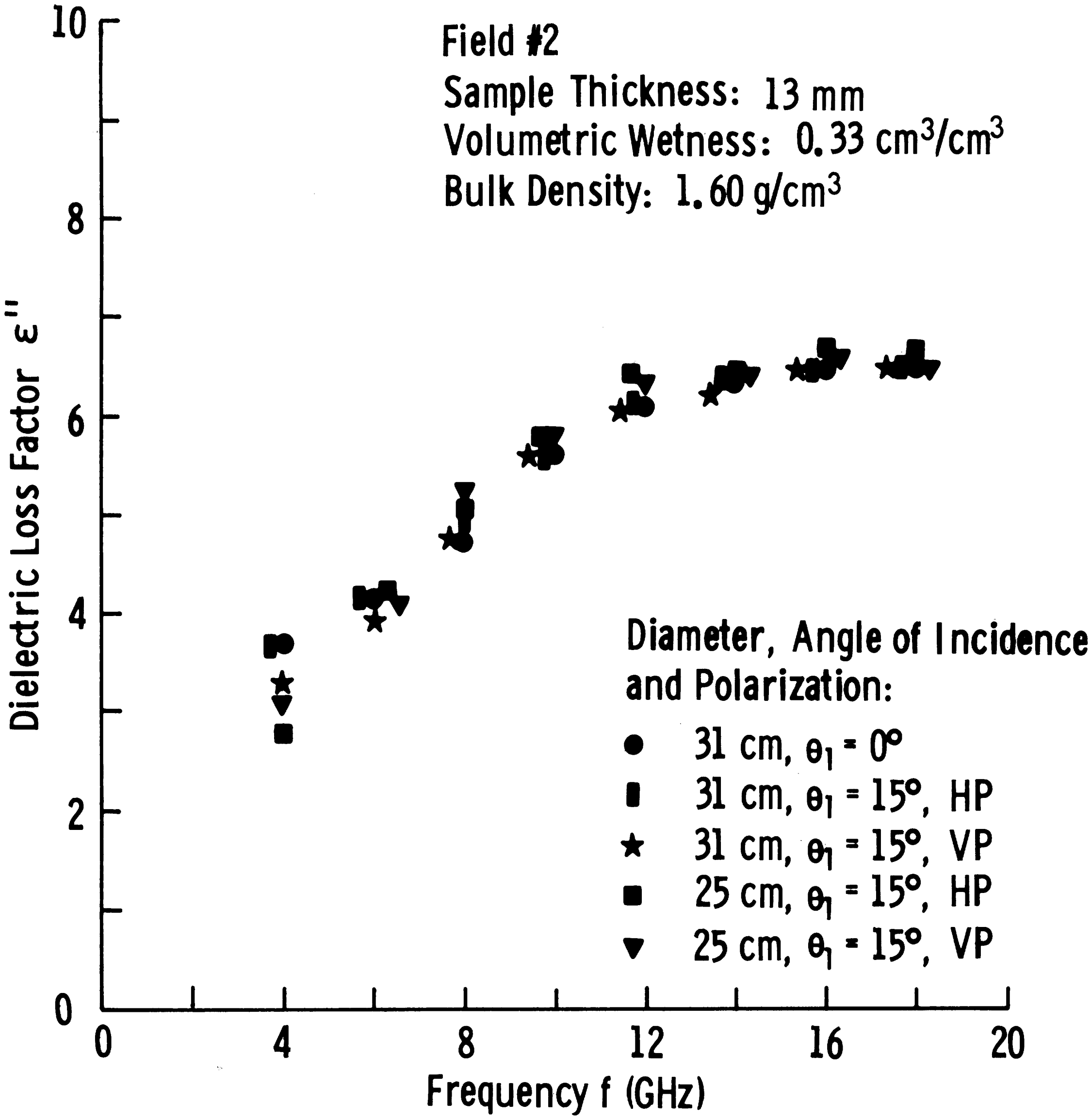

8 GHz
6 GHz
4 GHz
Loss L (dB)
50
45
40
35
30
25
20
15
10
5
0
0
4
8
12
16
20
24
28
Water Depth d (mm)
Distilled Water
T = 23 °C
Antennas 22 cm Apart
Perpendicular Incidence
Measured:
4 GHz
6 GHz
8 GHz
Theory

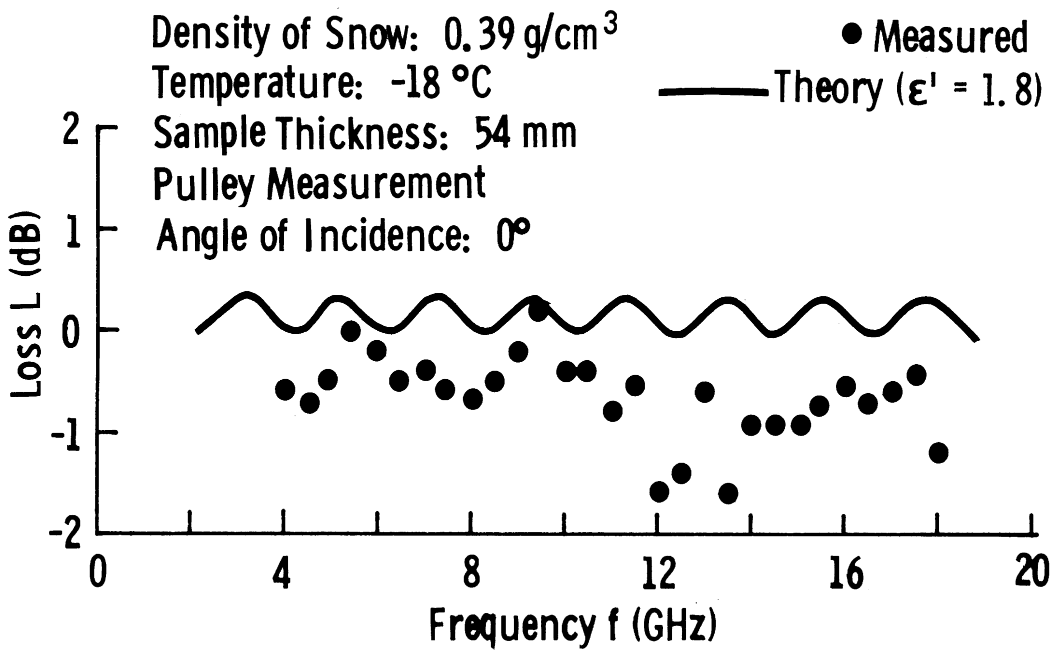

Distilled Water Temperature: 23 °C
Angle of Incidence: 45°
Vertical Polarization
Antennas 36 cm Apart
Distance from Transmitting Antenna to Sample: 12 cm
Transmitting Antenna: 4 - 18 GHz
Aperture: 6 x 6 cm2
Receiving Antenna: 4-6 GHz
Aperture: 16 x 22 cm2
Sample Size: 50 x 50 cm2
6 GHz
4 GHz
Measured:
▼ 4 GHz
● 6 GHz
Theory
Phase Shift ΔΦ (Degrees)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
4
8
12
16
20
24
28
32
36
Water Depth d (mm)

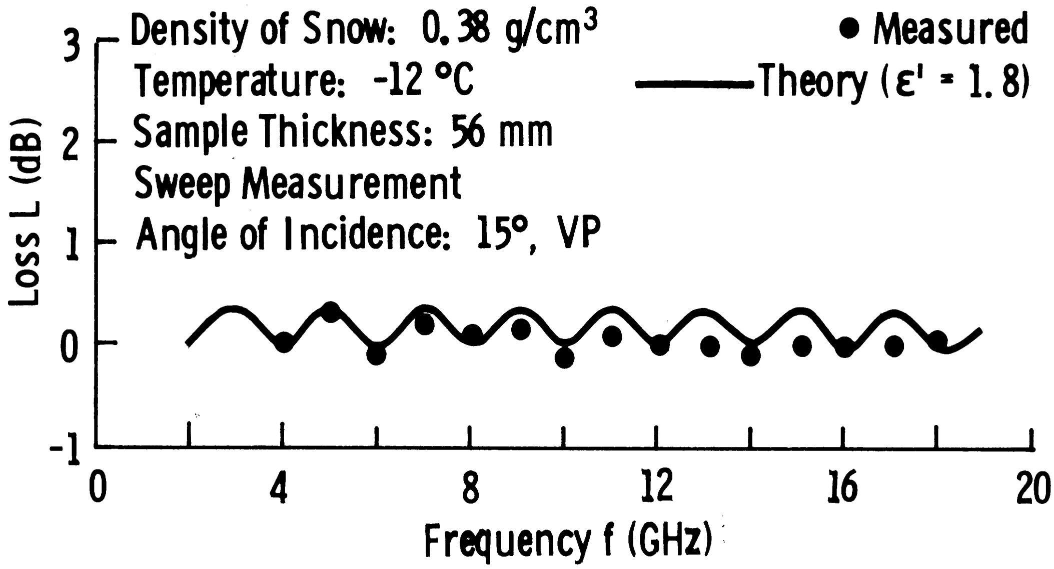

Distilled Water Temperature: 23 °C
Angle of Incidence: 45°
Vertical Polarization
Antennas 36 cm Apart
Distance from Transmitting Antenna to Sample: 12 cm
Transmitting Antenna: 4 - 18 GHz
Aperture: 6 x 6 cm2
Receiving Antenna: 4-6 GHz
Aperture: 16 x 22 cm2
Sample Size: 50 x 50 cm2
6 GHz
4 GHz
Measured:
4 GHz
6 GHz
Theory
Loss L (dB)
0
5
10
15
20
25
30
35
40
45
50
0
4
8
12
16
20
24
28
32
36
Water Depth d (mm)

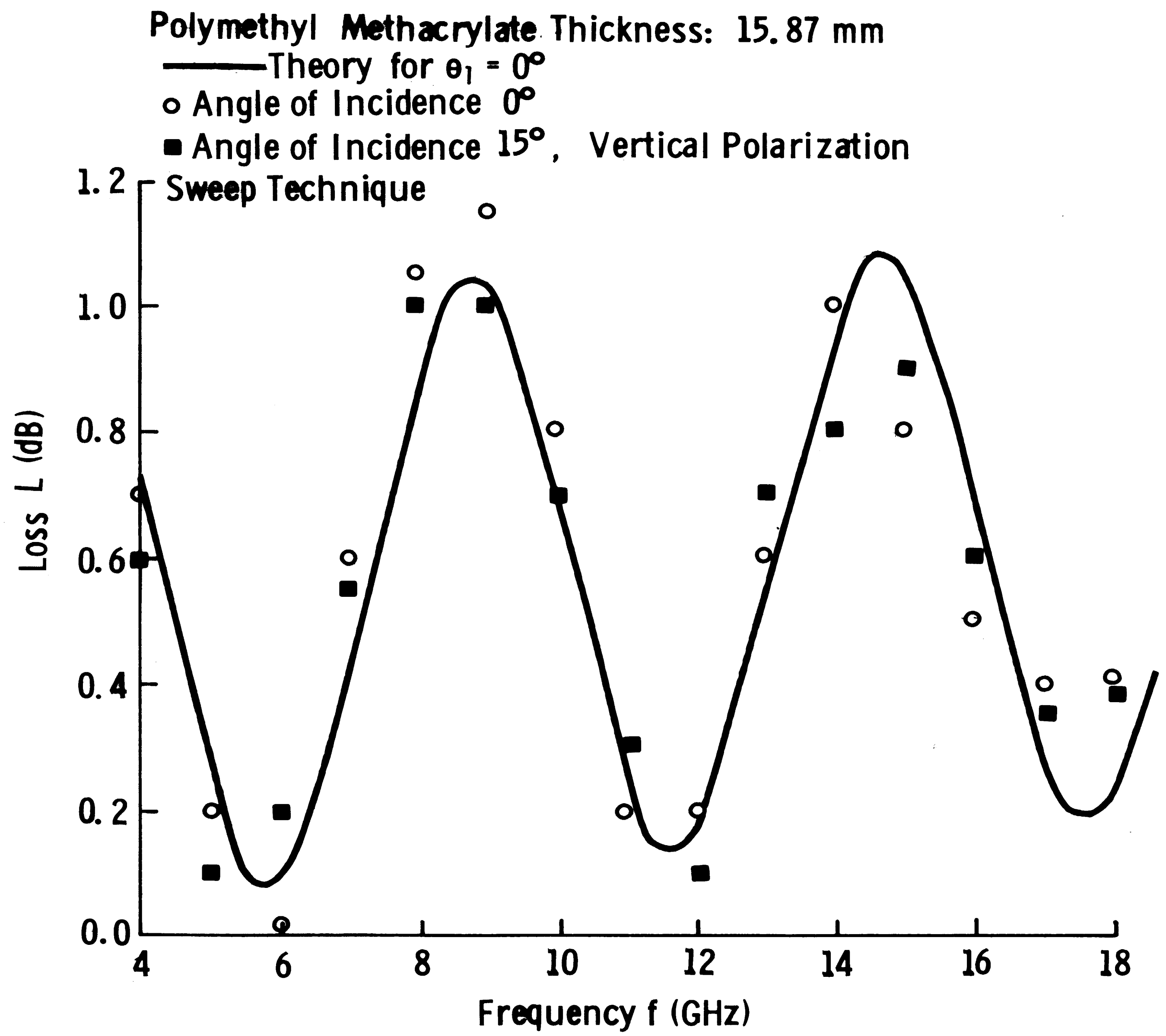

Distilled Water Temperature: 23 ° C
Angle of Incidence: 45°
Vertical Polarization
Antennas 36 cm Apart
Distance from Transmitting Antenna to Sample: 19cm
Both Antennas: 4 - 18 GHz
Aperture: 6 x 6 cm²
Sample Size: 50 x 50 cm²
6 GHz
4 GHz
Measured:
▼ 4 GHz
● 6 GHz
Theory
Loss L (dB)
0
5
10
15
20
25
30
35
40
45
50
0
4
8
12
16
20
24
28
32
36
Water Depth d (mm)


Field #2
Sample Thickness: 13 mm
Volumetric Wetness: 0.33 cm³/cm³
Bulk Density: 1.60 g/cm³
Dielectric Constant ε'
Frequency f (GHz)
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
22
20
18
16
14
12
10
0
4
8
12
16
20

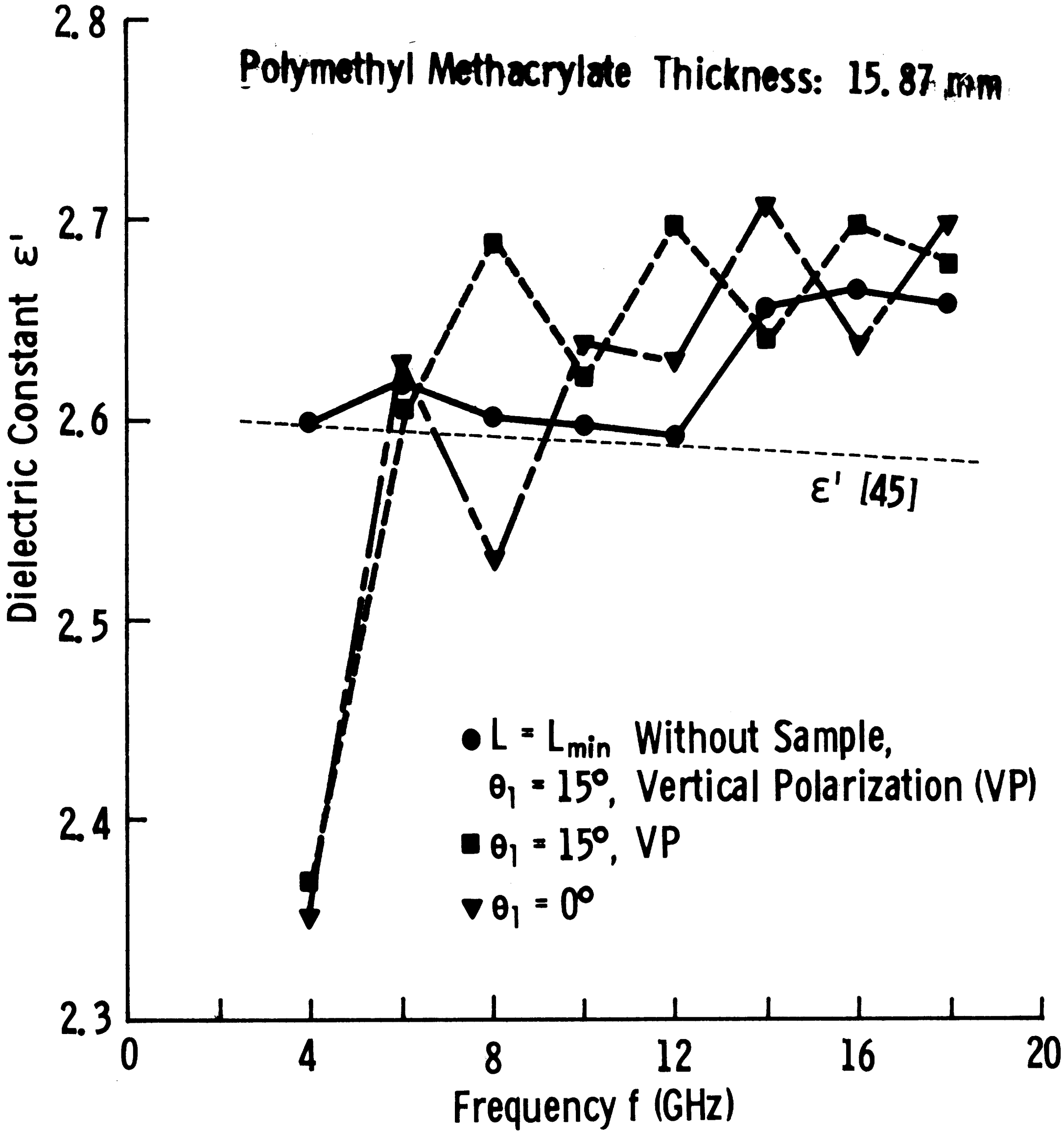

Field #2
Sample Thickness: 13 mm
Volumetric Wetness: 0.33 cm³/cm³
Bulk Density: 1.60 g/cm³
Dielectric Loss Factor ε''
Frequency f (GHz)
Diameter, Angle of Incidence and Polarization:
31 cm, θ1 = 0°
31 cm, θ1 = 15°, HP
31 cm, θ1 = 15°, VP
25 cm, θ1 = 15°, HP
25 cm, θ1 = 15°, VP
0
2
4
6
8
10
12
16
20

