

MICROWAVE DIELECTRIC BEHAVIOR OF VEGETATION MATERIAL

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ABSTRACT

The microwave dielectric behavior of vegetation was examined through the development of theoretical models involving dielectric dispersion by both "bound" and "free" water and supported by extensive dielectric measurements conducted over a wide range of conditions. The experimental data were acquired using an open-ended coaxial probe that was developed for sensing the dielectric constant of thin layers of materials, such as leaves, from measurements of the complex reflection coefficient using a network analyzer. The probe system was successfully used to record the spectral variation of the dielectric constant over a wide frequency range extending from 0.5 GHz to 20.4 GHz at numerous temperatures between $-40^{\circ}C$ and $+40^{\circ}C$. The vegetation samples – which included corn leaves and stalks, tree trunks, branches and needles, and other plant material – were measured over a wide range of moisture conditions (where possible). To model the dielectric spectrum of the bound water component of the water included in vegetation, dielectric measurements were made for several sucrose-water solutions as analogs for the situation in vegetation. The results were used in conjunction with the experimental data for leaves to determine some of the constant coefficients in the theoretical models. Two models, both of which provide good fit to the data, are proposed. The first model treats the water in vegetation as two independent components, a bound water component with a relaxation frequency of 0.178 GHz and a free water component with a relaxation frequency of 18 GHz at $22^{\circ}C$. The second model treats all the water as a single mixture with a relaxation frequency that increases with moisture content from about 0 for dry vegetation to 18 GHz for vegetation with very high moisture contents.

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Table of Contents

ABSTRACT	i
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS	iii
LIST OF FIGURES	vii
LIST OF TABLES	xxii
1. INTRODUCTION	1
2. BACKGROUND	6
2.1 Dielectric Properties Of Liquid Water	7
2.1.1 What Is A Relaxation Process	7
.....Polar Molecules	8
.....Debye's Equation	9
.....2.1.2 Pure Water	15
.....2.1.3 Saline Water	16
.....2.1.4 Bound Water	19
.....2.1.5 Temperature Dependence	23
2.2 Dielectric Mixing Models	25
.....2.2.1 DeLoor's Mixing Model	26
.....2.2.2 Semi-Empirical Models	28
.....2.2.3 Empirical Models	30
2.3 Water In Plant Materials	31
.....2.3.1 Ecological And Physiological Importance Of Water	31
.....2.3.2 Uses Of Water In Plants	31
2.4 Previous Studies	32
.....2.4.1 Carlson(1967)	33
.....2.4.2 Broadhurst(1970)	33
.....2.4.3 Tan(1981)	34
.....2.4.4 Ulaby And Jedlicka(1984)	35

.....2.4.5 Summary	35
3. DIELECTRIC MEASUREMENT SYSTEMS - GENERAL	38
3.1 Transmission Techniques	38
.....3.1.1 Waveguide System	39
.....3.1.2 Free-Space System	42
3.2 Reflection Technique	42
.....3.2.1 Slotted Line System	42
.....3.2.2 Probe System	48
3.3 Resonance Techniques	52
.....3.3.1 The Filled-Cavity Approach	52
.....3.3.2 The Partially-Filled Cavity Approach	54
3.4 Comparison	56
.....3.4.1 Usable Frequency Band	56
.....3.4.2 Measurement Accuracy And Precision	58
.....3.4.3 Dielectric Values Limit	60
.....3.4.4 Practical Aspects	61
4. OPEN-ENDED COAXIAL PROBE SYSTEM	63
4.1 System Description	63
4.2 Analysis	64
.....4.2.1 Error Correction	64
.....4.2.2 Equivalent Circuit Modeling	68
.....4.2.3 Calibration And The Inverse Problem	70
4.3 Probe Selection	71
.....4.3.1 Optimum Capacitance	71
.....4.3.2 Sensitivity	77
.....4.3.3 Higher Order Modes	87
.....4.3.4 Contact And Pressure Problem	90
4.4 Probe Calibration	91
.....4.4.1 Choice Of Calibration Materials	91
.....4.4.2 Error Analysis	92
.....4.4.3 Thin Sample Measurements	103
.....4.4.4 Comparison To The Waveguide Transmission System	123
.....4.4.5 Probe Usage And Limitations-Other Probe Configurations ..	123
5. MEASUREMENT RESULTS	126
5.1 Plant Type, Part, And Location	127

5.2	Frequency Dependence	132
5.3	Water Content Dependence	138
5.4	Salinity Effects	142
5.5	Bound Water Effects	156
5.6	Temperature Effects	178
5.7	Density Effects	209
6.	MODELING EFFORTS	212
6.1	Liquid Water Dielectric Properties	213
....6.1.1	Distilled Water	213
....6.1.2	Saline Water	213
....6.1.3	Temperature Effects	214
....6.1.4	Bound Water	216
....6.1.5	Temperature Effects (Bound Water)	217
6.2	Volume Fraction Calculations	220
....6.2.1	Assumptions And Definitions	220
....6.2.2	Volume Fractions For A Sample That Shrinks	222
....6.2.3	Volume Fractions For A Sample That Does Not Shrink	224
....6.2.4	Volume Fractions For Sucrose Solutions	228
6.3	Models	232
....6.3.1	DeLoor's Model (Upper Limit)	232
....6.3.2	Debye's Model (With Two Relaxation Spectra)	235
....6.3.3	Birchak Model (Semi-Empirical)	255
....6.3.4	Polynomial Fit (Empirical Model)	256
....6.3.5	Single-Phase Single-Relaxation Spectrum Debye Model	264
7.	CONCLUSIONS AND RECOMMENDATIONS	301
7.1	Conclusions	301
....7.1.1	Measurement System	301
....7.1.2	Measurements	303
....7.1.3	Modeling	304
7.2	Recommendations	305
....7.2.1	Measurement System	305
....7.2.2	Measurements And Modeling	306
	REFERENCES	310
	APPENDIX A. Dielectric Measurements at Room Temperature	A.0
	APPENDIX B. Dielectric Measurements as a Function of Temperature	B.0

APPENDIX C. Probe Modeling Program Listing C.0

LIST OF FIGURES

Figure 2.1. Dielectric constant spectra for liquid water with salinity (in ppt) as parameter at room temperature ($20^{\circ}C$). Calculated from [Stogryn, 1971].	17
Figure 3.1. Waveguide transmission measurement system.	41
Figure 3.2. 3-18 GHz free-space transmission measurement system.	44
Figure 3.3. A schematic diagram of the coaxial wave guide used for the leaf measurements and the corresponding standing wave patterns assumed in the derivation of the working equations [Broadhurst, 1971].	45
Figure 3.4. Block diagram of the probe dielectric system. Frequency coverage is 0.1-20 GHz.	50
Figure 3.5. Schematic diagram of the measurement set-up for microwave cavity measurements.	54
Figure 4.1. Error models used for test set connection errors.	67
Figure 4.2. Coaxial probe (a), and its equivalent circuit (b).	70
Figure 4.3. Calibration algorithm for the full equivalent circuit parameters, $C_f, C_0, B,$ and A	73

Figure 4.4(a). Calculated optimum capacitance for methanol(0.1-1 GHz).	74
Figure 4.4(b). Calculated optimum capacitance for methanol(1-20 GHz).	75
Figure 4.4(c). Calculated optimum capacitance for distilled water(0.1-1 GHz).	76
Figure 4.4(d). Calculated optimum capacitance for distilled water(1-20 GHz).	77
Figure 4.5. Calculated probe sensitivity for distilled water (0.1-1 GHz).	80
Figure 4.6. Calculated probe sensitivity for distilled water (1-20 GHz).	81
Figure 4.7. Calculated probe sensitivity for methanol (0.1-1 GHz).	82
Figure 4.8. Calculated probe sensitivity for methanol (1-20 GHz).	83
Figure 4.9. Calculated probe sensitivity for 1-butanol (0.1-1 GHz).	84
Figure 4.10. Calculated probe sensitivity for 1-butanol (1-20 GHz).	85
Figure 4.11. Calculated probe sensitivity for 1-octanol (0.1-1 GHz).	86
Figure 4.12. Calculated probe sensitivity for 1-octanol (1-20 GHz).	87
Figure 4.13. Estimated relative errors % for measurements on yellow cheese both accuracy and precision.	96
Figure 4.14. Estimated relative errors % for measurements on white cheese both accuracy and precision.	97

Figure 4.15. Estimated relative errors % for measurements on 1-octanol both accuracy and precision using the 0.250" probe.	98
Figure 4.16. Estimated relative errors % for measurements on 1-octanol both accuracy and precision using the 0.141" probe.	99
Figure 4.17. Estimated relative errors % for measurements on 1-butanol both accuracy and precision using the 0.250" probe.	100
Figure 4.18. Estimated relative errors % for measurements on 1-butanol both accuracy and precision using the 0.141" probe.	101
Figure 4.19. Comparison of calculated [ref. 2 is Bottreau et al, 1977] and measured data using the 0.141" probe for 1-butanol (real part).	102
Figure 4.20. Comparison of calculated [ref. 2 is Bottreau et al, 1977] and measured data using the 0.141" probe for 1-butanol (imaginary part). ...	103
Figure 4.21. Probe technique for measuring dielectric of (a) thick layers and (b) thin layers.	105
Figure 4.22(a). Comparison of a measured stack of sheets against a metal background and against a plexiglass background versus the stack's thickness at f=1 GHz.	106
Figure 4.22(b). Comparison of a measured stack of sheets against a metal background and against a plexiglass background versus the stack's thickness at f=5 GHz.	107
Figure 4.22(c). Comparison of a measured stack of sheets against a metal background and against a plexiglass background versus the stack's thickness at f=8 GHz.	108

Figure 4.23. Thin sample configuration against a background material (known). 110	
Figure 4.24(a). Evaluation of the thin-thick sample formula (refer to text) for the 0.250" probe at 1 GHz(real part).	113
Figure 4.24(b). Evaluation of the thin-thick sample formula (refer to text) for the 0.250" probe at 1 GHz(imaginary part).	114
Figure 4.25(a). Evaluation of the thin-thick sample formula (refer to text) for the 0.250" probe at 8 GHz(real part).	115
Figure 4.25(b). Evaluation of the thin-thick sample formula (refer to text) for the 0.250" probe at 8 GHz(imaginary part).	116
Figure 4.26(a). Evaluation of the thin-thick sample formula (refer to text) for the 0.141" probe at 1 GHz(real part).	117
Figure 4.26(b). Evaluation of the thin-thick sample formula (refer to text) for the 0.141" probe at 1 GHz(imaginary part).	118
Figure 4.27(a). Evaluation of the thin-thick sample formula (refer to text) for the 0.141" probe at 8 GHz(real part).	119
Figure 4.27(b). Evaluation of the thin-thick sample formula (refer to text) for the 0.141" probe at 8 GHz(imaginary part).	120
Figure 4.28(a). Spectra of measured one leaf/metal, one leaf/plexiglass, and thick stack/plexiglass along with the calculated values from the thin-thick formula (real parts). Above 11 GHz high-order modes propagation (upper curve) causes large errors.	121

Figure 4.28(b). Spectra of measured one leaf/metal, one leaf/plexiglass, and thick stack/plexiglass along with the calculated values from the thin-thick formula (imaginary parts). Above 11 GHz high-order modes propagation (upper curve) causes large errors. 122

Figure 4.29. Comparison between the probe and the waveguide systems. 125

Figure 5.1. Comparison between corn leaves and soybeans leaves. Curves were fitted to measured data using a second order polynomial fit. 129

Figure 5.2. Comparison between corn stalks(measured on the inside part) and tree trunk (Black-Spruce). Curves were fitted to measured data using a second order polynomial fit. 130

Figure 5.3. Comparison between corn leaves and corn stalks. Curves were fitted to measured data using a second order polynomial fit. 131

Figure 5.4. Measured dielectric constant and calculated volumetric moisture for fresh corn stalks as a function of height above the ground (cm). .. 133

Figure 5.5. Measured spectra of the dielectric constant of corn leaves with volumetric moisture M_v as parameter (real parts). 134

Figure 5.6. Measured spectra of the dielectric constant of corn leaves with volumetric moisture M_v as parameter (imaginary parts). 135

Figure 5.7. Measured spectra of the dielectric constant (real and imaginary parts) at the low frequency band (.1-2 GHz) for Crassulaceae Echeveria leaves. 137

Figure 5.8(a). Measured dielectric constant of corn leaves at 1, 4, and 17 GHz, respectively, with frequency as parameter. 139

Figure 5.8(b). Measured spectra of the dielectric constant of soybeans leaves with volumetric moisture M_v as parameter (real parts). 140

Figure 5.8(c). Measured spectra of the dielectric constant of soybeans leaves with volumetric moisture M_v as parameter (imaginary parts). 141

Figure 5.9. Measured salinity in (ppt) for extracted fluids from corn leaves at different volumetric moisture levels, plants were excised and naturally dried. 147

Figure 5.10 Spectra of the extracted fluids from corn leaves. The data points are measured and the solid lines are calculated from [Stogryn, 1971] for saline water solution with 8 ppt salinity. 150

Figure 5.11 Spectra of the extracted fluids from corn stalks. The data points are measured and the solid lines are calculated from [Stogryn, 1971] for saline water solution with 8 ppt salinity. 151

Figure 5.12 Spectra of the extracted fluids from corn stalks. The data points are measured and the solid lines are calculated from [Stogryn, 1971] for saline water solution with 8 ppt salinity (the pressure guage showed 10 tons during the extraction, 3 tons for Figure 5.11). 152

Figure 5.13. Measured spectra of the dielectric properties of potatoes and apples. The measured salinity of the extracted fluids were 7 and 0.8 ppt, respectively. 157

Figure 5.14. Measured spectra of the sucrose solution (A) with $x=0.5$. Two probes were used to measure the lower (.25") and upper (.141") bands. $V_s, V_b, \text{ and } V_f$ are sucrose, bound, and free water volume fractions, respectively. 161

Figure 5.15. Measured spectra of the sucrose solution (D) with $x=2$. Two probes were used to measure the lower (.25") and upper (.141") bands.

$V_s, V_b, \text{ and } V_f$ are sucrose, bound, and free water volume fractions, respectively.	162
Figure 5.16. Measured spectra of the sucrose solution (G) with $x=3.17$. Two probes were used to measure the lower (.25") and upper (.141") bands. $V_s, V_b, \text{ and } V_f$ are sucrose, bound, and free water volume fractions, respectively.	163
Figure 5.17. Measured spectrum of the imaginary part for sucrose solution (D) with $x=2$. The peak is at around 1 GHz. The agreement between the two sets of data produced by two different probes is fairly good.	164
Figure 5.18. Spectra for the sucrose solution (G) with $x=3.17$. The data points are measured and the solid lines are calculated using Equation 2.18 in the text.	166
Figure 5.19. Measured spectra for dextrose solution with $x=2$. Two probes were used to measure the lower(.25") and upper(.141") bands.	167
Figure 5.20. Measured spectra for Silica gel (X3) with $x=0.5$	168
Figure 5.21. Measured spectra for Gelatin (X1) with $x=1$. Two probes were used to measure the lower(.25") and upper(.141") bands.	169
Figure 5.22. Measured spectra for starch solution with $x=1$	171
Figure 5.23. Measured spectra for Accacia (Arabic Gum) solution with $x=0.8$. 172	
Figure 5.24. Measured spectra for natural honey. Two probes were used to measure the lower(.25") and upper(.141") bands.	173

Figure 5.25. Measured spectra for egg white. Two probes were used to measure the lower(.25") and upper(.141") bands.	174
Figure 5.26. Measured spectra for egg yolks.	175
Figure 5.27. Measured spectra for human skin (finger tips). Two probes were used to measure the lower(.25") and upper(.141") bands.	176
Figure 5.28. Dielectric constant behavior versus temperature with frequency as parameter for distilled water (s=0 ppt). Calculated from [Stogryn, 1971].	179
Figure 5.29. Dielectric constant behavior versus temperature with frequency as parameter for saline water solution (s=4 ppt). Calculated from [Stogryn, 1971].	180
Figure 5.30. Dielectric constant behavior versus temperature with frequency as parameter for saline water solution (s=8 ppt). Calculated from [Stogryn, 1971].	181
Figure 5.31. Measured dielectric constant versus temperature from $-40^{\circ}C$ to $+30^{\circ}C$ at 1 GHz for Fatshedera leaves. $M_g(\text{before}) = 0.745$ and $M_g(\text{after}) = 0.711$	185
Figure 5.32. Measured dielectric constant versus temperature from $-40^{\circ}C$ to $+30^{\circ}C$ at 4 GHz for Fatshedera leaves. $M_g(\text{before}) = 0.745$ and $M_g(\text{after}) = 0.711$	186
Figure 5.33. Measured dielectric constant versus temperature from $-40^{\circ}C$ to $+30^{\circ}C$ at 8 GHz for Fatshedera leaves. $M_g(\text{before}) = 0.745$ and $M_g(\text{after}) = 0.711$	187
Figure 5.34. Measured dielectric constant versus temperature from $-40^{\circ}C$ to $+30^{\circ}C$ at 20 GHz for Fatshedera leaves. $M_g(\text{before}) = 0.745$ and $M_g(\text{after})$	

= 0.711.	188
Figure 5.35. [Levitt, 1956].	189
Figure 5.36. Measured spectra for Fatshedera leaves with temperature as parameter (real parts) $M_g(\text{before}) = 0.745$ and $M_g(\text{after}) = 0.711$	191
Figure 5.37. Measured spectra for Fatshedera leaves with temperature above freezing as parameter (imaginary parts) $M_g(\text{before}) = 0.745$ and $M_g(\text{after}) = 0.711$	192
Figure 5.38. Measured spectra for Fatshedera leaves with temperature below freezing as parameter (imaginary parts) $M_g(\text{before}) = 0.745$ and $M_g(\text{after}) = 0.711$	193
Figure 5.39. Measured dielectric constant versus temperature from -45°C to $+50^{\circ}\text{C}$ at 1 GHz for a tropical tree leaves. $M_g(\text{before}) = 0.839$ and $M_g(\text{after}) = 0.818$	194
Figure 5.40. Measured spectra for a tropical tree leaves at -15°C	195
Figure 5.41. Measured dielectric constant versus temperature from -40°C to $+30^{\circ}\text{C}$ with frequency as parameter for Fatshedera leaves (real parts). $M_g(\text{before}) = 0.736$ and $M_g(\text{after}) = 0.718$	197
Figure 5.42. Measured dielectric constant versus temperature from -40°C to $+30^{\circ}\text{C}$ with frequency as parameter for Fatshedera leaves (imaginary parts). $M_g(\text{before}) = 0.736$ and $M_g(\text{after}) = 0.718$	198
Figure 5.43. Measured dielectric constant versus temperature from -40°C to $+30^{\circ}\text{C}$ at 1 GHz for Fatshedera leaves. A freezing-thawing cycle is shown for the real part.	199

- Figure 5.44.** Measured dielectric constant versus temperature from $-40^{\circ}C$ to $+30^{\circ}C$ at 1 GHz for Fatshedera leaves. A freezing-thawing cycle is shown for the imaginary part. 200
- Figure 5.45.** Measured dielectric constant versus temperature from $-35^{\circ}C$ to $+30^{\circ}C$ with frequency as parameter for corn leaves (real parts). $M_g(\text{before}) = 0.835$ and $M_g(\text{after}) = 0.781$ 202
- Figure 5.46.** Measured dielectric constant versus temperature from $-35^{\circ}C$ to $+30^{\circ}C$ with frequency as parameter for corn leaves (imaginary parts). $M_g(\text{before}) = 0.835$ and $M_g(\text{after}) = 0.781$ 203
- Figure 5.47.** Measured dielectric constant versus temperature from $-35^{\circ}C$ to $+30^{\circ}C$ at 1 GHz for corn leaves. A freezing-thawing-freezing cycle is shown for the real part. 204
- Figure 5.48.** Measured dielectric constant versus temperature from $-35^{\circ}C$ to $+30^{\circ}C$ at 1 GHz for corn leaves. A freezing-thawing-freezing cycle is shown for the imaginary part. 205
- Figure 5.49.** Measured dielectric constant versus temperature from $-20^{\circ}C$ to $+50^{\circ}C$ with frequency as parameter for sucrose solution (#9 or G) for the real parts. 207
- Figure 5.50.** Measured dielectric constant versus temperature from $-20^{\circ}C$ to $+50^{\circ}C$ with frequency as parameter for sucrose solution (#9 or G) for the imaginary parts. 208
- Figure 5.51.** Measured dielectric constant versus temperature from $-80^{\circ}C$ to $+30^{\circ}C$ at 1 GHz for sucrose solution (#9 or G). The measured solution in this case is not exactly (#9 or G) because of solid sucrose precipitation at low temperatures. 210
- Figure 6.1.** Calculated volume fractions for a vegetation sample that shrinks. V_a , V_f , V_b , and V_v are the volume fractions of air, free, bound water, and

bulk vegetation material that binds water, respectively.	225
Figure 6.2. Calculated volume fractions for a vegetation sample that shrinks. M_v , V_f , V_b , and V_v are the volume fractions of water, free water, bound water, and bulk vegetation material that binds water, respectively. ..	226
Figure 6.3. Calculated volume fractions for a vegetation sample that shrinks. M_v , V_v , V_{vr} , and V_{vm} are the volume fractions of water, bulk vegetation material that binds water, remaining bulk material that does not bind water, and the total or maximum bulk material, respectively.	227
Figure 6.4. Calculated volume fractions for a vegetation sample that does not shrink. V_a , V_f , V_b , and V_v are the volume fractions of air, free, bound water, and bulk vegetation material that binds water, respectively.	229
Figure 6.5. Calculated volume fractions for a vegetation sample that does not shrink. M_v , V_f , V_b , and V_v are the volume fractions of water, free water, bound water, and bulk vegetation material that binds water, respectively.	230
Figure 6.6. Calculated volume fractions for a vegetation sample that does not shrink. M_v , V_v , V_{vr} , and V_{vm} are the volume fractions of water, bulk vegetation material that binds water, remaining bulk material that does not bind water, and the total or maximum bulk material, respectively. ...	231
Figure 6.7. Comparison of calculated and measured dielectric spectra for corn leaves using DeLoor's model for randomly oriented and randomly distributed discs at $T=22^{\circ}\text{C}$ for $M_g=0.681$	236
Figure 6.8. Comparison of calculated and measured dielectric spectra for corn leaves using DeLoor's model for randomly oriented and randomly distributed discs at $T=22^{\circ}\text{C}$ for $M_g=0.333$	237

Figure 6.9. Comparison of calculated and measured dielectric spectra for corn leaves using DeLoor's model for randomly oriented and randomly distributed discs at $T=22^{\circ}\text{C}$ for $M_g=0.168$	238
Figure 6.10. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with two relaxation spectra at $T=22^{\circ}\text{C}$ for $M_g=0.681$	241
Figure 6.11. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with two relaxation spectra at $T=22^{\circ}\text{C}$ for $M_g=0.333$	242
Figure 6.12. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with two relaxation spectra at $T=22^{\circ}\text{C}$ for $M_g=0.168$	243
Figure 6.13. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with two relaxation spectra ($f=1$ GHz).	244
Figure 6.14. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with two relaxation spectra ($f=4$ GHz).	245
Figure 6.15. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with two relaxation spectra ($f=12$ GHz).	246
Figure 6.16. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with two relaxation spectra ($f=20$ GHz).	247
Figure 6.17. Calculated real parts spectra of all components for corn leaves using a Debye-like model with two relaxation spectra. ($M_g = 0.681$).	249

Figure 6.18. Calculated imaginary parts spectra of all components for corn leaves using a Debye-like model with two relaxation spectra. ($M_g = 0.681$). 250

Figure 6.19. Calculated real parts spectra of all components for corn leaves using a Debye-like model with two relaxation spectra. ($M_g = 0.333$). 251

Figure 6.20. Calculated imaginary parts spectra of all components for corn leaves using a Debye-like model with two relaxation spectra. ($M_g = 0.333$). 252

Figure 6.21. Calculated real parts spectra of all components for corn leaves using a Debye-like model with two relaxation spectra. ($M_g = 0.168$). 253

Figure 6.22. Calculated imaginary parts spectra of all components for corn leaves using a Debye-like model with two relaxation spectra. ($M_g = 0.168$). 254

Figure 6.23. Comparison of calculated and measured dielectric spectra for corn leaves using Birchak's model ($M_g = 0.681$).257

Figure 6.24. Comparison of calculated and measured dielectric spectra for corn leaves using Birchak's model ($M_g = 0.333$).258

Figure 6.25. Comparison of calculated and measured dielectric spectra for corn leaves using Birchak's model ($M_g = 0.168$).259

Figure 6.26. Comparison of calculated and measured dielectric spectra for corn leaves using a polynomial fit ($M_g = 0.681$).261

Figure 6.27. Comparison of calculated and measured dielectric spectra for corn leaves using a polynomial fit ($M_g = 0.333$).262

Figure 6.28. Comparison of calculated and measured dielectric spectra for corn leaves using a polynomial fit ($M_g = 0.168$).	263
Figure 6.29. Comparison of calculated and measured dielectric spectra for sucrose solution (A) using a Debye-like model with a single variable relaxation spectrum ($V_s = 0.239$ and $M_v = 0.761$).	268
Figure 6.30. Comparison of calculated and measured dielectric spectra for sucrose solution (B) using a Debye-like model with a single variable relaxation spectrum ($V_s = 0.385$ and $M_v = 0.615$).	269
Figure 6.31. Comparison of calculated and measured dielectric spectra for sucrose solution (C) using a Debye-like model with a single variable relaxation spectrum ($V_s = 0.485$ and $M_v = 0.515$).	270
Figure 6.32. Comparison of calculated and measured dielectric spectra for sucrose solution (D) using a Debye-like model with a single variable relaxation spectrum ($V_s = 0.559$ and $M_v = 0.441$).	271
Figure 6.33. Comparison of calculated and measured dielectric spectra for sucrose solution (E) using a Debye-like model with a single variable relaxation spectrum ($V_s = 0.613$ and $M_v = 0.387$).	272
Figure 6.34. Comparison of calculated and measured dielectric spectra for sucrose solution (F) using a Debye-like model with a single variable relaxation spectrum ($V_s = 0.655$ and $M_v = 0.345$).	273
Figure 6.35. Comparison of calculated and measured dielectric spectra for sucrose solution (G) using a Debye-like model with a single variable relaxation spectrum ($V_s = 0.667$ and $M_v = 0.333$).	274
Figure 6.36. For the single phase model, $y(V_{vm}/M_v)$ is plotted against gravimetric moisture M_g	275

Figure 6.37. The effective resonant frequency f_0 (GHz) of the single water phase versus gravimetric moisture M_g 279

Figure 6.38. Volume fractions of corn leaves as calculated from the single phase model. M_v , V_{vm} , V_a , and $V_{vm} + V_a$ are the volume fractions of water, bulk vegetation material, air, and dry vegetation material, respectively. ... 280

Figure 6.39. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.681$ 281

Figure 6.40. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.605$ 282

Figure 6.41. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.601$ 283

Figure 6.42. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.551$ 284

Figure 6.43. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.472$ 285

Figure 6.44. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.333$ 286

Figure 6.45. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.258$ 287

Figure 6.46. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.252$	288
Figure 6.47. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.168$	289
Figure 6.48. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.074$	290
Figure 6.49. Comparison of calculated and measured dielectric spectra for corn leaves using a Debye-like model with a single relaxation spectrum (variable) for $M_g = 0.041$	291
Figure 6.50. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with a single variable relaxation spectrum for $f = 0.7$ GHz.	292
Figure 6.51. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with a single variable relaxation spectrum for $f = 1$ GHz.	293
Figure 6.52. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with a single variable relaxation spectrum for $f = 2$ GHz.	294
Figure 6.53. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with a single variable relaxation spectrum for $f = 4$ GHz.	295
Figure 6.54. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with a single variable re-	

laxation spectrum for $f = 8$ GHz. 296

Figure 6.55. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with a single variable relaxation spectrum for $f = 17$ GHz. 297

Figure 6.56. Comparison of calculated and measured dielectric constant versus moisture for corn leaves using a Debye-like model with a single variable relaxation spectrum for $f = 20.4$ GHz. 298

LIST OF TABLES

Table 1.1. Examples of space missions.	2
Table 1.2. Available and desired ranges of parameters.	4
Table 2.1. Comparison between previous microwave dielectric measurements on vegetation materials.	37
Table 3.1. Comparison between different microwave dielectric measurement techniques.	63
Table 4.1. Dimensions and cut-off wavelengths for the TM_{01} mode for the probes used in this study.	89
Table 4.2. $(\lambda_{\epsilon})_c$ for distilled water.	90
Table 4.3. Evaluation of the thin-thick formula for the 0.141" probe.	123
Table 5.1. Measured salinity of liquids extracted from corn plants at different pressures (in tons per unit area) and at different plant heights.	144
Table 5.2. Salinity and gravimetric moisture for corn leaves and stalks. ..	145
Table 5.3. Comparison between measured corn leaves grown in Kansas and Michigan.	148

Table 5.4. Comparison between salinity measurements using conductivity meter and using dielectric measurements.	149
Table 5.5. Fresh corn leaves and stalks at 1.0 GHz (Michigan, Dec. 1985, samples grown in Botanical Gardens).	153
Table 5.6. Freshly cut desert plants (at 1 GHz).	155
Table 5.7. Dielectric of potatos, tomatos, and apples ($M_g \geq 0.8$ and $f=1$ GHz). 155	
Table 5.8. Volume fractions and dielectric constants of sucrose solutions at 1 GHz).	159
Table 5.9. Measured ϵ' and ϵ'' of various materials (some with known water-binding capacity, $X = \text{solid weight} / \text{water weight}$) at 1 GHz.	177
Table 5.10. Liquid water temperature coefficients.	182
Table 5.11. Measured data for poplar tree trunk at 1 and 5 GHz.	211
Table 6.1. Statistics associated with the regression fits given by 6.29 to 6.33. 219	
Table 6.2. Model accuracy for corn leaves, DeLoor's model with $A_j=(0,0,1)$ and $\epsilon^* = \epsilon_m$ at $T = 22^{\circ}C$	235
Table 6.3. Model accuracy for corn leaves data, Debye-like model at $T = 22^{\circ}C$. 240	
Table 6.4. Model accuracy for corn leaves, Birchak model ($\alpha = 0.873$) at $T = 22^{\circ}C$	256

Table 6.5. Model accuracy for corn leaves data, polynomial fit at $T = 22^{\circ}C$.	260
Table 6.6. Model accuracy of single-phase Debye model as applied to the sucrose solutions data at $T = 22^{\circ}C$.	267
Table 6.7. Model accuracy for corn leaves data, single-phase Debye model, $T = 22^{\circ}C$.	278
Table 6.8. Comparison between different models for corn leaves data at $22^{\circ}C$ (real parts).	299
Table 6.9. Comparison between different models for corn leaves data at $22^{\circ}C$ (imaginary parts).	300

Chapter 1

Introduction

Over the past two decades, spaceborne microwave sensors have been playing an increasingly important role in the study of the earth's surface and atmosphere. They can provide near-global coverage of the earth's surface unhampered by cloud cover and with independence of sun angle. Furthermore, the ability of microwave energy to penetrate through dry media has proved useful for studying subsurface terrain features (Carver et al, 1985). In recent years, the field of microwave remote sensing has made significant advances along several fronts. A prime example of a major technological development is the recent realization of digital techniques that can provide real-time processing of SAR images. Also, improved scattering and emission models are now available to relate the backscattering coefficient σ^0 and emissivity e of a distributed target to its dielectric and geometric properties.

Since 1962, numerous microwave radiometers have been flown on earth-orbiting satellites; some examples of these space missions are given in Table 1.1(Ulaby et

al, 1982):

Year	1962	1972	1973	1978
Spacecraft	Mariner 2	Nimbus 5	Skylab	Nimbus 7
Instrument acronym			S193	SMMR
Frequency(GHz)	15.8,22.2	19.3	13.9	6.6,10.7,18,21,37
Type Of Scanning	Mechanical	Electrical	Mechanical	Mechanical
Swath-Width (Km)	Planetary	3000	180	800
Resolution (Km)	1300	25	16	18×27

Table 1.1 Examples of space missions.

Also, several SAR systems have been flown in space including Seasat(1978), SIR-A (1981), and SIR-B (1984). Many experiments have been conducted to relate σ^0 and ϵ to target characteristics at various frequencies and polarizations. Some of these experiments have utilized truck-mounted radar systems to observe the backscattering and emission from natural targets as a function of frequency, look angle, and polarization (Ulaby et al, 1982).