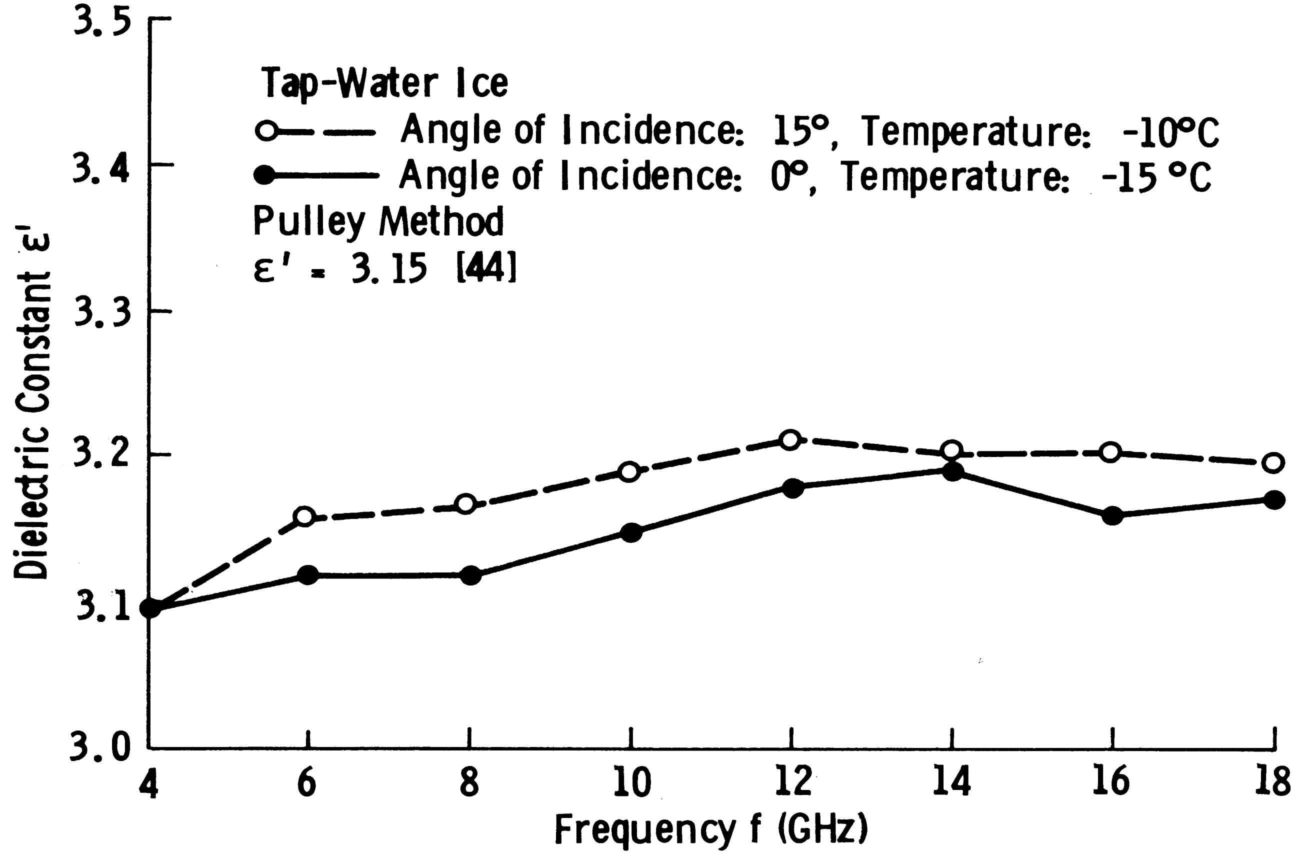

Density of Snow: 0.39 g/cm3
Temperature: -18 °C
Sample Thickness: 54 mm
Pulley Measurement
Angle of Incidence: 0°
• Measured
Theory (ε' = 1.8)
Loss L (dB)
2
1
0
-1
-2
0
4
8
12
16
20
Frequency f (GHz)

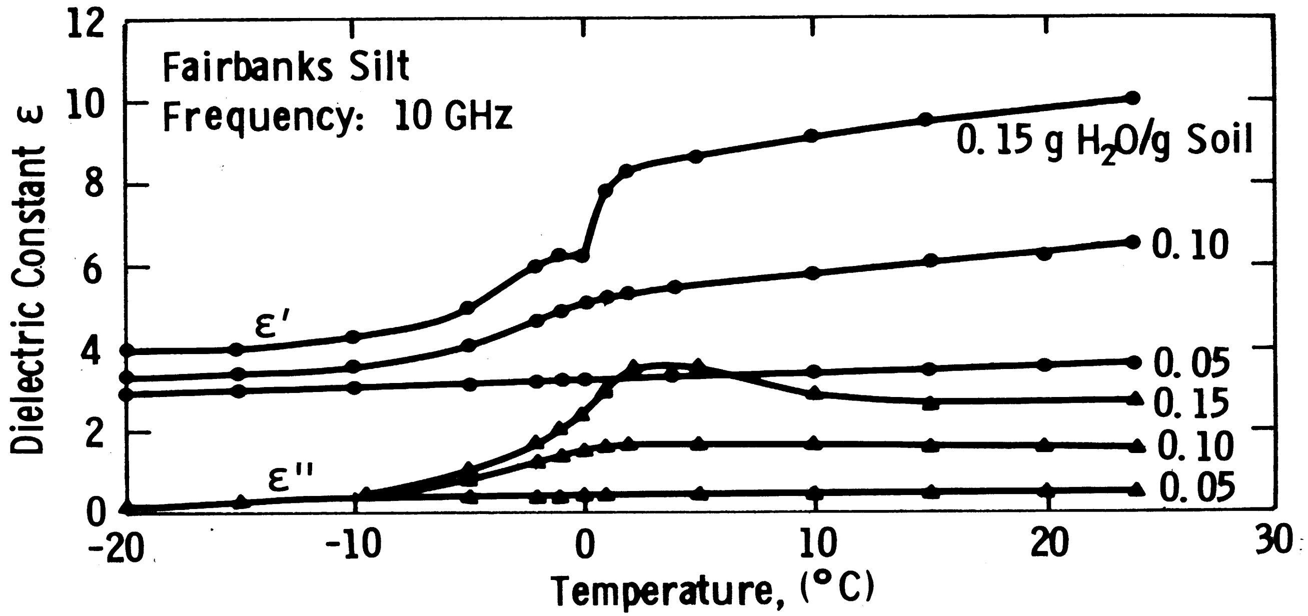

Density of Snow: 0.38 g/cm3
Temperature: -12 °C
Sample Thickness: 56 mm
Sweep Measurement
Angle of Incidence: 15°, VP
• Measured
Theory (ε' = 1.8)
Loss L (dB)
3
2
1
0
-1
0
4
8
12
16
20
Frequency f (GHz)



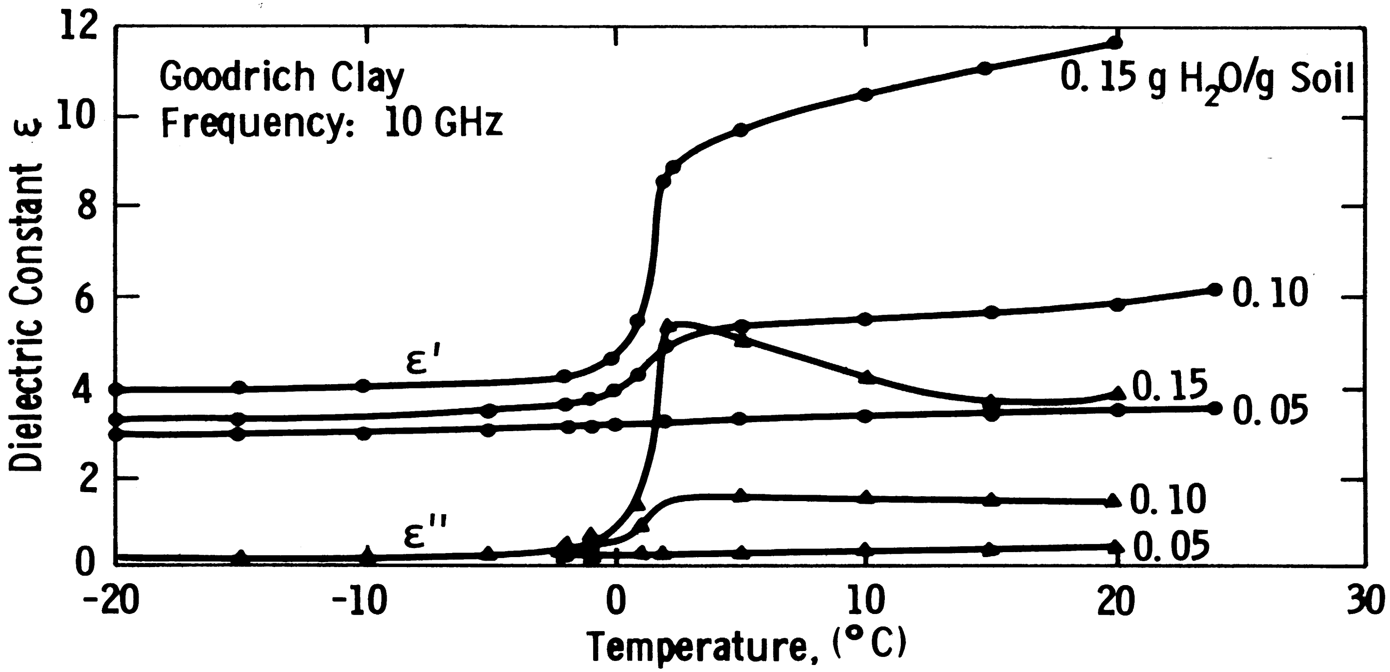
Polymethyl Methacrylate Thickness: 15.87 mm
Theory for θ1 = 0°
Angle of Incidence 0°
Angle of Incidence 15°, Vertical Polarization
Sweep Technique
Loss L (dB)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
4
6
8
10
12
14
16
18
Frequency f (GHz)

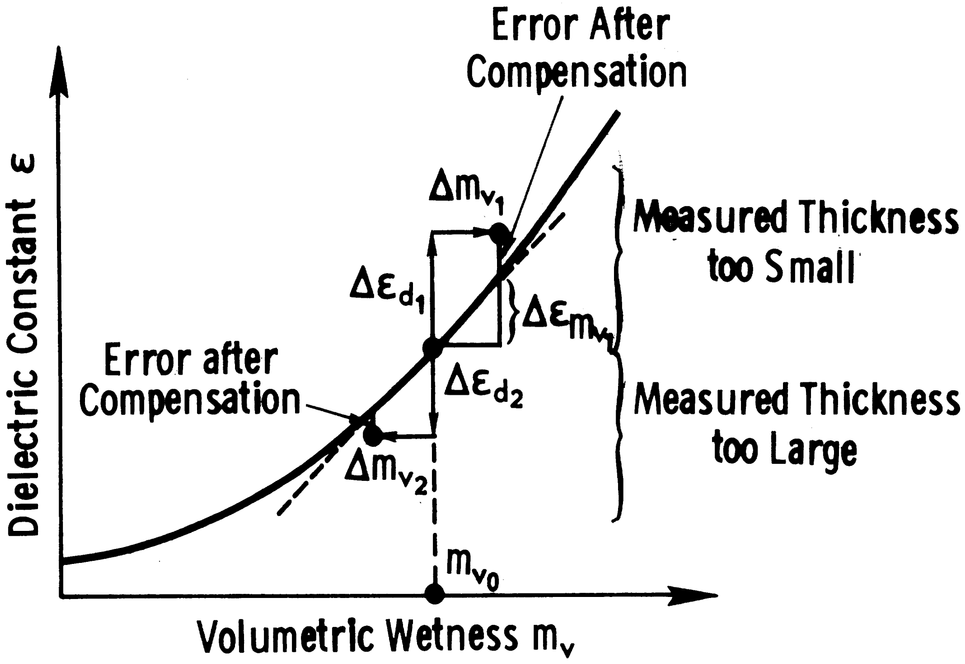

Polymethyl Methacrylate Thickness: 15.87 mm
Dielectric Constant ε'
2.8
2.7
2.6
2.5
2.4
2.3
ε' [45]
● L = L_min Without Sample, θ_1 = 15°, Vertical Polarization (VP)
■ θ_1 = 15°, VP
▼ θ_1 = 0°
0
4
8
12
16
20
Frequency f (GHz)

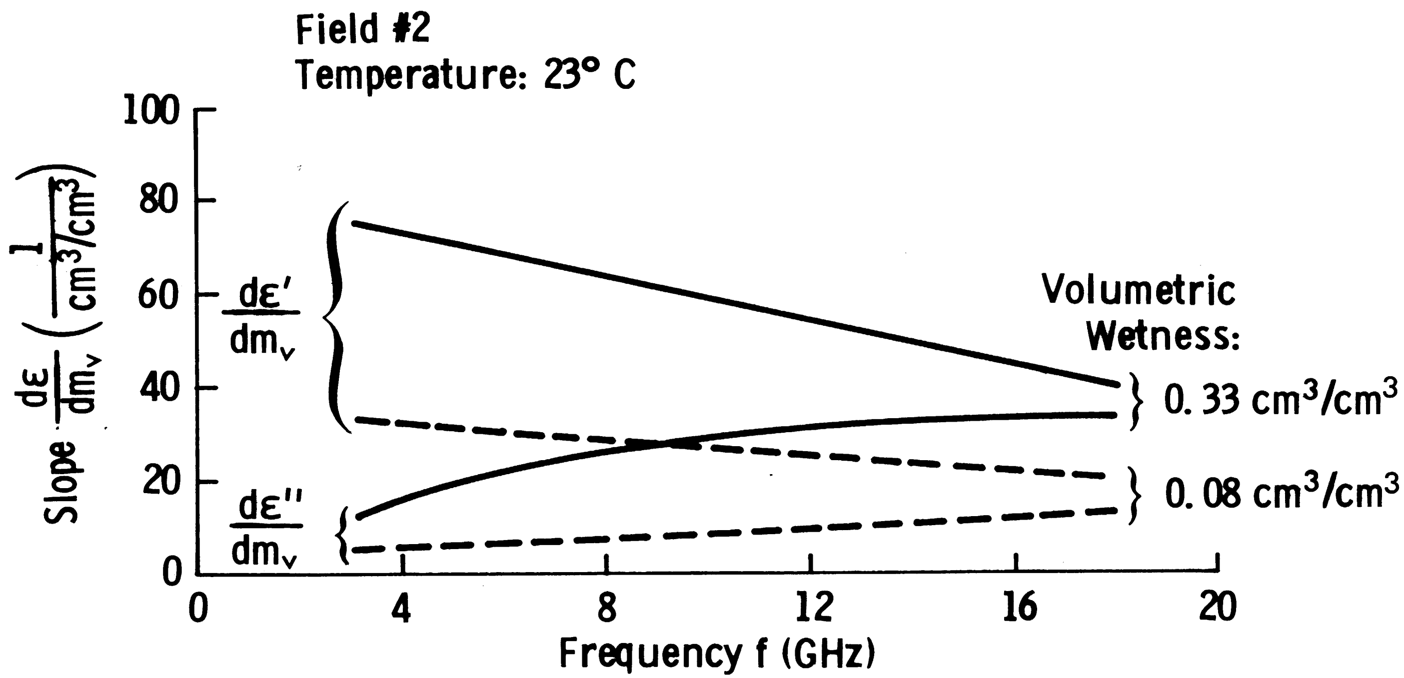

3.5
3.4
3.3
3.2
3.1
3.0
Dielectric Constant ε'
Tap-Water Ice
Angle of Incidence: 15°, Temperature: -10°C
Angle of Incidence: 0°, Temperature: -15 °C
Pulley Method
ε' = 3.15 [44]
4
6
8
10
12
14
16
18
Frequency f (GHz)


Fairbanks Silt
Frequency: 10 GHz
Dielectric Constant ε
ε'
ε''
0.15 g H2O/g Soil
0.10
0.05
0.15
0.10
0.05
Temperature, (°C)
12
10
8
6
4
2
0
-20
-10
0
10
20
30

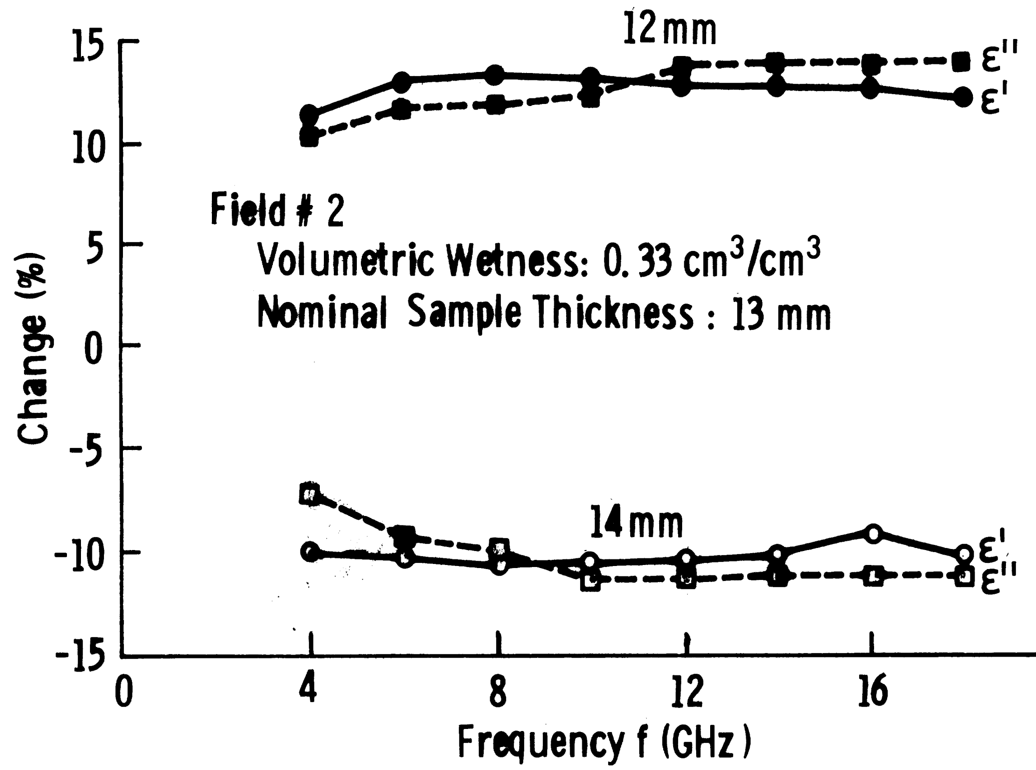
(two fig. same page)

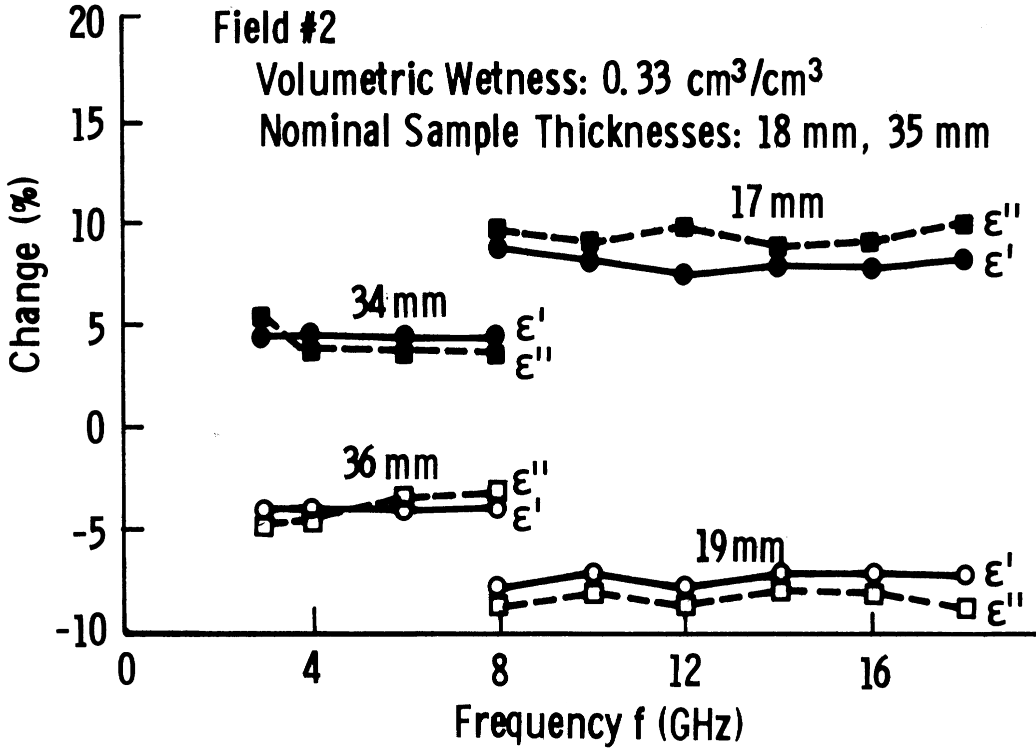


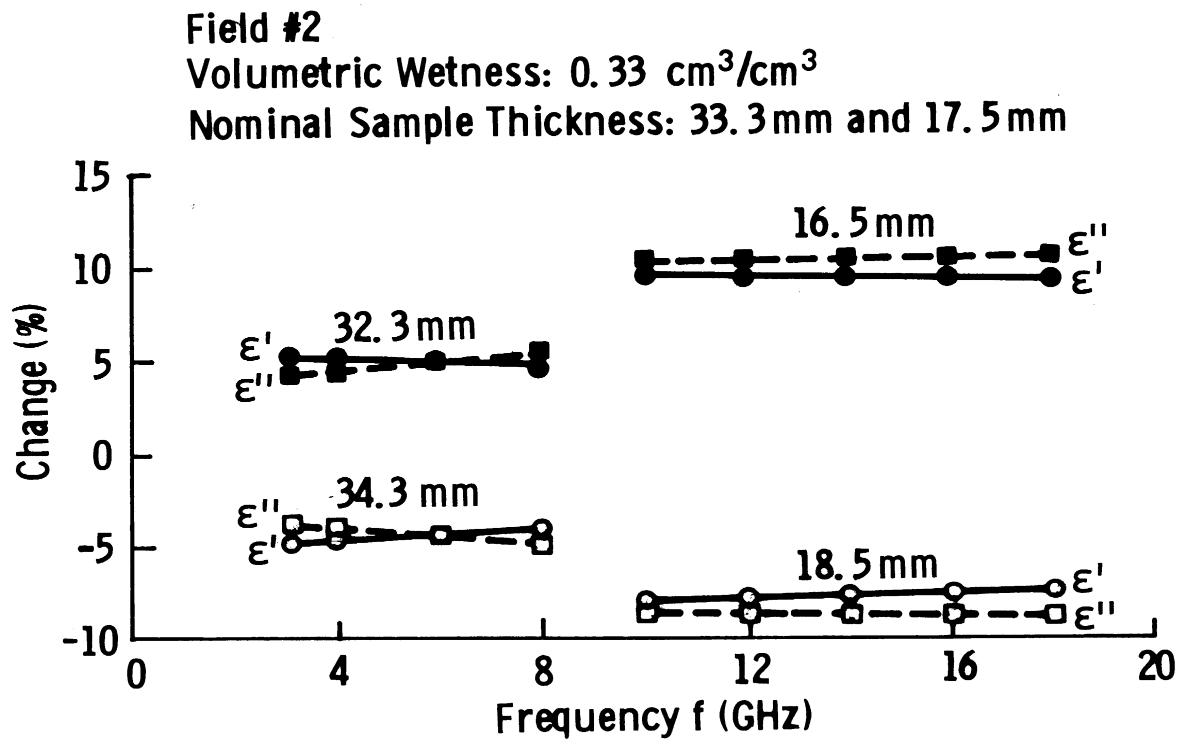

Error After
Compensation
Dielectric Constant ε
Δm$_{v_1}$
Δε$_{d_1}$
Δε$_{m_{v_1}}$
Measured Thickness
too Small
Error after
Compensation
Δε$_{d_2}$
Δm$_{v_2}$
Measured Thickness
too Large
m$_{v_0}$
Volumetric Wetness m$_v$

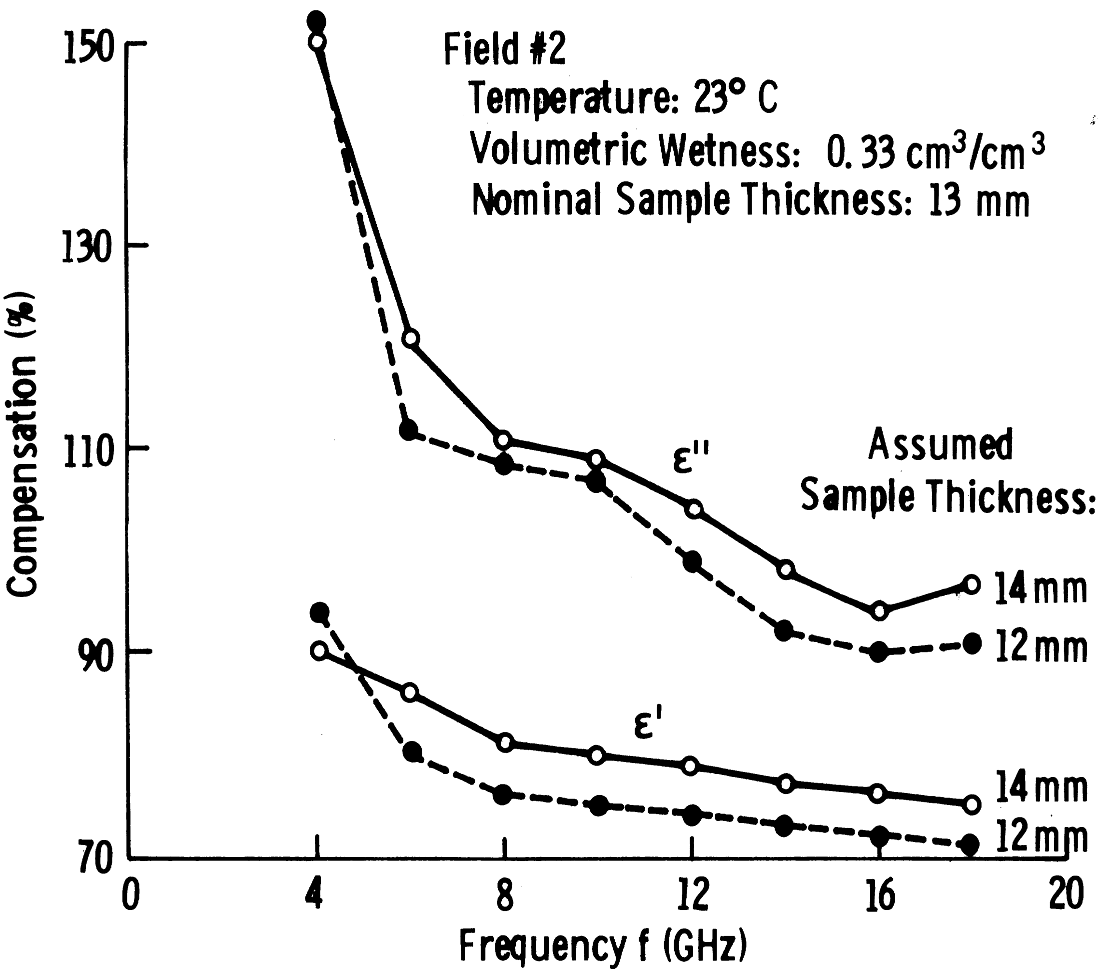


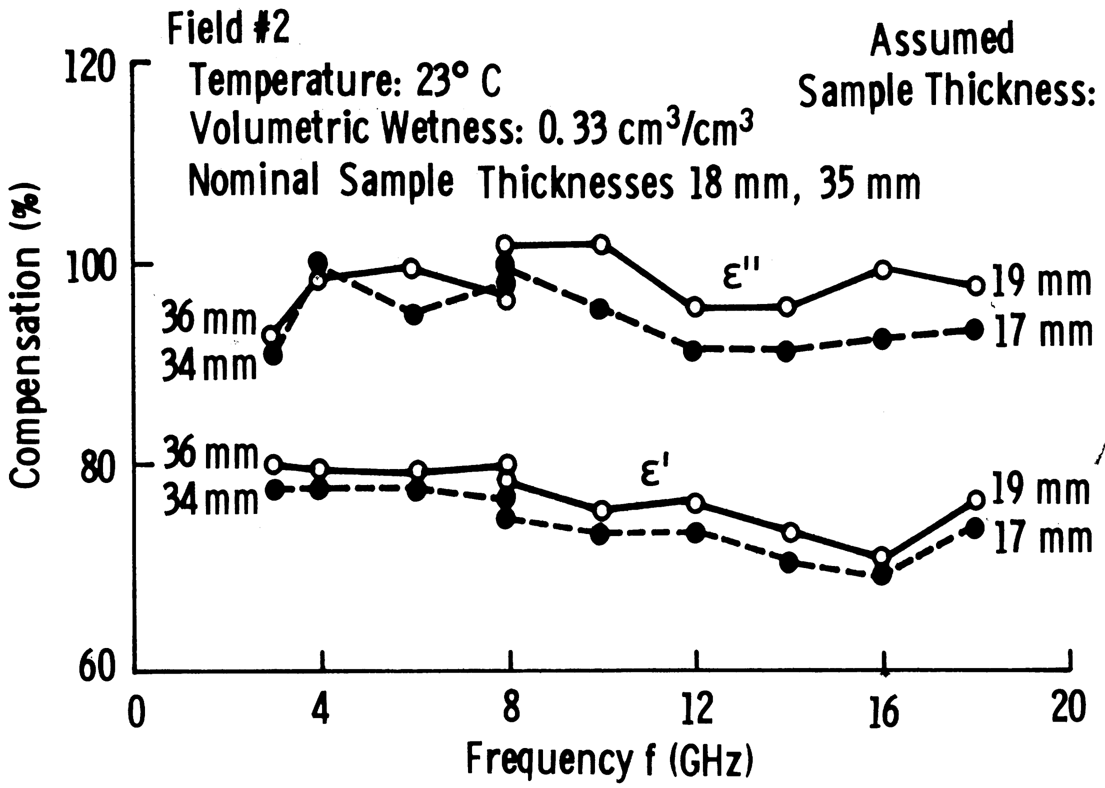
Field #2
Temperature: 23° C
Slope $\frac{d\varepsilon}{dm_v}\left(\frac{1}{cm^3/cm^3}\right)$
100
80
60
40
20
0
$\frac{d\varepsilon'}{dm_v}$
$\frac{d\varepsilon''}{dm_v}$
Volumetric Wetness:
0.33 cm^3/cm^3
0.08 cm^3/cm^3
0
4
8
12
16
20
Frequency f (GHz)


12 mm
ε''
ε'
Field # 2
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thickness : 13 mm
14 mm
ε'
ε''
Change (%)
15
10
5
0
-5
-10
-15
0
4
8
12
16
20
Frequency f (GHz)


Field #2
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thicknesses: 18 mm, 35 mm
17 mm
ε''
ε'
34 mm
ε'
ε''
36 mm
ε''
ε'
19 mm
ε'
ε''
Change (%)
20
15
10
5
0
-5
-10
0
4
8
12
16
20
Frequency f (GHz)