The dielectric properties of natural targets play a key role in remote sensing. Its importance stems from the fact that it determines, besides the sensor parameters and the target geometrical features, the backscattering and natural emission from a distributed target. Also, the dielectric properties of a target relate its physical properties (e.g. its water content or temperature) to its σ^0 and ϵ . This feature is very important in remote sensing science because it is a

critical ingredient of the inverse scattering process. Yet, understanding of the dielectric behavior of natural materials remains superficial at the present time and this is particularly true in the case of vegetation. Only a few experiments have been conducted to date to examine the dielectric properties of vegetation material. Reviewing the literature requires a minor effort because only a few measurements and modelling attempts (Carlson, 1967; Broadhurst, 1971; Tan, 1981; Ulaby and Jedlicka, 1984) have been conducted so far. Moreover, these attempts were limited to narrow ranges of the major parameters of interest, namely plant type and parts, frequency band, moisture content, effective salinity, and temperature. The following table provides a comparison between the range of parameters already tested and those desired from the standpoint of natural variability -as far as the physical parameters are concerned- and in terms of the frequency range of interest to the remote sensing community:

Measured Parameter	Available Data	Desired Range
Frequency (GHz)	1-2,3.5-6.5,7.5-8.5	.1-20
Moisture Content (percent gravimetric)	0-60	0-90
Temperature ($^{\circ}$ C)	20 to 25	-40 to +40
Effective NaCl (Parts Per Thousands)	11	4 to 40

Table 1.2 Available and desired ranges of parameters.

Another shortcoming of the studies already conducted on this subject is the lack of a comprehensive model that relates different plant physical parameters to the dielectric properties using as a few free parameters as possible. This lack of knowledge motivated the current research to study these missing pieces and to try to develop a universal model for vegetation materials. The parameters of interest are frequency (.1 to 20 GHz), temperature (-40 to +40 ° C), water content (0 to 90 % gravimetric), vegetation density (by testing different plants and parts), and salinity (4 to 40 parts per thousand). An additional major goal is to establish the role of bound water in the dielectric process.

The goals of this study can be summed up as follows:

1. To develop a dielectric measurement system suitable for dielectric measurements of plant parts. The system should be fast, reliable, accurate, operate over a broad frequency range, and suitable for temperature measurements.
2. To generate a dielectric constant database for a variety of plant types and parts as a function of:
 - (a) moisture level,
 - (b) electromagnetic frequency,

- (c) vegetation bulk density,
 - (d) effective NaCl salinity of included liquids,
 - (e) temperature, and
 - (f) part location relative to root system.
3. To develop an understanding of the different mechanisms that contribute to the overall dielectric behavior of vegetation materials, and to establish, if possible, the roles of salinity and bound water.
 4. To develop a general physical mixing model for plant materials that incorporates all of the previously mentioned parameters. Empirical and semi-empirical models will be developed as well.

Chapter 2

Background

A vegetation material, such as a leaf, can be considered a heterogeneous vegetation-water mixture consisting of four components: (1) free water, (2) bound water, (3) bulk vegetation matter, and (4) air. Since plants are, in general, found in nature with a very high water content, their dielectric properties are mainly determined by the properties of included water. It was found (Ulaby and Jedlicka, 1984) however, that these fluids have a finite salinity equivalent to an NaCl salinity of about 10 ppt¹. Therefore, the first section of this chapter will provide the background material for the dielectric properties of liquid water as a function of various physical parameters. It is of great importance to note the similarity between the general dielectric behavior of liquid water and that of wet plants. Any deviation however, should be studied and properly attributed to other causes. Some of these causes may include the effects of bound water which differs substantially from free water. Another important cause may be the various structural differences within a plant part which may affect the de-

¹Parts Per Thousand

polarization shape factors (DeLoor, 1968;DeLoor, 1982), which , in turn, may have a significant influence upon the dielectric constant of the vegetation-water mixture. This topic is examined in section 2.2. Next, in section 2.3, a short review is presented of the general principles of plant physiology as they relate to the study of the dielectric properties of vegetation material. Finally, in section 2.4, a brief discussion of previous studies is presented.

2.1 Dielectric Properties Of Liquid Water

The dielectric properties of water have been extensively studied, and are quite well understood with regard to the dependence on salinity, frequency, and temperature. A complete analysis is presented in Hasted (Hasted, 1973). Also, a comprehensive summary of the dielectric properties of natural targets, including water, is provided by Ulaby et al (Ulaby et al, 1986). Since the dielectric properties of liquid water are based on the well known Debye equation (Debye, 1912), it will prove useful to provide a brief background of the Debye equation and the associated relaxation process.

2.1.1 What Is A Relaxation Process

This section is intended to present a brief description of the mechanism by which water molecules exhibit a spectral absorption line at microwave frequencies. For a complete analysis the reader is referred to the classical book of Debye (Debye, 1912), or those by Hasted (Hasted, 1973) and Pethig (Pethig, 1979).

Polar Molecules

The permittivity of a material may be regarded as the proportionality factor between electric charge and electric field intensity. Also, it reflects the extent to which a localized charge distribution can be distorted through polarization by an external electric field. The polarizability, α , is defined as the dipole moment induced by a unit electric field and is given by

$$\alpha_t = \alpha_e + \alpha_a + \alpha_0 \quad (2.1)$$

where α_t is the total polarizability, α_e is the electric polarizability (due to displacement of the electron cloud relative to the nuclei), α_a is the atomic polarizability (due to displacement of the atomic nuclei relative to one another), and α_0 is the orientational polarizability (due to a permanent electric dipole moment). Thus, α_0 only exists in polar materials, e.g. water, and the higher the polarizability of a material, the higher its static dielectric constant. For non-polar materials, the polarizability arises from two effects, namely electronic and atomic polarization. Since the dispersion due to the fall-off of the atomic polarization, α_a , occurs at frequencies comparable with the natural frequencies of vibrations of the atoms in a molecule (i.e. in the infrared spectrum around 10^{14} Hz), and that for electronic polarization, α_e , occurs at still higher frequencies corresponding to electronic transitions between different energy levels in the atom (visible, UV, and X-ray frequencies), the dielectric properties of non-polar materials are constant in the microwave band and do not show any temperature dependence either.

Polar molecules, although electrically neutral, have a charge distribution such that the centers of positive and negative charge are not coincidental. These molecules are termed polar, and were found to have a high static dielectric constant (e.g., ϵ_s of water is about 80.). The slowest polarization mechanism is often that of dipolar reorientation. The dipole moments are just not able to orient fast enough to keep in alignment with the applied electric field and the total polarizability falls from α_t to $(\alpha_t - \alpha_o)$. This fall in polarizability, with its related reduction in dielectric constant (e.g., ϵ_s drops roughly from 80 to 4.5 for water), and the occurrence of energy absorption is referred to as dielectric relaxation or dispersion. It is worth noting here that the dispersion due to α_o is completely different from that due to α_a or α_e . The former is a relaxation dispersion while the later is a resonance dispersion ².

Debye's Equation

The total dipole moment of molecules in a polar material represents the degree of polarization acquired after the application of an external electric field

$$\bar{m} = \alpha_t \bar{E}_1 \quad (2.2)$$

where \bar{m} is the dipole moment and \bar{E}_1 is the local electric field. This equation may be written in the form

$$\bar{m} = \bar{\mu} + \alpha \bar{E}_1 \quad (2.3)$$

²e.g. relaxation dispersion has the broadest spectrum known in physics which is approximately 1.4 decades wide.

where $\bar{\mu}$ is the permanent dipole moment and $\alpha = \alpha_a + \alpha_e$.

Since $\bar{\mu}$ is a permanent moment, the application of an electric field will generate a torque $\bar{\mu} \times \bar{E}$ tending to align the molecules with the field. Obviously, this orienting tendency is opposed by thermal agitation. The potential energy of a dipole moment $\bar{\mu}$ in a field \bar{E}_1 is given by

$$U = -\bar{\mu}\bar{E}_1 = -\mu E_1 \cos \theta \quad (2.4)$$

where θ is the angle between $\bar{\mu}$ and \bar{E}_1 . According to the Boltzmann distribution law, the relative probability of finding a dipole oriented in an element of solid angle $d\theta$ is proportional to $\exp(-U/KT)$ and the thermal average of $\cos \theta$ can be shown to be (Pethig, 1979)

$$\langle \cos \theta \rangle = \coth x - \frac{1}{x} \quad (2.5)$$

where $x = \frac{\mu E_1}{KT}$. It was shown, for $\bar{E}_1 < 10^5 \nu/m$, that

$$\langle \cos \theta \rangle \simeq \frac{\mu E_1}{3KT} \quad (2.6)$$

and that the average moment per dipole in the direction of the applied field, $\bar{\mu}_d$, is given by

$$\bar{\mu}_d = \mu \langle \cos \theta \rangle = \frac{\mu^2 \bar{E}_1}{3KT}. \quad (2.7)$$

Hence, the total polarizability is

$$\alpha_t = \frac{\mu^2}{3KT} + \alpha_e + \alpha_a. \quad (2.8)$$

We must keep in mind, however, that equation (2.8) is only valid for small values of electric field ($E_1 \leq 10^5 \nu/m$); if the fields are higher than that, a more complicated expression is required (Hasted, 1973).

One of the most difficult problems in dielectric theory is to relate the local field (acting on a molecular dipole), to the externally applied field (macroscopic field). Many researchers have tried to relate \bar{E}_1 to \bar{E} and their results were not generally satisfactory (e.g. the Mossotti-Clausius-Lorentz formulation). To derive a mathematical model for the orientational relaxation process, we shall assume that the polarization, P is given by

$$P = P_1 + P_2 = X_1 E + P_2 \quad (2.9)$$

where P_1 is the polarization due to atomic and molecular displacements (it responds instantly to \bar{E} , at least at microwave frequencies), P_2 is the polarization due to dipolar reorientation (it lags behind \bar{E} at microwave frequencies), and X_1 is the dielectric susceptibility. It can be shown that (Pethig, 1979)

$$\frac{dP_2}{dt} = \frac{1}{\tau}(X_2 E - P_2) \quad (2.10)$$

where $X_2 E$ is the final value of P_2 , and τ is the relaxation time constant. Solving equation (2.10) for E as a step function at $t = 0$ when $P_2 = 0$ yields

$$P = P_1 + P_2 = (X_1 + X_2(1 - \exp \frac{-t}{\tau}))E, \quad (2.11)$$

which shows that the polarization reaches its final value exponentially with a time constant τ . A solution for (2.11) of an alternating field, $\bar{E} = \bar{E}_0 \exp(j\omega t)$, can be shown to be (Pethig, 1979)

$$P = P_1 + P_2 = (X_1 + \frac{X_2}{1 + j\omega\tau})E \quad (2.12)$$

which corresponds to a complex dielectric constant of the form

$$\epsilon = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + j\omega\tau} \quad (2.13)$$

where ϵ is the macroscopic complex dielectric constant, ϵ_{∞} is its high frequency (or optical) limit, ϵ_s is its low frequency (or static) limit, and τ is the relaxation characteristic time. The complex dielectric constant can be expressed in real numbers as

$$\epsilon = \epsilon' - \epsilon'' \quad (2.14)$$

and the real and imaginary parts can be expressed as

$$\epsilon' = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + \omega^2\tau^2} \quad (2.15)$$

and

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_{\infty})\omega\tau}{1 + \omega^2\tau^2}. \quad (2.16)$$

Equations (2.13) to (2.16) are commonly known as the Debye dispersion formulas.

Some of the interesting features of the Debye relaxation process are:

1. Its transition extends roughly over four decades in frequency.
2. The width of the ϵ'' peak at the half-height value is roughly 1.4 decades in frequency (very broad !).
3. It is possible to represent a relaxation graphically in two different ways:

- (a) *Two straight lines:* If we plot the following relations $\epsilon''\omega = (\epsilon_s - \epsilon')/\tau$ and $\epsilon''/\omega = (\epsilon' - \epsilon_\infty)\tau$, we will have two straight lines whereby τ can be estimated from their slopes (Pethig, 1979). This is a useful technique if the measurement data are not enough to describe the relaxation behavior (e.g. measurement frequency band is either lower or higher than resonance frequency).
- (b) *Cole-Cole plot:* In order to check for single or multiple relaxation times, this plot can prove very useful. Using equations (2.15) and (2.16), and by eliminating $\omega\tau$, we can show that

$$\left(\epsilon' - \frac{\epsilon_s - \epsilon_\infty}{2}\right)^2 + (\epsilon'')^2 = \left(\frac{\epsilon_s - \epsilon_\infty}{4}\right)^2 \quad (2.17)$$

Equation (2.17) is an equation of a circle. A Cole-Cole plot can be easily constructed by plotting ϵ'' versus ϵ' with frequency as a variable parameter.

4. Since relaxation time τ represents a molecular process that usually follows an Arrhenius temperature law, we can write

$$\tau = A \exp\left(\frac{\Delta H}{RT}\right) \quad (2.18)$$

where ΔH is the Arrhenius activation enthalpy per mole, and A is a constant. From equation (2.18)

$$\frac{\partial(\ln \tau)}{\partial\left(\frac{1}{T}\right)} = \frac{\Delta H}{R} \quad (2.19)$$

so that a plot of $\ln \tau$ against $\frac{1}{T}$ gives a straight line of slope $\frac{\Delta H}{R}$. A more complete expression for (2.18) can be given as (Pethig, 1979).

$$\tau = \frac{h}{KT} \exp\left(\frac{-\Delta S}{R}\right) \exp\left(\frac{\Delta H}{RT}\right) \quad (2.20)$$

where h is Planck's constant and ΔS is the molar entropy of activation. A plot of $\ln(\tau T)$ or $\ln\left(\frac{\omega_s}{T}\right)$ against $\frac{1}{T}$ should be a straight line of negative slope, from which ΔH can be calculated. It is generally the practice to plot simply $\ln(\omega_s)$ against $\frac{1}{T}$ and compare with other activation energy graphs (because of the approximate nature of this treatment).

5. Deviation from an ideal Debye-type single relaxation could occur for many molecular systems. This effect tends to *smear* the relaxation pattern (ϵ'' curve becomes broader). Examples of this phenomena and their respective representation can be given as follows:

(a) *Cole-Cole equation*

$$\epsilon = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + (j\omega\tau)^{\alpha}} \quad (2.21)$$

where α represents the width of the symmetrical distribution of relaxation times. A graphical technique (using chords) was designed (Hasted, 1973) to analyze data that has a symmetrical distribution of relaxation times.

(b) *Modified Cole-Cole equation*

$$\epsilon = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + j^{1-\alpha}(\omega\tau)^{1-\beta}} \quad (2.22)$$

where β is a constant less than unity.

(c) *Cole-Davidson equation*

$$\epsilon = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{(1 + j\omega\tau)^{\alpha}}. \quad (2.23)$$

This equation corresponds to an asymmetrical distribution of relaxation times and gives rise to a skewed arc in $\epsilon'(\epsilon'')$ diagram.

(d) *In general*, we can write

$$\epsilon = \epsilon_{\infty} + (\epsilon_s - \epsilon_{\infty}) \int_0^{\infty} \frac{G(\tau) d\tau}{1 + j\omega\tau} \quad (2.24)$$

where $G(\tau)$ represents a general distribution of relaxation times.

2.1.2 Pure Water

For pure water, it is assumed that the ionic conductivity is zero, which means that there are no free ions to contribute to the total loss (especially at low frequencies). The frequency dependence is given by the Debye equations (2.13)-(2.16):

$$\epsilon_w = \epsilon_{w\infty} + \frac{\epsilon_{ws} - \epsilon_{w\infty}}{1 + j\omega\tau_w} \quad (2.25)$$

It was found experimentally that $\epsilon_{w\infty}$, ϵ_{ws} , and $f_w (=1/2\pi\tau_w)$ are functions of temperature, especially ϵ_{ws} and f_w . Complete analysis and polynomial expressions can be found in (Hasted, 1973; Stogryn, 1971; Klein & Swift, 1977; and Ulaby et al, 1986).

The importance of liquid water at microwave frequencies stems from the fact that its relaxation frequency lies within this band. For example,

$$f_w(0^0C) = 9\text{GHz} \quad (2.26)$$

and

$$f_w(20^0C) = 17\text{GHz} \quad (2.27)$$

It was found that $\epsilon_{w\infty} \simeq 4.9$ by Lane and Saxton (1952). Figure 2.1 illustrates the frequency behavior of ϵ'_w and ϵ''_w for water at 20^0C . Curves for sea water ($s \simeq 30$ ppt) are shown also for comparison purposes.

2.1.3 Saline Water

A saline solution is defined as a solution that contains free ions whether these ions are of organic or non-organic nature. The salinity, s , of a solution is defined as the total mass of dissolved solid salts in grams in one kilogram of solution. An equivalent Debye-like equation could be used to represent saline solutions in the following modified form

$$\epsilon'_{sw} = \epsilon_{sw\infty} + \frac{\epsilon_{sws} - \epsilon_{sw\infty}}{1 + (\frac{f}{f_{sw}})^2} \quad (2.28)$$

and

$$\epsilon''_{sw} = \frac{(\epsilon_{sws} - \epsilon_{sw\infty})(\frac{f}{f_{sw}})}{1 + (\frac{f}{f_{sw}})^2} + \frac{\sigma_i}{2\pi\epsilon_0 f} \quad (2.29)$$

where the subscript sw refers to saline water, σ_i is the ionic conductivity in *Siemens/m*, and ϵ_0 is the free space dielectric constant ($\epsilon_0 = 8.854 \times 10^{-12} f/m$).

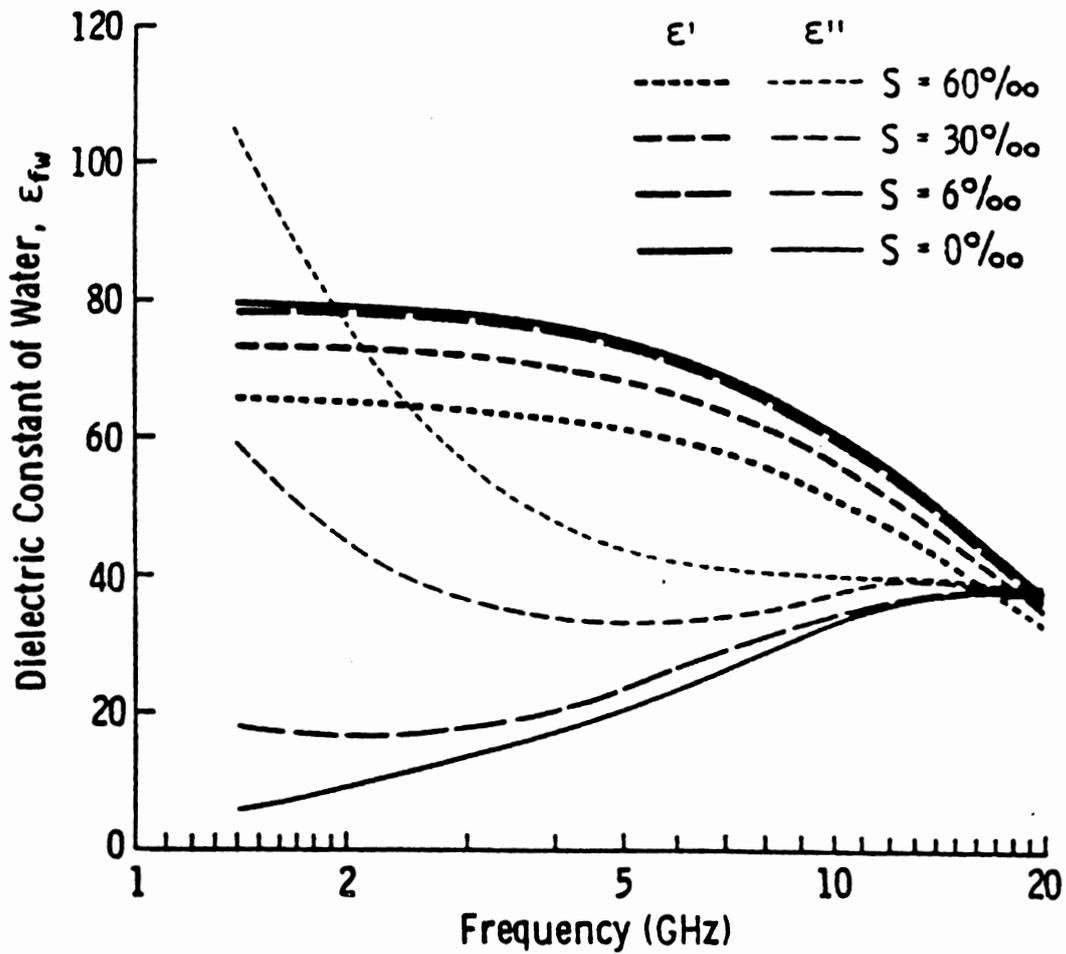


Figure 2.1. Dielectric constant spectra for liquid water with salinity (in ppt) as parameter at room temperature ($20^{\circ}C$). Calculated from [Stogryn, 1971].

Again, σ_i , ϵ_{sw0} , and f_{sw0} were found to be functions of salinity (in addition to their temperature dependence). Complete expressions are given in (Stogryn, 1971) and (Klein and Swift, 1977) in the form of polynomial fits. The equations are repeated here because they will be used in future chapters:

$$\epsilon_{sw\infty} = 4.9, \quad (2.30)$$

$$\epsilon_{sws}(T, 0) = 87.74 - 4.0008T + 9.398 \times 10^{-4}T^2 + 1.410 \times 10^{-6}T^3, \quad (2.31)$$

$$2\pi\tau(T, 0) = 1.1109 \times 10^{-10} - 3.824 \times 10^{-12}T + 6.938 \times 10^{-14}T^2 - 5.096 \times 10^{-16}T^3, \quad (2.32)$$

$$\sigma_{sea\ water}(T, S) = \sigma_{sea\ water}(25, S) \exp(-\Delta\alpha), \quad (2.33)$$

where $\Delta = 25 - T$ and α is a function of T and S ,

$$\alpha = 2.033 \times 10^{-2} + 1.266 \times 10^{-4}\Delta + 2.464 \times 10^{-6}\Delta^2 - S[1.849 \times 10^{-5} - 2.551 \times 10^{-7}\Delta + 2.551 \times 10^{-8}\Delta] \quad (2.34)$$

and

$$\sigma_{sea\ water}(25, S) = S[0.182521 - 1.46192 \times 10^{-3}S + 2.09324 \times 10^{-5}S^2 - 1.28205 \times 10^{-7}S^3], \quad (2.35)$$

in the range $0 \leq S \leq 40$.

2.1.4 Bound Water

The term *bound water* is always encountered in the literature of plant physiology, especially that dealing with cold and drought resistance (Kramer, 1955). The concept of bound water is founded on the observation that a part of the water in both living and nonliving materials behaves in a different manner from free water. While free water freezes at 0°C , acts as a solvent, and is usually available for physiological processes, bound water does not. It remains unfrozen at some low temperature, usually -20°C or -25°C , it is also known not to function as a solvent, and in general it seems to be unavailable for physiological processes. It should be understood here that there is no sharp distinction between unbound and bound water ; rather, there exists a gradual transition between free water and completely bound water. Bound water was found to resist oven drying even at 100°C for a long period of time. Obviously, water bound that firmly plays an important role as a cell constituent in the tolerance of drying of some seeds, spores, microorganisms, and a few higher plants (Kramer, 1983).

Much of the bound water is held on the surfaces of hydrophilic colloids ³, but some is associated with hydrated ions and molecules. Kramer (Kramer, 1955) wrote a thorough review on bound water and described 14 different methods for measuring it:

³A colloid is a phase dispersed to such a degree that the surface forces become an important factor in determining its properties

1. *The Cryoscopic Method*, based on the assumption that bound water does not act as a solvent.
2. *The Dilatometric Method*, using the fact that ice occupies more volume than water and that bound water does not freeze at normal freezing temperatures.
3. *The Calorimetric Method*, since one gram of free water ice absorbs about 79.75 calories when it thaws, it is possible to estimate the amount of total free water in plant tissues using a calorimeter.
4. *The Direct Pressure Method*, differences in the amount of water expressed from various materials under a given pressure can indicate differences in bound water contents.
5. *Refractometric Method*, using a refractometer (Dumanskii, 1933; and Simionova, 1939).
6. *Polarimetric Method*, (Koets, 1931)
7. *The X-ray Method*, the presence of shells of oriented water molecules should give X-ray patterns similar to those produced by ice, this method is useful qualitatively and not quantitatively.
8. *Infrared Absorption*, Infrared transmission curve for bound water was found to be different from that of free water.

9. *Heat Of Welting*, it is known that when colloids imbibe water, heat is released because water molecules lose part of their kinetic energy when they are adsorbed on the interfaces.
10. *Specific Heat Method*, it was observed that bound water has an abnormally low specific heat.
11. *Drying Method*, since bound water is so tightly held by colloids, it remains in samples dried at temperatures as high as 200°C.
12. *Osmotic Pressure Method* (Levitt and Scarth, 1936).
13. *Dielectric Constant Method*, since, in general, the dielectric constant of free water is much higher than that of bound water (Marinsco 1931), it is possible to estimate bound water content using dielectric measurements (as will be discussed in Chapter 5).
14. *Vapor-pressure Method*, adding a nonelectrolyte to free water lowers its vapor pressure. If adding sucrose, e.g., results in an abnormally large decrease in vapor pressure, this indicates that a certain amount of the water is bound.

Although there are many methods to measure the amount of bound water in plant tissues, only a few of them proved to be accurate enough to produce meaningful results. The calorimetric, dilatometric, and cryoscopic methods are used most frequently. According to Kramer (Kramer, 1955), the amount of bound

water found in plant tissues varies with the species tested, the environment in which the plants are grown, and the method used to measure it. There is more bound water in woody plants than there is in herbacious plants. Also some research (Levitt, 1980) indicates that plants have more bound water in the winter than in the summer and more in plants from dry habitats than in those from moist habitats. As a final remark, bound water exists in general in cell walls where it can scarcely affect the protoplasm, and it is held so firmly that it can not act as a solvent or take part in physiological processes. Hence, bound water may have some importance in seeds, spores, and other air-dry plant structure, but it probably is of little significance in growing plants.

The last remark underscores the bound water importance in physiological processes; however, its importance in determining the dielectric properties of vegetation materials is significant, especially at microwave frequencies. Many researchers claimed to observe a relaxation frequency for bound water similar to that of free water, except it takes place at frequencies well below that of free water (e.g. Hoekstra and Doyle, 1971). A possible peak of power absorption takes place around 500 – 1500 *MHz* and was attributed to bound-water relaxation. There are two factors, however, that hold back a proper characterization of this relaxation:

1. *Ionic Conductivity* dominates losses at and below 1 GHz and tends to mask the effect of bound water. It would be useful to test a plant tissue that has very low values of salinity, if such a plant really exists.

2. *Small Volume Fractions* of bound water pose another serious problem, especially for fresh plants, where the free water volume is the largest component. If we attempt to examine a dried plant part that has a low moisture level, the increase in salinity would tend to counteract the relative increase in the volume ratio of bound water to free water and hence ionic conductivity would still be dominant.

In Chapter 5, an attempt was made to isolate an appreciable amount of bound water that has no free ions and hence, no conductivity losses. This water was bound on the surfaces of sugar molecules (e.g., sucrose and dextrose) and was tested over the frequency range from .2-20 GHz. The observed relaxation frequency was found to be in agreement with previous reports which place it at around 1 GHz. A complete description and analysis of the experiment will be given in Chapter 5.

In Chapter 6, however, a conclusion was reached that the nature of bound water is subjective and it depends entirely on how we look at it. Two approaches were used: (i) the dual relaxation spectrum (refer to Sec. 6.3.1 to 6.3.4) and (ii) the single relaxation spectrum (refer to Sec. 6.3.5).

2.1.5 Temperature Dependence

As mentioned in Section 2.1.1 and 2.1.2, the dielectric behavior of liquid water has a strong dependence on temperature above freezing. The dependence is even more drastic below freezing, which is called the *freezing point discontinuity* ,

where the magnitudes of the real and imaginary parts drop rather sharply⁴. One way to detect a relaxation behavior is to measure the dielectric constant of a material as a function of temperature and observe the gradient of the imaginary part. Three cases would arise:

1. If $\frac{\partial \epsilon''}{\partial T}$ is *negative*, the dominant loss mechanism is relaxation and the measurement frequency is below the relaxation frequency ($f < f_0$).
2. If $\frac{\partial \epsilon''}{\partial T}$ is *positive*, then either:
 - (a) losses are completely or partially caused by a relaxation process and in this case $f > f_0$,
 - (b) losses are completely or partially caused by conductivity, or
 - (c) both relaxation ($f > f_0$) and conductivity losses exist.
3. If $\frac{\partial \epsilon''}{\partial T}$ is $\simeq 0$ then either:
 - (a) the material is lossless (e.g. dry),
 - (b) there are two different mechanisms affecting the losses, relaxation (with $f < f_0$) and conductivity, and they are comparable in magnitude, or
 - (c) a relaxation peak ($f = f_0$) exists at that particular temperature.

As mentioned above, at the freezing point discontinuity the dielectric properties of a sample drastically change because liquid water (with, e.g., $\epsilon \simeq 80 - j4$

⁴free water freezes at $0^{\circ}C$ while bound water freezes around (or even below) $-25^{\circ}C$

at 1 GHz) changes into ice (whose $\epsilon \simeq 3.15 - j0$ at 1 GHz) which represents big steps in both the real and imaginary parts. Bound water, however, freezes at temperatures well below free water; it was reported in several papers (e.g., Hoekstra and Doyle, 1971) to have a freezing point between $-20^{\circ}C$ and $-30^{\circ}C$. This last observation could prove useful in studying the bound water in plant tissues by extending the temperature measurements down to $-50^{\circ}C$. A complete report of these measurements will be given in Chapter 5.

2.2 Dielectric Mixing Models

A vegetation part, such as a leaf, is considered to be a heterogeneous mixture of free water, bound water, bulk vegetation material, and air. An average dielectric constant can be measured for a particular heterogeneous mixture consisting of two or more substances. This average quantity depends on the volume fractions, the dielectric constants, the shape factors, and the orientation (relative to the applied electric field) of each and every constituent in the mixture. The continuous medium (or the host material) is usually taken to be the substance with the largest volume fraction in the mixture. For a more complete review, the reader is referred to (Ulaby et al, 1986). For the purpose of this study, only randomly oriented and randomly distributed inclusions will be considered. In the general development of most dielectric mixing models, it is assumed that the inclusions are much smaller in size than the applied wavelength in order for the equations to hold. These conditions are suitable assumptions for vegetation

materials in most cases. However, a study of the effect of inclusions' orientations could be useful in future research, especially for parts that have an obvious orientation pattern (e.g., a tree trunk). In the following three sections, a brief discussion of the mixing models used in the course of this study is given. They include theoretical models (DeLoor, 1968), semi-emperical models (Birchak et al, 1974), and emperical models (Dobson et al, 1985).

2.2.1 DeLoor's Mixing Model

The mixing formula as proposed by Polder and Van Santan (Polder and Van Santan, 1946) and DeLoor (DeLoor, 1956) for a host medium with dispersed randomly-oriented and randomly-distributed inclusions is given by:

$$\epsilon_m = \epsilon_h + \sum_{i=1}^n \frac{v_i(\epsilon_i - \epsilon_h)}{3} \sum_{j=1}^3 \frac{1}{1 + (\frac{\epsilon_i}{\epsilon^*} - 1)A_j} \quad (2.36)$$

where ϵ_m is the macroscopic dielectric constant of the mixture, ϵ_h is the host or continuum dielectric constant, v_i and ϵ_i are the volume filling factor and the dielectric constant of the i_{th} dispersed inclusion, respectively, ϵ^* is the effective relative dielectric constant near an inclusion-host boundary, A_j are the depolarization factors along the main axes of the ellipsoidal inclusions, and n is the number of different inclusions in the mixture. The sum of the depolarization factors is equal to

$$\sum_{j=1}^3 A_j = 1 \quad (2.37)$$

These factors, known also as shape factors, are determined by the inclusion shapes. Three special cases are considered as follows:

1. *Circular discs* ; $A_j = (0, 0, 1)$ Equation (2.36) will reduce to the following form

$$\epsilon_m = \epsilon_h + \sum_{i=1}^n \frac{v_i}{3} (\epsilon_i - \epsilon_h) \left(2 + \frac{\epsilon^*}{\epsilon_i}\right) \quad (2.38)$$

2. *Spheres* ; $A_j = \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$

$$\epsilon_m = \epsilon_h + \sum_{i=1}^n v_i (\epsilon_i - \epsilon_h) \frac{3\epsilon^*}{2\epsilon^* + \epsilon_i} \quad (2.39)$$

3. *Needles* ; $A_j = \left(\frac{1}{2}, \frac{1}{2}, 0\right)$

$$\epsilon_m = \epsilon_h + \sum_{i=1}^n \frac{v_i}{3} (\epsilon_i - \epsilon_h) \frac{5\epsilon^* + \epsilon_i}{\epsilon^* + \epsilon_i}. \quad (2.40)$$

Equation 2.36 can not be used in its present form, since no information is available on ϵ^* . However, after a thorough investigation of the available data, it was found (DeLoor, 1956; DeLoor, 1968) that ϵ^* , in general, lies between ϵ_m and ϵ_h . An upper and a lower limit for ϵ_m can be established by setting $\epsilon^* = \epsilon_m$ and $\epsilon^* = \epsilon_h$ in (2.36), respectively. Moreover, when the depolarization factors are not known, which is generally the case, it is still possible to estimate the limits of ϵ_m . The limits in this latter case lie further apart than when the shape factors are known. These limits are given by (DeLoor, 1968):

1. *Upper Limit* (circular discs; $\epsilon^* = \epsilon_m$)

$$\epsilon_m = \frac{\epsilon_h + \frac{2}{3} \sum_{i=1}^n v_i (\epsilon_i - \epsilon_h)}{1 - \frac{1}{3} \sum_{i=1}^n v_i \left(1 - \frac{\epsilon_h}{\epsilon_i}\right)} \quad (2.41)$$

2. *Lower Limit* (spheres ; $\epsilon^* = \epsilon_h$)

$$\epsilon_m = \epsilon_h + 3 \sum_{i=1}^n v_i \frac{\epsilon_h (\epsilon_i - \epsilon_h)}{(2\epsilon_h + \epsilon_i)} \quad (2.42)$$

where the variables used in (2.38)-(2.42) are as defined in connection with (2.36). These limits are of great help in studying the unknown shape factors for any system by plotting the measured data along with the expected limits.