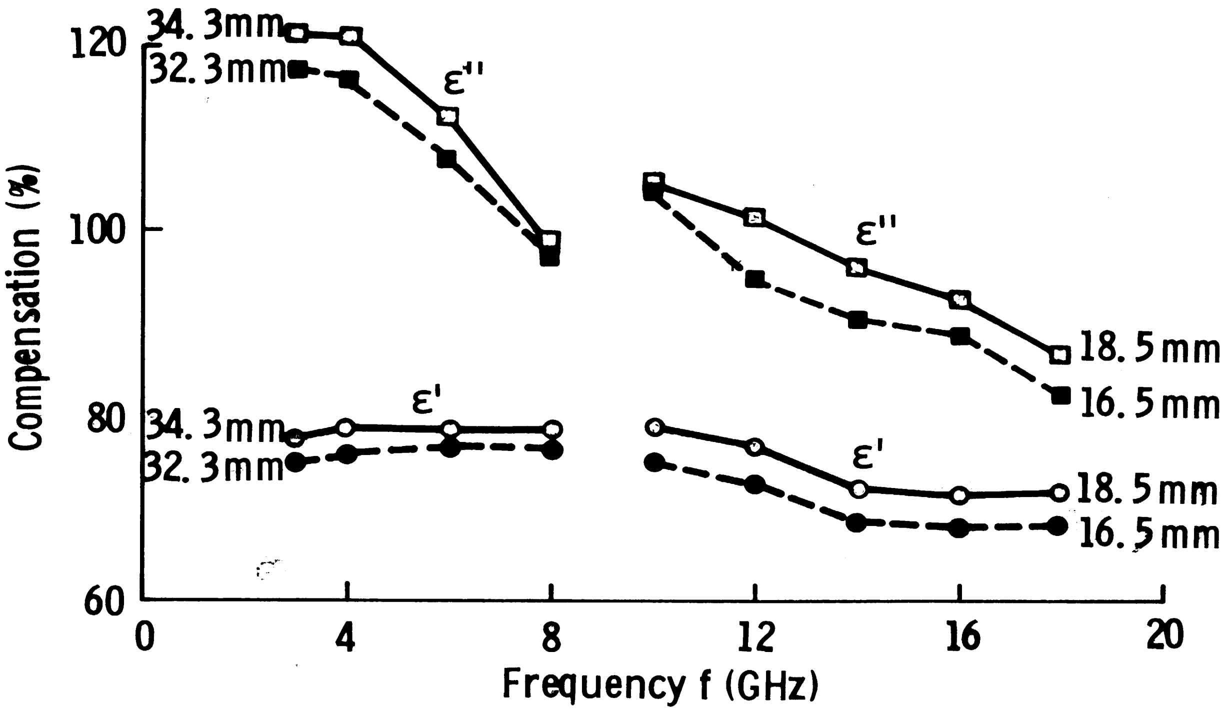

Field #2
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thickness: 33.3mm and 17.5mm
Change (%)
15
10
5
0
-5
-10
0
4
8
12
16
20
Frequency f (GHz)
32.3mm
34.3 mm
16.5mm
18.5mm
ε'
ε''

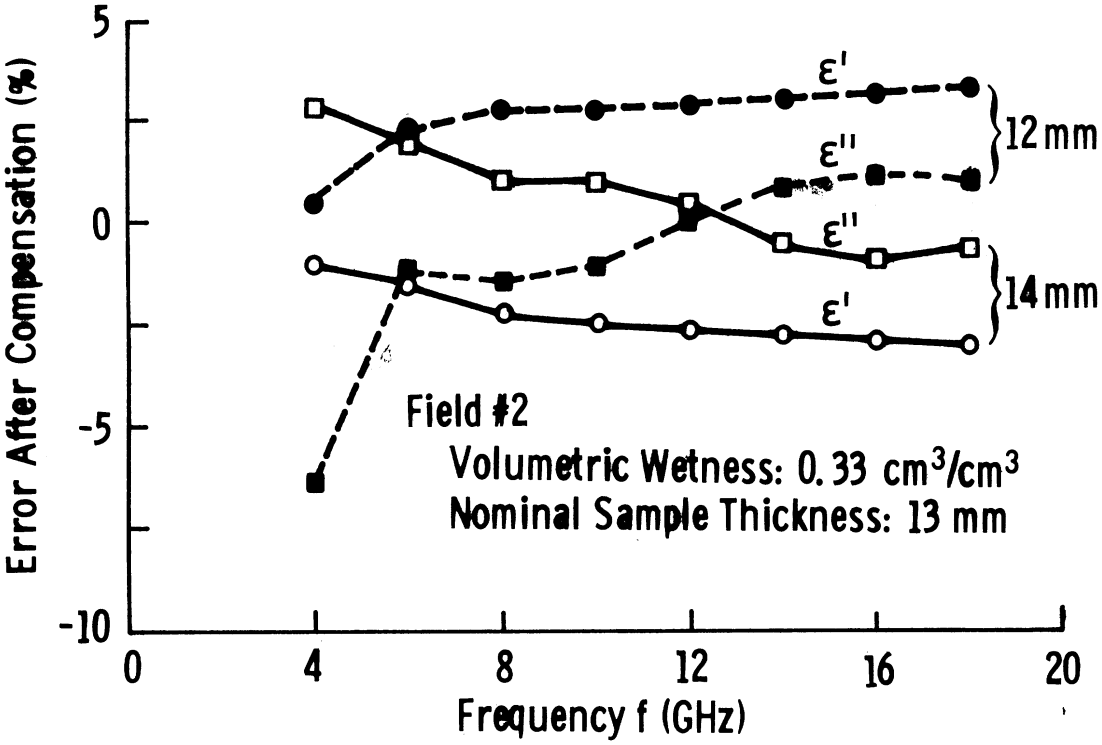

Field #2
Temperature: 23° C
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thickness: 13 mm
Assumed Sample Thickness:
ε''
ε'
14 mm
12 mm
14 mm
12 mm
Compensation (%)
150
130
110
90
70
0
4
8
12
16
20
Frequency f (GHz)

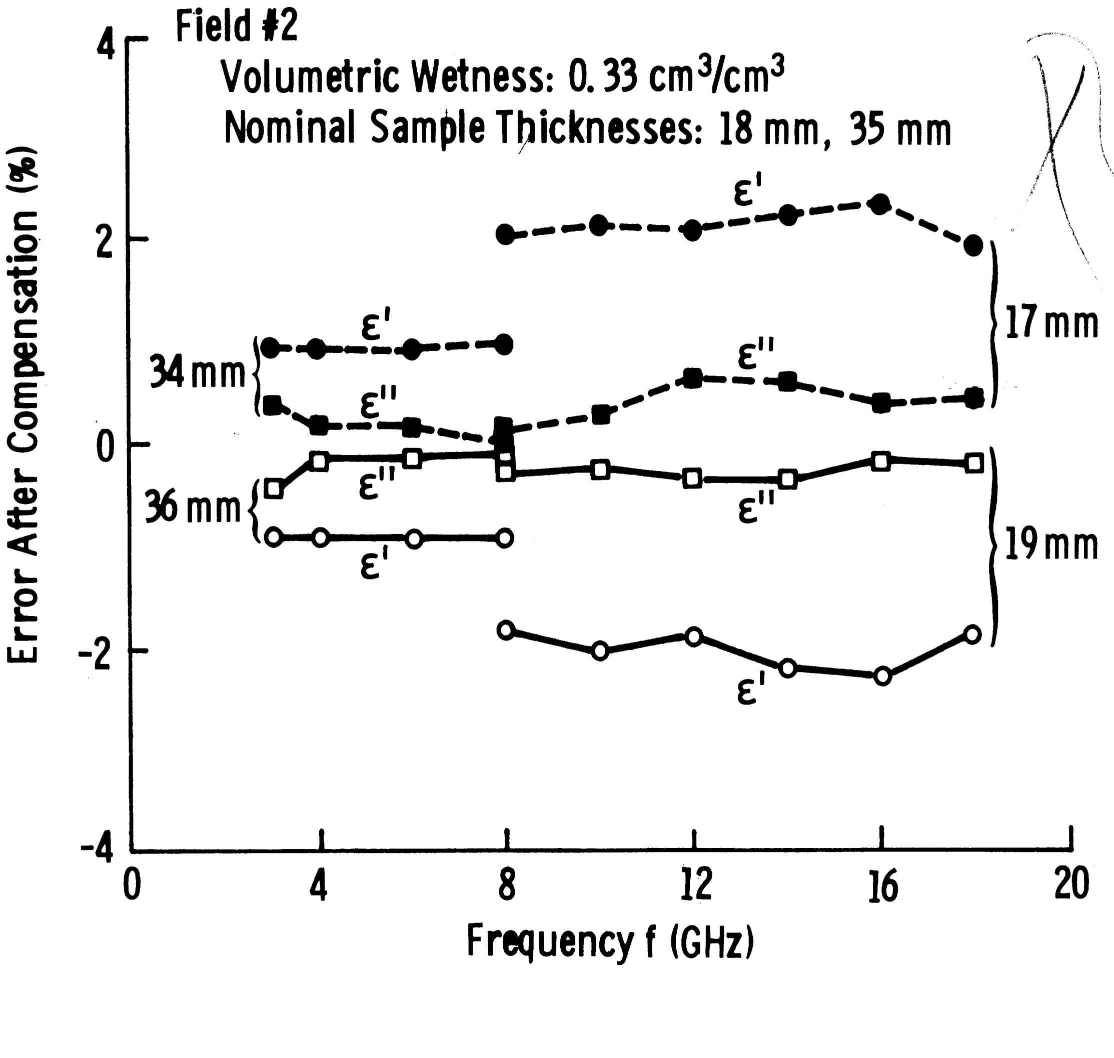

Field #2
Temperature: 23° C
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thicknesses 18 mm, 35 mm
Assumed Sample Thickness:
ε''
ε'
36 mm
34 mm
36 mm
34 mm
19 mm
17 mm
19 mm
17 mm
Compensation (%)
120
100
80
60
0
4
8
12
16
20
Frequency f (GHz)

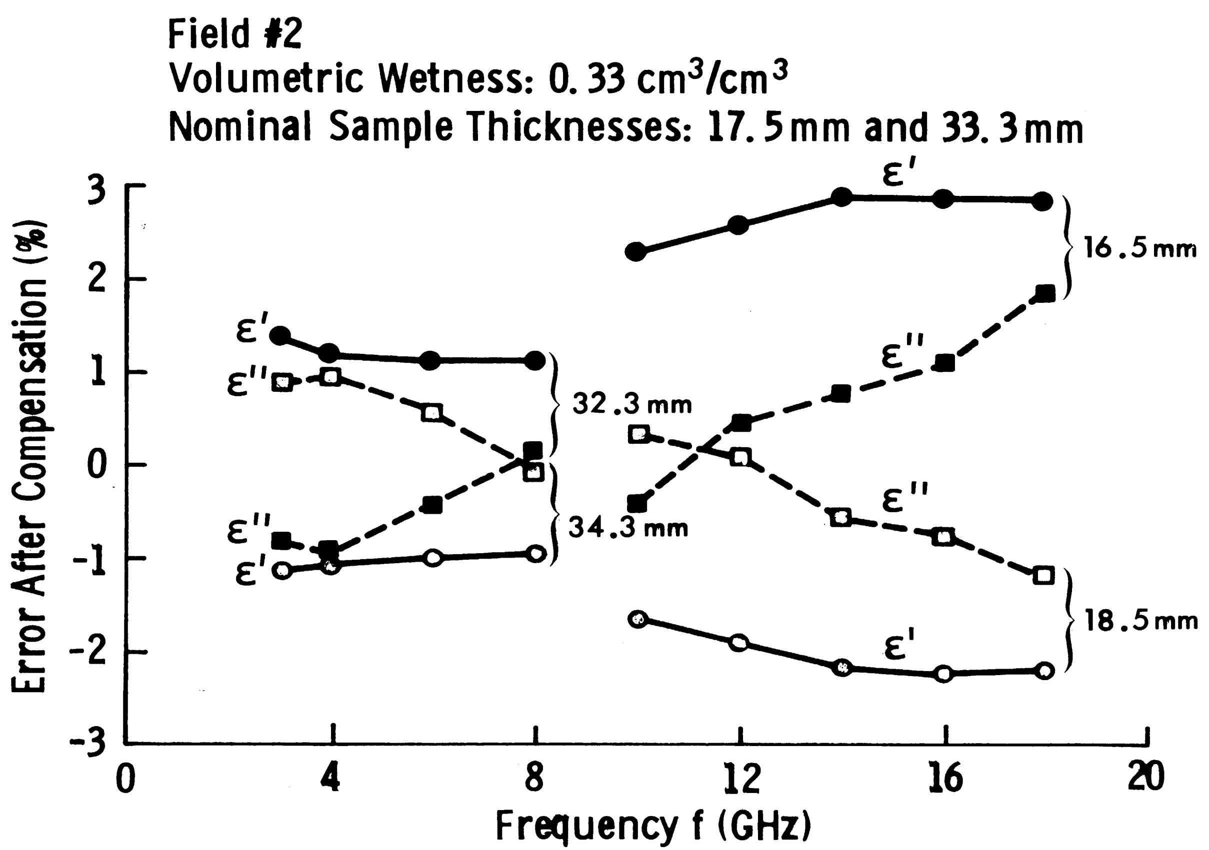
NO

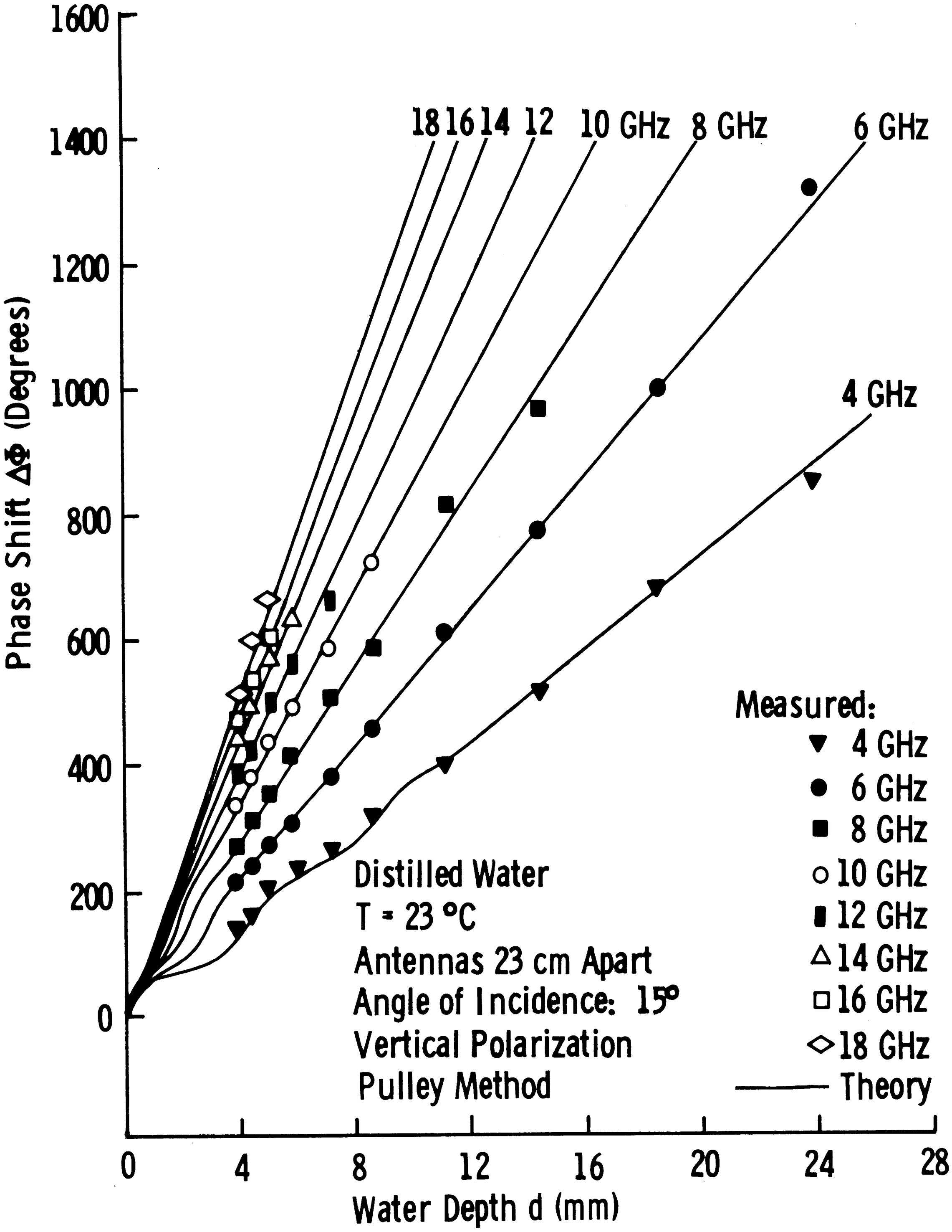
Field #2
Volumetric Wetness: 0.33 cm^3/cm^3
Nominal Sample Thicknesses: 17.5 mm and 33.3 mm



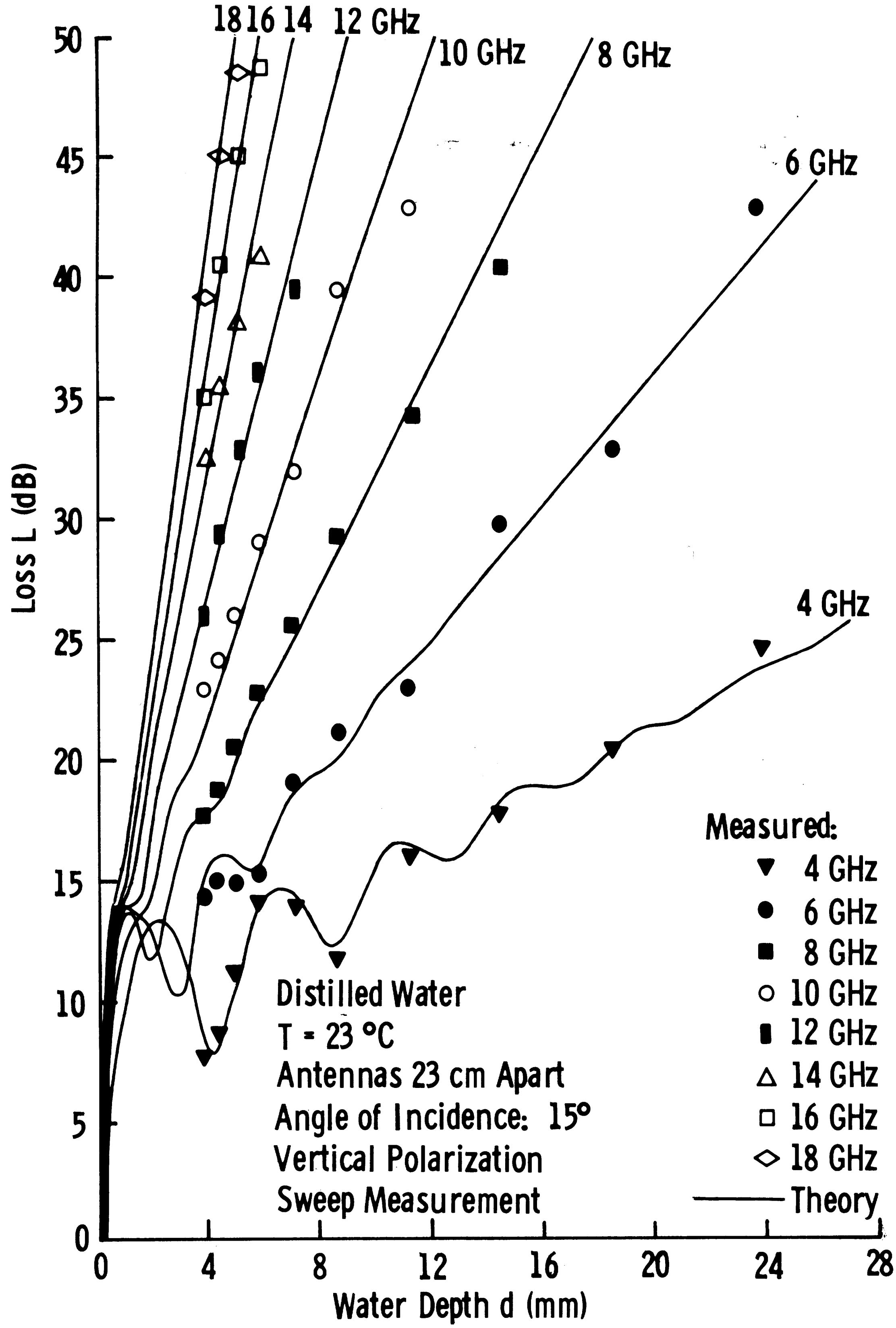

Error After Compensation (%)
Frequency f (GHz)
ε'
ε''
12 mm
14 mm
Field #2
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thickness: 13 mm


Field #2
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thicknesses: 18 mm, 35 mm
Error After Compensation (%)
Frequency f (GHz)
ε'
ε''
34 mm
36 mm
17 mm
19 mm

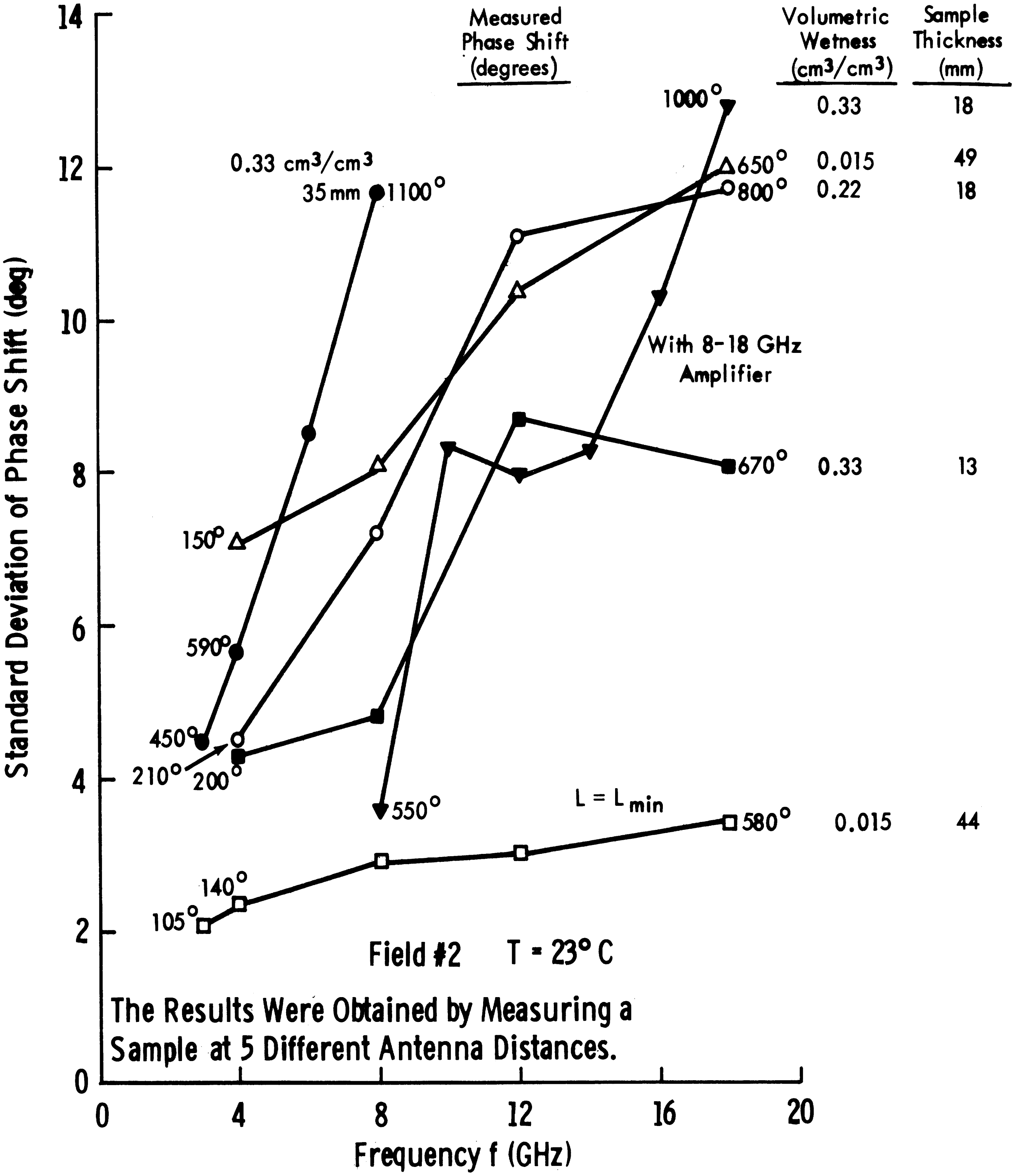

Field #2
Volumetric Wetness: 0.33 cm³/cm³
Nominal Sample Thicknesses: 17.5mm and 33.3mm
Error After Compensation (%)
Frequency f (GHz)
32.3mm
34.3mm
16.5mm
18.5mm
ε'
ε''



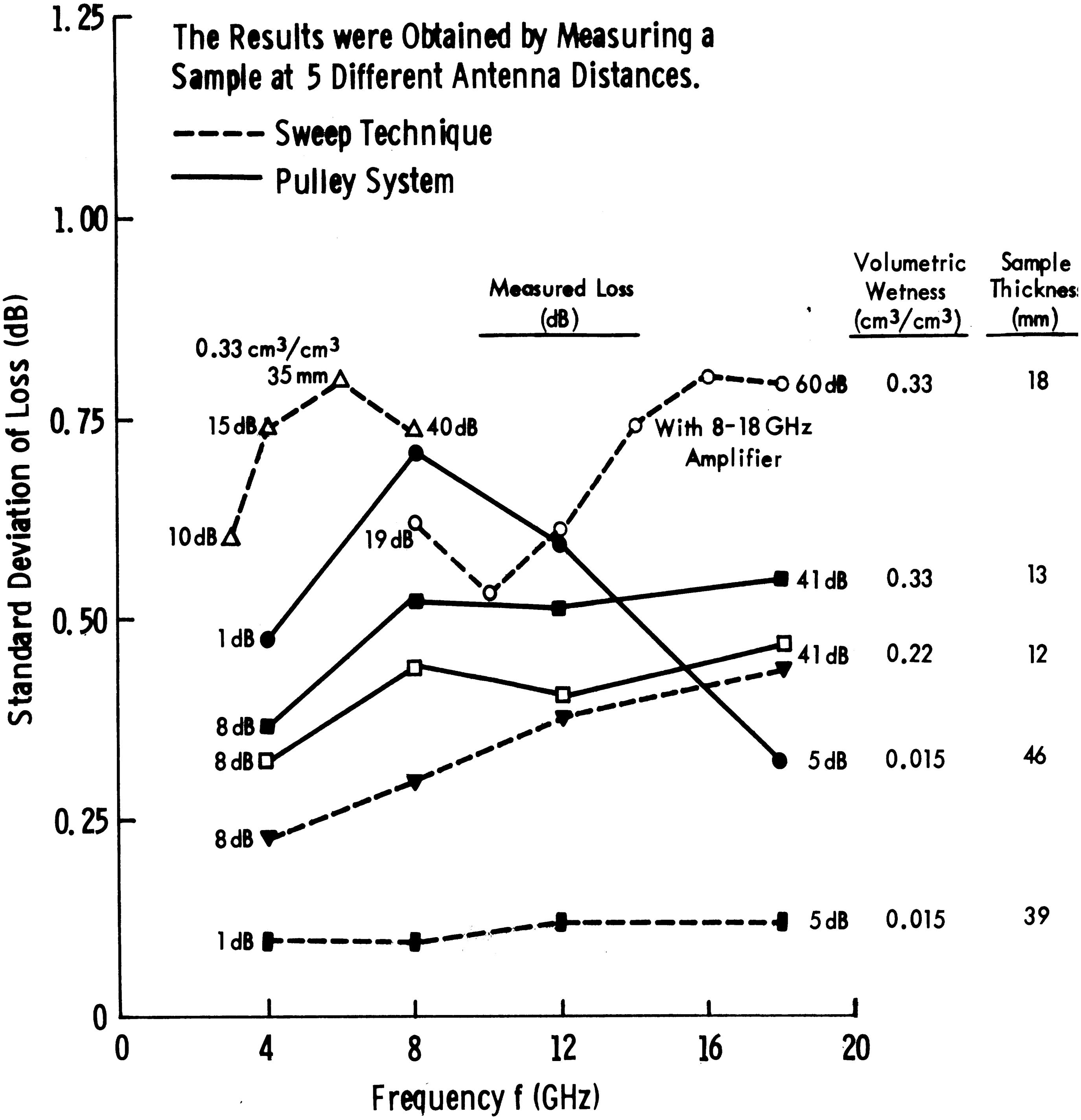
1600
1400
1200
1000
800
600
400
200
0
Phase Shift ΔΦ (Degrees)
18 16 14 12 10 GHz 8 GHz 6 GHz
4 GHz
Measured:
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
Theory
Distilled Water
T = 23 °C
Antennas 23 cm Apart
Angle of Incidence: 15°
Vertical Polarization
Pulley Method
0 4 8 12 16 20 24 28
Water Depth d (mm)

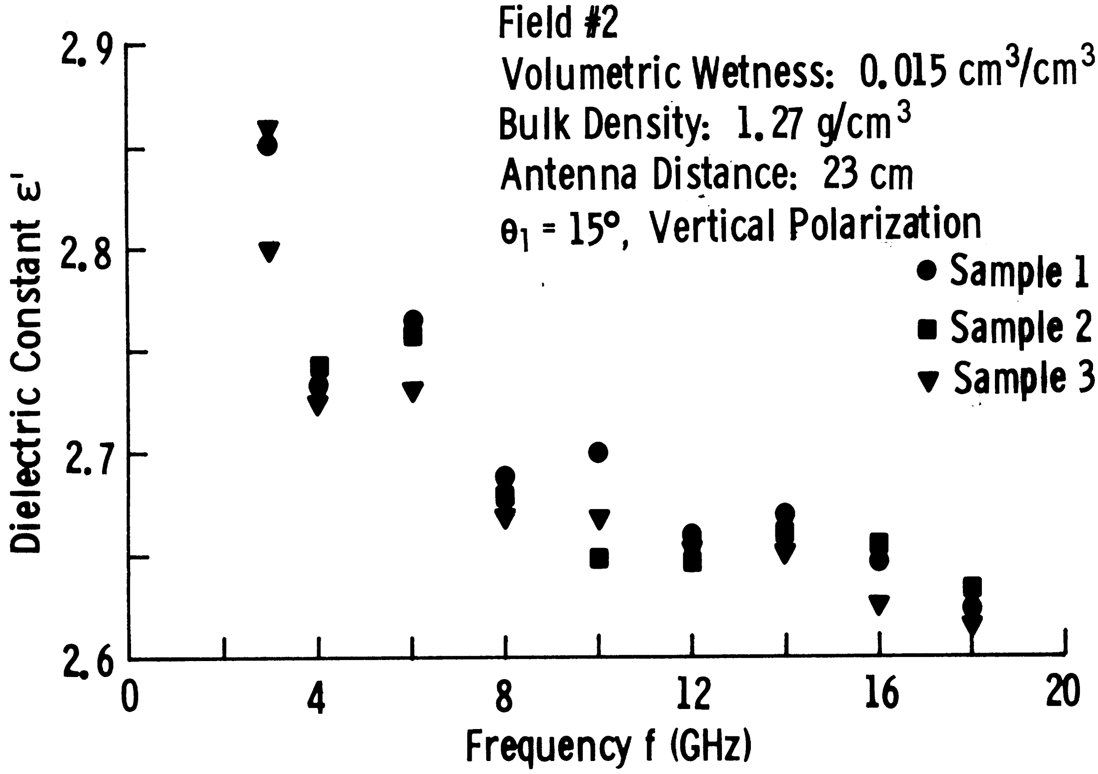


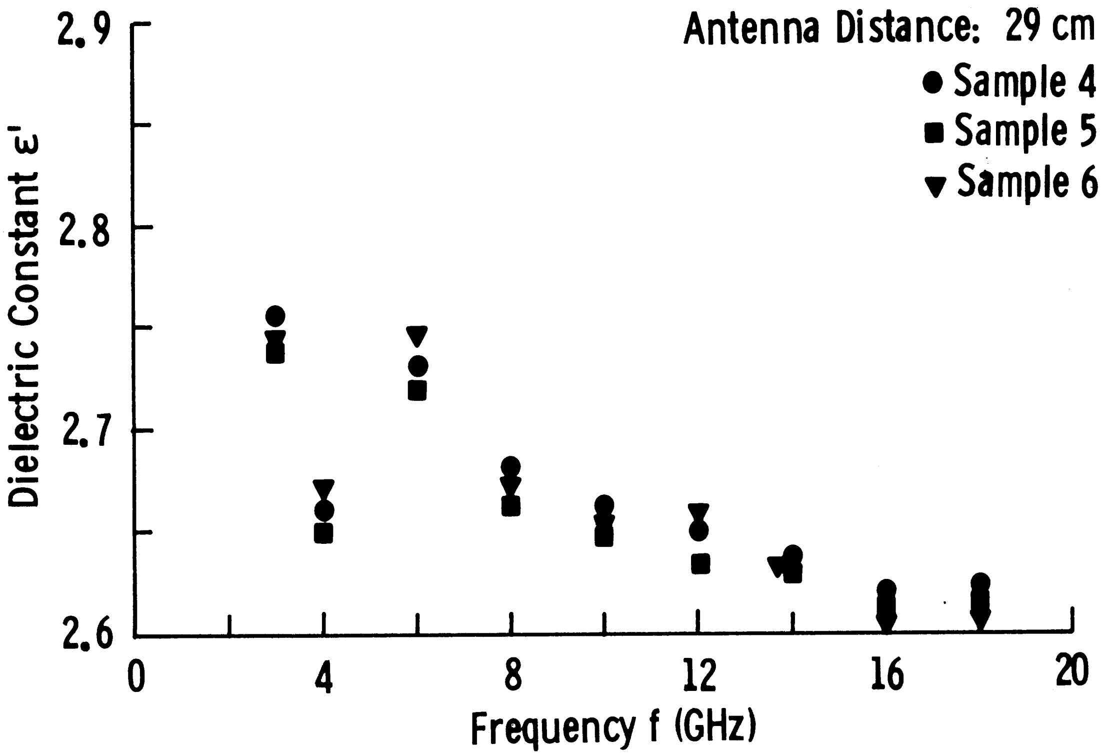
18 16 14 12 GHz
10 GHz
8 GHz
6 GHz
4 GHz
Loss L (dB)
Water Depth d (mm)
Distilled Water
T = 23 °C
Antennas 23 cm Apart
Angle of Incidence: 15°
Vertical Polarization
Sweep Measurement
Measured:
4 GHz
6 GHz
8 GHz
10 GHz
12 GHz
14 GHz
16 GHz
18 GHz
Theory