2.2.2 Semi-empirical Models

There are two semi-empirical models that have proved to be useful for modeling vegetation material, namely, Birchak and the Debye-like models.

1. *Birchack Model*

$$\epsilon = \left(\sum_{i=1}^n \epsilon_i^\alpha v_i \right)^{1/\alpha} \quad (2.43)$$

where α is the only free parameter. When α is equal to .5, the Birchak model is called *the refractive model*.

2. *Debye-like Model* Since the dielectric properties of biological materials are dominated by the dielectric properties of liquid water, a Debye-like model would, in general, be the obvious choice for semi-empirical modeling. Of course, a slight modification is necessary to this formulation in order to include conductivity losses and a spread of relaxation times. The proposed form of Debye's equation is as follows

$$\epsilon_m = \epsilon_{m\infty} + \frac{\epsilon_{ms} - \epsilon_{m\infty}}{1 + j \frac{f}{f_m}} - j \frac{\sigma_m}{\omega \epsilon_0} \quad (2.44)$$

where the variables are as defined earlier and the subscript m indicates the vegetation mixture. $\epsilon_{m\infty}$ and ϵ_{ms} could be evaluated for a particular

mixture provided that we know the following:

- (a) the volume fractions, v_i , of all the constituents,
- (b) $\epsilon_{\infty i}$ and ϵ_{si} of all the constituents, and
- (c) the proper mixing formulas relating $\epsilon_{m,s}$ to ϵ_{si} of the constituents, and similarly for ϵ_{∞} .

Since volume fractions can be determined from vegetation physical parameters,⁵ and $\epsilon_{\infty i}$ and ϵ_{si} are known, the only unknown is the proper mixing formulas.

It is possible, for convenience, to use Birchack model, which gives

$$\epsilon_{m\infty}^{\alpha} = \sum_{i=1}^N v_i \epsilon_{\infty i}^{\alpha}, \quad (2.45)$$

and

$$\epsilon_{m,s}^{\alpha} = \sum_{i=1}^N v_i \epsilon_{si}^{\alpha}. \quad (2.46)$$

The problem now is to determine a suitable value (or values) for α to best fit the measured data. Similarly, f_m can be selected by optimizing the model to fit the data points, and the relaxation frequency of liquid water can be used as an initial condition. The form of σ_m is not known, since the effective *NaCl* salinity changes as a function of moisture content. Hence, in general,

$$\sigma_m = f(M_v) \quad (2.47)$$

where M_v is the volumetric moisture of the material. Two possible representations for σ_m may be proposed

⁵As will be discussed in chapter 6

1. $\sigma_m = A - BM_v$, and

2. $\sigma_m = \frac{A}{M_v}$

Obviously, the first form is more suitable since σ_m remains finite even at $M_v = 0$. For a vegetation mixture, the number of constituents can be two, three, or four depending on the model used. Since the bulk vegetation material and air are *non-polar* materials, they do not have any temperature sensitivity. The only temperature-dependent constituents are the free and bound water.

2.2.3 Empirical Models

The most suitable and most commonly used empirical model for the dielectric constant of vegetation materials is simply a polynomial function. Linear regression can be used to determine the unknown coefficients and an evaluation of the fit is performed in terms of correlation and mean-squared errors. Individual polynomials are generated for ϵ' and ϵ'' as a function of M_v (volumetric moisture) for a particular plant type, part, and at a given frequency and temperature. The disadvantages of this approach are

1. there is no physical significance for the coefficients, and
2. the model is not easily extendable to other moisture, temperature, and/or frequency conditions.

On the other hand, the major advantages are

- Simplicity, and

- The ability to achieve almost a perfect fit to the data by properly choosing the order of the polynomial.

2.3 Water in Plant Materials

Water is one of the most common and most important substances on the earth's surface. It is the most significant single environmental factor that determines the kinds and amounts of vegetation cover on various parts of the globe.

2.3.1 Ecological and Physiological Importance of Water

It is almost a general rule that wherever water is abundant, vegetation cover is lush, and deserts are where water is scarce. The ecological importance of water stems from its physiological importance. Every plant process is affected directly or indirectly by the water supply. If the water supply is decreased, plants will suffer loss of turgor and wilting, cessation of cell enlargement, closure of stomata, reduction in photosynthesis, interference with many basic metabolic processes, and continued dehydration will, eventually, cause death of most organisms (Kramer, 1983).

2.3.2 Uses of Water in Plants

According to Kramer, the function of water in plant materials may be listed as follows:

1. *Constituent*: Fresh weight of most herbaceous plant parts is 80-90% water, and water constitutes over 50% of the fresh weight of woody plants. Some

plant parts, e.g. seeds, can be dehydrated to the air-dry condition, or even to the oven-dry condition without loss of viability, but a marked decrease in physiological activity accompanies the loss of water.

2. *Solvent*: Gases, minerals, and other solutes can enter plant cells and move from cell to cell and organ to organ through the continuous liquid phase throughout the plant.
3. *Reactant*: Water is essential to many processes such as photosynthesis and hydrolytic processes.
4. *Maintenance of Turgidity*: This is important for cell enlargement and growth and for maintaining the form of herbaceous plants. It is also important for various plant structures (Kramer, 1983).

2.4 Previous Studies

Very few studies have been conducted to date with the goal of measuring and modeling the microwave dielectric properties of green vegetation. Extensive dielectric measurements have been conducted and reported for grains (Nelson, 1978) however. This short section reviews some of the reported data for green vegetation, and provides brief discussions of the measurement systems used and their reliability.

2.4.1 Carlson (1967)

A cavity perturbation technique was employed to measure the relative dielectric constant of green vegetation samples (grass, corn, spruce, and taxus) at room temperature and at a single frequency of 8.5 GHz. The measurements were made as a function of water content from freshly-cut samples to perfectly dry ones. The relative dielectric constant was found to be roughly proportional to the moisture content and can be modeled as

$$(\epsilon' - j\epsilon'') = 1.5 + \left(\frac{\epsilon'_w}{2} - j\frac{\epsilon''_w}{3}\right)f \quad (2.48)$$

for the samples of corn, grass, and taxus, where $\epsilon' - j\epsilon''$ is the relative dielectric constant of vegetation samples, $\epsilon'_w - j\epsilon''_w$ is the relative dielectric constant of water, and f is the fractional amount of water in the sample. The major source of errors in this experiment was due to the measurement uncertainty of the sample size.

2.4.2 Broadhurst (1970)

Broadhurst (1970) used a TEM coaxial waveguide with a specimen of the material under test occupying some of the space between the coaxial conductors. His measurements were conducted at room temperature ($23^{\circ}C$) on living foliage, plant materials, and clay soil over a wide frequency band extending from 100 *KHz* to 4.2 GHz. In order to calibrate the system for accuracy, distilled water was measured and compared to reported data. The results were within 10% accuracy for the real part, while sizeable errors were observed for the imaginary part. Also, a check on the precision of the leaf measurements was made

by taking six separate samples from a leaf type and by measuring each sample three different times (after each measurement the sample was removed from the chamber and then repacked and measured). An analysis of variance was then conducted on the data to ascertain the components of variance for instrumental error and for variability between leaves. The scatter in the data due to the leaf was, generally, greater than that due to instrumental errors. The scatter due to the leaf was primarily due to measurement errors of leaf thickness, and secondarily due to variations in leaf biological structure. The uncertainty in the thickness measurements amounts to 5 – 10% and the overall uncertainty was below 20%. Excessive scatter in the data above 1 GHz was caused by higher-order mode propagation in the line.

2.4.3 Tan (1981)

Similar to Carlson's set-up, Tan used a cavity waveguide resonator at 9.5 GHz to measure tropical vegetation samples (grass, casuarina, rubber leaf, rubber wood) at room temperature. Measurements were made as a function of sample water content. The overall accuracy of the system is estimated to be 10 – 15% for both the real and imaginary parts of ϵ . Extending Carlson's modeling approach, Tan used six different mixing formulas to model his data. He concluded that the best model that fits his data was the Polder and Van Santen model (1946) with parameters $\epsilon^* = \epsilon_m$ and $A_j = (0, 0, 1)$. In other words the water inclusions have a circular disc shape within the vegetation host. Again, the main source of error is due to thickness measurements of the plant samples.

2.4.4 Ulaby and Jedlicka (1984)

These measurements (Ulaby and Jedlicka, 1984) were conducted using a waveguide transmission technique in three different bands, namely, L-band (1.1–1.9 GHz), C-band (3.5–6.5 GHz), and X-band (7.6–8.4 GHz). Vegetation types investigated included wheat, corn, and soybeans. Leaves, stalks, and corn heads were measured as a function of their water content. Also, extracted fluids from these parts were measured and compared to saline solutions. An accurate systematic procedure (McKinley, 1983) was developed to measure vegetation densities as they change with volumetric moisture.

Uncertainties in the data were due to sample preparation and data-reduction techniques rather than to variations in measurement system stability. In the modeling efforts conducted, the vegetation medium was considered to be a four-component mixture with the vegetation bulk material as the host and free water, bound water, and air as the inclusions. Also, a three-phase mixture model was attempted with dry vegetation as the host (bulk vegetation material and air) and free water, and bound water as inclusions. The volume of bound water and its dielectric properties were chosen arbitrarily to be 5% and $(3.15 - j0)$, respectively. The reason behind the latter assumption is the view of bound water as a state where water molecules are so strongly bound to colloidal surfaces that they assume the dielectric properties of ice. Another modeling approach was adopted using a two-phase mixture model, in which the host was taken to be the dry vegetation part (bulk vegetation and air) and the inclusions were taken to

be liquid water with effective (or depressed) dielectric properties.

2.4.5 summary

Table 2.1 shows a summary of the previous studies:

Parameter	Carlson,1967	Broadhurst,1970	Tan,1981	Ulaby and Jedlicka,1984
System	Partially-filled cavity	TEM Coaxial Cell	Partially-filled Cavity	Waveguides, Transmission
Frequency	8.5 GHz	100 KHz-4.2 GHz	9.5 GHz	1.1-1.9 GHz 3.5-6.5 GHz 7.6-8.4 GHz
Moisture %	65	80	60	80
Temperature	23°C	23°C	21°C	23°C
Accuracy ϵ' %	10-20	10	10-20	5
Accuracy ϵ'' %	10-20	10-100	10-20	5-37
Plants	grass corn taxus blue spruce	bampoo Tulip tree	grass casuarina rubber	corn wheat soybeans
Parts	leaves	leaves branches	leaves wood	leaves stalks fluids

Table 2.1: Comparison between previous microwave dielectric measurements on vegetation material.

From the brief discussion in the previous subsections, we can conclude the following:

1. Only a few attempts have been made to date to study the microwave dielectric properties of plants.
2. The available measurements were made in limited microwave frequency bands.
3. None of these measurements covered temperature ranges beyond room temperatures ($20 - 25^{\circ}C$).
4. Attempts to model the dielectric behavior of vegetation-water mixtures have been only marginally successful, at best.

These shortcomings motivated the development and use of a measurement technique that would operate over a wide frequency range, that is suitable for dielectric measurements as a function of temperature, and that can measure the dielectric constant accurately, rapidly, and non-destructively. This technique is the subject of Chapter 4.

Chapter 3

Dielectric Measurement Systems-General

Many studies have been conducted in the past (Von Hippel,1954) to examine the dielectric properties of natural and artificial materials. However, very few of these were concerned with vegetation materials. In the past three decades, great improvements have been realized in terms of microwave measurement techniques. The development of automatic network analyzers and sweep frequency measurements has led to the development of better and faster dielectric measurement techniques. This chapter will provide a review of microwave dielectric measurement techniques and systems, with particular emphasis placed on those that may be suitable for vegetation materials.

3.1 Transmission Techniques

The measured quantity in this case is the transmission coefficient (both amplitude and phase, T_m and ϕ_m). The problem is to measure it accurately and then use it to infer the dielectric constant of the unknown material. The most com-

monly used transmission systems are the waveguide and the free space systems and these will be the subject of the next two sections.

3.1.1 Waveguide System

The block diagram shown in Fig. 3.1 represents a standard system used for measuring the amplitude and phase of the TE_{10} mode transmission coefficient. The main part of the system is a network analyzer capable of comparing the phase and amplitude of both arms, when the sample holder is empty, and again when the sample holder is filled with the unknown material. If we assume that the sample holder is of length L , we can write (Hallikainen et al, 1985).

$$T_m = |T_m|e^{j\phi_m} = \frac{(1 - R^2)e^{-\gamma L}}{1 - R^2e^{-2\gamma L}} \quad (3.1)$$

where $\gamma \equiv$ propagation constant of the dielectric-filled waveguide and $\gamma = \alpha + j\beta$.

$R \equiv$ the field reflection coefficient = $\frac{Z - Z_0}{Z + Z_0}$ where $Z_0 \equiv$ the characteristic impedance of the waveguides connected to the sample holder. Z and Z_0 are given by

$$Z = \frac{j\omega\mu_0}{\gamma} = \frac{2\pi\eta_0}{\lambda_0} \frac{\beta(1 + j\alpha/\beta)}{\alpha^2 + \beta^2}, \quad (3.2)$$

and

$$Z_0 = \frac{j\omega\mu_0}{\gamma_0} = \frac{2\pi\eta_0}{\lambda_0\beta_0} \quad (3.3)$$

where $\omega = 2\pi f$,

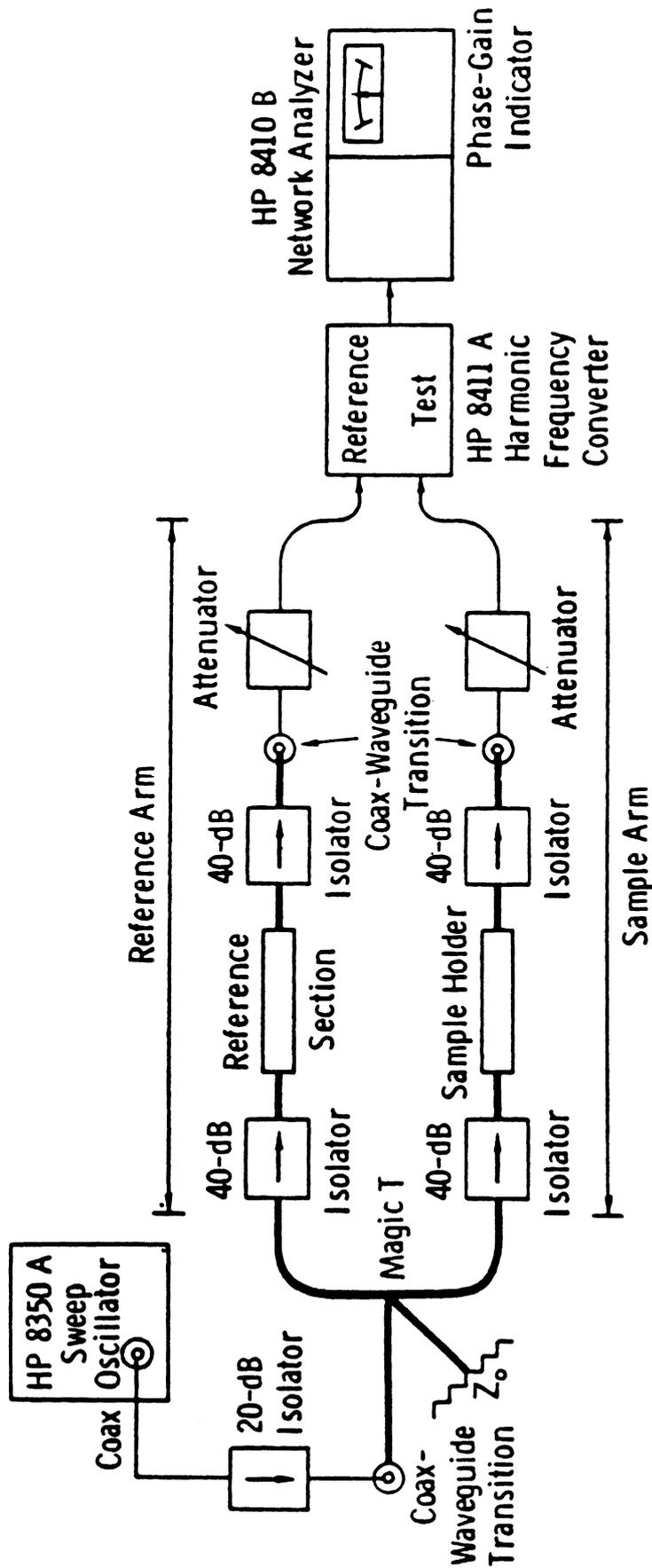


Figure 3.1. Waveguide transmission measurement system.

$\mu_0 \equiv$ permeability of free space,

$\lambda_0 \equiv$ free space wavelength,

$\eta_0 = (\mu_0/\epsilon_0)^{1/2}$, \equiv the intrinsic impedance of free space,

$\gamma_0 = j\beta_0 \equiv$ the propagation constant in the air-filled waveguide connected to the sample holder.

β_0 and γ are given by

$$\beta_0 = \frac{2\pi}{\lambda_0} [1 - (\frac{\lambda_0}{\lambda_c})^2]^{1/2} \quad (3.4)$$

$$\gamma = \alpha + j\beta = \frac{2\pi}{\lambda_0} [(\frac{\lambda_0}{\lambda_c})^2 - \epsilon]^{1/2} \quad (3.5)$$

where $\lambda_c = a/2$ is the cutoff wavelength of the guide of width a (for TE_{10} mode).

From measurements of $|T_m|$ and ϕ_m , it is possible to determine α and β , from which the real and imaginary parts of ϵ may be determined:

$$\epsilon' = (\frac{\lambda_0}{2\pi})^2 [(\frac{2\pi}{\lambda_c})^2 - (\alpha^2 - \beta^2)], \quad (3.6)$$

$$\epsilon'' = (\frac{\lambda_0}{2\pi})^2 (2\alpha\beta), \quad (3.7)$$

In practice, because of the nonlinear relationships between the measured quantities $|T_m|$ and ϕ_m and the quantities α and β , an iterative procedure is used to solve for α and β . The details of the procedure are given in Hallikainen et al (1985).

3.1.2 Free-Space System

As shown in Fig. 3.2, the free-space transmission system is basically similar to the waveguide system. The only difference is the utilization of two antennas and a sample holder, in the form of a dielectric slab, instead of waveguide sections. Consequently, the analysis is the same if we set $1/\lambda_c = 0$ in (3.4), (3.5), and (3.6). Again, an iterative procedure is used to determine ϵ .

3.2 Reflection Techniques

The problem here is to measure the reflection coefficient at the end of a transmission line (both amplitude, $|\rho_m|$ and phase, ϕ_m) and to try to relate it to ϵ of an unknown medium. Reflection techniques have, in general, two major problems: first, since the reflection coefficients for most natural materials are very close to unity, great care has to be taken in measuring $|\rho_m|$, and second, the mathematical expressions relating ρ_m to ϵ are usually derived for an infinite sample, a condition that can not be satisfied in practice. In the next two subsections a brief description will be given for two measurement systems based on the reflection technique.

3.2.1 Slotted Line System

This system was used by Broadhurst, as discussed earlier in Section 2.5, and it is shown schematically in Fig.3.3 (Broadhurst, 1970). The measurement of dielectric constant can be related to the measurement of the admittance of a

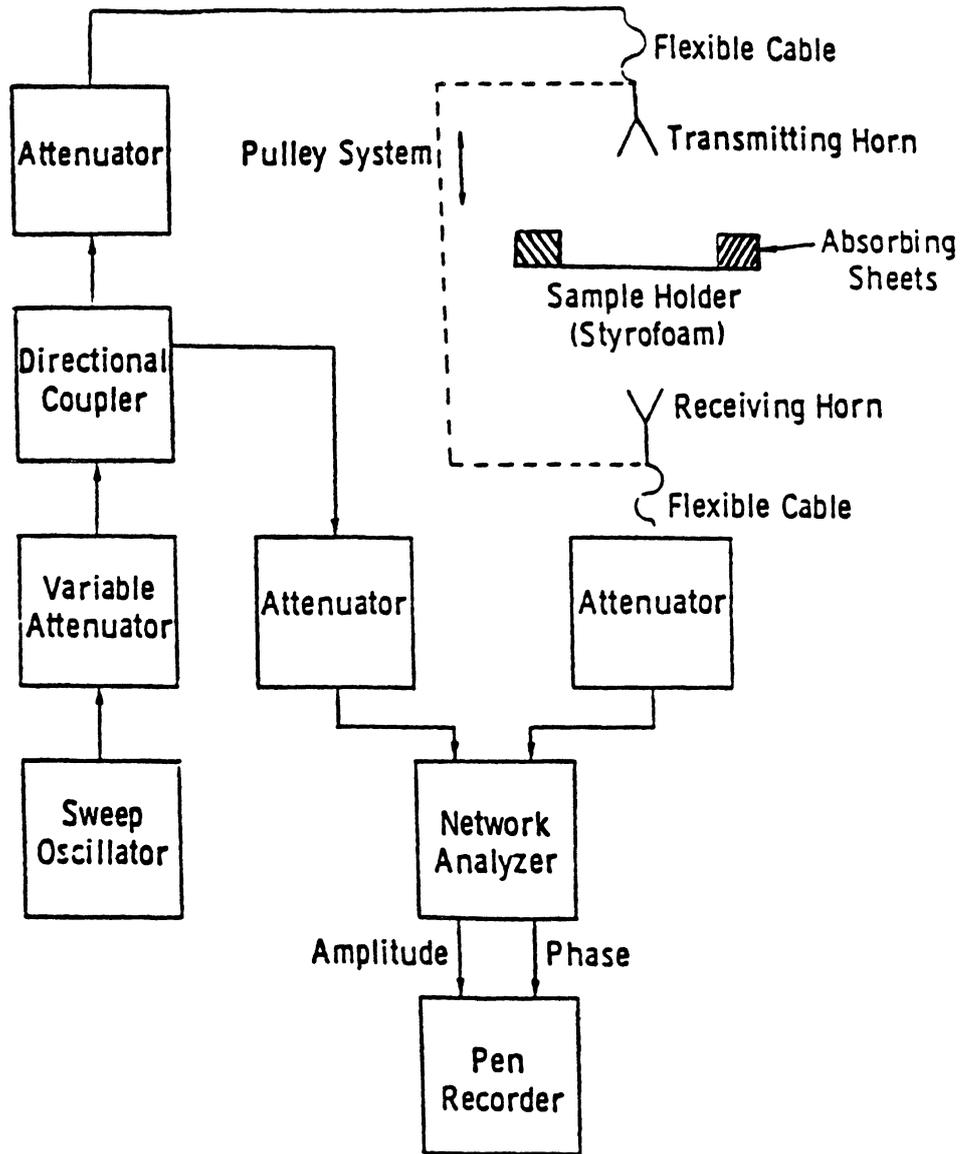


Figure 3.2. 3-18 GHz free-space transmission measurement system.

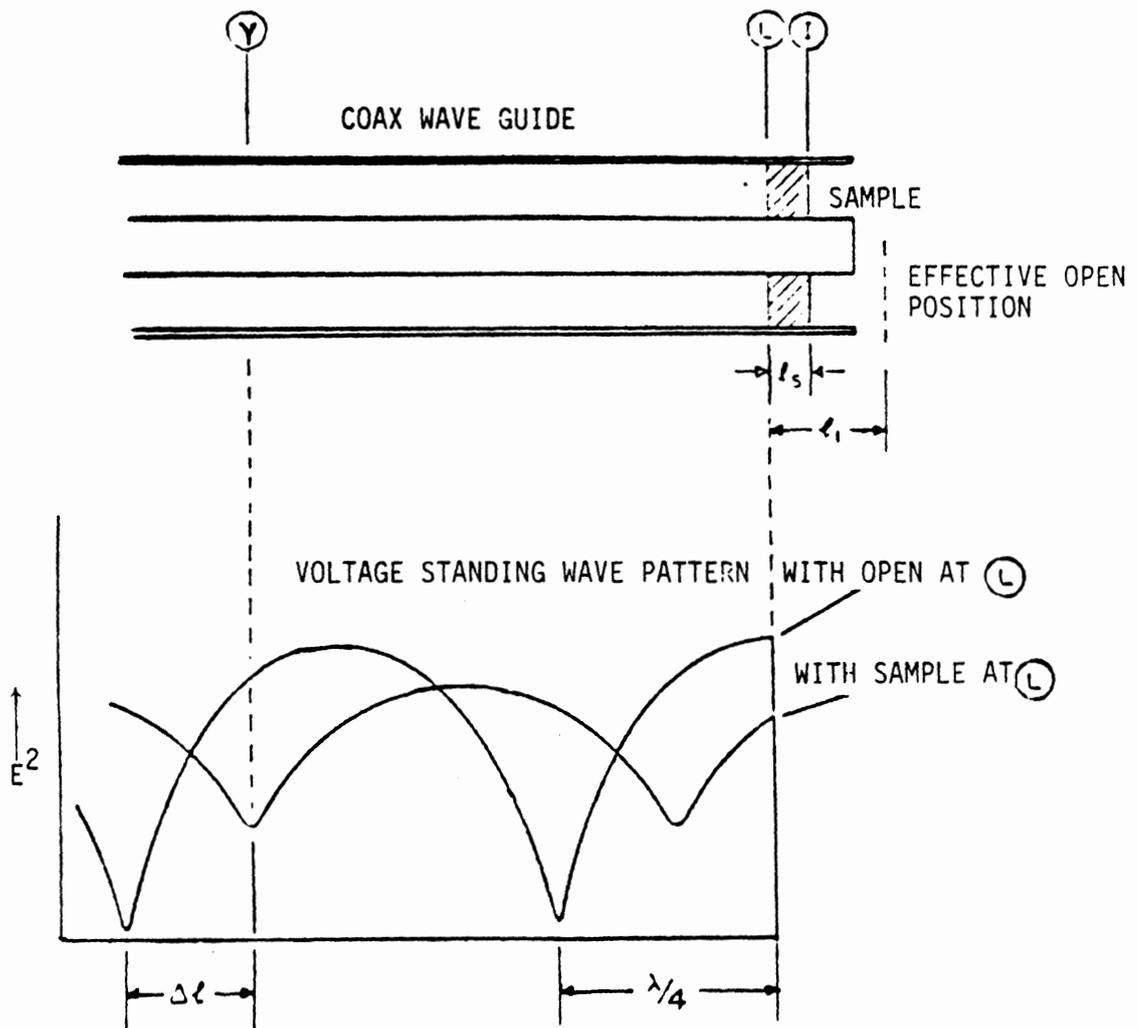


Figure 3.3. A schematic diagram of the coaxial wave guide used for the leaf measurements and the corresponding standing wave patterns assumed in the derivation of the working equations [Broadhurst, 1971].

coaxial transmission line with a specimen of the material occupying some of the space between the coaxial conductors (Broadhurst, 1970). The measurement of the admittance of a coaxial line is equivalent to the measurement of reflection coefficient at the same plane of reference.

The characteristic admittance Y_ϵ of a section of the line filled with an unknown material of permittivity $\epsilon = \epsilon' - j\epsilon''$ is given by (Kraus and Carver, 1973)

$$Y_\epsilon = \frac{\sqrt{\epsilon}}{60 \ln(a/b)} \quad (3.8)$$

where a and b are the outer and inner radii of the line. Similarly, for an air-filled coaxial line, the characteristic admittance and propagation factor are given by

$$Y_0 = \frac{1}{60 \ln(a/b)}, \quad (3.9)$$

And the propagation constants γ_ϵ and γ_0 are given by

$$\gamma_\epsilon = j \frac{\omega}{c} \sqrt{\epsilon}, \quad (3.10)$$

and

$$\gamma_0 = j \frac{\omega}{c} \quad (3.11)$$

where $c \equiv \text{speed of light} = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$.

In the following mathematical treatment, it will be assumed that the operating frequency is low enough for the line to propagate in the TEM mode only.

The admittance Y_M at point M, refer to Fig. 3.3, can be expressed in terms of the admittance Y_L at point L, Y_0 , and γ_0 as follows:

$$Y_M = Y_0 \frac{Y_L + Y_0 \tanh(\gamma_0 l)}{Y_0 + Y_L \tanh(\gamma_0 l)}, \quad (3.12)$$

where l is the length of line between M & L.

Since it is impossible to achieve an open circuit at the end of the line, an extra length, l_1 , is determined where the actual open circuit is located. Using equation (3.12) to transform the effective open circuit to point I,

$$Y_I = Y_0 \tanh \gamma_0 (l_1 - l_s) \quad (3.13)$$

If we transform this admittance from point I to point L (through the sample), we can show that

$$Y_L = Y_\epsilon \frac{Y_I + Y_\epsilon \tanh(\gamma_\epsilon l_s)}{Y_I + Y_\epsilon \tanh(\gamma_\epsilon l_s)}, \quad (3.14)$$

or

$$Y_L = Y_\epsilon \frac{Y_0 \tanh \gamma_0 (l_1 - l_s) + Y_\epsilon \tanh(\gamma_\epsilon l_s)}{Y_\epsilon + Y_0 \tanh \gamma_0 (l_1 - l_s) \tanh(\gamma_\epsilon l_s)} \quad (3.15)$$

Substituting $Y_\epsilon = Y_0 \sqrt{\epsilon}$ and $\gamma_\epsilon = \gamma_0 \sqrt{\epsilon}$ and simplifying we obtain

$$Y_L = Y_0 \frac{\tanh[\gamma_0 (l_1 - l_s)] + \sqrt{\epsilon} \tanh(\sqrt{\epsilon} \gamma_0 l_s)}{1 + \frac{1}{\sqrt{\epsilon}} \tanh[\gamma_0 (l_1 - l_s)] \tanh(\sqrt{\epsilon} \gamma_0 l_s)} \quad (3.16)$$

Equation (3.16) relates a measurable quantity, the admittance Y_L , to the unknown dielectric constant of the sample ϵ . The relationship, however, is not simple and suitable approximations must be used. Broadhurst used frequencies up to 4.2 GHz ($\lambda = 7.1\text{cm}$) and samples of thicknesses less than .04 cm. l_1 was found experimentally to be about .3 cm. Hence the maximum values of the above arguments can be shown to be less than .26. Using equation (3.16) and the approximation $\tanh(u) \approx u$, leads to

$$Y_L \approx Y_0 \frac{\gamma_0(l_1 - l_s) + \epsilon\gamma_0 l_s}{1 + \gamma_0^2(l_1 - l_s)l_s} \quad (3.17)$$

The resulting error is about 7 percent or less. Using the above argument, we can also neglect the second term in the denominator, leading to

$$Y_L \approx Y_0[\gamma_0(l_1 - l_s) + \epsilon\gamma_0 l_s] \quad (3.18)$$

Using equation 3.18, ϵ can be calculated from the measured value of Y_L ,

$$\epsilon = \frac{1}{\gamma_0 l_s} \left[\frac{Y_L}{Y_0} - \gamma_0(l_1 - l_s) \right] \quad (3.19)$$

It should be noted here that equation (3.19) is only valid under the following assumptions:

- (i) Pure TEM propagation mode.

$$(ii) \frac{2\pi}{\lambda} l_s \leq .25.$$

$$(iii) \frac{2\pi}{\lambda} (l_1 - l_s) \leq .25.$$

Condition (ii) limits the maximum measureable sample thickness to .3 cm at 4 GHz. Broadhurst reported f_c , the upper limit of frequencies that can be used before higher order modes start to propagate, as

$$f_c = 9.5/\sqrt{|\epsilon|} \quad (3.20)$$

This limit depends on the coaxial line dimensions as well as ϵ (as will be shown in Chapter 4).

3.2.2 Probe System

Open-ended coaxial lines can be used successfully in measuring the permittivity of unknown materials (Burdette et al, 1980; Athey et al, 1982; Stuchly et al, 1982). A complete description and analysis of this system will be delayed until the next chapter. However, a brief discussion of the theory of operation is given here for the sake of completeness. Figure 3.4 shows a block diagram of the measurement system. It is basically a standard reflection coefficient measurement system with the probe tip acting as the termination load (either immersed or in contact with the sample). The input reflection coefficient at the probe tip, ρ , is given by

$$\rho = \frac{Z_L - Z_0}{Z_L + Z_0}, \quad (3.21)$$

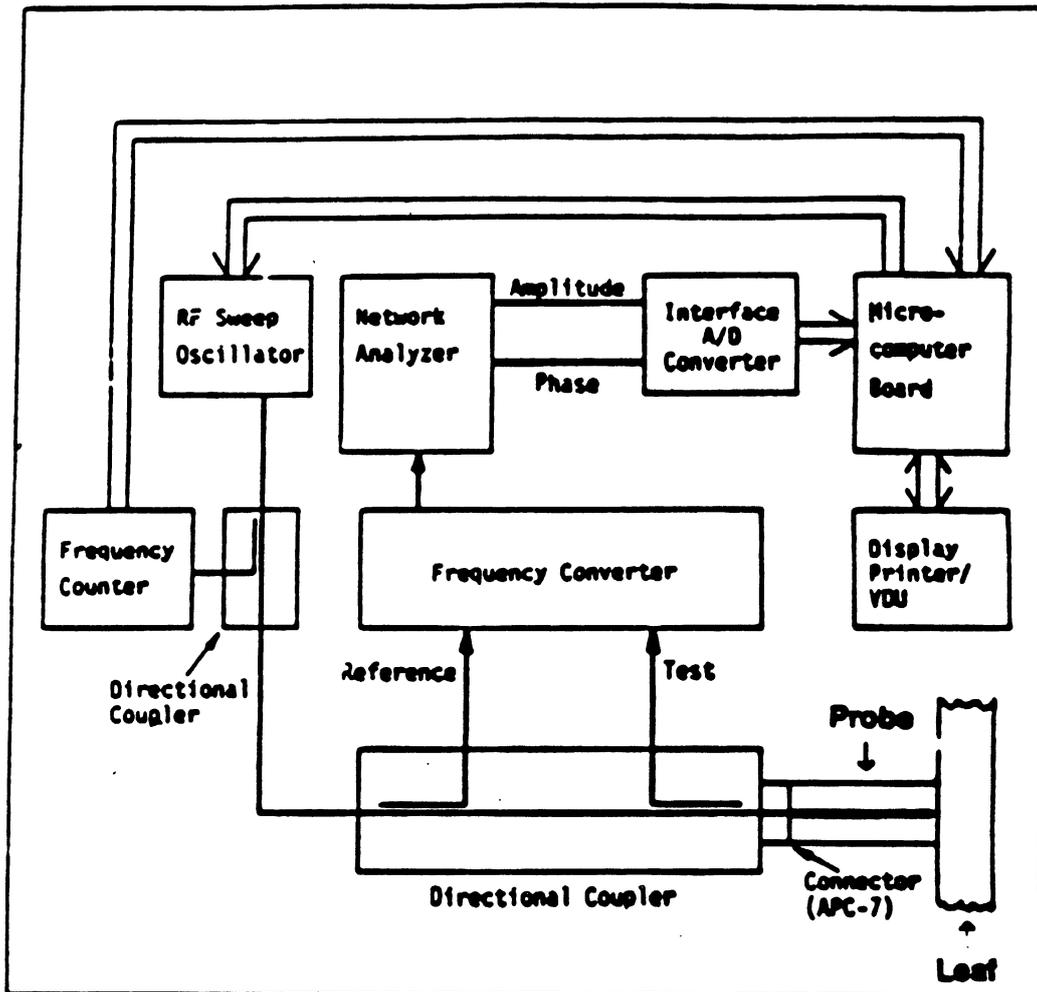


Figure 3.4. Block diagram of the probe dielectric system. Frequency coverage is 0.1-20 GHz.

where Z_0 is the line impedance (50Ω usually) and Z_L is the load impedance given by (Deschamps, 1962; Burdette et al, 1980)

$$\frac{Z_L(w, \epsilon)}{\eta} = \frac{Z_L(\sqrt{\epsilon}w, \epsilon_0)}{\eta_0}, \quad (3.22)$$

where η_0 and η are the intrinsic impedances of free space and the measured dielectric medium respectively, ϵ_0 and ϵ are the complex dielectric constant of free space and the medium under test respectively, and w is the angular frequency. For a non-magnetic medium where $\mu = \mu_0$, Z_L simplifies to

$$Z_L(w, \epsilon) = \frac{1}{\sqrt{\epsilon}} Z_L(\sqrt{\epsilon}w, \epsilon_0). \quad (3.23)$$

If the probe equivalent circuit can be modelled analytically, the medium dielectric constant can be retrieved from the measured reflection coefficient; sometimes an iterative solution is required depending upon the complexity of the form of Z_L .

It is possible, albeit difficult, to relate the measured reflection coefficient directly (e.g., the Method of Moments, MOM) to the unknown ϵ (Gajda and Stuchly, 1983). The analysis, e.g. MOM, and processing time would be enormous using this approach. On the other hand, if we choose the frequency range and the line dimensions such that the field distribution around the probe-tip is dominantly capacitive we could develop a lumped-element equivalent circuit which would facilitate the analysis and data processing.

The equivalent circuit elements could be chosen on the basis of the line dimensions and the operating frequency. In this section only the low frequency

equivalent circuit will be analyzed and the complete one will be discussed in the following chapter.

The input impedance for the low frequency equivalent circuit is given by

$$Z_L = 1/j\omega(C_f + C_0) \text{ in free space,}$$

and $Z_L = 1/j\omega(C_f + \epsilon C_0)$ in the medium. where, C_f is the fringing field inside the teflon, and C_0 is the fringing field outside the teflon and inside the medium. The reflection coefficient can then be expressed as

$$\rho = \frac{1 - j\omega Z_0(C_f + \epsilon C_0)}{1 + j\omega Z_0(C_f + \epsilon C_0)}, \quad (3.24)$$

and, solving for ϵ we get

$$\epsilon = \frac{1 - \rho}{j\omega Z_0 C_0 (1 + \rho)} - \frac{C_f}{C_0}. \quad (3.25)$$

This equivalent circuit is only valid at frequencies where the line dimensions are small compared to λ ; i.e., only the reactive field exists with no radiation. C_f and C_0 are not known and should be estimated using calibration against a standard material such as distilled water. This technique is quite attractive because ϵ can be computed from ρ in a straightforward manner.

3.3 Resonance Technique

In the following two sections a brief description will be given of the use of resonant cavities in the measurement of the microwave dielectric properties of matter.

3.3.1 The Filled-Cavity Approach

A block diagram of a typical cavity measurement system is shown in Fig. 3.5 . A complete theoretical analysis of this problem was given by Harrington (Harrington, 1961). The basic idea is that the dielectric constant of a material filling a cavity is determined by the shift in the resonant frequency f_0 and the change in the quality factor Q (Russ, 1983). An air-filled cavity is assumed to be the reference with f_0 and Q_0 ; while the dielectric-filled cavity has f_s and Q_s . The dielectric constant can then be calculated from

$$\epsilon'_r = (f_0/f_s)^2, \quad (3.26)$$

and,

$$\epsilon''_r = \epsilon'_r \left[\frac{1}{Q_s} - \frac{1}{Q_0} \sqrt{\frac{f_0}{f_s}} \right]. \quad (3.27)$$

The quality factor Q_i is in general given by

$$Q_i = f_i/\Delta f_i \quad (3.28)$$

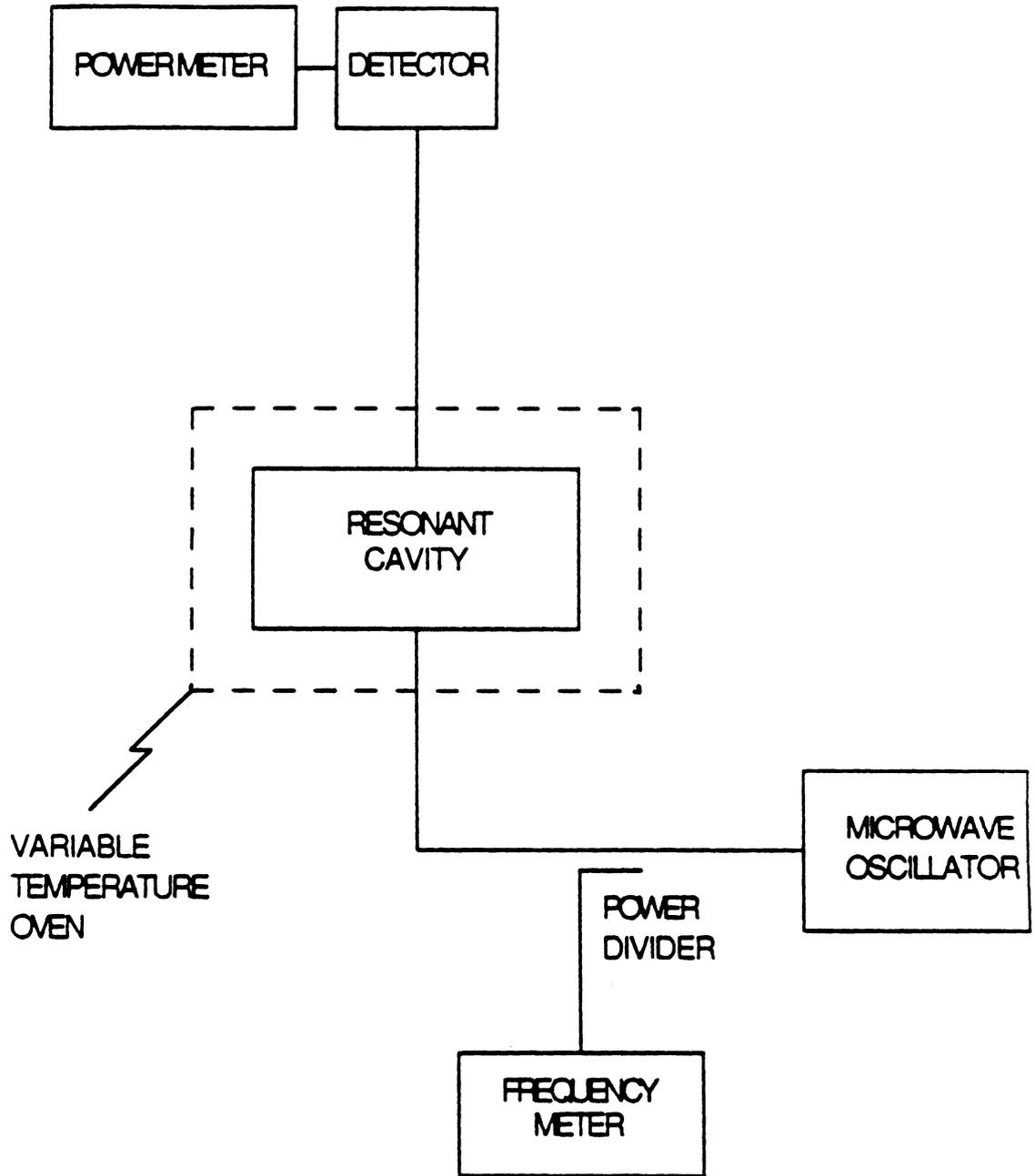


Figure 3.5. Schematic diagram of the measurement set-up for microwave cavity measurements.

where f_i is the resonant frequency and Δf_i is the 3-db bandwidth. Equations (3.26- 3.28) are evidently very simple and easy to use, yet there are two problems encountered:

1. If ϵ_r is too high, an undesirable large frequency shifts and/or reduction in the value of Q would preclude an accurate measurement of f_s and Q_s .
2. For some materials, such as vegetation, it is very difficult to fill the cavity with solid material without some air pockets remaining. This complicates the inference of the dielectric constant of the material.

3.3.2 The Partially-filled Cavity Approach

This technique is also called the perturbation technique. Small resonant frequency shifts are attainable by the proper selection of the sample size. The perturbation analysis is given in details in (Harrington, 1961; Russ, 1983). These derivations were based on the assumption that either the sample volume or its dielectric constant are small enough so that the field structure in the cavity is not substantially changed by the insertion of the sample. The shape of the sample is an important factor in determining the appropriate approximate formula to be used. Spheres, discs, and needles are the most commonly used shapes, and among these the needles are the most popular. Let us take, as an example, a TM_{010} cylindrical cavity with

$$d < 2a \tag{3.29}$$

where, d is the cavity length and a is the cavity radius.

For a cylindrical sample of radius c and length d , (Russ, 1983) shows the derivations leading to

$$\frac{w_s - w_0}{w_0} = -1.855(\epsilon_r - 1)\left(\frac{c}{a}\right)^2, \quad (3.30)$$

$$w'_s = w_s + j\frac{w_s}{2Q}, \quad (3.31)$$

$$\epsilon'_r = \frac{w_0 - w_s}{1.855w_s V_v} + 1, \quad (3.32)$$

and

$$\epsilon'' = \frac{w_0}{3.71w_s v_r} \left(\frac{1}{Q_s} - \frac{1}{Q_0} \right), \quad (3.33)$$

where equations 3.32 and 3.33 were derived using equations 3.30, which is only applicable for a needle-shaped sample, and 3.31, which represents the resonant frequency for a lossy circuit. Data processing in this case is very straightforward. However, special care should be taken in the following cases: (i) If the sample length is not equal to the cavity length, a different set of equations is valid (Parkash et al, 1979). (ii) If the sample volume is very small, the changes it produces may not be detectable, and if the sample volume is very large, it could modify the fields, thereby destroying the validity of the perturbation equations.

3.4 Comparison

Table 3.1 provides a summary of the pertinent features of the various microwave dielectric measurement techniques. An analysis of these features will be given next.

3.4.1 Usable Frequency Band

(i) The Waveguide Transmission System

L, *S*, *C*, and *X* band systems are possible frequency bands for the measurements, yet for each band a separate waveguide system is needed. This fact makes measurements across a wide band, e.g. 1-12 GHz, discontinuous due to calibration problems. Also, packing an *X*-band waveguide is very difficult and it is hard to achieve a homogeneous sample. One of the major limitations of the waveguide system is the possible propagation of higher-order modes in the guide, especially in the upper end of the range. Above *X*-band, the waveguide size becomes impractically small to use.

(ii) Free-Space System

The free-space system was used successfully in measuring dielectric properties of wet soils and snow samples over the 3-18 GHz (Hallikainen and Ulaby, 1983). The lower frequency limit was imposed by the required sample size and the upper limit by the cut-off frequency of the antennas. A similar system at 37 GHz was also constructed and calibrated. The only high frequency limit seems to be the required smoothness of the sample surface (surface rms roughness should be less

than $\lambda/10$).

(iii) Slotted Line System

Since this system utilizes a TEM cell in a coaxial line, it has a much larger bandwidth compared to a waveguide system (Broadhurst, 1970). Broadhurst reported a slotted line system that operated from 100 kHz to 4.2 GHz but he also concluded that excessive scatter in the data above 1 GHz was due to high-order mode propagation. For the coaxial line used in his experiment the cutoff frequency of these modes is given by

$$f_c = 9.5/\sqrt{|\epsilon|},$$

which means that a moist leaf can be measured up to 1 or 2 GHz without the occurrence of moding problems.

(iv) Probe System

Since the probe system is basically an open-ended coaxial line, the usable bandwidth is expected to be as high as that of the slotted line system. In the course of this study, however, it was only attempted to operate the system from 100 MHz to 20 GHz. Reduction in the system sensitivity was observed in the low frequency range and an increase of higher-order mode propagation in the high end. A satisfactory compromise can be achieved by using larger probes at low frequencies and smaller probes at high frequencies as will be discussed in the next chapter.

(v) Resonant Cavity Systems

The frequency of operation is limited to only one single frequency for each cavity.

3.4.2 Measurement Accuracy and Precision

(i) Waveguide System

The relative measurement errors $\Delta\epsilon'/\epsilon'$ and $\Delta\epsilon''/\epsilon''$ were estimated on the basis of the precision specifications of the network analyzer /phase gain indicator. They were compared to those observed during the course of measurement and found to be in complete agreement. The results may be summarized as follows:

- (a) $\Delta\epsilon' \leq .15$ and $\Delta\epsilon'' \leq .17$ for all samples tested.
- (b) $(\Delta\epsilon'/\epsilon') \leq .9\%$ at 1.4 GHz and $< .7\%$ at 5 GHz for all samples tested.
- (c) $\Delta\epsilon''/\epsilon''$ decreases from 37% at low values of ϵ'' to 6% for high values of ϵ'' .

The 37% relative precision was observed for $\epsilon'' = .06$ and the standard deviation was $\Delta\epsilon'' = .022$. So, even though the relative precision is large, the absolute precision is small.

(ii) Free-Space System

The total calculated worst case error bounds were plotted against frequency for different sample lengths and for various dielectric constant magnitudes for both ϵ' and ϵ'' and were found to be around 10% (except for very low loss materials where the error can be as high as 60 %). The error bounds include uncertainties in both the equipment and in sample preparation. The system was calibrated for absolute accuracy using polymethyl methacrylate (a low-loss material) and water (a high-loss material) and the errors were within the worst case bounds.

It was found that the system accuracy improves with increasing frequency, magnitude of ϵ , and sample thickness.

(iii) Slotted Line System

The accuracy of measuring the real part was within 10%, while for the imaginary part sizeable errors were reported (Broadhurst, 1970). It was found generally that the accuracy improves at low frequencies. A check of the precision of leaf measurements was conducted by packing the sample, measuring it, unpacking it, then packing it and measuring it again. The previously mentioned procedure was repeated several times for different samples and at different frequencies and an analysis of variance was conducted to separate the instrumental errors from those due to sample variations. The uncertainties in the leaf-thickness measurements amounts to 5 – 10%. In general, the total uncertainties in the measurement system was much better than 20%.

(iv) Probe system

Athey et al (part 1, 1982) grouped the errors in their measurement system into two types: (1) Systematic errors and (2) nonsystematic errors. The systematic errors, which are due to the network analyzer system, were assumed to be $\Delta|\rho| = .003$ and $\Delta\phi = .3^\circ$. The estimated uncertainties around 1 GHz were found to be within 2% for ϵ' and 8% for ϵ'' . The nonsystematic errors, on the other hand, were attributed to repeatability of connections, temperature drift, noise, nonperfect probe connector, dirt, imperfect contact with the sample, and inhomogeneities in the substance under test. The system overall accuracy depends on how far the

probe capacitance is from the optimum capacitance value (a discussion of this condition will be given in the next chapter).

The nonsystematic errors can be avoided if proper care is exercised during the measurements and by repeating suspicious data sets. According to Athey (1982), the overall system accuracy and precision were within the limits estimated on the basis of the systematic errors alone.

(v) The Cavity Systems

The precision of the filled cavity measurement system is almost perfect especially if care is taken in replacing the cover and tightening the bolts using a torque wrench. The measurement error for Q_L for a partially filled cavity is $\pm 1.25\%$ (for $Q_L \geq 500$) and $\pm 7\%$ for($Q_L = 200$) (Chao, 1985), which means that the measurement error is negligible for ϵ' and less than $\pm 2\%$ for ϵ'' (compared to 37% in the waveguide system).

However, the smaller the sample volume the larger are the errors associated with ϵ' and ϵ'' due to dimensions measurement errors. These errors can be as large as 10%.

3.4.3 Dielectric Values Limit

It is probably a general rule that the higher the magnitude of ϵ is, the better becomes the accuracy and precision of the measurements, as long as the values of ϵ do not allow higher-order modes to propagate.

3.4.4 Practical Aspects

(1) Sample Size and Preparation

From a vegetation dielectric-measurement-system point of view, the waveguide, the free-space, and the cavity techniques are not suitable because it is impossible to achieve a unity filling factor (because of unavoidable air voids inside the measured sample). Also it is impossible to achieve the smooth surface required for free-space system samples. Slotted line and cavity perturbation measurements on a vegetation sample will always suffer from inaccuracies in thickness measurements.

The probe system on the other hand, requires a relatively thin sample (at most a few leaves-thick). However, special care has to be taken to insure that the pressure applied by the probe against the sample is high enough to ensure good contact, but not too high to cause squeezing of fluid out of the vegetation tissue or changing the vegetation bulk density (as will be discussed in the next Chapter).

(2) Temperature Measurements

The best system for the purpose of making dielectric measurements as a function of temperature is probably the free-space system because there are no metal parts in contact with the sample. The waveguide is probably the hardest because large pieces of metal would need to be insulated. The probe system (as will be shown in the next chapter) operates satisfactorily with regard to temperature measurements.

(3) Field Measurement

The probe system, no doubt, is superior to any other system for field operation because it is the only nondestructive tool capable of measuring samples without destroying them.

Technique Feature	Waveguide System	Free-Space System	Slotted-Line	Probe System	Filled-Cavity	Partially-filled
Usable Band (GHz)	1-2,2-4, 4-8,8-12 4 systems	3-18 1 system	100 KHz- 4.2 GHz 2 systems	.05-20.4 1 system, 2 probes	single frequency per cavity	single frequency per cavity
Accuracy Low loss	reasonable	reasonable	bad	bad	the best	very good
Accuracy high loss	very good	good	good	good	Does not work	good
Sample Size	small at HF large at LF	large at HF	reasonable	small	small at HF large at LF	small
Sample Preparation	Easy but lengthy	hard and tedious	easy	easy	hard/ impossible	hard/ impossible
temperature	hard	perfect	hard	easy	perfect	perfect
Field Measurements	hard	hard	hard	easy	hard	hard

Table 3.1 Comparison between different microwave dielectric measurement techniques.

Chapter 4

Open-Ended Coaxial Probe System

4.1 System Description

As previously discussed in section 3.2.2, an open-ended coaxial line and a short monopole probe are found to be viable sensors for dielectric constant measurements at microwave frequencies. We shall restrict the discussion here to only open-ended coaxial line probes. As shown in Fig. 3.4, the main part of the system is the microcomputer-controlled network analyzer (HP 8410C) which is employed to measure the input impedance at the probe tip. The probe translates changes in the permittivity of a test sample into changes in the input reflection coefficient of the probe. The automation of the reflectometry system made data acquisition, correction, and processing a straight forward task in addition to the achieved speed of operation. Indeed, the development of such a system would have been impossible only 15 years ago, since the concept of automated network analyzer measurements was introduced recently.

The open-ended coaxial line probe system operates over a very wide frequency band. The .141" probe model, for example, covers the range extending from .5 GHz to 20 GHz. The overall error bounds for both ϵ' and ϵ'' were found to be within 10 % of the measured values. The 10% figure is very conservative and in some cases it is even better than 1%. Also, since the rounding error in ϵ' and ϵ'' is ± 1 , at low dielectric values the relative errors can be too large. The lower frequency limit is set by the degraded sensitivity while the upper limit is determined by the cut-off frequency of the next propagating high-order mode as will be discussed later in section 4.3.2 and 4.3.3. Besides the wide frequency band of operation, the probe has the capability of measuring the dielectric constant of test materials nondestructively and rapidly.

4.2 Analysis

The analysis of the probe system can be divided into the following steps: error correction, equivalent circuit modeling, and calibration and the inverse problem.

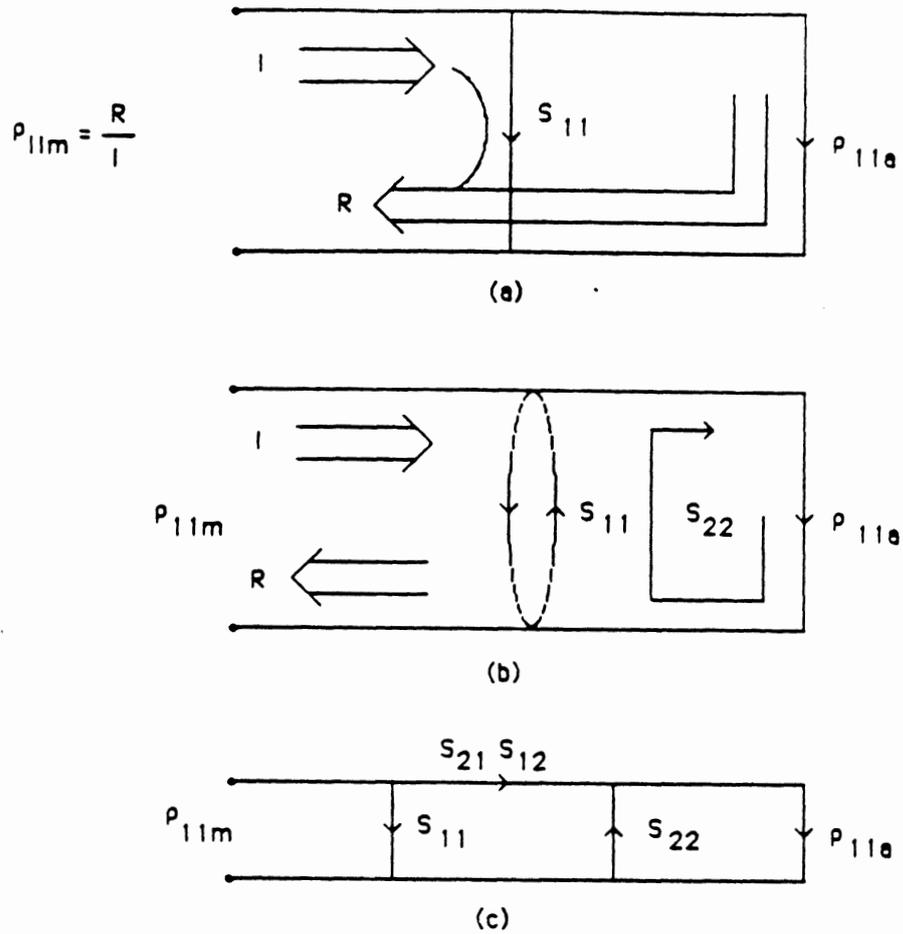
4.2.1 Error Correction

There are certain inherent measurement errors when the network analyzer system is used for microwave measurements. These errors can be separated into two categories: (a) instrument errors and (b) test set/connection errors (HP application Note and Burdette, 1980). Instrument errors are those related to random variations due to noise, imperfect conversions in such equipment as the frequency converter, crosstalk, inaccurate logarithmic conversion, nonlinearity

in displays, and overall drift of the system. Test set/connection errors are due to the directional couplers in the reflectometer, imperfect cables, and the use of connector adaptors. Among these two error sources, the latter is the major source of error at UHF and microwave frequencies. These uncertainties are quantified as directivity, source match, and frequency tracking errors. The analytical model used for correcting test set/connection errors is based on the model used by Hewlett-Packard for correcting reflectivity measurements (HP Application note). This model accounts for the three types of systematic errors. Each of them is shown schematically in Fig. (4.1). The measured reflection coefficient can be derived as

$$\rho_{11m} = S_{11} + \frac{S_{12}S_{21}\rho_{11a}}{1 - S_{22}\rho_{11a}} \quad (4.1)$$

S_{11} is the directivity term and is due to (a) direct leakage of the incident signal into the test channel via the reflectometer directional couplers and (b) to further degradation by connectors and adaptors. S_{22} is the source match term and is caused by multiple reflections into the unknown load. The product ($S_{21}S_{12}$) is the frequency tracking term and is due to small variations in gain and phase flatness between the test and reference channels as a function of frequency. The reflection coefficients ρ_{11m} and ρ_{11a} are the measured and actual reflection coefficients, respectively. These three error factors can be determined and calibrated out using three known standard loads with known ρ_{11a} across the required frequency band. Hence, ρ_{11a} can then be determined from



$$\rho_{11m} = \frac{\rho_{11a}(S_{21}S_{12})}{1 - S_{22}\rho_{11a}} + S_{11}$$

$$\rho_{11a} = \frac{\rho_{11m} - S_{11}}{S_{22}(\rho_{11m} - S_{11}) + S_{21}S_{12}}$$

Figure 4.1. Error models used for test set connection errors.

$$\rho_{11a} = \frac{(\rho_{11m} - S_{11})}{S_{22}(\rho_{11m} - S_{11}) + S_{12}S_{21}} \quad (4.2)$$

S_{11} can be determined separately using a sliding matched load termination. The reflection coefficient of the load can be eliminated by multiple load measurements at different path lengths. The loci of these points form a circle whose center is the true directivity error vector. Using short-circuit and open-circuit loads, S_{22} and $S_{12}S_{21}$ can be determined (S_{12} and S_{21} were lumped together because they always appear as a product). Since the open-circuit condition is hypothetical, because of radiation and fringing fields, a correction to $(\rho_{11a})_{O.C.}$ is always made. Also, since the calibration should be done with the probe tip as the reference plane, and since there is no standard short circuit for that situation, liquid mercury has been used as the short circuit termination. This approach proved successful as long as care is taken to ensure an approximate phase shift of 180° from the open-circuit reading. A final remark that should be made here about S_{11} is that its determination is made at the APC-7 connector reference plane and it is used at the probe tip reference plane. This approach neglects the reflections due to the APC-7 connector and any other reflections along the probe especially due to the bent, along the probe line, and any inhomogeneity in the teflon. This approximation is justified by assuming that the APC-7 connector and the probe line are free of defects. This approximation is probably accountable for most of the system errors (accuracy), while instrumental errors can be greatly reduced by data averaging.

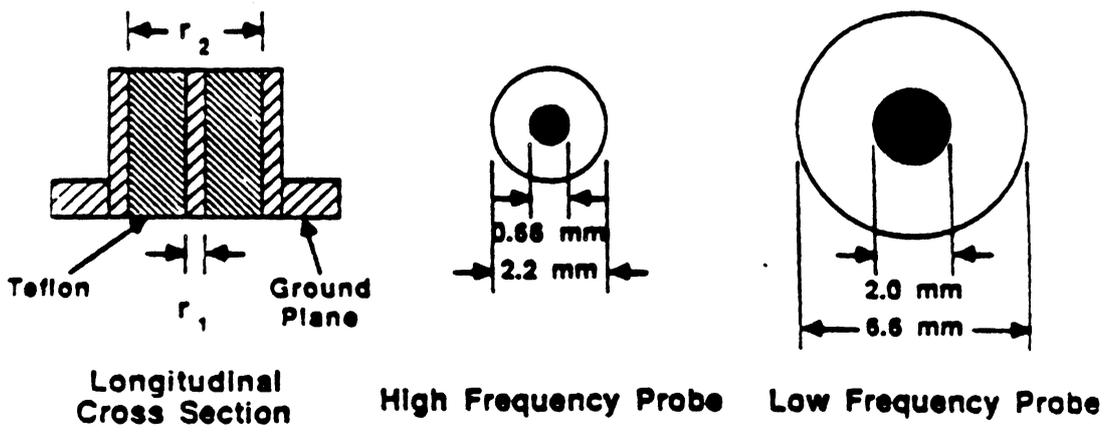
4.2.2 Equivalent Circuit Modeling

In general, there are two approaches to handling the probe analysis: an exact electromagnetic treatment or an approximate modeling approach. The exact electromagnetic treatment uses either the variational or the moment methods. These approaches are exact, but they have a few problems:

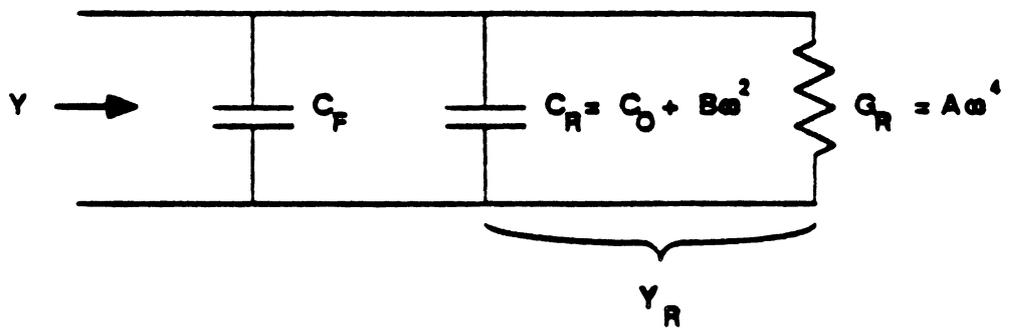
1. Computer- time consuming,
2. The exact inverse problem is impossible, and
3. The loss of accuracy due to the approximate inverse problem is high.

On the other hand, the approximate modeling treatment is less accurate and more efficient in terms of computer time. The model used to describe the probe behavior has, as shown in Fig.(4.2), the following equivalent circuit parameters (Marcuvitz, 1951; Tai, 1961; Kraszewski and Stuchly, 1983; Gajda and Stuchly, 1983):

1. C_0 , the fringing field capacitance,
2. C_f , the fringing field (inside the teflon) capacitance,
3. $B\omega^2$, the increase in the fringing field capacitance with frequency because of the evanescent TM modes excited at the junction discontinuity, and
4. A , the factor representing the radiative discontinuity field.



(a) Dielectric Probes



(b) Probe Equivalent Circuit

Figure 4.2. Coaxial probe (a), and its equivalent circuit (b).

These four parameters are a function of the transmission line dimensions. The admittance in free space is given by

$$Y(\epsilon = 1) = j\omega(C_f + C_0 + B\omega^2) + A\omega^4 \quad (4.3)$$

when the load is a lossy dielectric medium with complex dielectric constant ϵ , $Y(\epsilon)$ is given by:

$$Y(\epsilon) = j\omega(C_f + C_0\epsilon + B\omega^2\epsilon^2) + A\omega^4\epsilon^{2.5} \quad (4.4)$$

This is a linear equation with four unknowns C_f, C_0, B , and A . In order to determine the equivalent circuit unknowns, two standard materials need to be measured to provide two complex equations or four real ones. Usually distilled water and methanol were used for calibration in this work. Equation (4.4) can be solved for the unknown equivalent circuit parameters by solving the matrix equation (4×4).

It is possible to solve this equation for C_f, C_0, B , and A using standard matrix techniques (e.g. diagonal method). After calculating the equivalent circuit parameters, the system will be ready to process the reflection coefficient data for the unknown materials.