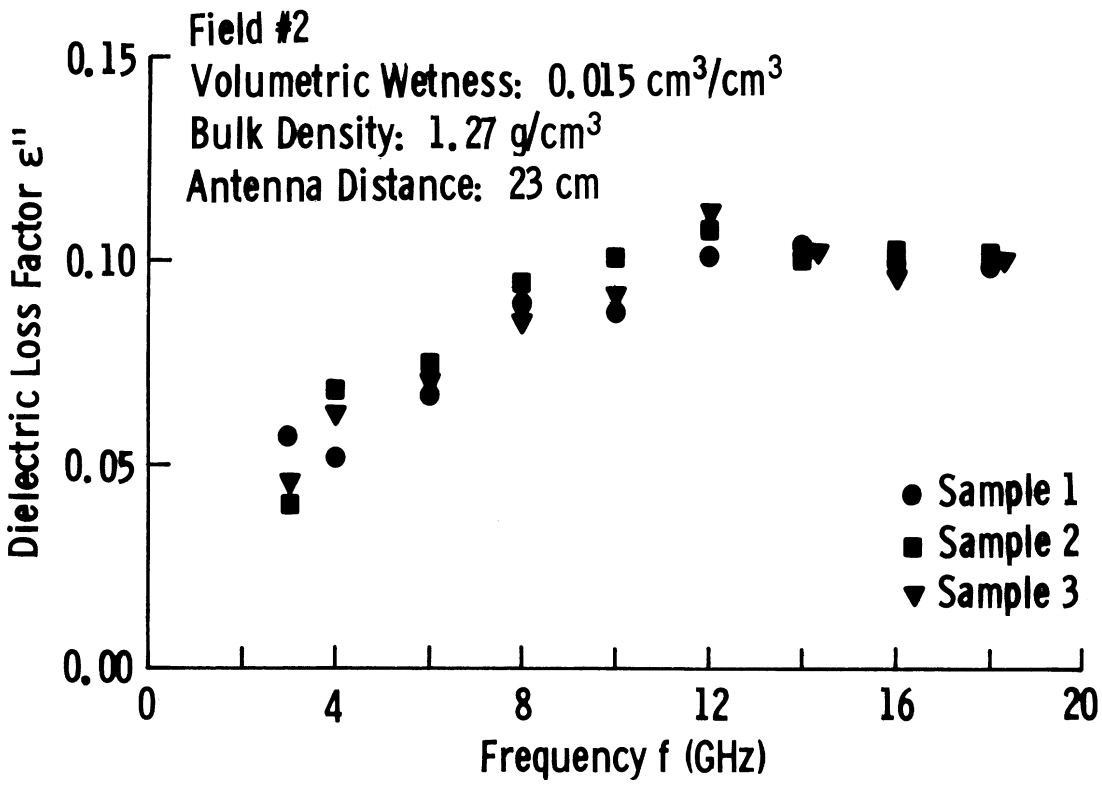


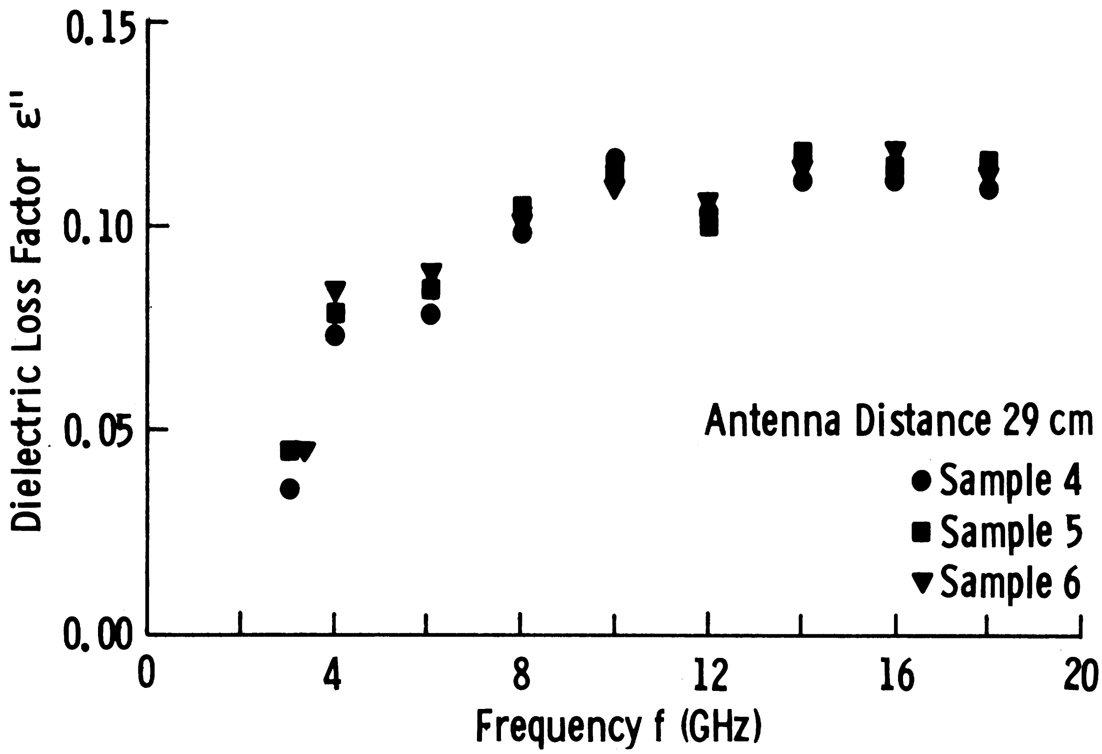
Measured Phase Shift (degrees)
Volumetric Wetness (cm³/cm³)
Sample Thickness (mm)
1000° 0.33 18
650° 0.015 49
800° 0.22 18
670° 0.33 13
580° 0.015 44
0.33 cm³/cm³
35 mm 1100°
With 8-18 GHz Amplifier
150°
590°
450°
210°
200°
550°
L = L min
140°
105°
Field #2 T = 23° C
The Results Were Obtained by Measuring a Sample at 5 Different Antenna Distances.
Standard Deviation of Phase Shift (deg)
Frequency f (GHz)
0
2
4
6
8
10
12
14
16
20

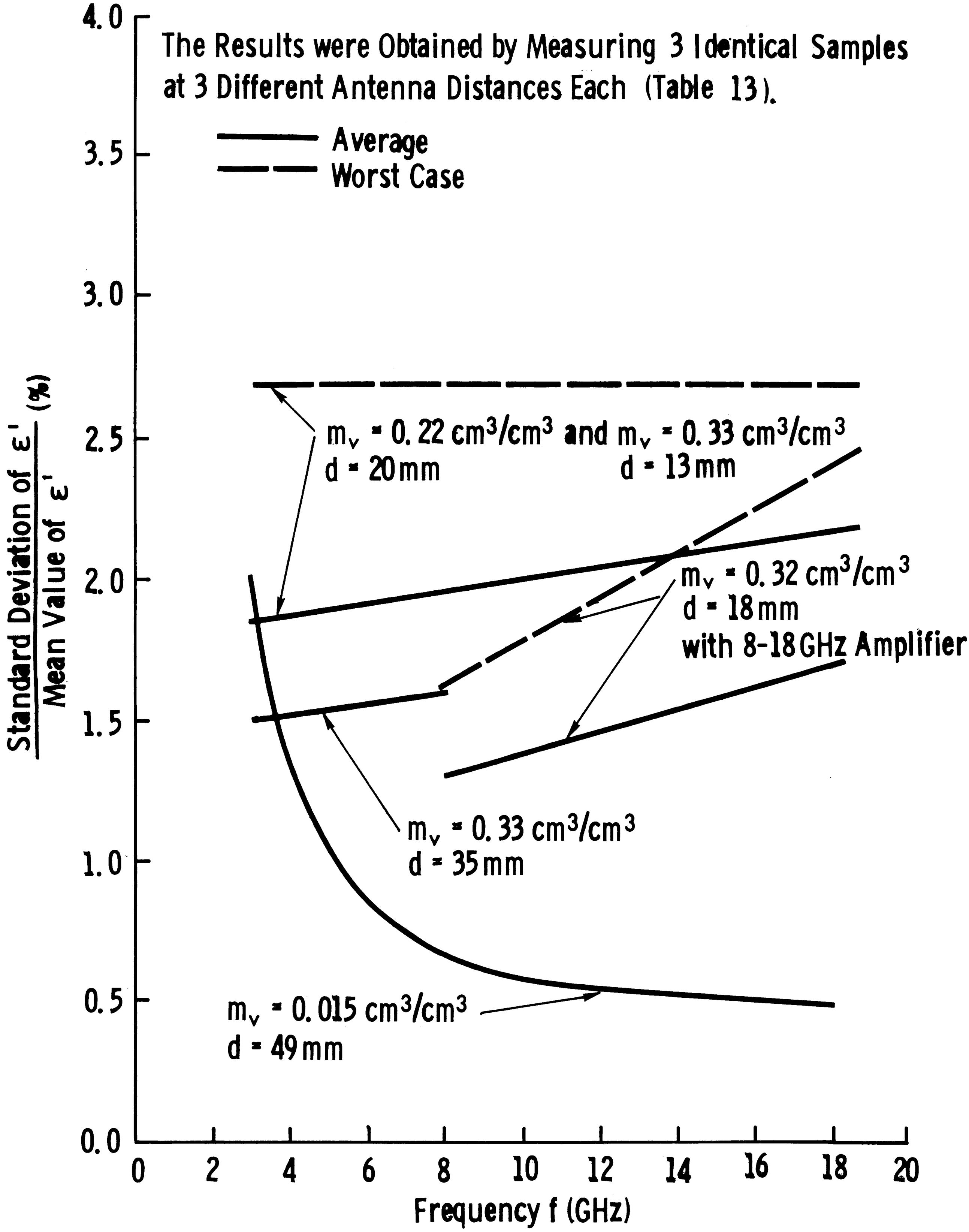

The Results were Obtained by Measuring a
Sample at 5 Different Antenna Distances.
Sweep Technique
Pulley System
Standard Deviation of Loss (dB)
Frequency f (GHz)
1.25
1.00
0.75
0.50
0.25
0
0
4
8
12
16
20
Measured Loss
(dB)
Volumetric
Wetness
(cm3/cm3)
Sample
Thickness
(mm)
0.33 cm3/cm3
35 mm
15 dB
40 dB
10 dB
19 dB
60 dB
0.33
18
With 8-18 GHz
Amplifier
1 dB
41 dB
0.33
13
8 dB
8 dB
41 dB
0.22
12
5 dB
0.015
46
8 dB
1 dB
5 dB
0.015
39

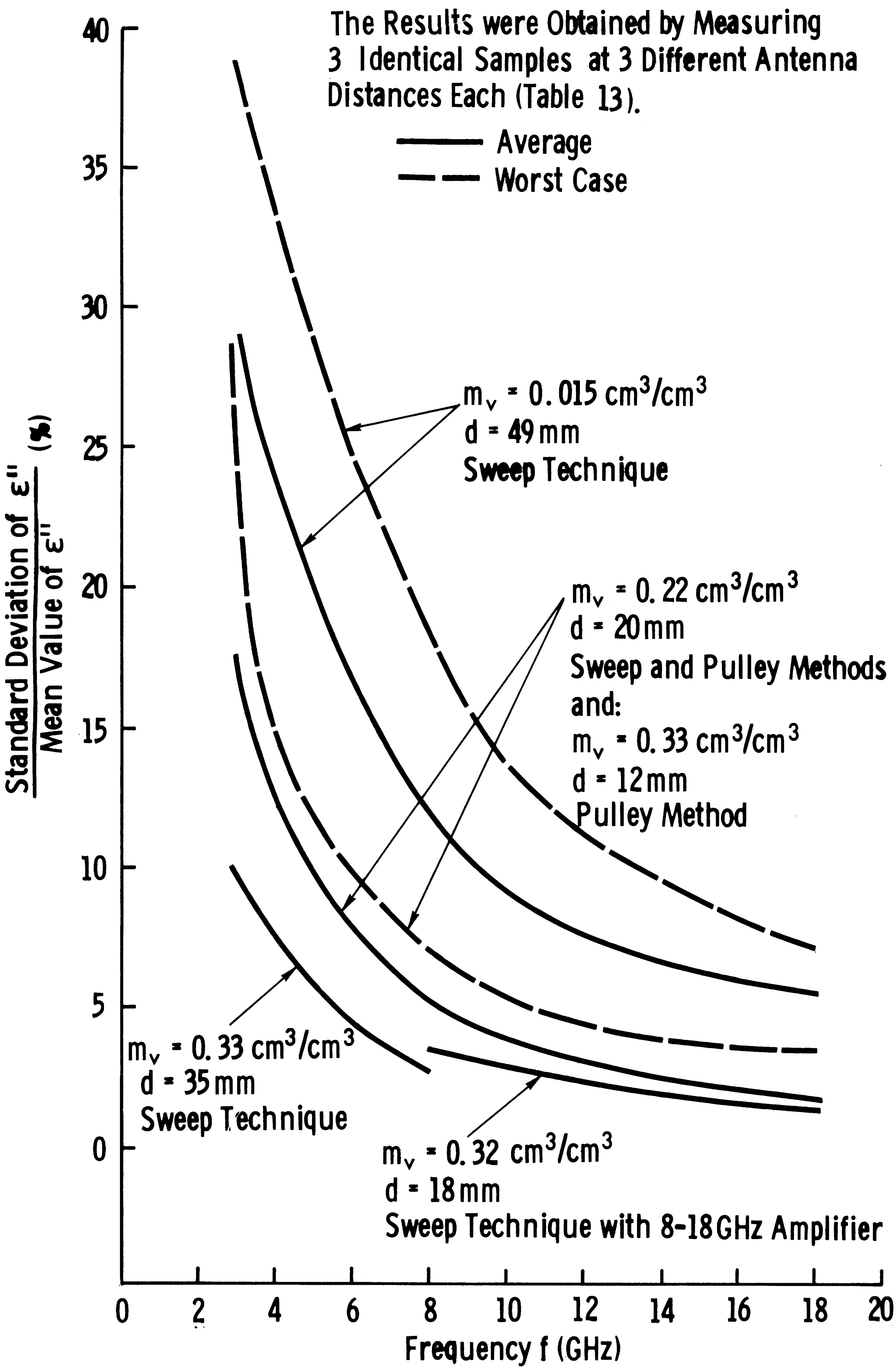

Field #2
Volumetric Wetness: 0.015 cm³/cm³
Bulk Density: 1.27 g/cm³
Antenna Distance: 23 cm
θ₁ = 15°, Vertical Polarization
● Sample 1
■ Sample 2
▼ Sample 3
Dielectric Constant ε'
2.9
2.8
2.7
2.6
0
4
8
12
16
20
Frequency f (GHz)

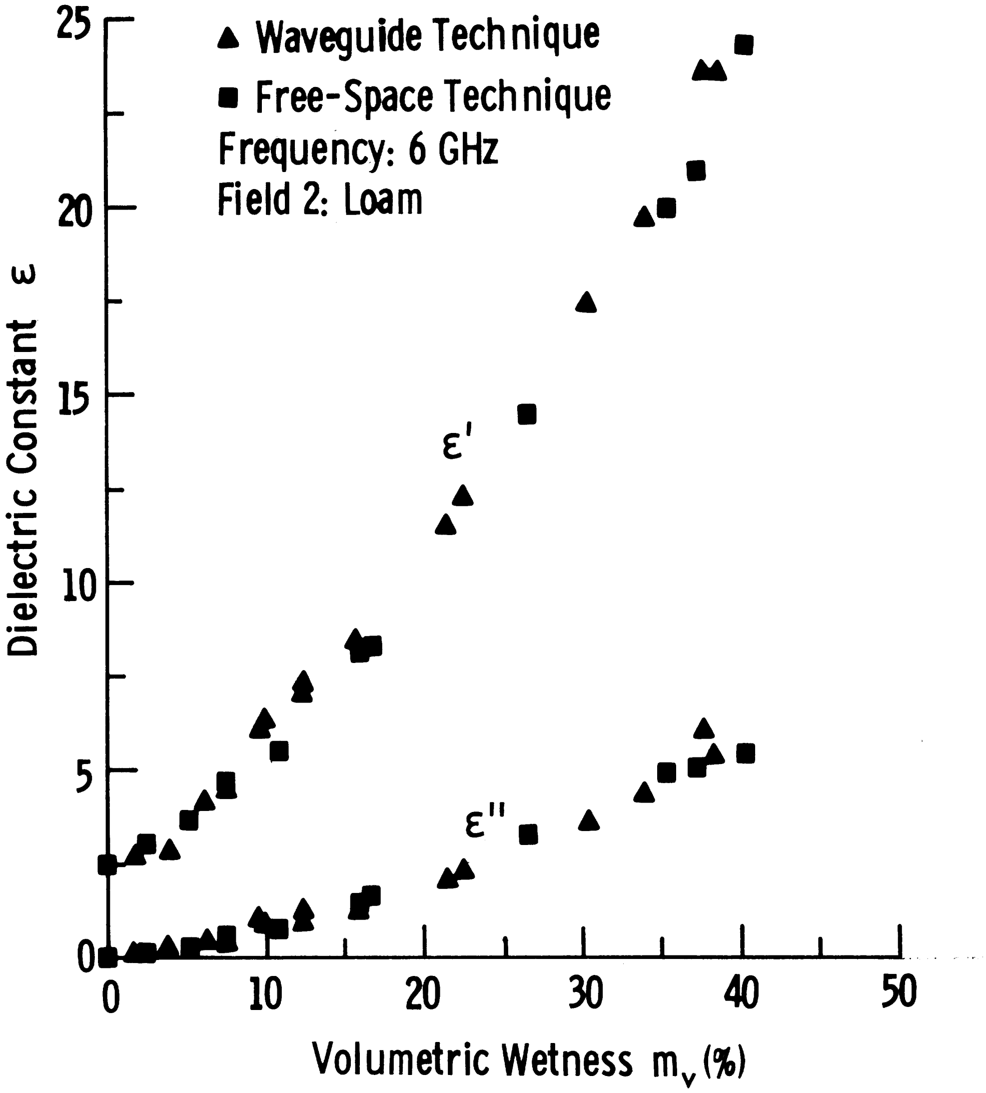

Antenna Distance: 29 cm
● Sample 4
■ Sample 5
▼ Sample 6
Dielectric Constant ε'
2.9
2.8
2.7
2.6
0
4
8
12
16
20
Frequency f (GHz)


Field #2
Volumetric Wetness: 0.015 cm³/cm³
Bulk Density: 1.27 g/cm³
Antenna Distance: 23 cm
Dielectric Loss Factor ε''
0.15
0.10
0.05
0.00
0
4
8
12
16
20
Frequency f (GHz)
Sample 1
Sample 2
Sample 3

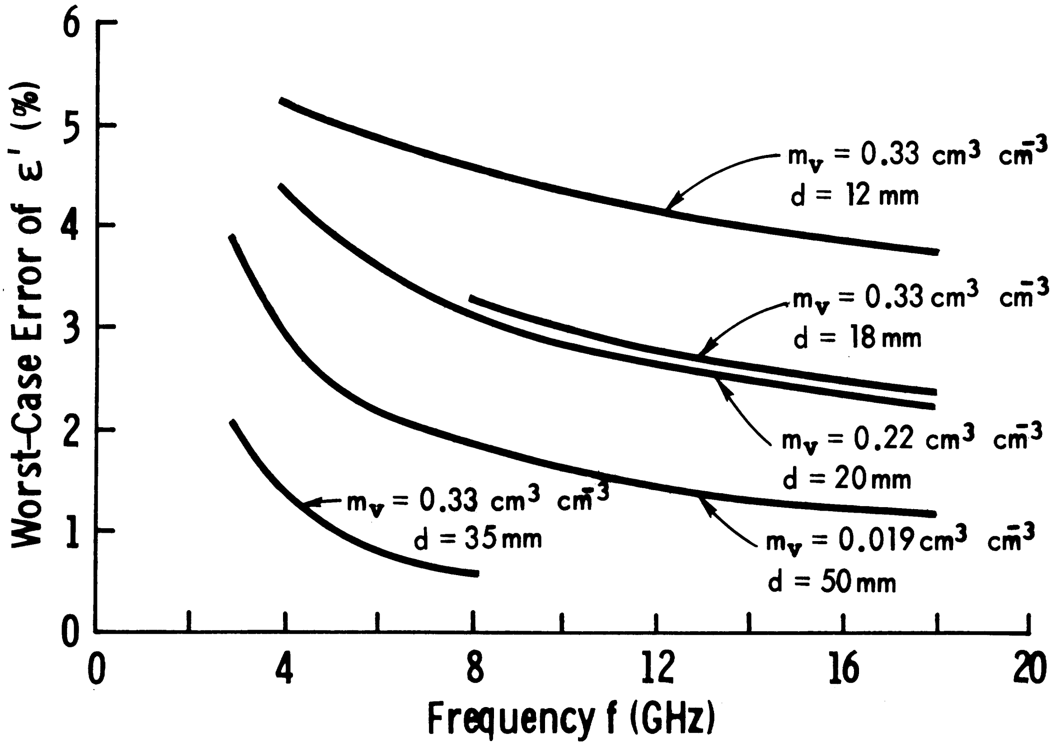

Dielectric Loss Factor ε''
0.15
0.10
0.05
0.00
0
4
8
12
16
20
Frequency f (GHz)
Antenna Distance 29 cm
Sample 4
Sample 5
Sample 6


The Results were Obtained by Measuring 3 Identical Samples at 3 Different Antenna Distances Each (Table 13).
Average
Worst Case
m_v = 0.22 cm³/cm³ and m_v = 0.33 cm³/cm³
d = 20mm
d = 13mm
m_v = 0.32 cm³/cm³
d = 18mm
with 8-18GHz Amplifier
m_v = 0.33 cm³/cm³
d = 35mm
m_v = 0.015 cm³/cm³
d = 49mm
Standard Deviation of ε' / Mean Value of ε' (%)
Frequency f (GHz)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
2
4
6
8
10
12
14
16
18
20

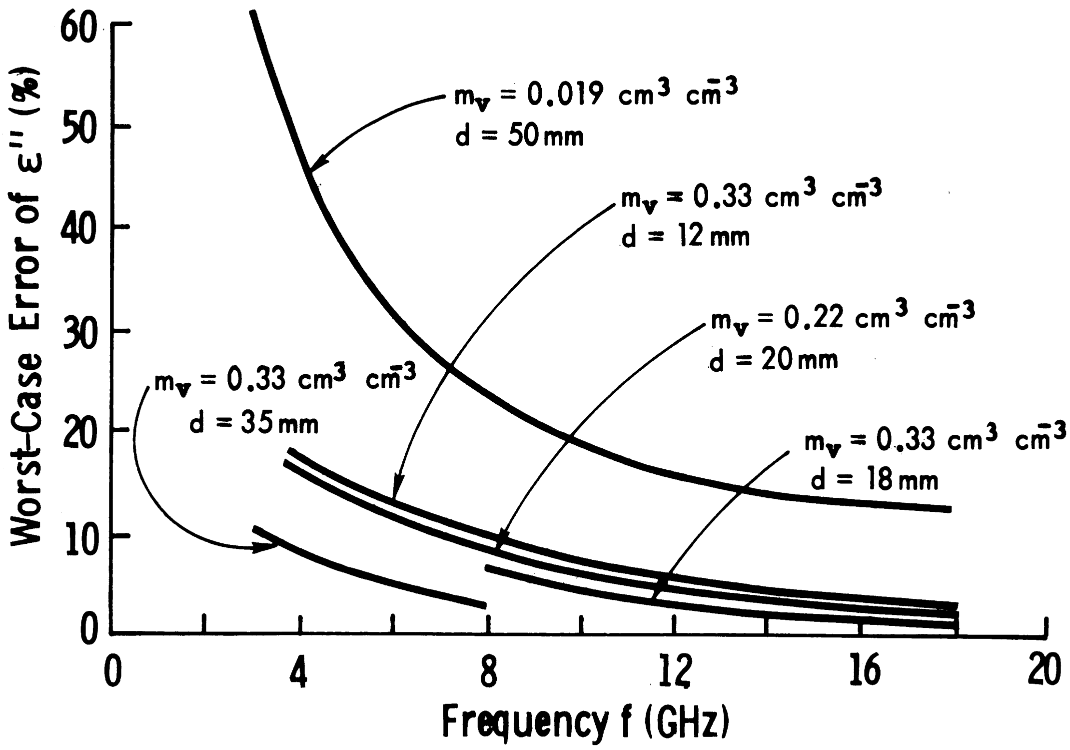

The Results were Obtained by Measuring 3 Identical Samples at 3 Different Antenna Distances Each (Table 13).
Average
Worst Case
m_v = 0.015 cm^3/cm^3
d = 49mm
Sweep Technique
m_v = 0.22 cm^3/cm^3
d = 20mm
Sweep and Pulley Methods
and:
m_v = 0.33 cm^3/cm^3
d = 12mm
Pulley Method
m_v = 0.33 cm^3/cm^3
d = 35mm
Sweep Technique
m_v = 0.32 cm^3/cm^3
d = 18mm
Sweep Technique with 8-18GHz Amplifier
Standard Deviation of ε'' / Mean Value of ε'' (%)
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
16
18
20
Frequency f (GHz)



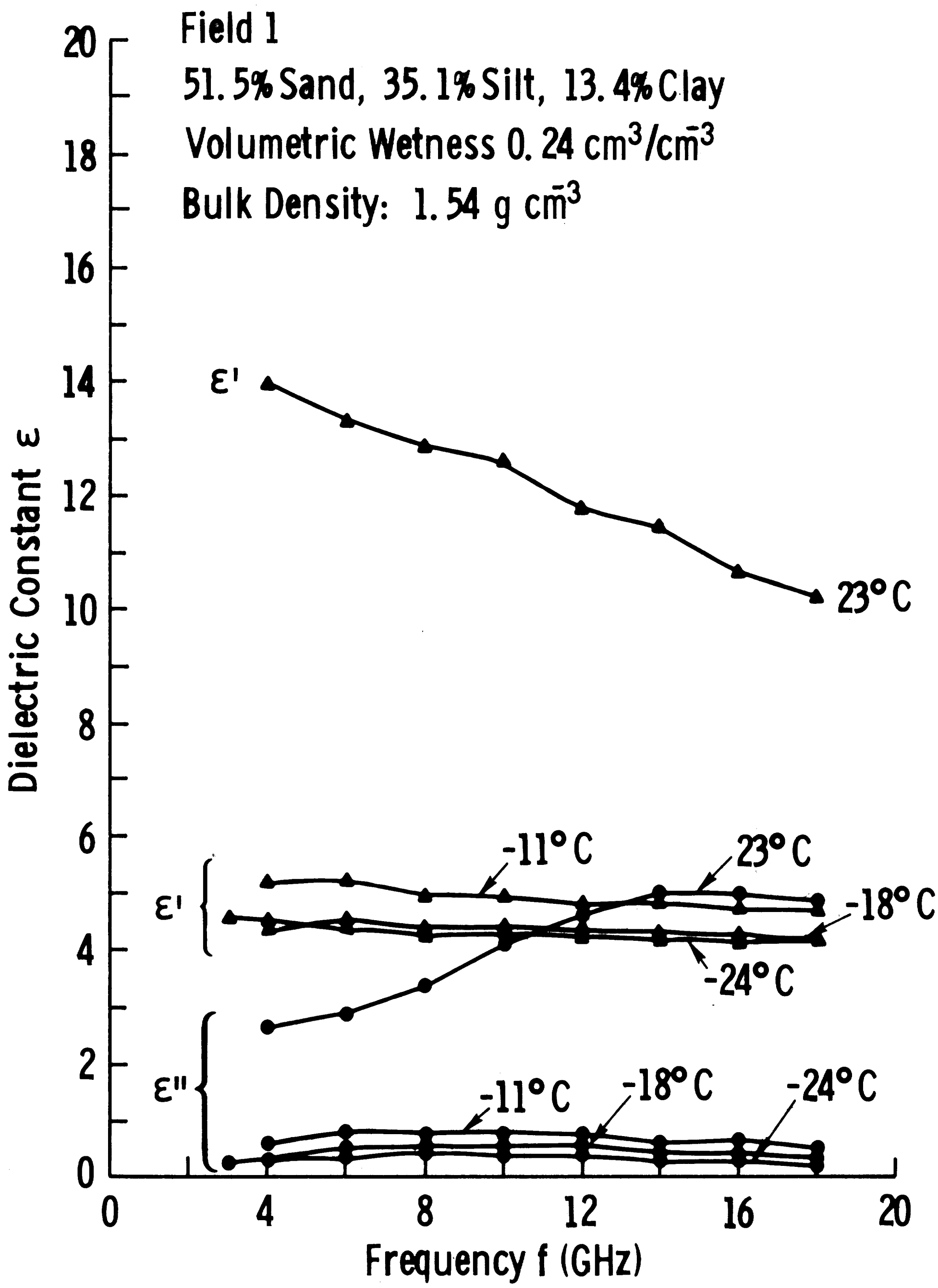
▲ Waveguide Technique
■ Free-Space Technique
Frequency: 6 GHz
Field 2: Loam
ε'
ε"
Dielectric Constant ε
Volumetric Wetness m_v (%)
0
5
10
15
20
25
0
10
20
30
40
50



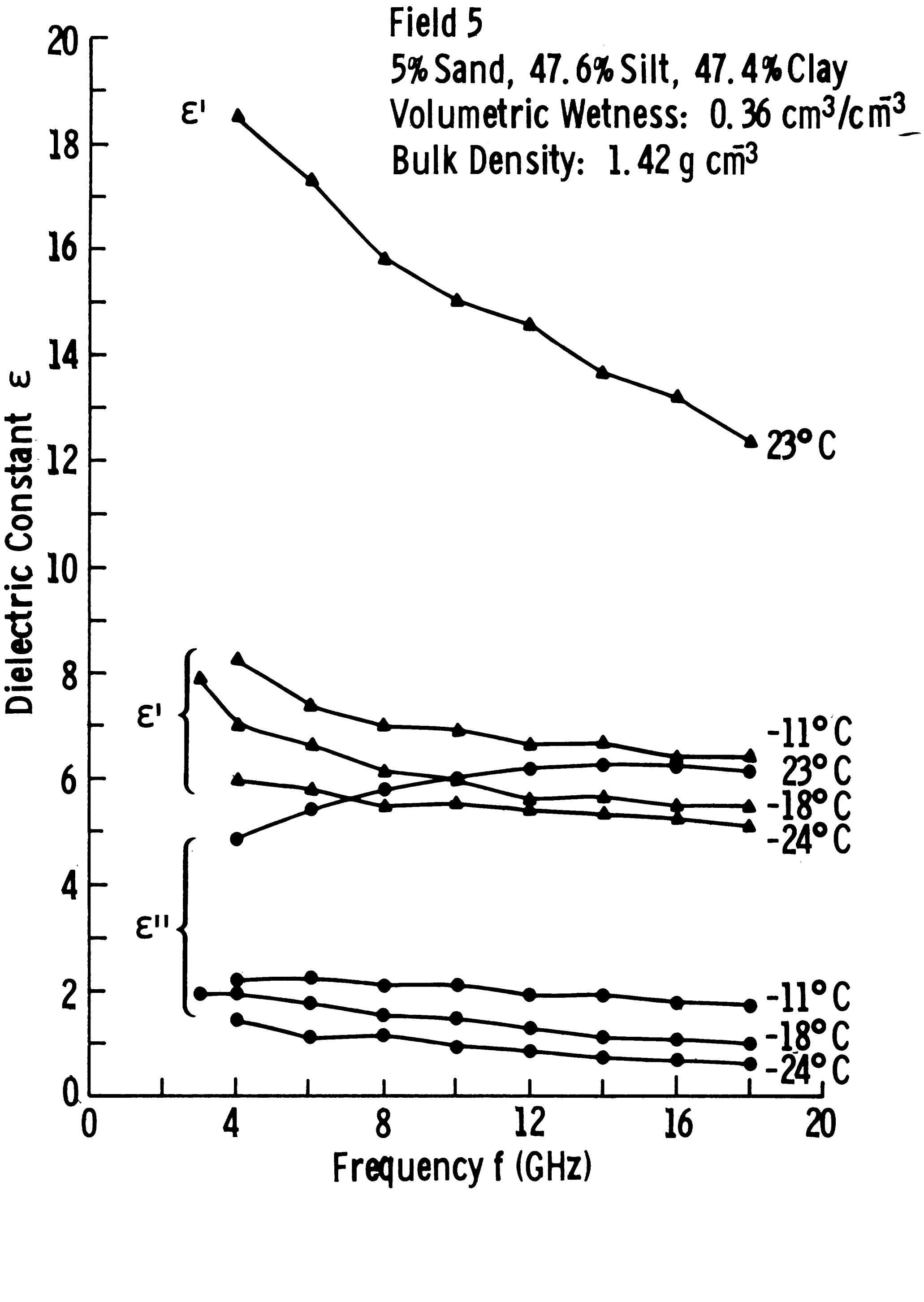
Worst-Case Error of ε' (%)
Frequency f (GHz)
m_v = 0.33 cm³ cm⁻³ d = 12 mm
m_v = 0.33 cm³ cm⁻³ d = 18 mm
m_v = 0.22 cm³ cm⁻³ d = 20 mm
m_v = 0.019 cm³ cm⁻³ d = 50 mm
m_v = 0.33 cm³ cm⁻³ d = 35 mm