4.2.3 Calibration and the Inverse problem

In calibration we need to solve a (4×4) matrix for the equivalent circuit parameters, but in calculating the unknown ϵ of the material under test Equation

(4.4) should be solved for ϵ . This equation is a complex equation of the fifth order. It was found that an easy method for solving it is through an iterative routine. The algorithm used for correction, calibration, and data processing is given in Fig.(4.3).

4.3 Probe Selection

The overall accuracy and precision of any probe system depends on the frequency range of operation, the accuracy of the dielectric constant of the calibration materials, the value of the unknown dielectric, and the nature of the sample under test.

4.3.1 Optimum Capacitance

It has been shown (Stuchly et al, 1974) that for a given accuracy of the reflection coefficient measurement, the accuracy in determining the permittivity ϵ is greatest when

$$C_0 = \frac{1}{wZ_0\sqrt{\epsilon'^2 + \epsilon''^2}} \quad (4.5)$$

where Z_0 is the characteristic impedance of the line. The expression strictly holds only when the uncertainties in the magnitude and phase of the reflection coefficient are approximately the same, i.e., $\Delta\varphi \simeq \frac{\Delta\rho}{\rho}$. For other cases the optimum value of C_0 is different for ϵ' and ϵ'' ; nonetheless, in general the value given by (4.5) is a good compromise. Figures 4.4(a) to (d) show the calculated optimum capacitance for a variety of materials plotted against frequency. Since the

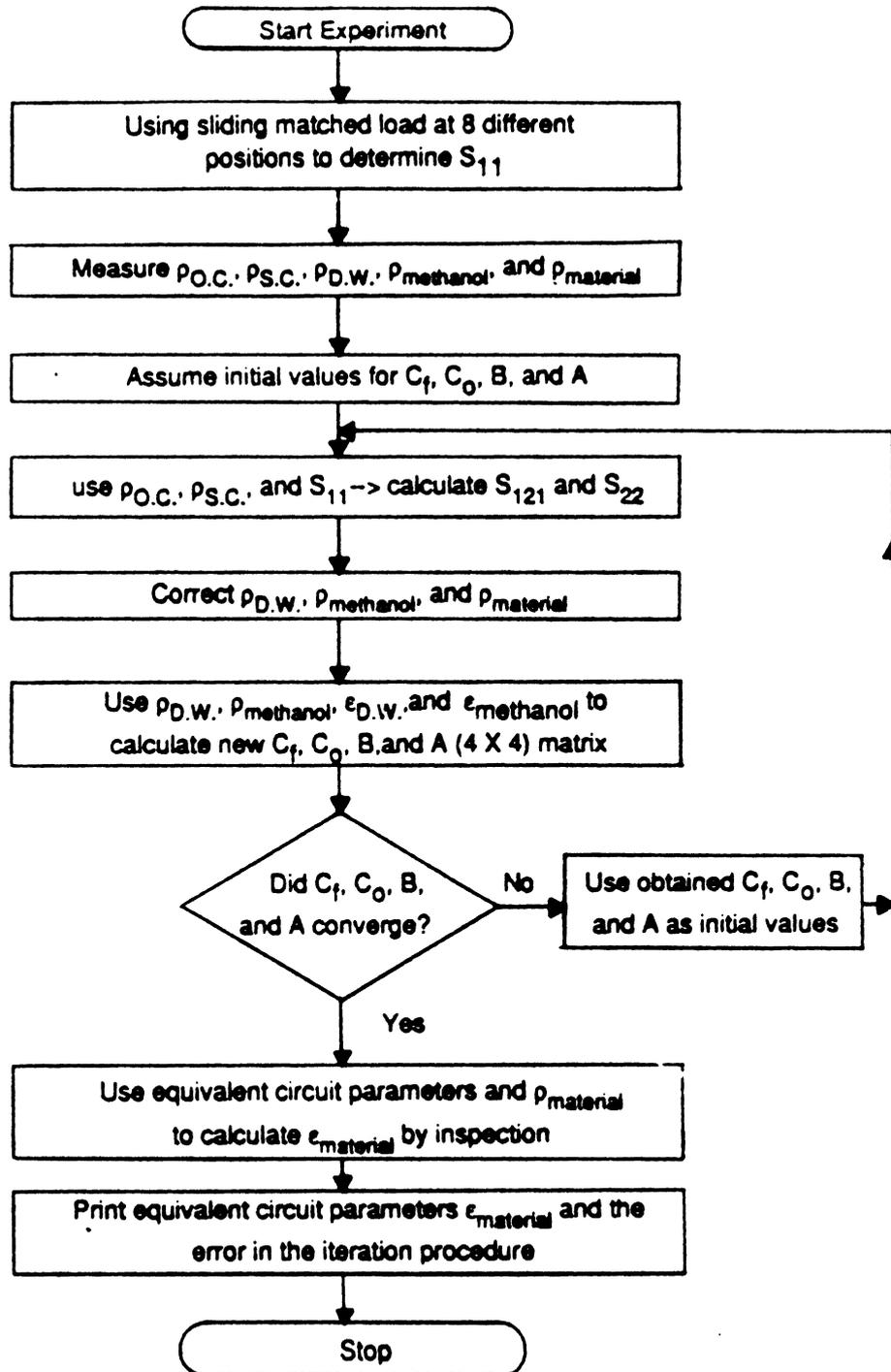


Figure 4.3. Calibration algorithm for the full equivalent circuit parameters, C_f , C_o , B , and A .

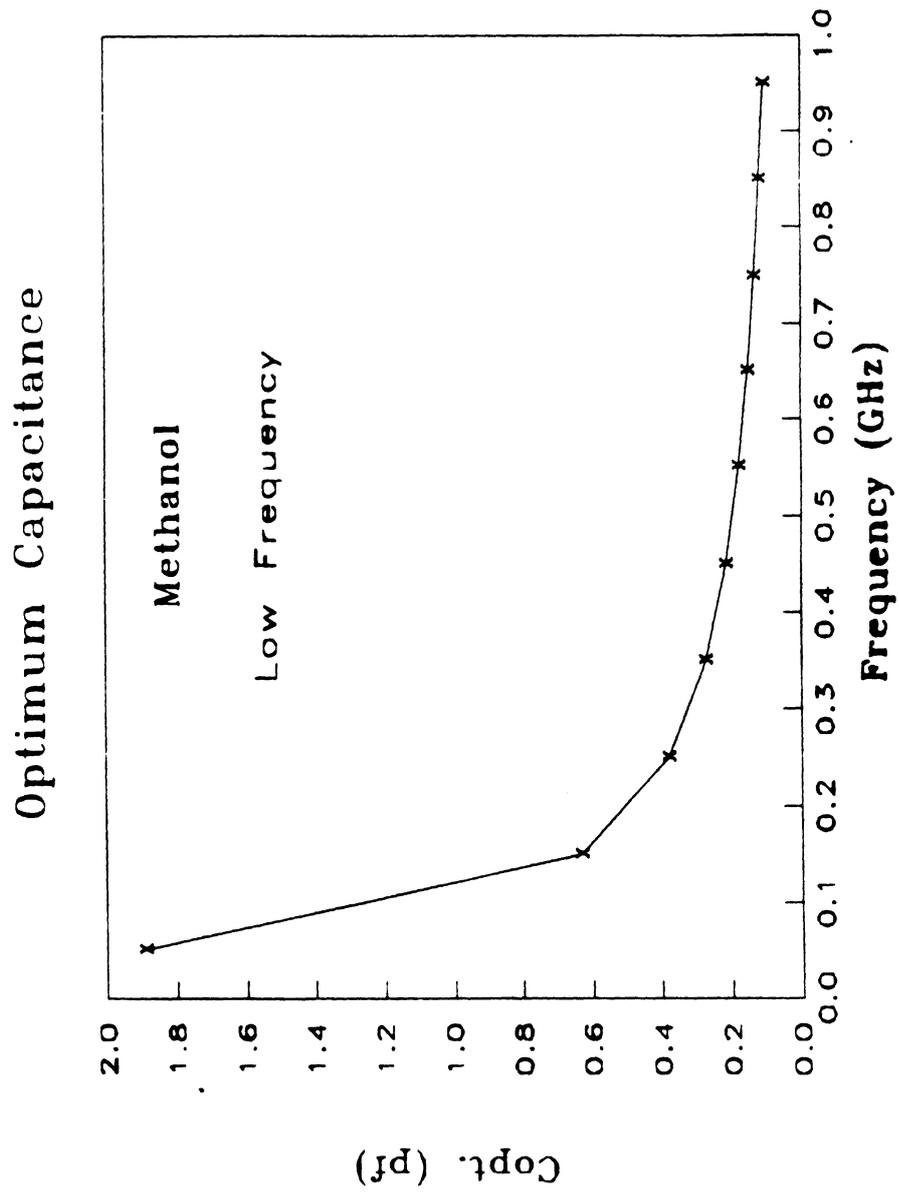


Figure 4.4(a). Calculated optimum capacitance for methanol(0.1-1 GHz).

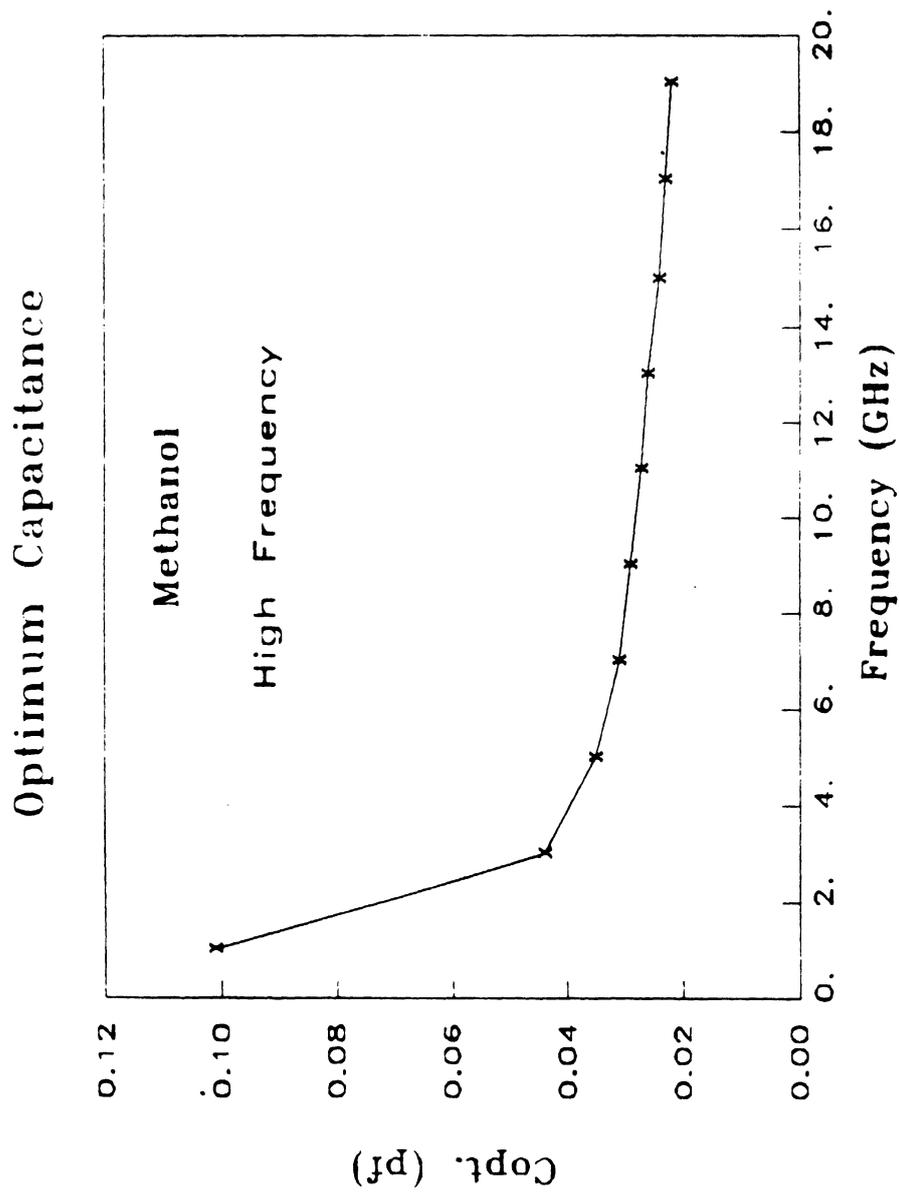


Figure 4.4(b). Calculated optimum capacitance for methanol(1-20 GHz).

Optimum Capacitance

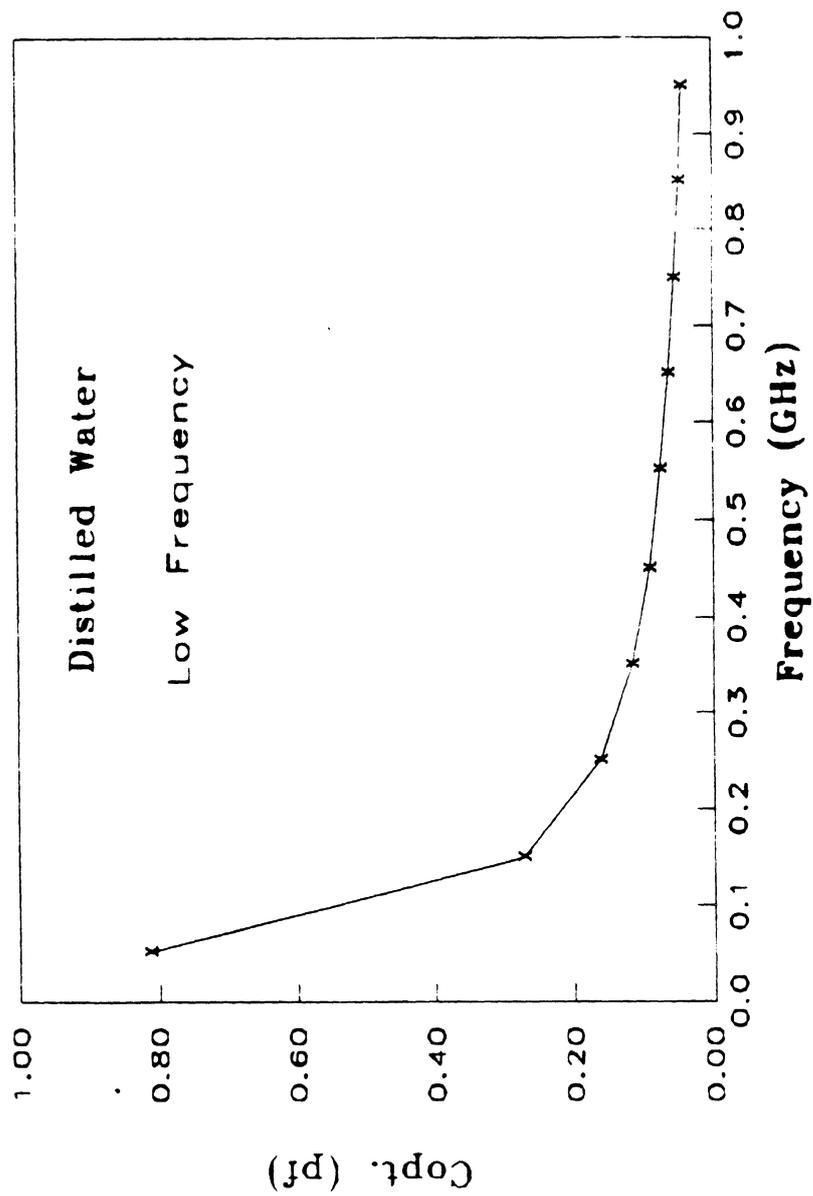


Figure 4.4(c). Calculated optimum capacitance for distilled water(0.1-1 GHz).

Optimum Capacitance

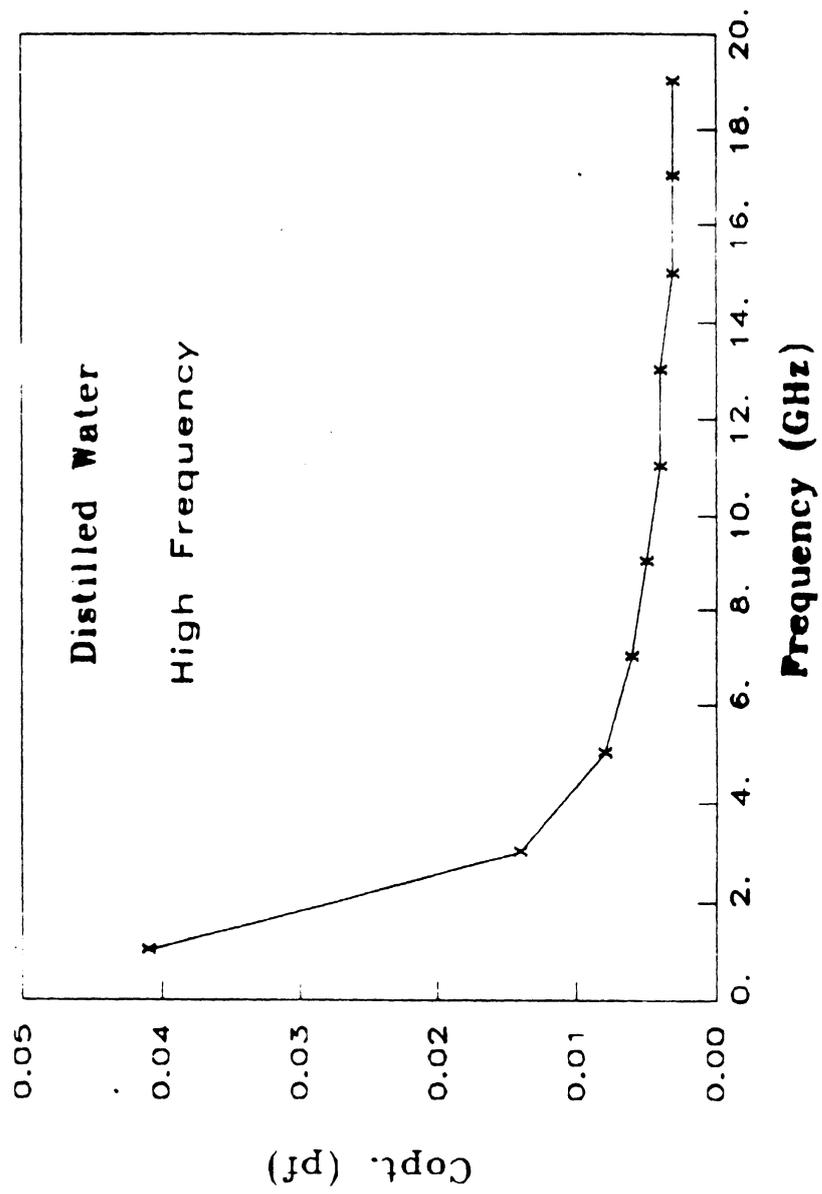


Figure 4.4(d). Calculated optimum capacitance for distilled water(1-20 GHz).

capacitance of an open-ended coaxial line is typically between .02 and .04 pf, the optimum capacitance condition is satisfied for only some materials over a limited frequency range (e.g., distilled water above 2 GHz). The practical situation is not really that stringent and a typical probe can operate satisfactorily over quite a wide band of frequency and range of dielectrics as will be discussed in the next section. The optimum capacitance condition is only useful as a design guideline because the probe would still function satisfactorily in completely different situations, albeit with some degradation in performance.

4.3.2 Sensitivity

The probe translates variations in the permittivity of the test material into variations in the measured amplitude and phase of the reflection coefficient. The variation in the measured phase depends on ϵ'' as well as ϵ' . However, the effect of ϵ'' on $\Delta\varphi$ is of less importance compared to the effect of ϵ' specially at low frequencies. Thus,

$$\Delta\varphi = f(\epsilon', \epsilon'') \approx f(\epsilon').$$

A similar argument for ΔA can lead us to

$$\Delta A = f(\epsilon', \epsilon'') \approx f(\epsilon'')$$

We can define $S_{\epsilon'}^{\varphi}$, the probe phase-sensitivity to ϵ' , as

$$S_{\epsilon'}^{\varphi} = \lim_{\Delta\epsilon' \rightarrow 0} \left[\frac{\Delta\varphi/\varphi}{\Delta\epsilon'/\epsilon'} \right] \quad (4.6)$$

$$= \left(\frac{\epsilon'}{\varphi} \right) \frac{\partial\varphi}{\partial\epsilon'} \quad (4.7)$$

We can interpret the sensitivity $S_{\epsilon'}^{\varphi}$ as the ratio of the fractional change in the function φ to the fractional change in the parameter ϵ' , provided that the changes are sufficiently small (approaching zero). Similarly, $S_{tan\delta}^{\varphi}$ can be defined as

$$S_{tan\delta}^{\varphi} = \left(\frac{tan\delta}{\varphi}\right) \frac{\partial\varphi}{\partial tan\delta} \quad (4.8)$$

A third sensitivity term

$$S_{\epsilon''}^{\varphi} = \left(\frac{\epsilon''}{\varphi}\right) \frac{\partial\varphi}{\partial\epsilon''} \quad (4.9)$$

may also be defined for A . The corresponding relations for A , where A is the magnitude of the reflection coefficient, can be defined as follows:

$$S_{\epsilon'}^A = \left(\frac{\epsilon'}{A}\right) \frac{\partial A}{\partial\epsilon'}, \quad (4.10)$$

$$S_{tan\delta}^A = \left(\frac{tan\delta}{A}\right) \frac{\partial A}{\partial tan\delta}, \quad (4.11)$$

and

$$S_{\epsilon''}^A = \left(\frac{\epsilon''}{A}\right) \frac{\partial A}{\partial\epsilon''}. \quad (4.12)$$

Figures (4.5)-(4.12) show plots of $S_{\epsilon'}^{\varphi}$, $S_{\epsilon'}^A$, $S_{\epsilon''}^{\varphi}$, and $S_{\epsilon''}^A$, versus frequency for 4 different materials: distilled water, methanol, 1-butanol, and 1-octanol. The following conclusions can be drawn:

1. $S_{\epsilon''}^A$ has the highest value especially at low frequencies (Fig.4.6). This shows that ϵ'' has a large sensitivity to the amplitude measurements, and shows how critical the amplitude is in this type of measurements.
2. $S_{\epsilon'}^{\varphi}$ is larger than $S_{\epsilon'}^A$ at low frequencies and for high loss materials (Fig.4.8). As the frequency increases, $S_{\epsilon'}^{\varphi}$ decreases while $S_{\epsilon'}^A$ increases and they become equal around 5 GHz (for distilled water). This trend continues as

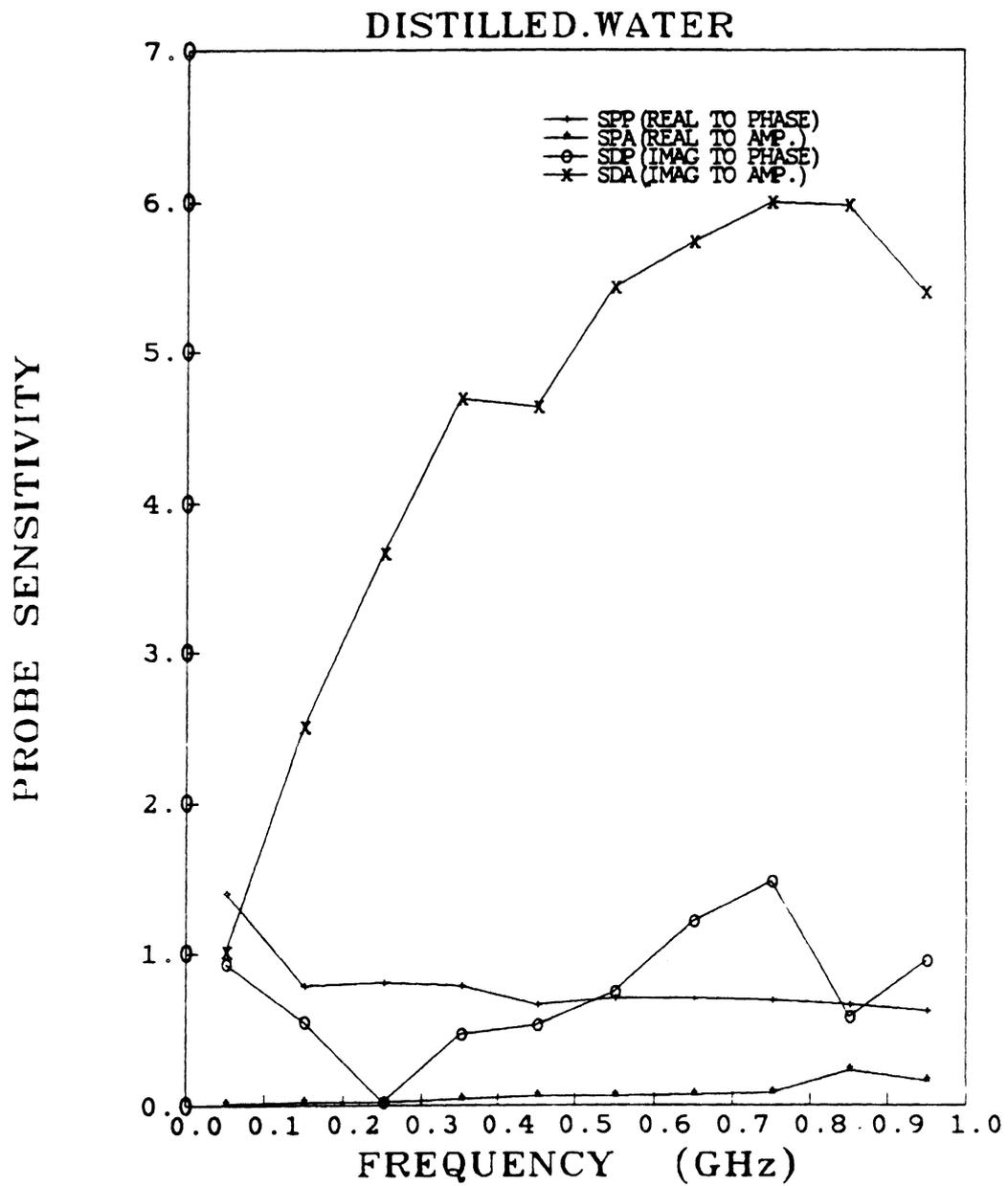


Figure 4.5. Calculated probe sensitivity for distilled water (0.1-1 GHz).

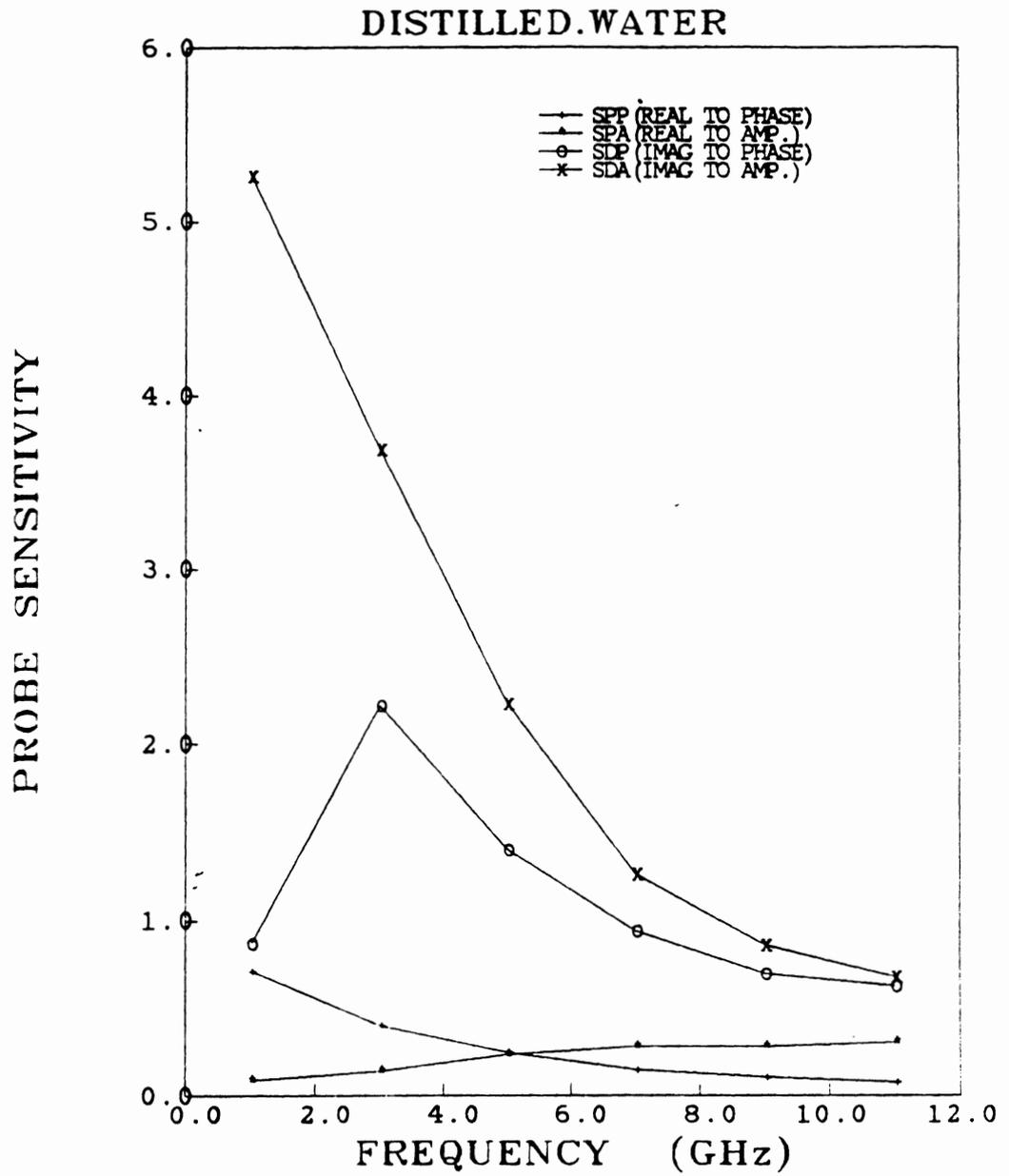


Figure 4.6. Calculated probe sensitivity for distilled water (1-20 GHz).

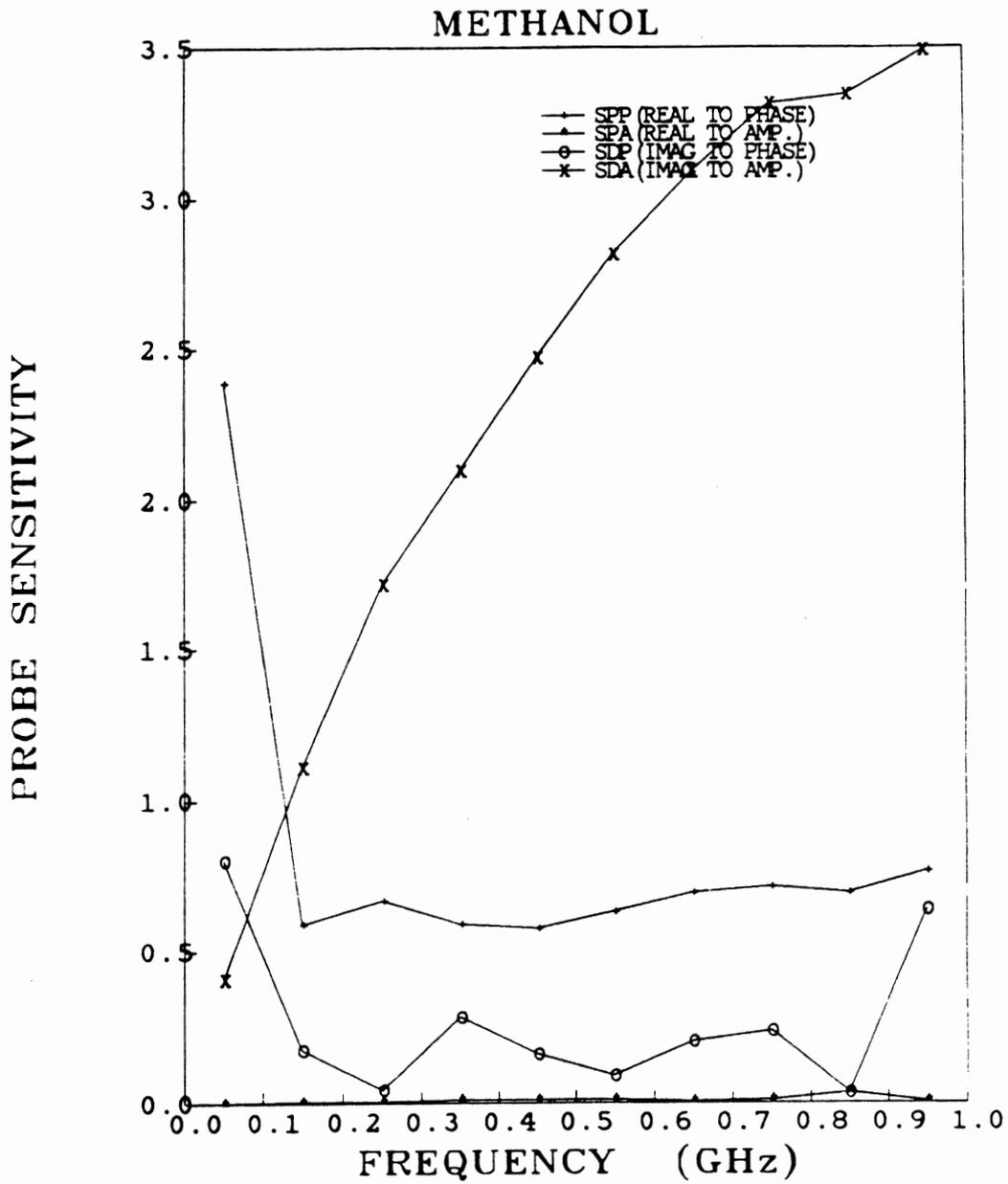


Figure 4.7. Calculated probe sensitivity for methanol (0.1-1 GHz).

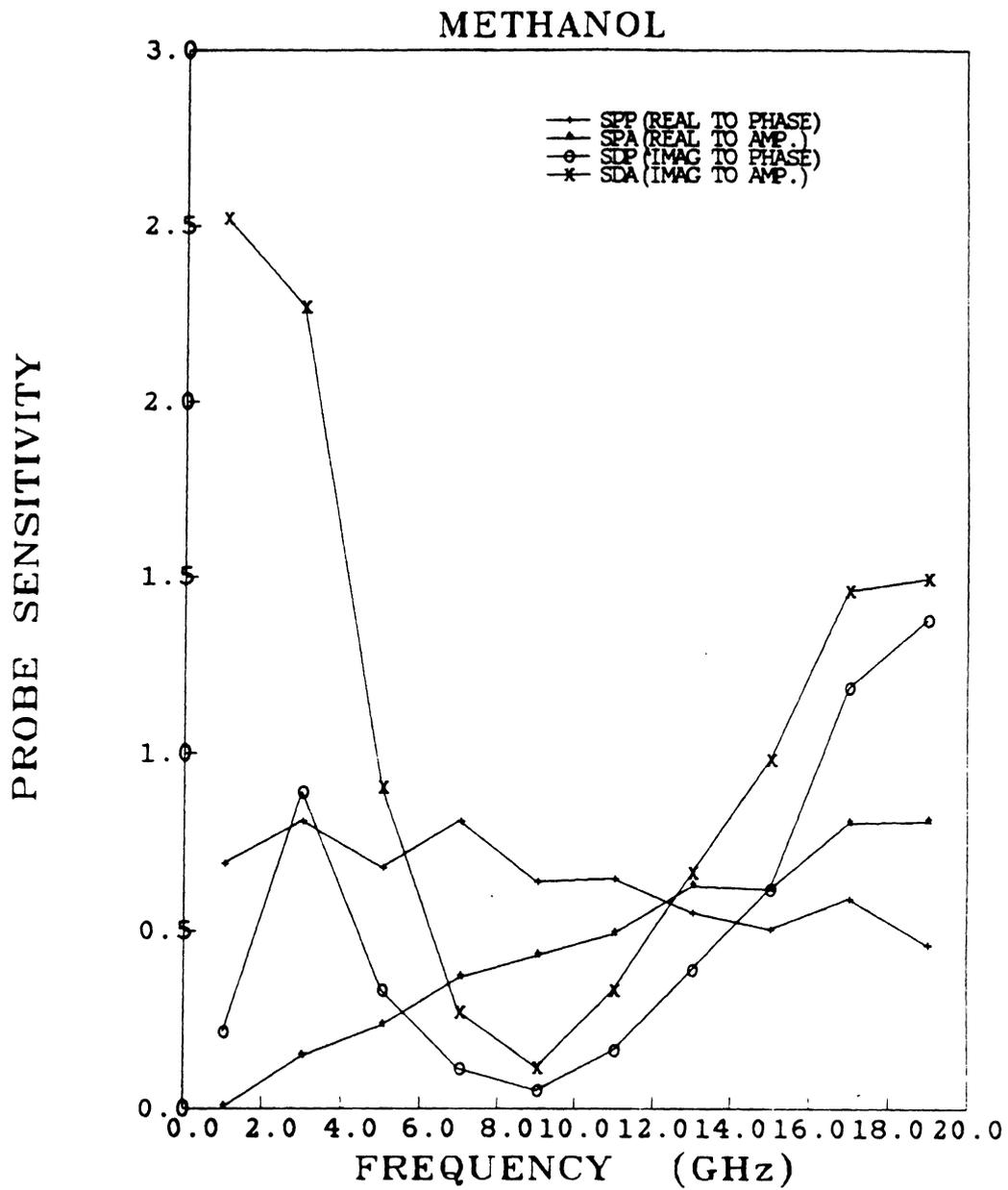


Figure 4.8. Calculated probe sensitivity for methanol (1-20 GHz).

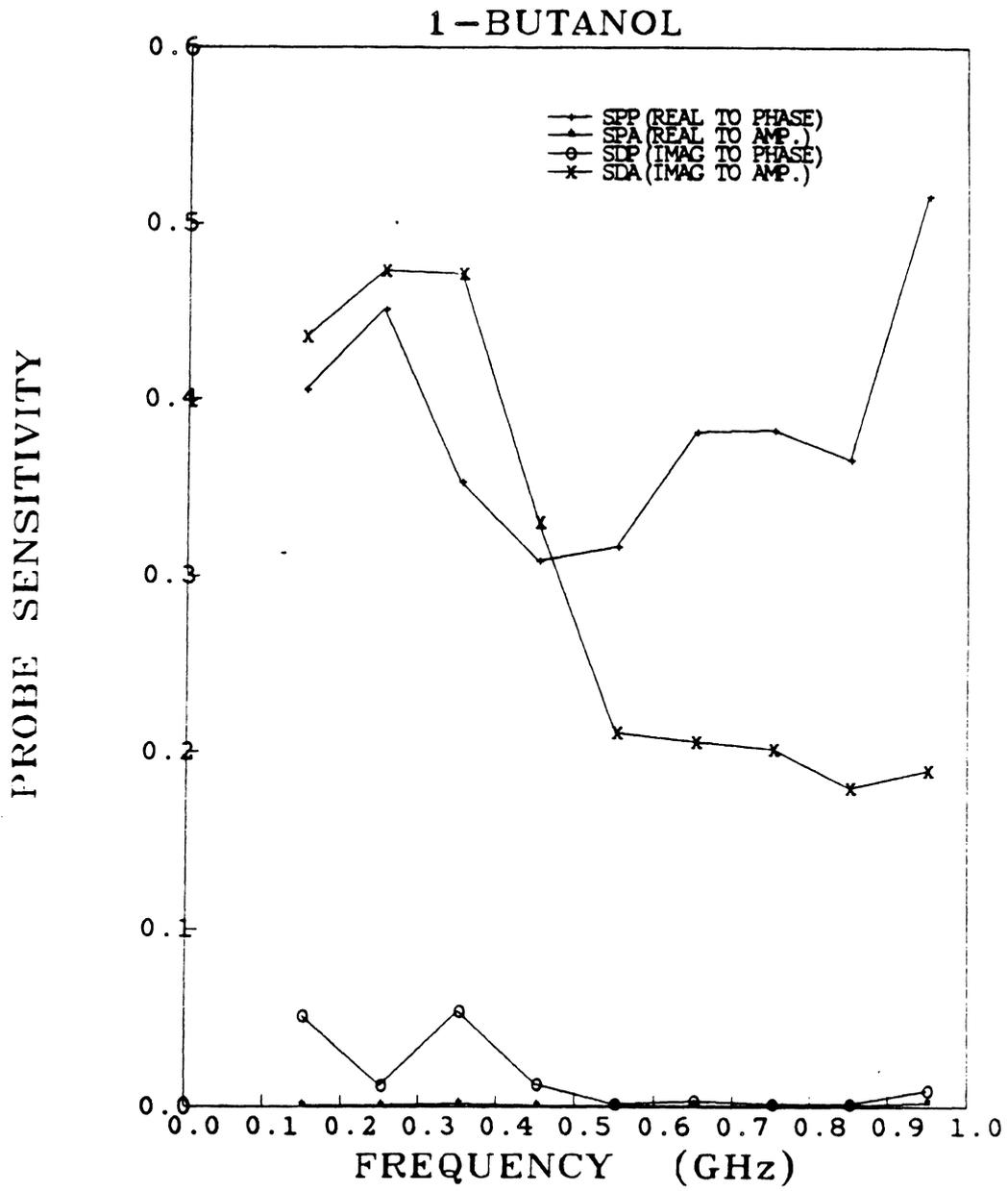


Figure 4.9. Calculated probe sensitivity for 1-butanol (0.1-1 GHz).

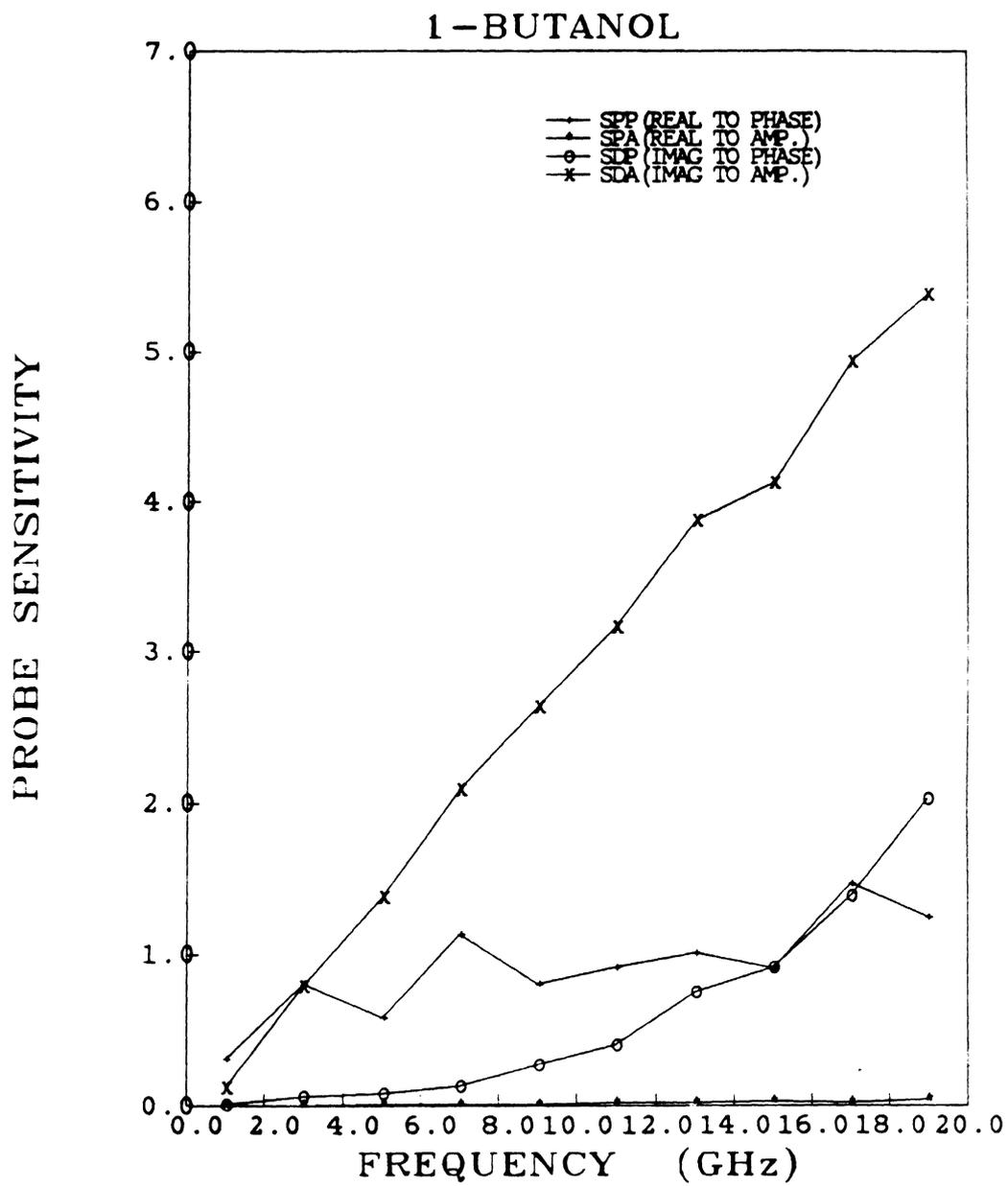


Figure 4.10. Calculated probe sensitivity for 1-butanol (1-20 GHz).

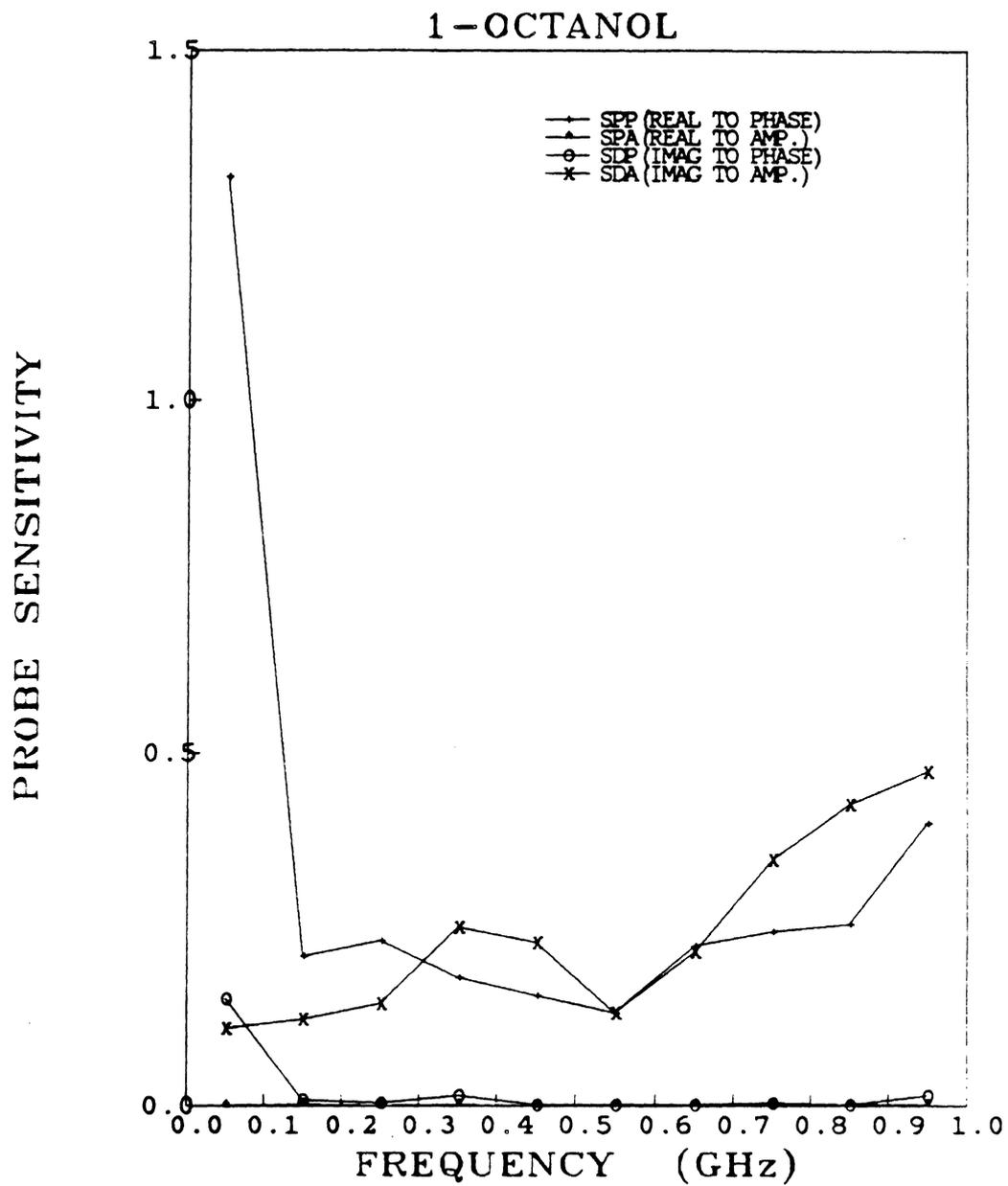


Figure 4.11. Calculated probe sensitivity for 1-octanol (0.1-1 GHz).

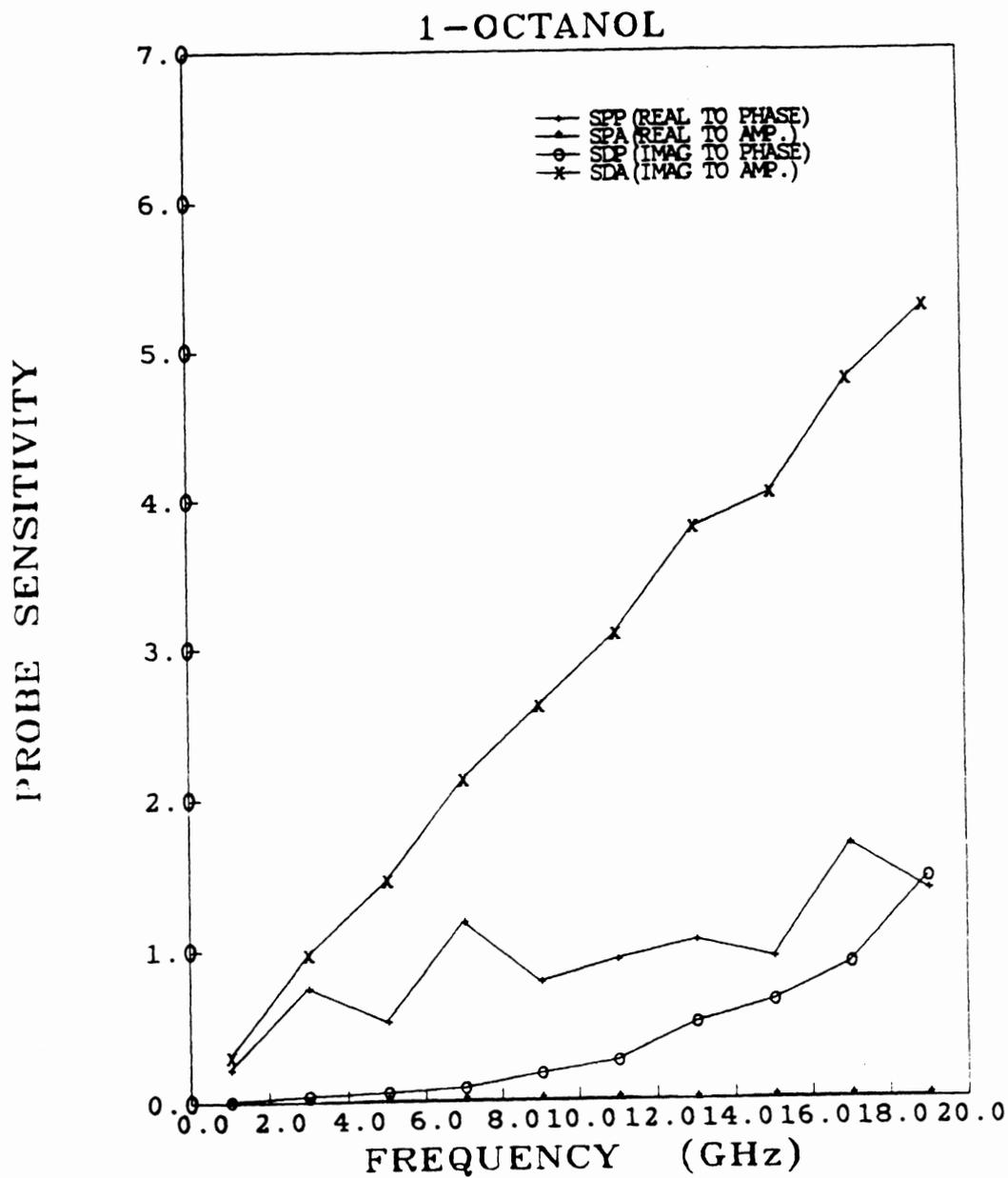


Figure 4.12. Calculated probe sensitivity for 1-octanol (1-20 GHz).

the frequency increases, and $S_{\epsilon'}^A$ becomes larger than $S_{\epsilon'}^{\varphi}$. This observation shows the increased importance of the amplitude measurement at high frequencies. In other words, ϵ' at low frequencies depends mainly on φ , while at high frequency it is more sensitive to A. This is due to the increased role of the radiation term $A\omega^4$ in Eq. (4.4) with increasing frequency.

3. $S_{\epsilon''}^{\varphi}$ is generally higher than $S_{\epsilon''}^A$ (e.g., Fig.4.7), which shows that ϵ'' is more sensitive to φ than ϵ' is sensitive to A.
4. For 1-Butanol and 1-Octanol (Fig.4.10 to 4.13), $S_{\epsilon''}^A$ and $S_{\epsilon''}^{\varphi}$ increase with frequency, $S_{\epsilon'}^{\varphi}$ is roughly constant with frequency, and $S_{\epsilon'}^A$ is almost zero.
5. The sensitivity of the probe generally increases with an increase in its diameter (and hence its lumped capacitance and radiation resistance).

4.3.3 Higher Order Modes

Open-ended coaxial lines can be modeled as a simple capacitance, C_0 , especially at low frequencies (where the free space wavelength is much larger than the line cross-sectional dimensions). When the frequency of operation increases, the line starts to radiate and the energy is not concentrated in the reactive fringing field any longer. In this situation C_0 increases with frequency due to the increase in the evanescent TM modes being excited at the junction discontinuity. An expression of the form $C_0 + B\omega^2$, where B is a constant dependent on the line dimensions, should be used in place of the constant value C_0 . Furthermore, when the medium has a high dielectric constant, these modes may become propagating

modes. The first of these modes is the TM_{01} mode which can propagate when $\lambda_c \leq 2.03(a - b)$, where λ_c is the wavelength in the medium, and a and b are the outer and inner line radii. Table (4.1) shows the cut-off wavelength for the probe types used in this study along with their line dimensions (Athey, 1982):

Cable	type	a(mm)	b(mm)	a/b	λ_c (mm)
.085"	Teflon	.838	.255	3.282	1.177
.141"	Teflon	1.499	.455	3.295	2.129
.250"	Teflon	2.655	.824	3.222	3.764
.350"	Teflon	3.620	1.124	3.221	5.067

Table (4.1): Dimensions and cut-off wavelengths for the TM_{01} mode for the probes used in this study.

If the frequency is high enough such that the wavelength in the medium is shorter than λ_c , moding will occur. To calculate the wavelength in the medium, the following equation can be used (Ulaby et al, 1982):

$$\lambda_c = \frac{\lambda_0}{\sqrt{\epsilon'} \sqrt{\frac{\sec \delta + 1}{2}}}$$

where λ_ϵ , λ_0 , ϵ' and δ are as defined earlier. In order to avoid the moding problem, care must be taken when materials with high dielectric constants are measured.

Usually this problem is encountered in two situations:

1. distilled water and saline solutions at high frequency, and
2. thin samples placed against metal background.

Table (4.2) shows the calculated wavelength in the medium λ_ϵ as a function of frequency for distilled water:

f(GHz)	1	2	4	6	9	10	20	30	40
$(\lambda_\epsilon)_c(mm)$	33.7	16.9	11.7	5.825	4.05	3.70	2.21	1.75	1.49

Table (4.2): $(\lambda_\epsilon)_c$ for distilled water.

From this table we can conclude the following:

1. The .085" probe may be operated at frequencies higher than 40 GHz,
2. The .141" probe may be operated at $f \leq 21$ GHz,

3. The .250" probe may be operated at $f \leq 9$ GHz, and

4. The .350" probe may be operated at $f \leq 6$ GHz.

It was found experimentally, however, that this theoretical limit does not strictly apply. The practical cut-off frequencies are slightly lower than the calculated values. It should be noted that whereas a smaller probe can operate over a wider frequency range, its sensitivities are smaller in magnitude than those of larger probes.

4.3.4 Contact and Pressure Problem

The calibration procedure involves measuring two standard liquids (usually distilled water and methanol). The open-ended coaxial line (with or without a ground plane) is suitable for measuring liquids as long as care is exercised to avoid air bubbles at the probe tip. Also, the fact that the calibration was carried out using liquids made the probe more suitable and more accurate for measuring liquid and semi-liquid materials. Semi-solid materials can also be measured accurately since the surface can deform to comply with the probe tip and achieve a good contact (an example of semi-solid materials is cheese). On the other hand, solid materials are very hard to measure using ordinary probes. When measuring the dielectric constant of a solid material, it is crucial to achieve a perfect contact with the material under test particularly in the immediate vicinity of the probe tip. As will be discussed later in this chapter, some new probe designs with very smooth surfaces and ground planes were built, tested

and found suitable to measure solid materials. Measuring vegetation materials, particularly leaves, is usually a problem since any deformation of the plant part would cause an immediate cellular rupture and possible flow of the included liquids, in addition to the change in density with increasing pressure. It was found that for each vegetation material and plant part there is an optimum pressure above which the part will be crushed and below which the contact will not be perfect. This optimum pressure is found experimentally for each part and should be maintained constant during the experiment (a digital scale was used to check pressure). Usually a pressure of few hundred grams applied on the .141" probe tip ($\sim .1cm^2$) is sufficient.

4.4 Probe Calibration

4.4.1 Choice of Calibration Materials

The overall performance of the system depends on the choice of calibration materials as well as the accuracy with which we know their dielectric properties. This section gives few guidelines regarding the selecting of proper materials for a particular application. During the course of this work only distilled water and methanol were used for calibration. The dielectric constant of water is the highest known in the microwave band and that of methanol is approximately one half of it. For wet vegetation materials, it is a good idea to use water as a calibration material. On the other hand, for dry vegetation materials, a different combination may be better. Butanol, e.g., can be used in place of water since its

dielectric constant is about half that of methanol. The calibration liquids should have, in general, the following features:

1. their dielectric properties should be known fairly accurately as a function of frequency and temperature.
2. both must have a reasonably large imaginary part (any lossless material is not suitable for calibration).
3. the dielectric properties of the two materials should be significantly different (e.g., it is not recommended using two saline solutions with different salinities).
4. the two materials should have dielectric values that cover the expected range of the material under test.

4.4.2 Error Analysis

A measurement system usually suffers from three major sources of error, namely the systematic, the random, and the illegitimate errors. The errors in the probe measurement technique can be summed up as follows:

1. Systematic Errors

- (a) System S parameters (S_{11} , S_{12} , S_{21} , and S_{22}),
- (b) Probe model accuracy,
- (c) Experimental conditions and standards, and

(d) Conditions of the sample under test.

2. Random Errors

(a) Network analyzer precision,

(b) Harmonic skip problem,

(c) Noise, and

(d) Sample conditions.

3. Illegitimate errors

(a) Blunders, and

(b) Chaotic.

Before proceeding into quantitative estimation of errors, the following assumptions will be made:

1. The error correction procedure is perfect (for the system S parameters).
2. The sample conditions problem does not exist for liquids (since they are homogeneous and since care was taken to avoid air bubbles at the probe tip).
3. The harmonic skip problem is cured through averaging (of 4 sweeps and 4 independent measurements).
4. Since each time the computer reads the A/D board it actually reads it 30 times, the noise is eliminated.

5. Illegitimate errors can be detected and eliminated by inspection.

Comparing this list to the errors' list, the remaining errors are:

1. Model accuracy, experimental conditions, and standards.
2. Network analyzer precision.

In this analysis, it was assumed that

1. $\Delta\epsilon = \pm 2\%$,
2. $\Delta A = \pm 0.05\text{dB}$,
3. $\Delta\phi = \pm 0.3^\circ$, and
4. Since the number of independent samples is 4, then $\Delta\epsilon$ (4 independent measurements) = $\Delta\epsilon$ (1 measurement)/2. The estimated precision and accuracy of the probe system were evaluated and plotted as shown in Figs. 4.13-4.18 for yellow cheese (.141"), white cheese (.141"), 1-octanol (.250"), 1-octanol (.141"), 1-butanol (.250"), and 1-butanol (.141"), respectively. In order to evaluate the probe performance; several standard materials were measured and plotted along with the calculated values. An example is shown in Figs. 4.19 and 4.20 for 1-butanol.

From this error analysis, it was found that the overall system accuracy and precision are within 10.% (including system and sample errors). The estimated precision and accuracy of the probe system were evaluated and plotted as shown in Fig.(4.19)-(4.20) for 1-Butanol.

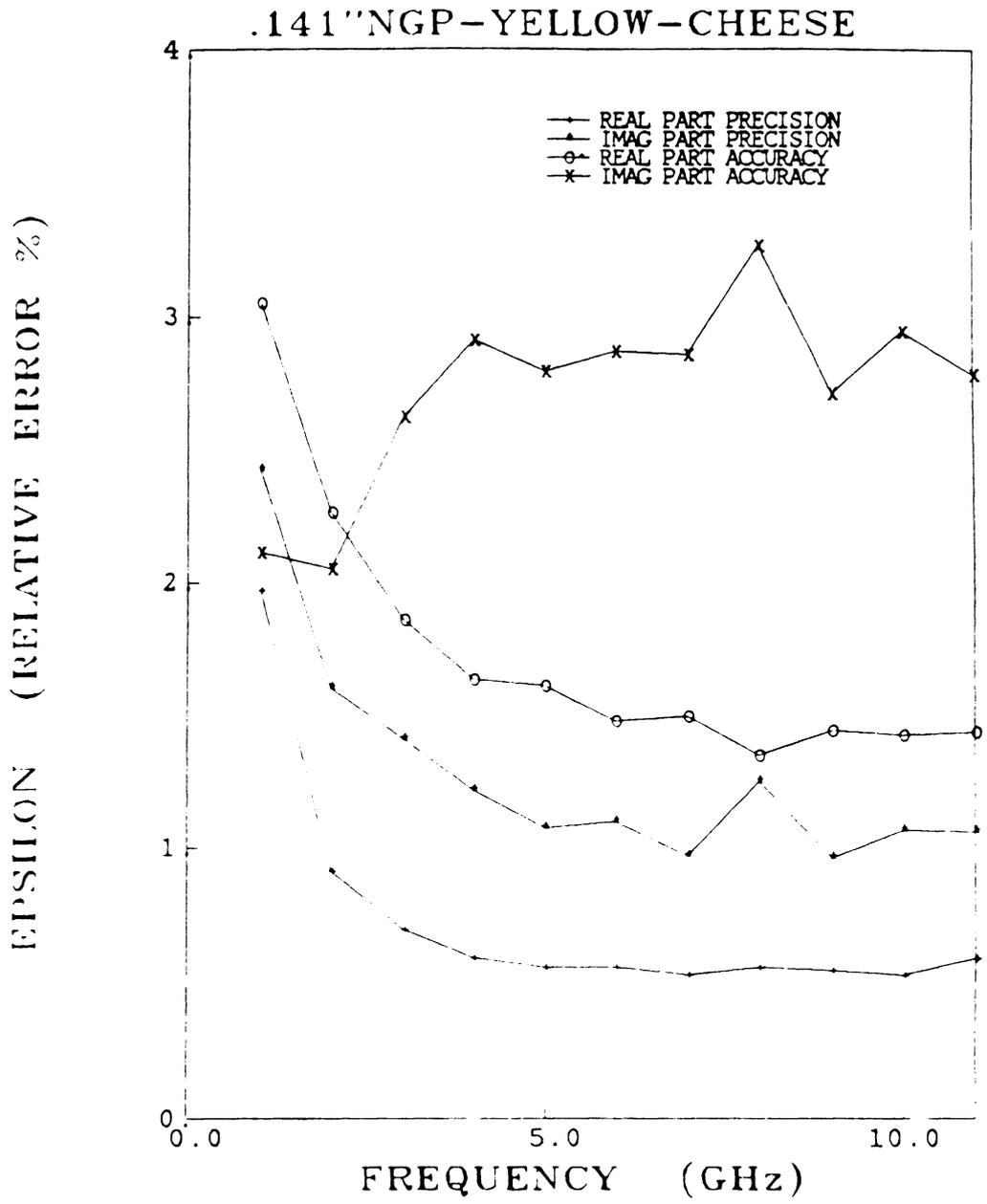


Figure 4.13. Estimated relative errors % for measurements on yellow cheese both accuracy and precision.