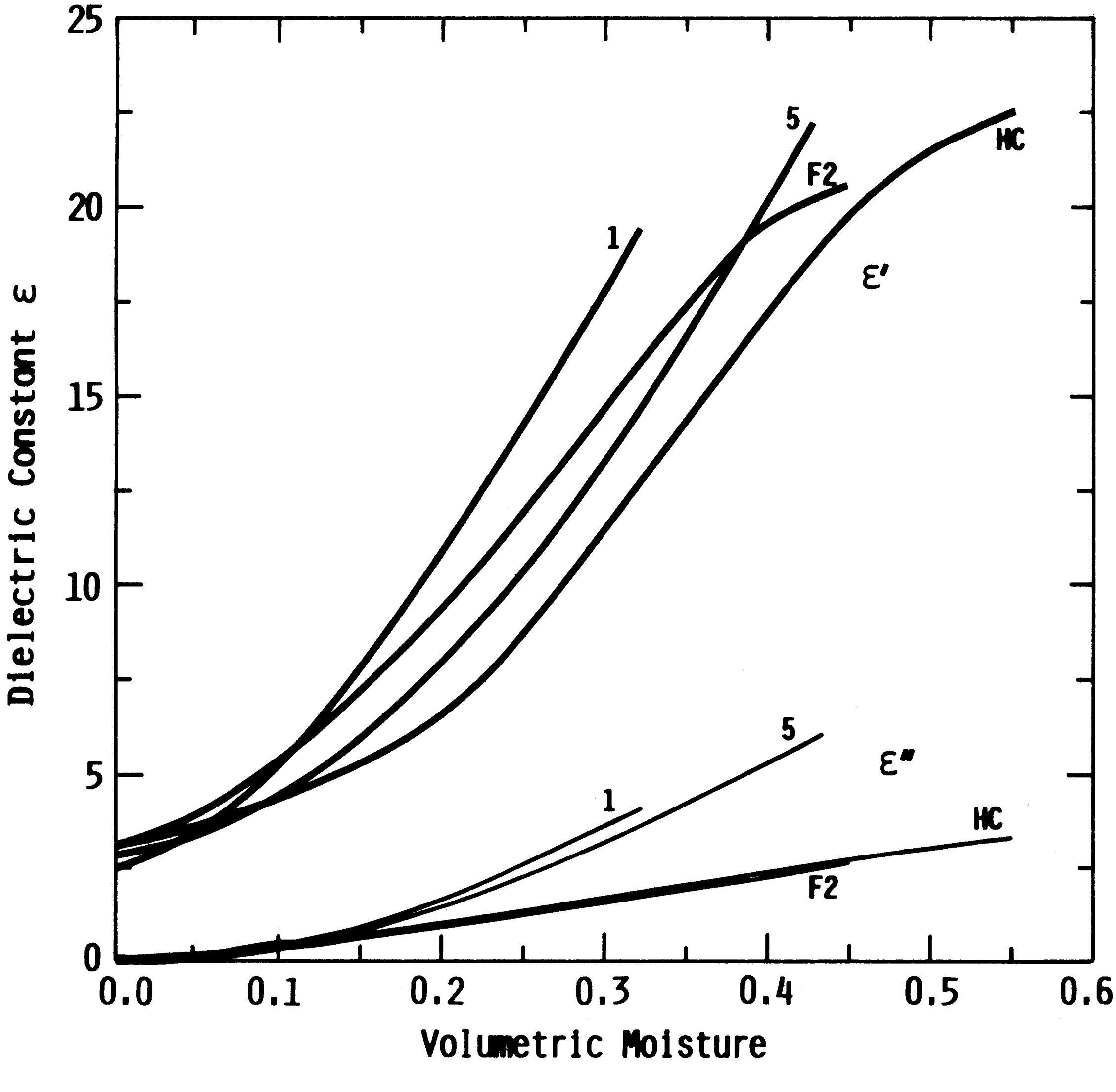
Worst-Case Error of ε'' (%)
Frequency f (GHz)
m_v = 0.019 cm³ cm⁻³ d = 50 mm
m_v = 0.33 cm³ cm⁻³ d = 12 mm
m_v = 0.22 cm³ cm⁻³ d = 20 mm
m_v = 0.33 cm³ cm⁻³ d = 35 mm
m_v = 0.33 cm³ cm⁻³ d = 18 mm



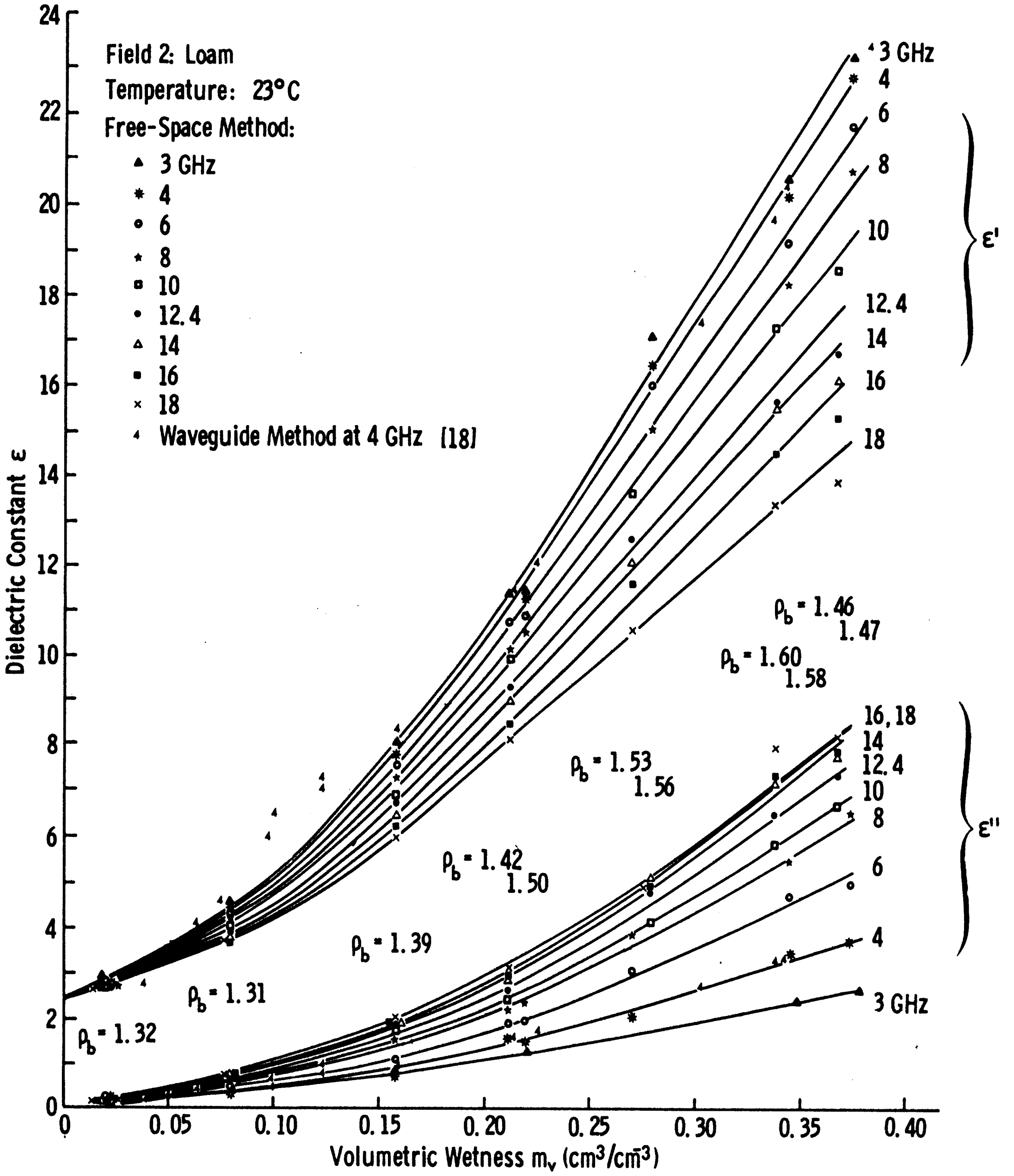
Field 1
51.5% Sand, 35.1% Silt, 13.4% Clay
Volumetric Wetness 0.24 cm³/cm⁻³
Bulk Density: 1.54 g cm⁻³
Dielectric Constant ε
Frequency f (GHz)
ε'
23° C
ε'
-11° C
23° C
-18° C
-24° C
ε"
-11° C
-18° C
-24° C
0
4
8
12
16
20
2
6
10
14
18

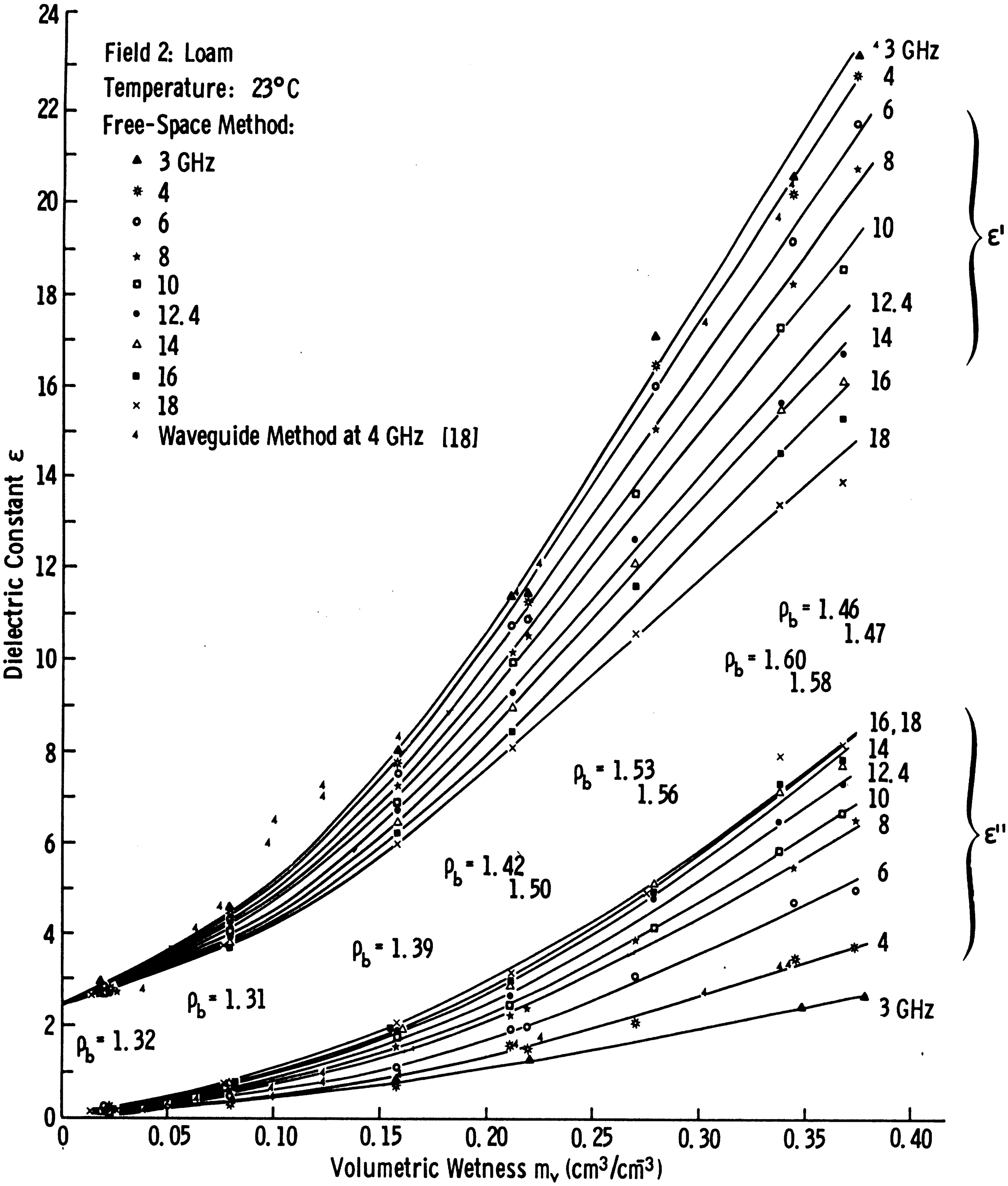


Field 5
5% Sand, 47.6% Silt, 47.4% Clay
Volumetric Wetness: 0.36 cm³/cm⁻³
Bulk Density: 1.42 g cm⁻³
ε'
23° C
ε'
-11° C
23° C
-18° C
-24° C
ε''
-11° C
-18° C
-24° C
Dielectric Constant ε
Frequency f (GHz)
0
2
4
6
8
10
12
14
16
18
20
0
4
8
12
16
20

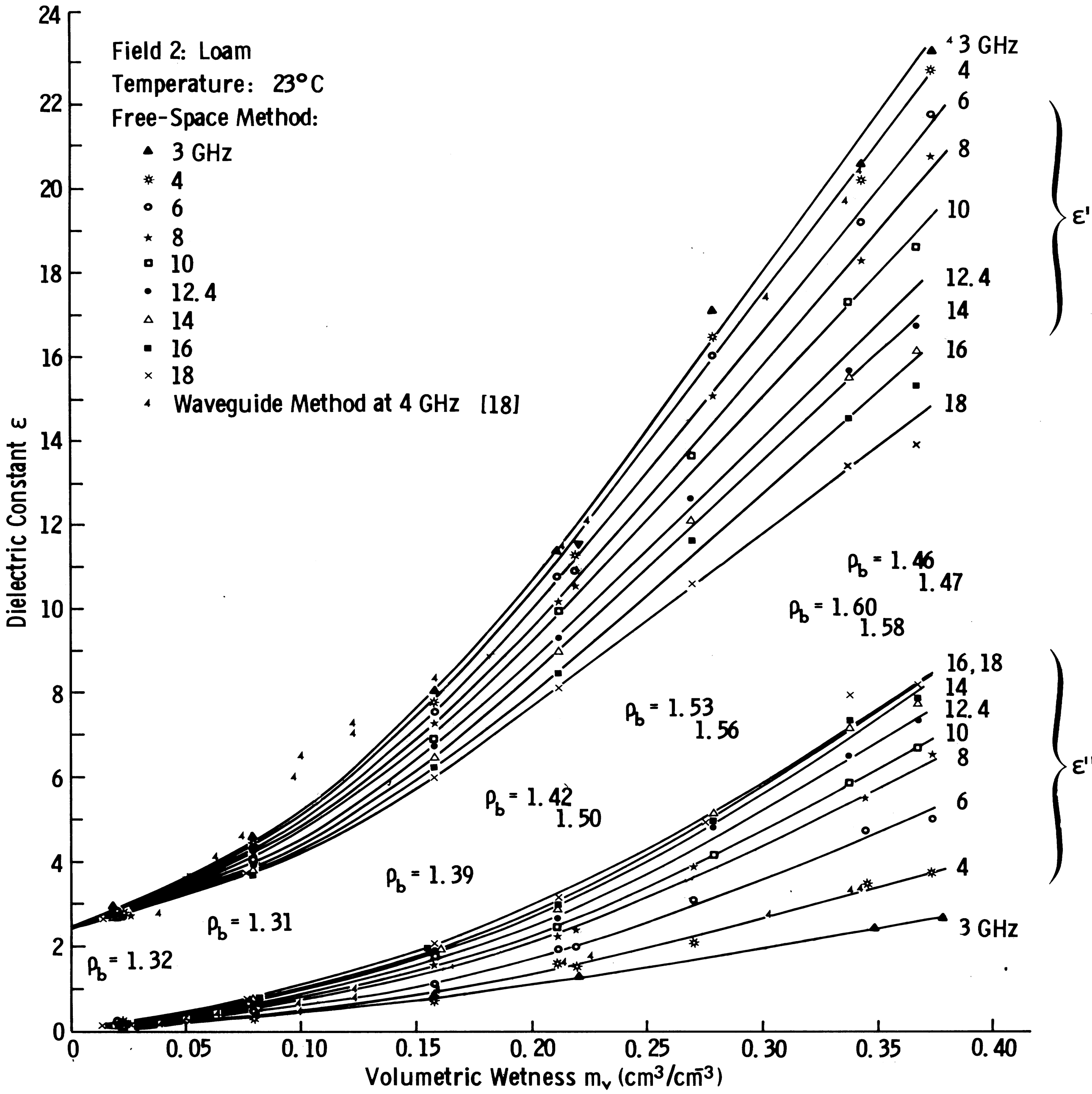


25
20
15
10
5
0
Dielectric Constant ε
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Volumetric Moisture
1
5
F2
HC
ε'
1
5
ε"
HC
F2


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 ε
Volumetric Wetness m_v (cm³/cm³)
ε'
ε''
3 GHz
4
6
8
10
12.4
14
16
18
16, 18
14
12.4
10
8
6
4
3 GHz
ρ_b = 1.46
1.47
ρ_b = 1.60
1.58
ρ_b = 1.53
1.56
ρ_b = 1.42
1.50
ρ_b = 1.39
ρ_b = 1.31
ρ_b = 1.32
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
2
4
6
8
10
12
14
16
18
20
22
24



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 ε
Volumetric Wetness m_v (cm³/cm³)
ε'
ε''
ρ_b = 1.32
ρ_b = 1.31
ρ_b = 1.39
ρ_b = 1.42
1.50
ρ_b = 1.53
1.56
ρ_b = 1.60
1.58
ρ_b = 1.46
1.47
16, 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 [18]
Dielectric Constant ε
Volumetric Wetness m_v (cm^3/cm^3)
ε'
ε''
ρ_b = 1.32
ρ_b = 1.31
ρ_b = 1.39
ρ_b = 1.42
1.50
ρ_b = 1.53
1.56
ρ_b = 1.60
1.58
ρ_b = 1.46
1.47
16, 18