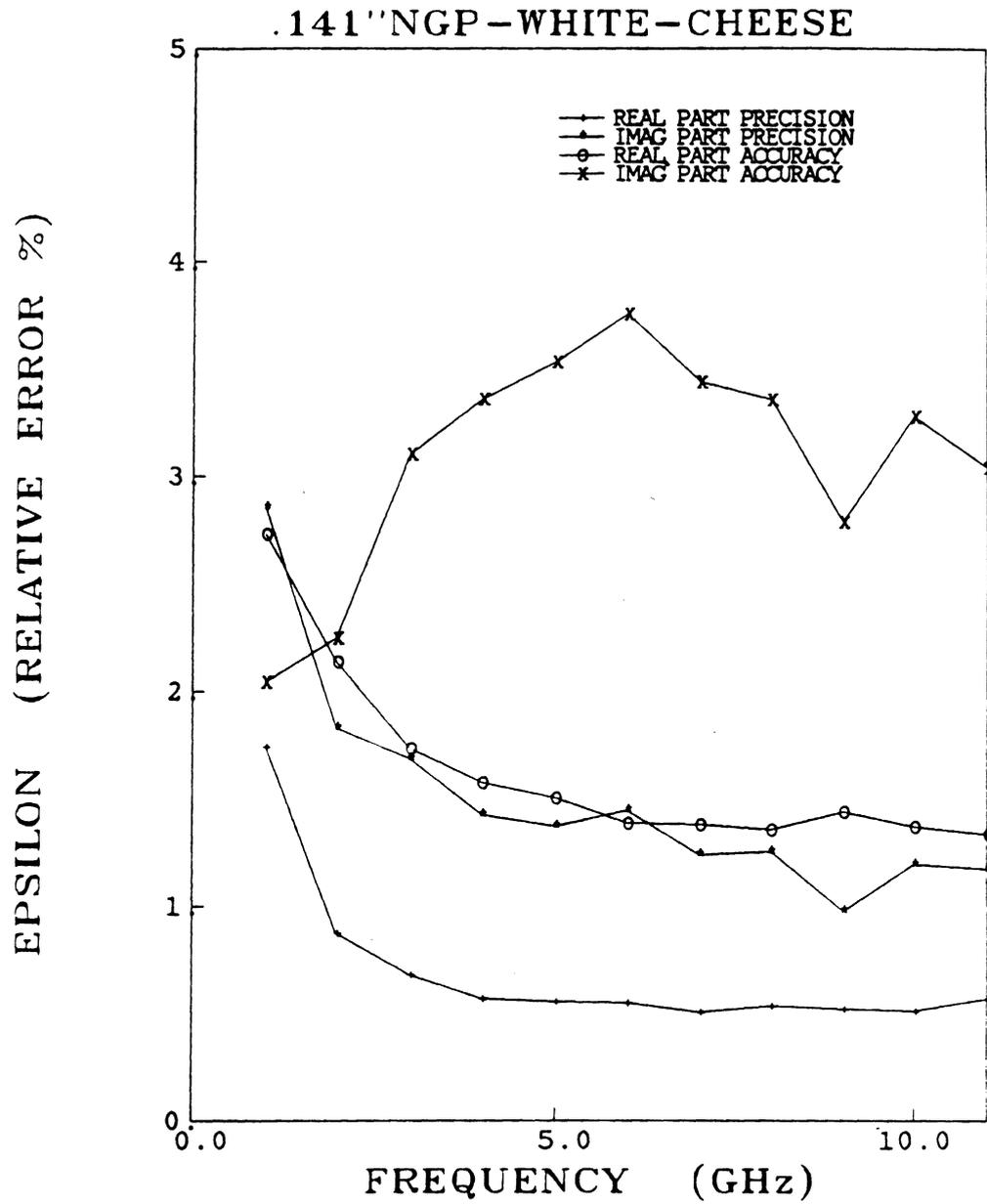


Figure 4.14. Estimated relative errors % for measurements on white cheese both accuracy and precision.

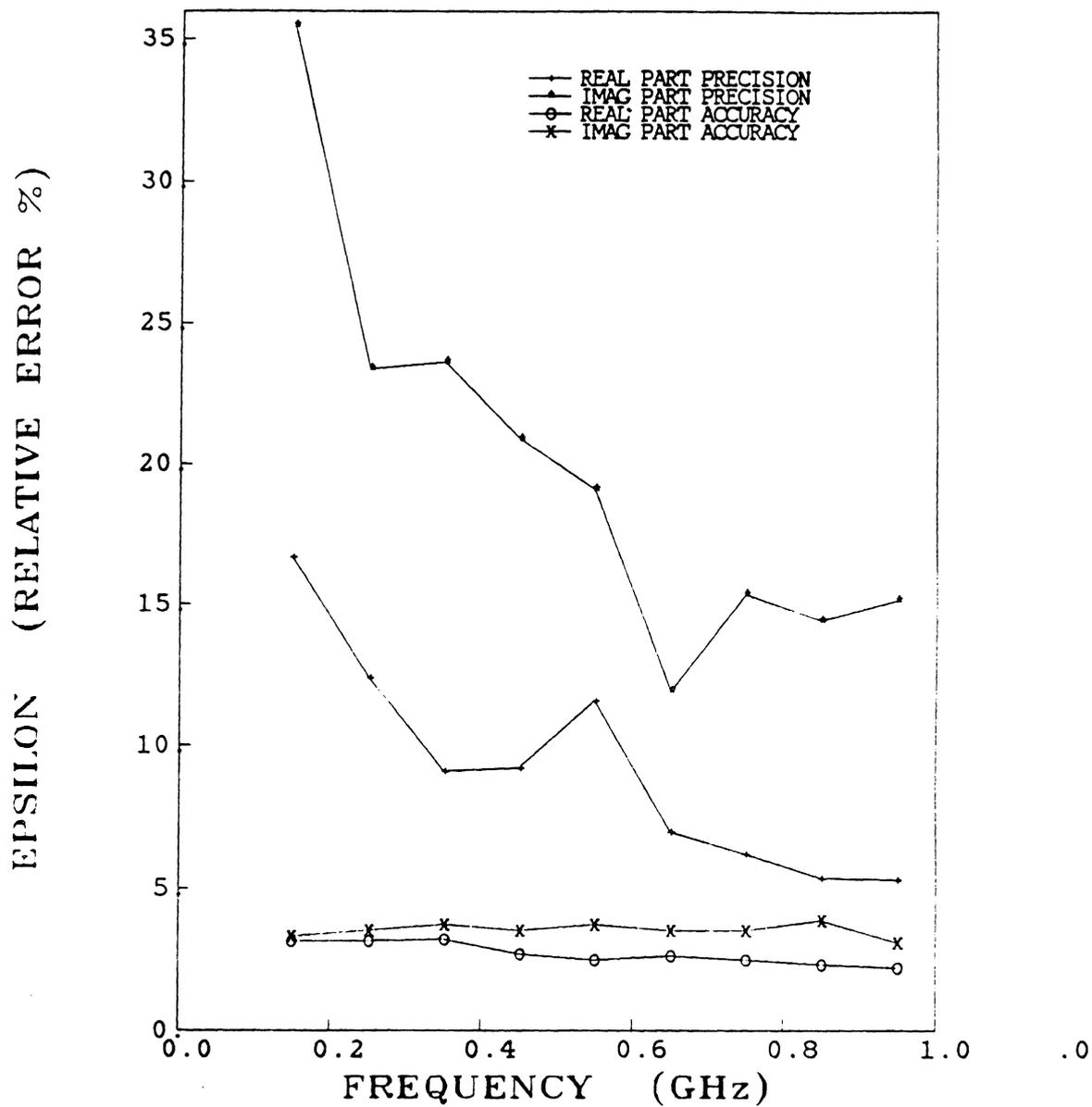


Figure 4.15. Estimated relative errors % for measurements on 1-octanol both accuracy and precision using the 0.250" probe.

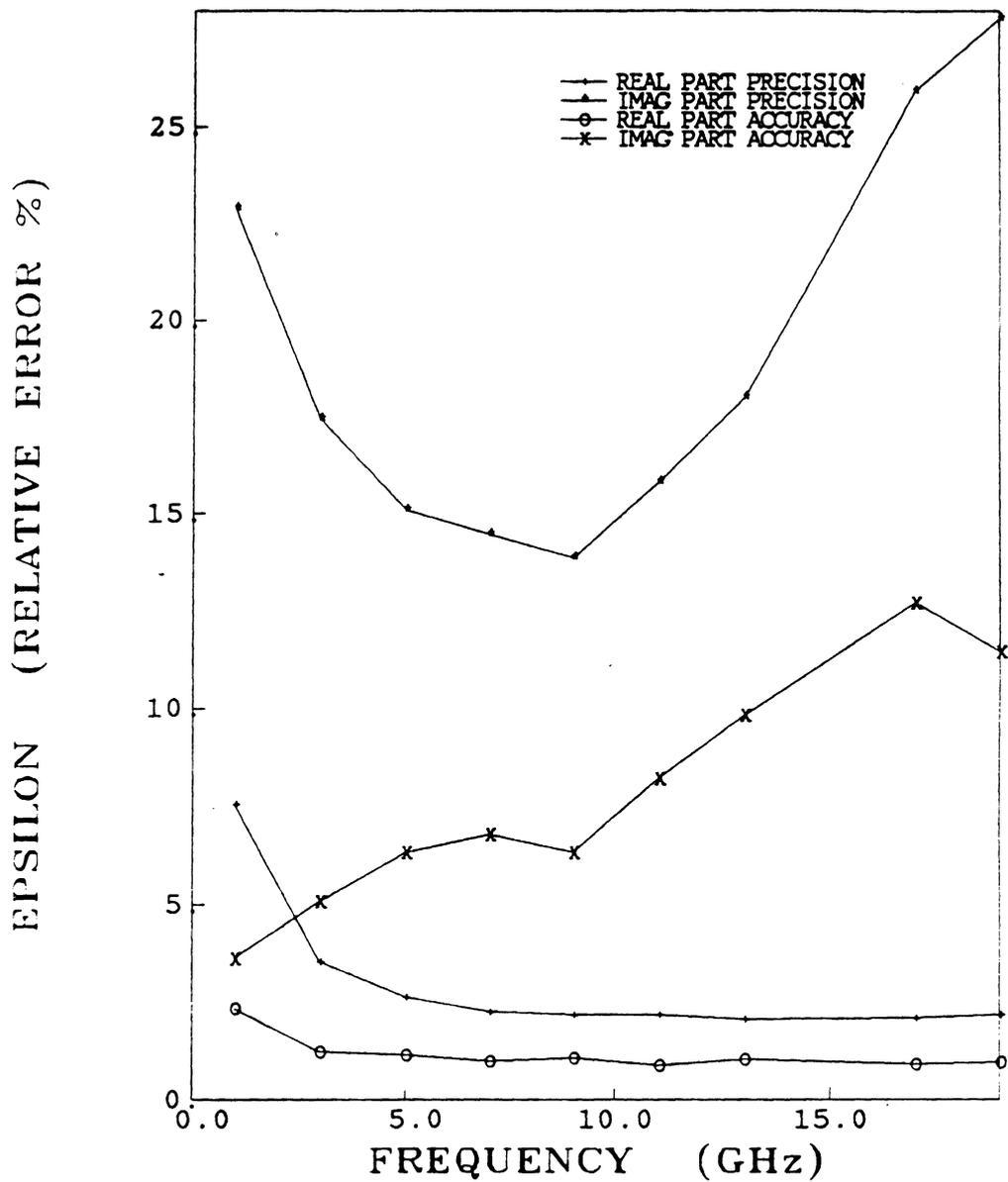


Figure 4.16. Estimated relative errors % for measurements on 1-octanol both accuracy and precision using the 0.141" probe.

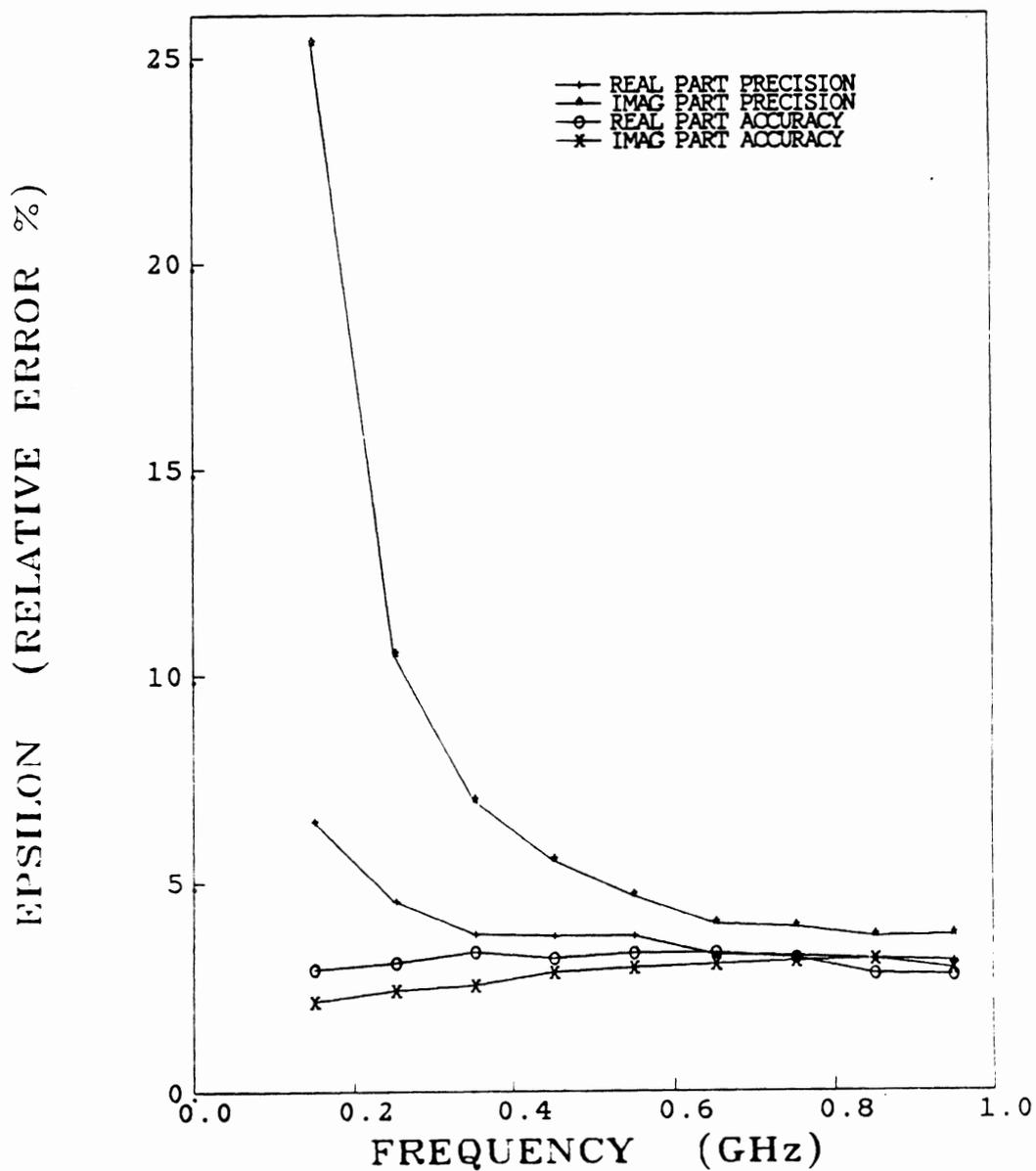


Figure 4.17. Estimated relative errors % for measurements on 1-butanol both accuracy and precision using the 0.250" probe.

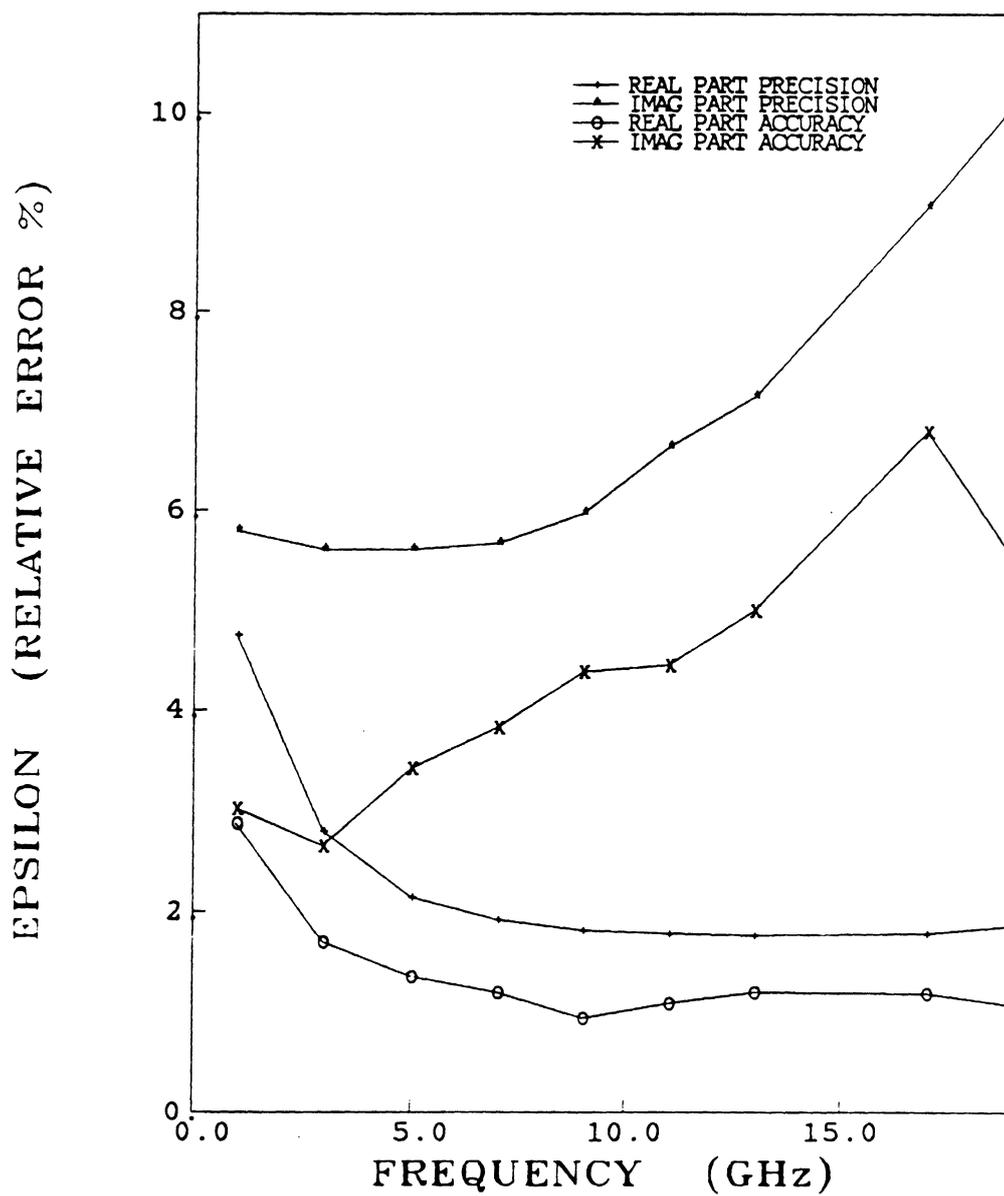


Figure 4.18. Estimated relative errors % for measurements on 1-butanol both accuracy and precision using the 0.141" probe.

1-Butanol (Prob System Calibration)

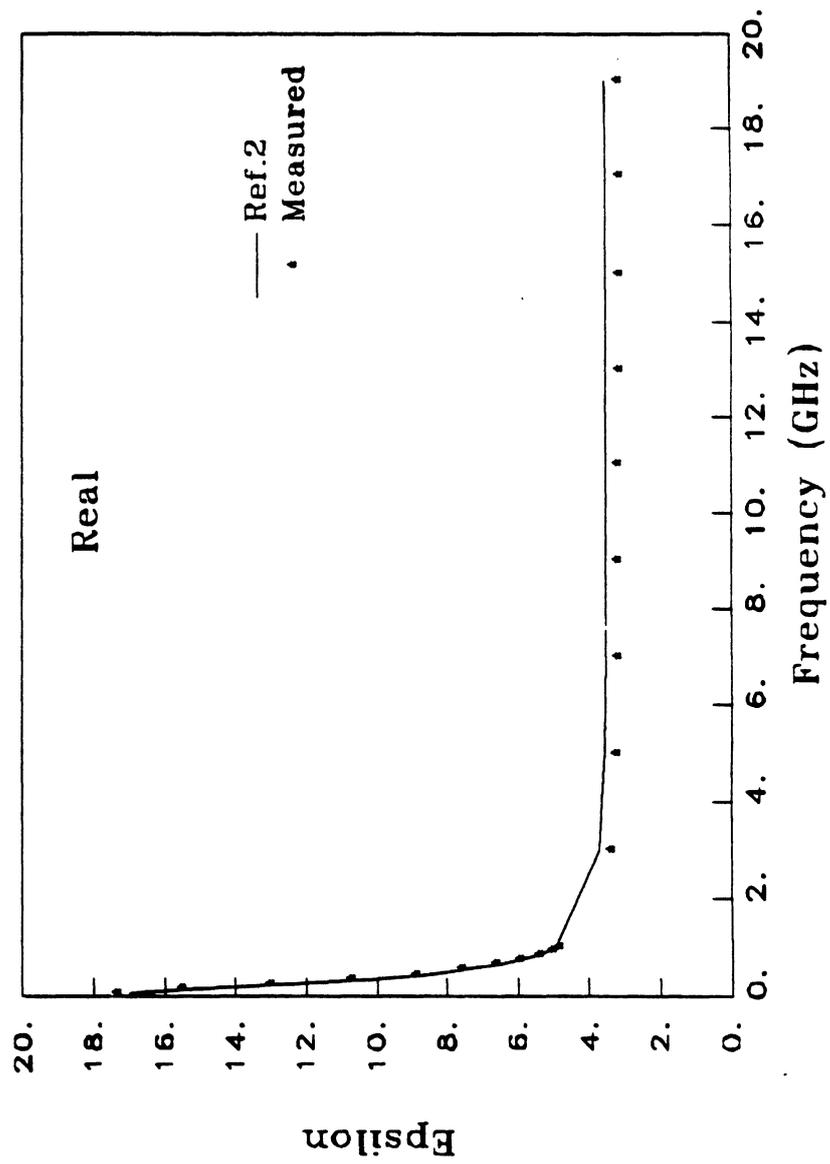


Figure 4.19. Comparison of calculated [ref. 2 is Bottreau et al, 1977] and measured data using the 0.141" probe for 1-butanol (real part).

1-Butanol (Prob System Calibration)

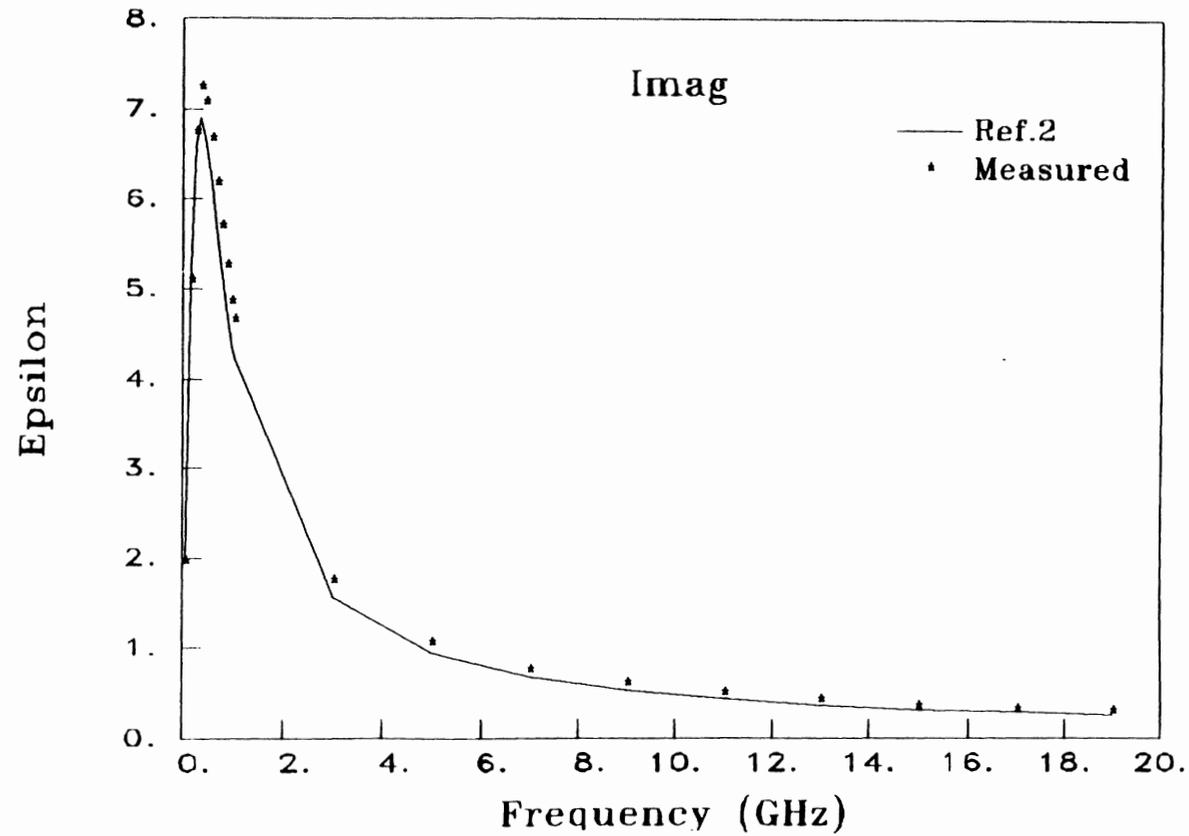


Figure 4.20. Comparison of calculated [ref. 2 is Bottreau et al, 1977] and measured data using the 0.141" probe for 1-butanol (imaginary part).

4.4.3 Thin Sample Measurements

The sample under test was assumed to be a semi-infinite medium. This assumption is impossible to achieve practically; however, it was found that the fringing and radiating fields decay rapidly with distance away from the probe tip. A simple experiment was designed to show the validity of the semi-infinite assumption. A stack of paper sheets, with variable thickness (1 up to 30 sheets), was measured against two different backgrounds. The background materials were selected to be plexiglass and metal in order to provide a large contrast (refer to Fig. 4.21). The results of this measurement are shown in Fig. 4.22(a) to (c). The following observations can be made regarding these figures:

1. One sheet ($\sim .1$ mm) is too thin and does not satisfy the semi-infinite medium condition.
2. At 1 GHz, at least 30 sheets are required to satisfy the thick sample condition (3 mm).
3. The higher the frequency, the less stringent this condition becomes (at 8 GHz it is about 2 mm).
4. Since paper sheets are practically lossless, this condition is even easier to satisfy for lossy materials.
5. By intuition, we can state that the larger the probe diameter is, the thicker the required sample gets.

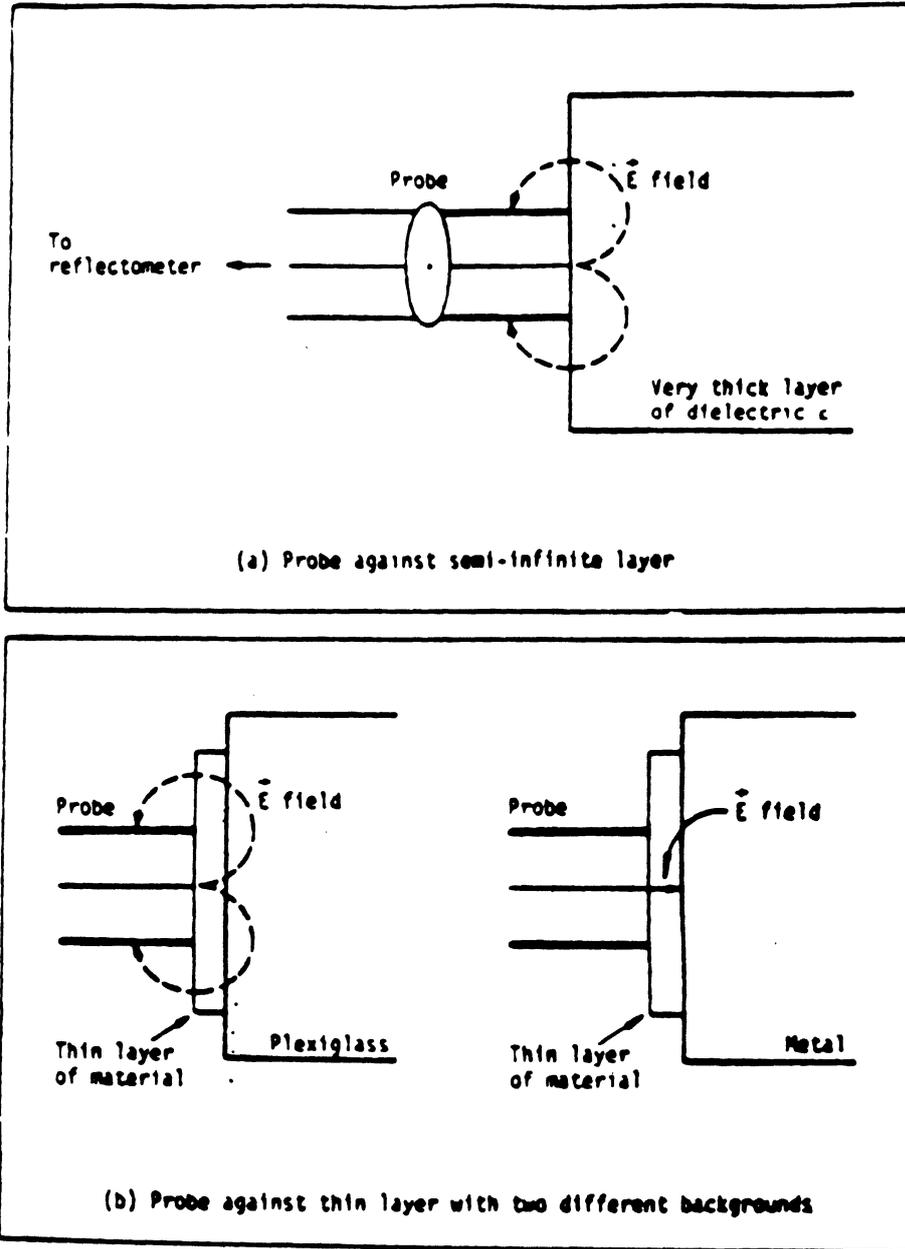


Figure 4.21. Probe technique for measuring dielectric of (a) thick layers and (b) thin layers.

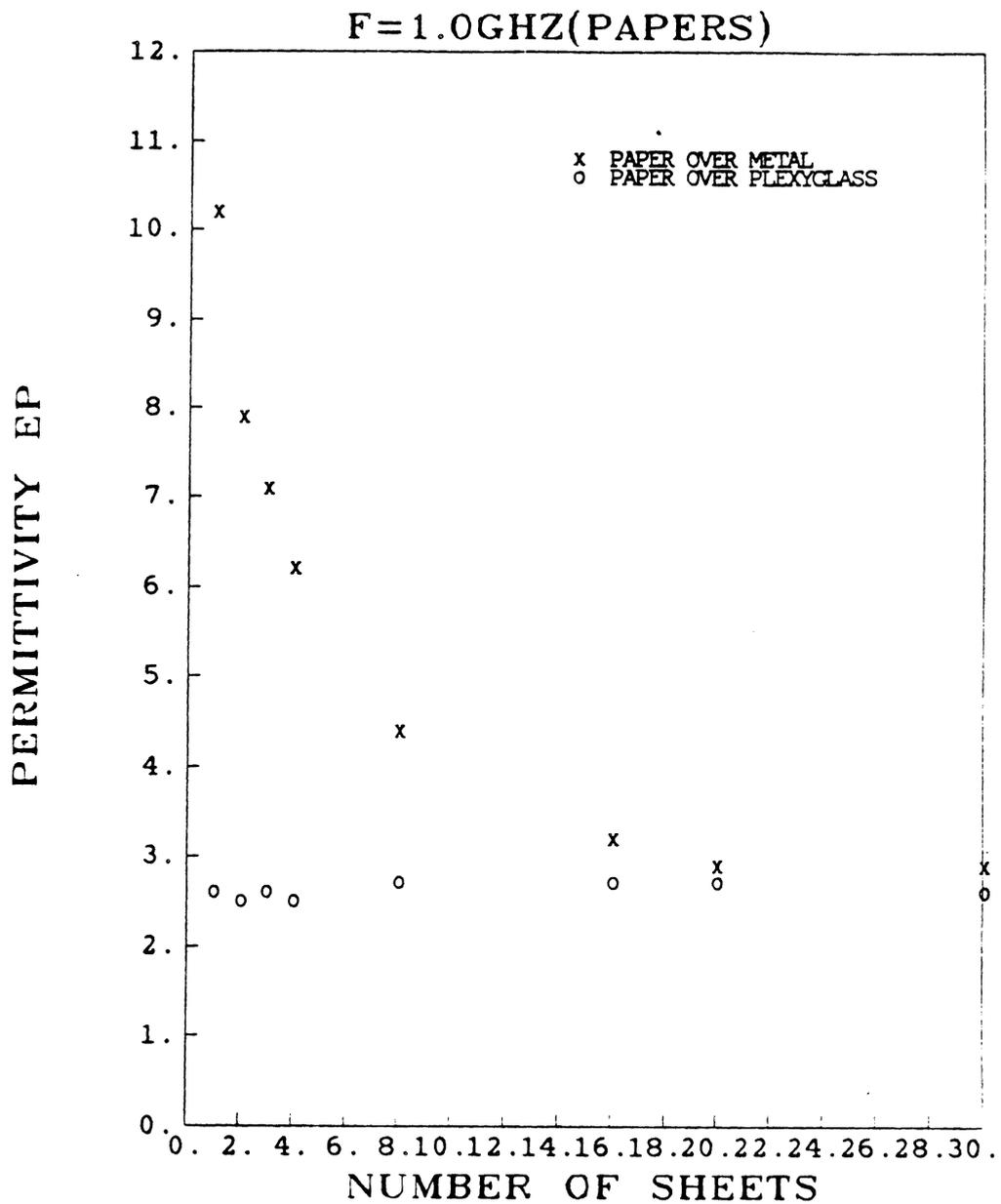


Figure 4.22(a). Comparison of a measured stack of sheets against a metal background and against a plexiglass background versus the stack's thickness at $f=1$ GHz.

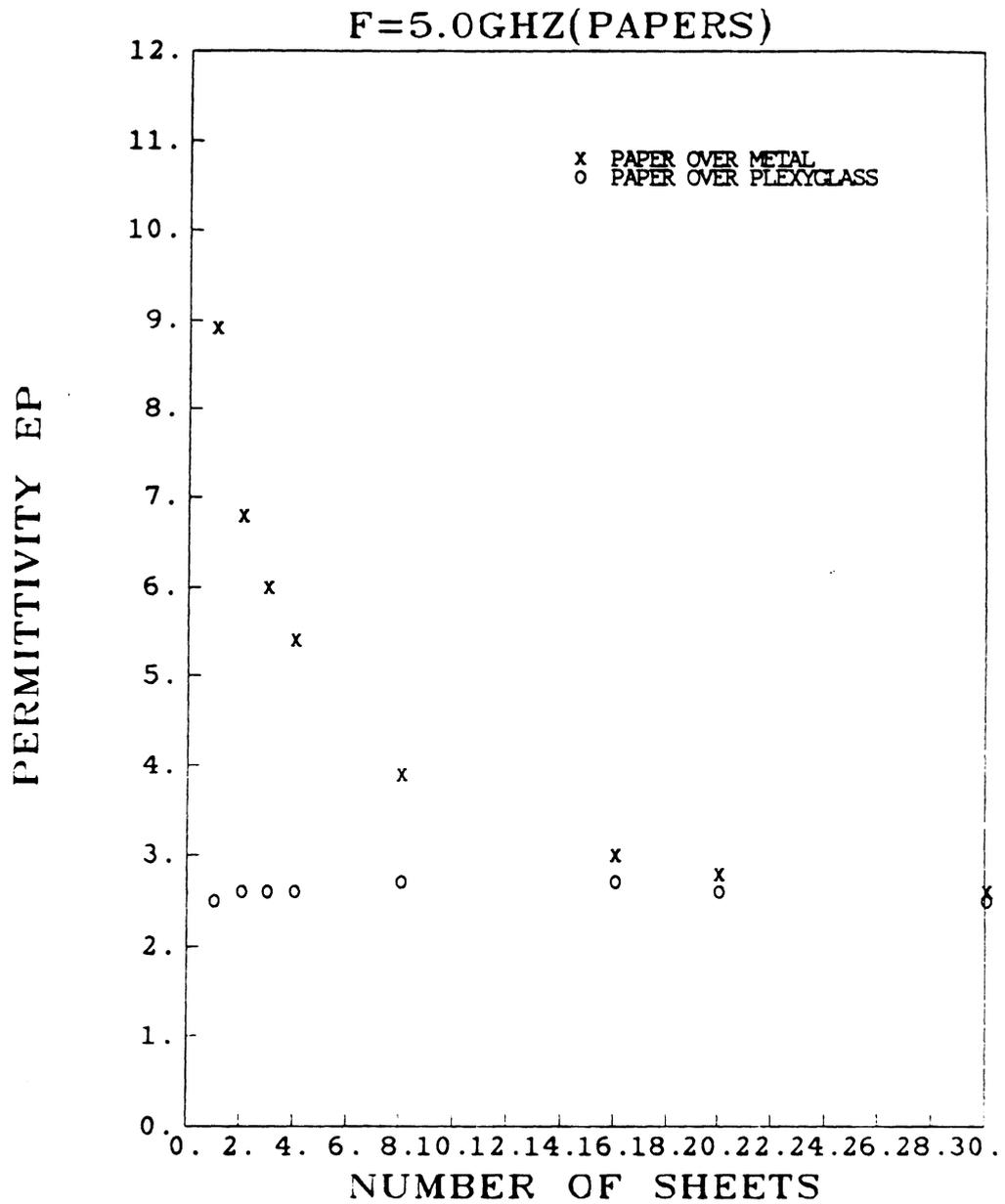


Figure 4.22(b). Comparison of a measured stack of sheets against a metal background and against a plexiglass background versus the stack's thickness at $f=5$ GHz.

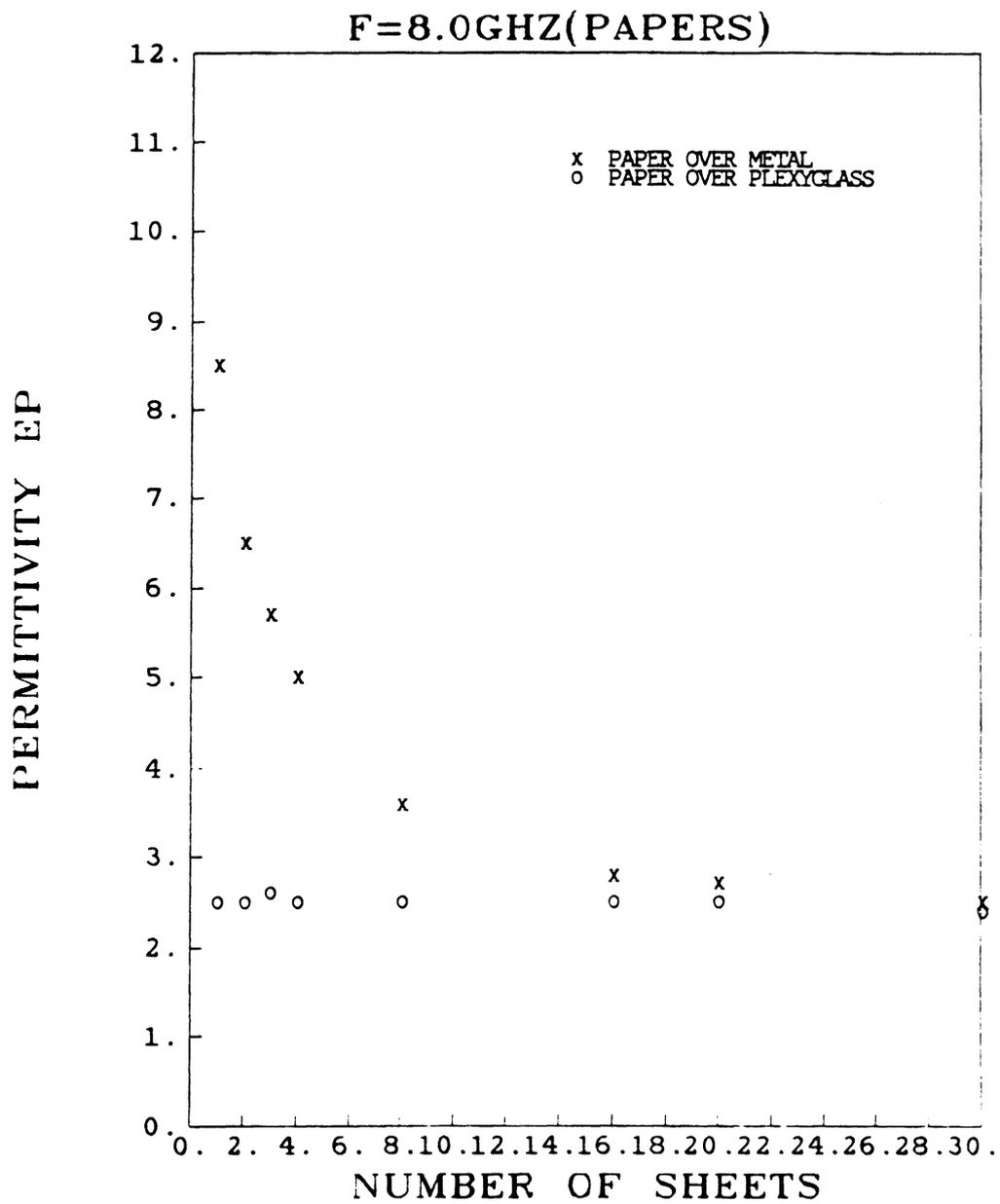


Figure 4.22(c). Comparison of a measured stack of sheets against a metal background and against a plexiglass background versus the stack's thickness at $f=8$ GHz.

As a rule of thumb, the sample thickness should be approximately equal to the probe radius.

The previous discussion has shown that a sample 3 mm in thickness is sufficient (using the .25" probe) to satisfy the semi-infinite condition for any material and across the entire frequency band of interest (.1-20 GHz). For dielectric measurements of vegetation leaves, however, a single leaf does not have sufficient thickness to satisfy the above conditions. So, a stack of leaves, usually 8 or more, is used and 2 measurements are taken against plexyglass (or teflon) as background and another 2 measurements are taken with a metal background. It is advisable to check that these 4 measurements are consistent and that the variations, if any, can be attributed to sample conditions (and not to sample thickness). In order for the probe to be useful for measuring live or intact plants, it should be able to measure samples that are thinner than the minimum thickness required (3 mm). A semi-empirical formula was developed, tested, and has proved to work satisfactorily over the frequency band of interest. The exact mathematical analysis was fairly complex and hence we took a semi-empirical approach.

Assume that a TEM signal is propagating in medium 1 and impinging on a dielectric slab of known thickness d and known permittivity ϵ_2 . The slab is terminated in a semi-infinite medium of dielectric constant ϵ_3 (as shown in Fig. 4.23). If all multiple reflections are considered, we end up with the following general equation for the input impedance at the interface between media 1 and 2 (Ulaby et al, 1982):

The Sample Configuration

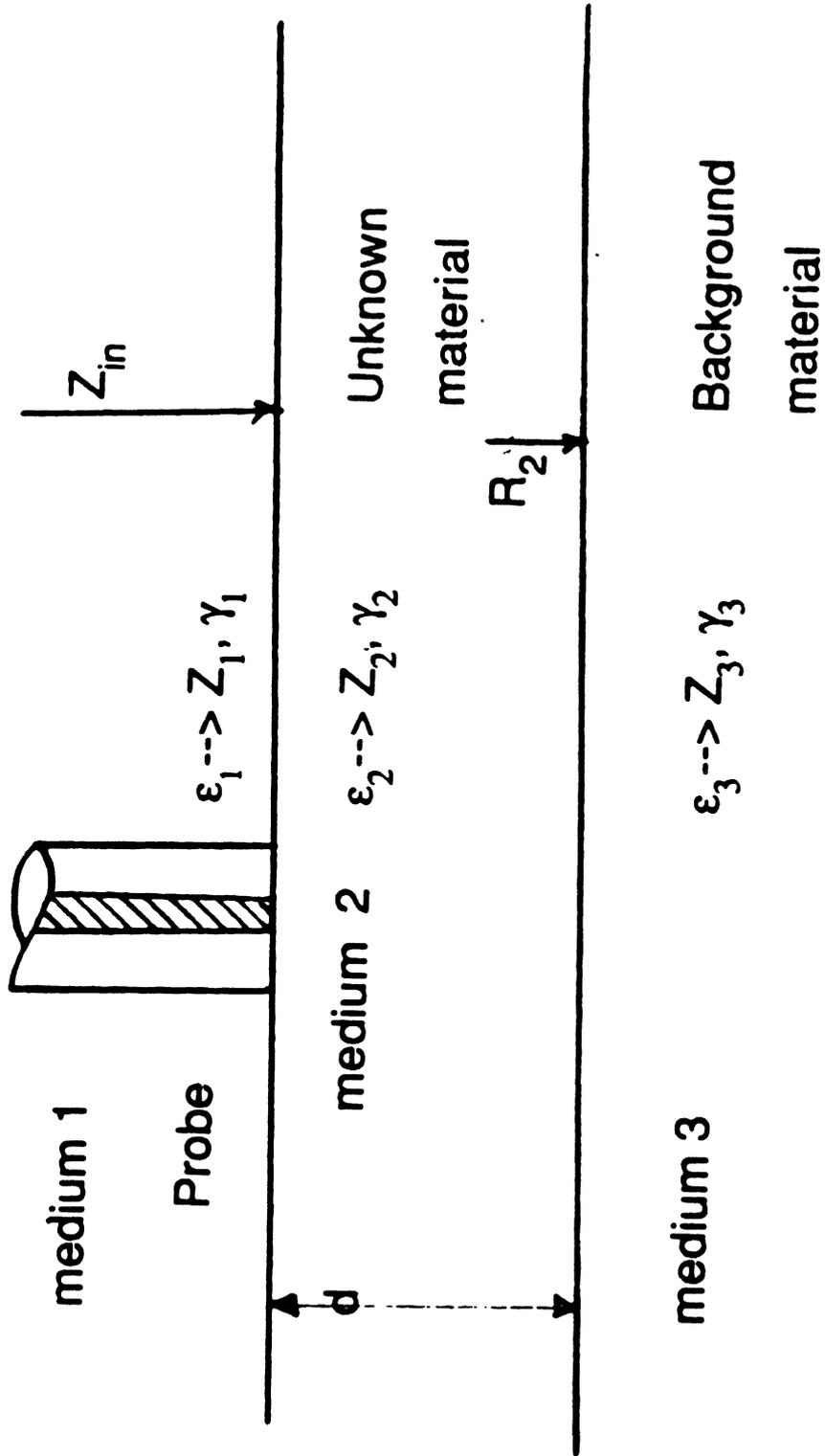


Figure 4.23. Thin sample configuration against a background material (known).

$$Z_{in} = Z_2 \left(\frac{1 + R_2 e^{-j\gamma_2 d}}{1 - R_2 e^{-j\gamma_2 d}} \right) \quad (4.13)$$

where,

$$R_2 = \frac{Z_3 - Z_2}{Z_3 + Z_2}, \quad (4.14)$$

$$\gamma_2 = \frac{2\pi}{\lambda_0} \sqrt{\epsilon_2}, \quad (4.15)$$

and $Z_1, Z_2,$ and Z_3 are the effective impedances of media 1, 2, and 3, respectively.

Equation (4.13) can be rewritten as:

$$e^{-j\gamma_2 d} = \left(\frac{Y_2 + Y_3}{Y_2 - Y_3} \right) \left(\frac{Y_2 - Y_{in}}{Y_2 + Y_{in}} \right), \quad (4.16)$$

where $Y_2, Y_3,$ and Y_{in} are the admittances for media 2, 3, and the input admittance respectively. This equation can be solved for Y_2 by iteration if we know the thickness $d,$ Y_3 of a known background, and the measured $Y_{in}.$ The material under test is generally very thin (e.g., a vegetation leaf), so the error in measuring d can be large, in addition to the fact that the solution is oscillatory and a very strong function of thickness. It was suggested to use two different background materials to eliminate the errors associated with the thickness measurement. We will denote the two different backgrounds by the superscripts 1 and 2; hence,

$$e^{-j\gamma_2 d} = \frac{(Y_2 + Y_3^{(1)})(Y_2 - Y_{in}^{(1)})}{(Y_2 - Y_3^{(1)})(Y_2 + Y_{in}^{(1)})}, \quad (4.17)$$

also,

$$e^{-j\gamma_2 d} = \frac{(Y_2 + Y_3^{(2)})(Y_2 - Y_{in}^{(2)})}{(Y_2 - Y_3^{(1)})(Y_2 + Y_{in}^{(1)})} \quad (4.18)$$

After straightforward manipulation we obtain the general equation:

$$Y_2^2 = \sqrt{\frac{Y_{in}^{(1)} Y_{in}^{(2)} (Y_3^{(1)} - Y_3^{(2)}) + Y_3^{(1)} Y_3^{(2)} (Y_{in}^{(2)} - Y_{in}^{(1)})}{(Y_{in}^{(2)} - Y_{in}^{(1)}) - (Y_3^{(2)} - Y_3^{(1)})}} \quad (4.19)$$

This equation is valid for any 2 media with known $Y_3^{(1)}$ and $Y_3^{(2)}$ and 2 known measured input admittances $Y_{in}^{(1)}$ and $Y_{in}^{(2)}$. A special and useful case can, however, be deduced by putting $Y_3^{(1)} = \infty$ (i.e., medium 1 is metal). Y_2 , in this case, will be given by

$$Y_2 = \sqrt{Y_{in}^{(1)} Y_{in}^{(2)} + Y_3^{(2)} (Y_{in}^{(2)} - Y_{in}^{(1)})} \quad (4.20)$$

The admittances of the media are those seen by the probe; hence, they depend on the probe equivalent circuit. A special case can simplify the last expression by assuming the simplest equivalent circuit, which is a capacitor. ϵ_2 , in this case, is given by

$$\epsilon_2 = \sqrt{\epsilon_{in}^{(1)} \epsilon_{in}^{(2)} + \epsilon_3^{(2)} (\epsilon_{in}^{(2)} - \epsilon_{in}^{(1)})} \quad (4.21)$$

where ϵ_2 , $\epsilon_3^{(2)}$, $\epsilon_{in}^{(1)}$, and $\epsilon_{in}^{(2)}$ are the relative dielectric constants for the sample under test, the second background medium (the first is metal), the measured input ϵ for background material 1 and material 2, respectively. It was found experimentally that Equation (4.21) is valid only at low frequencies, while Equation (4.20) is valid across the entire frequency range of interest (except when the frequency is high enough to cause moding). The validity of this semi-empirical approach

1.0 GHz

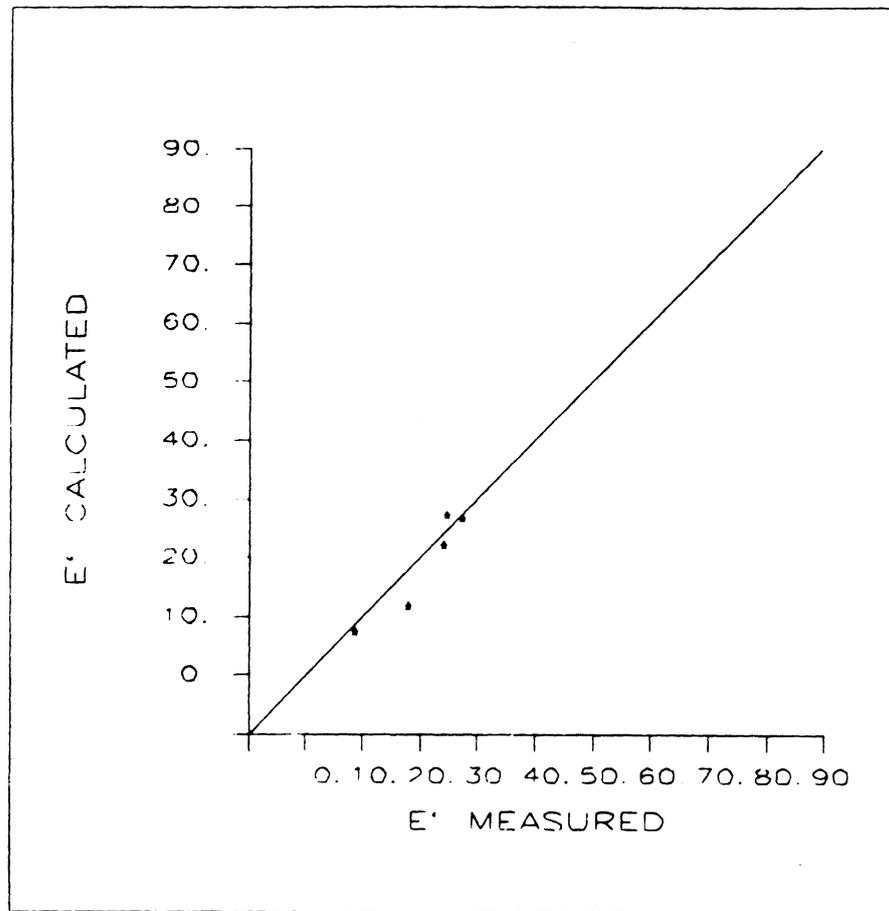


Figure 4.24(a). Evaluation of the thin-thick sample formula (refer to text) for the 0.250" probe at 1 GHz(real part).

1.0 GHz

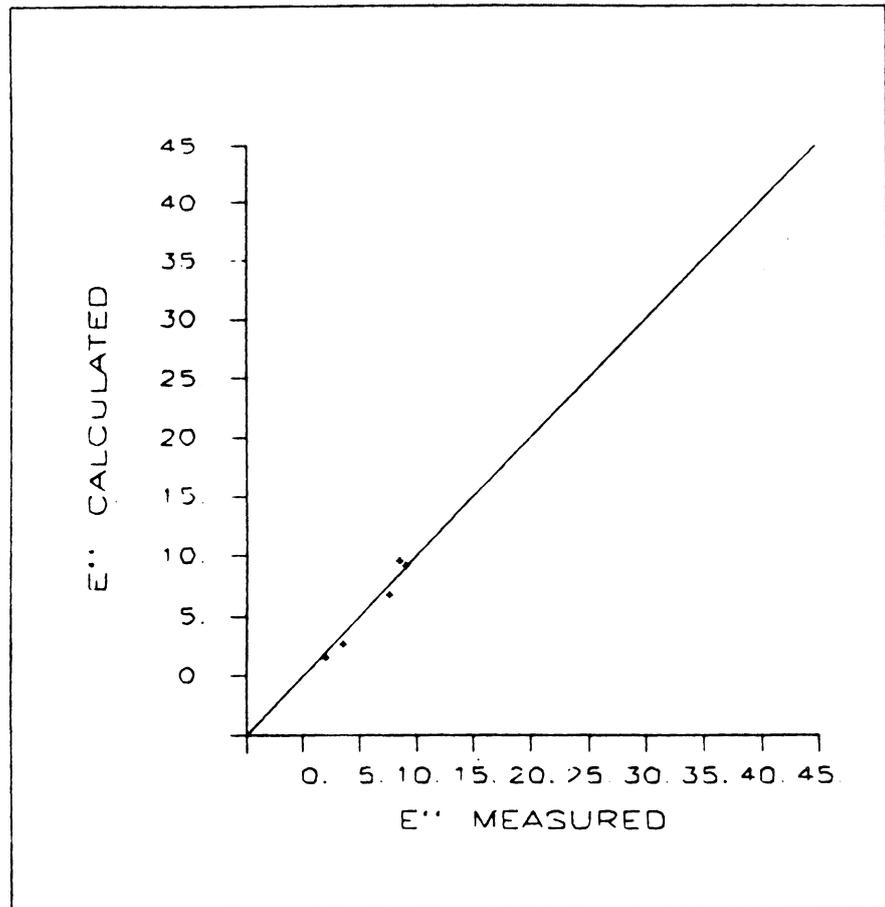


Figure 4.24(b). Evaluation of the thin-thick sample formula (refer to text) for the 0.250" probe at 1 GHz(imaginary part).

8.0 GHz

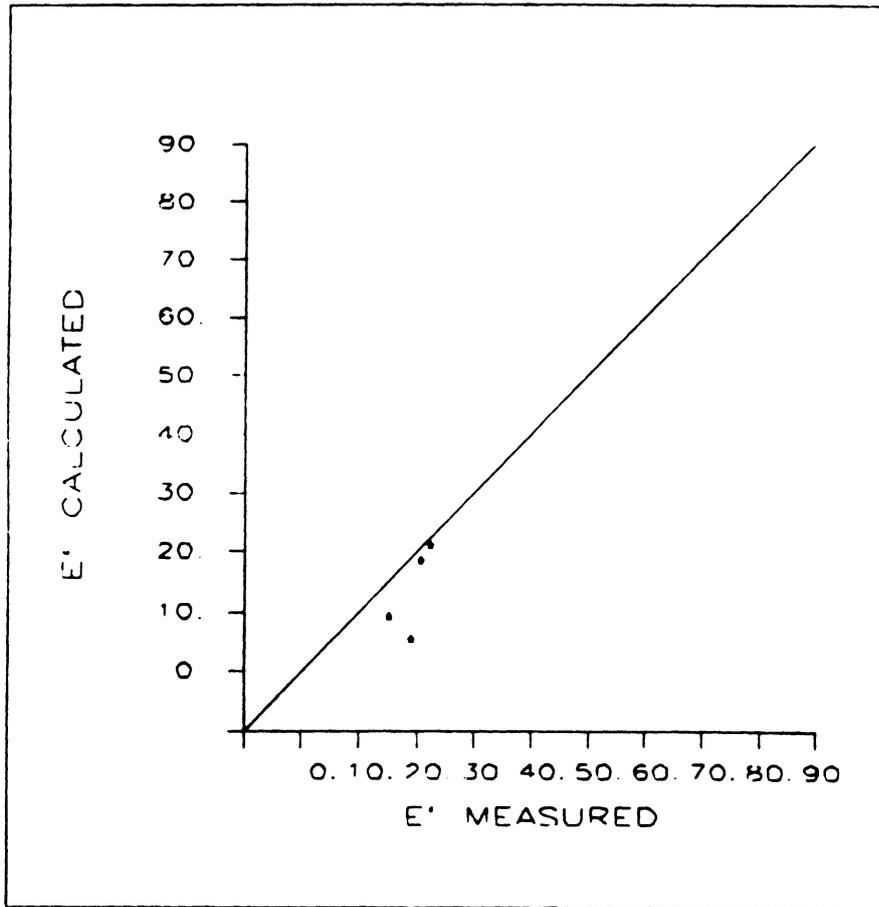


Figure 4.25(a). Evaluation of the thin-thick sample formula (refer to text) for the 0.250" probe at 8 GHz(real part).

8.0 GHz

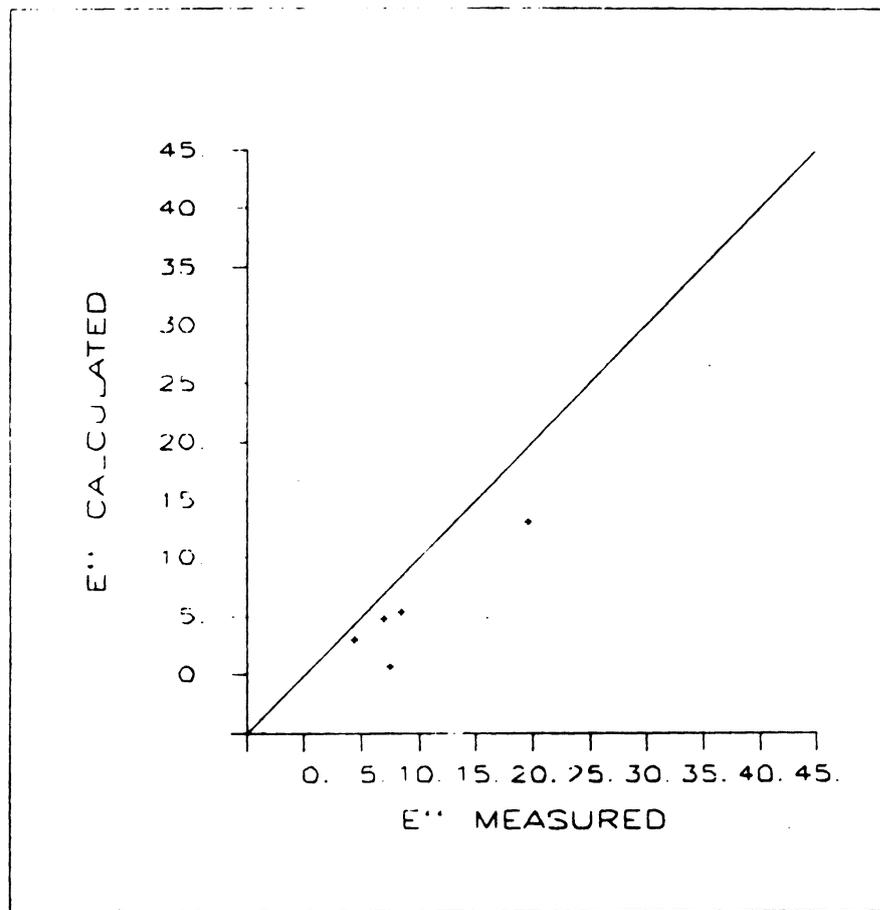


Figure 4.25(b). Evaluation of the thin-thick sample formula (refer to text) for the 0.250" probe at 8 GHz(imaginary part).

1.0 GHz

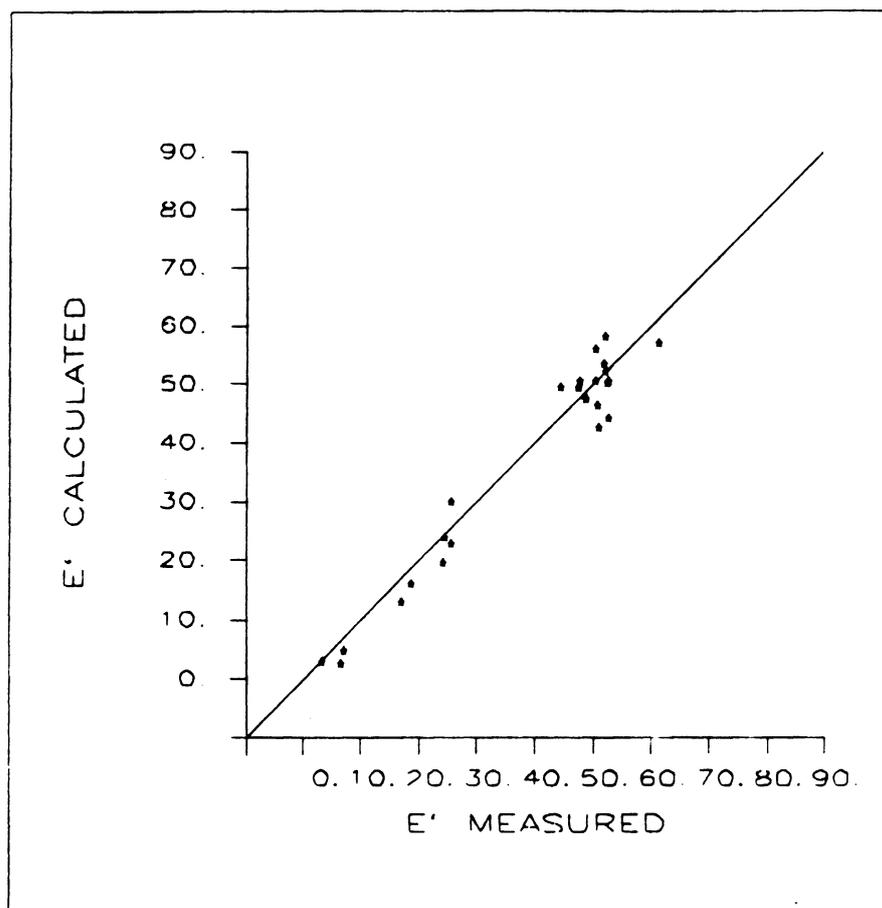


Figure 4.26(a). Evaluation of the thin-thick sample formula (refer to text) for the 0.141" probe at 1 GHz(real part).

1.0 GHz

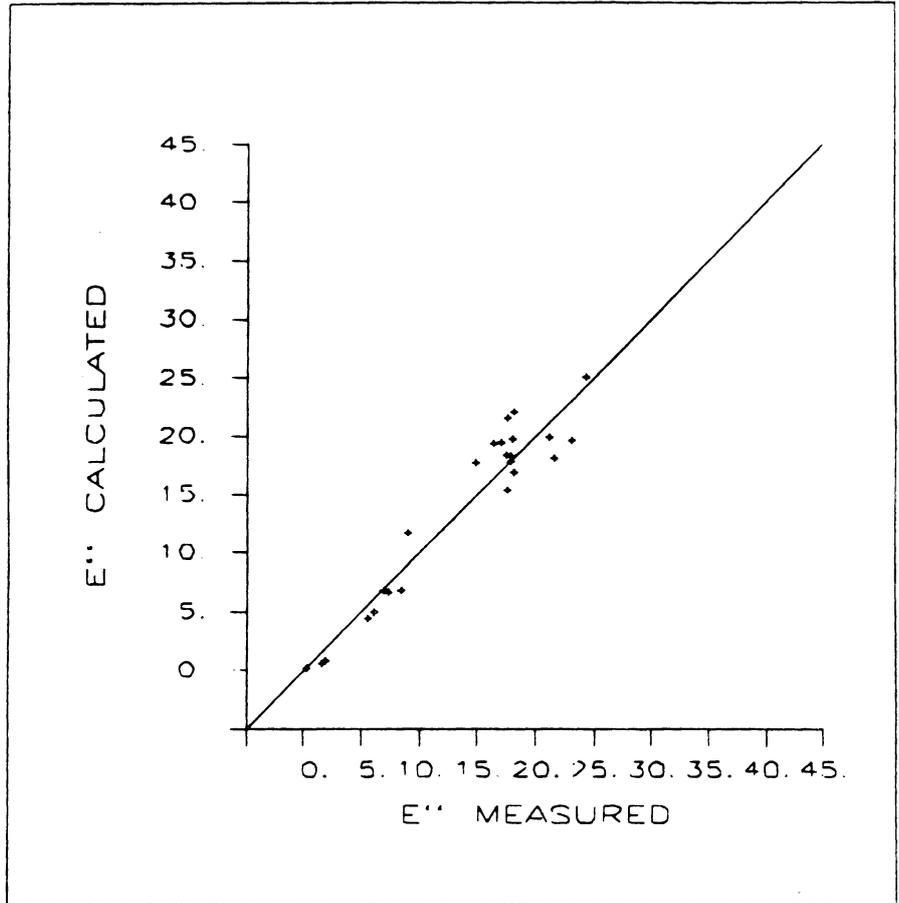


Figure 4.26(b). Evaluation of the thin-thick sample formula (refer to text) for the 0.141" probe at 1 GHz(imaginary part).

8.0 GHz

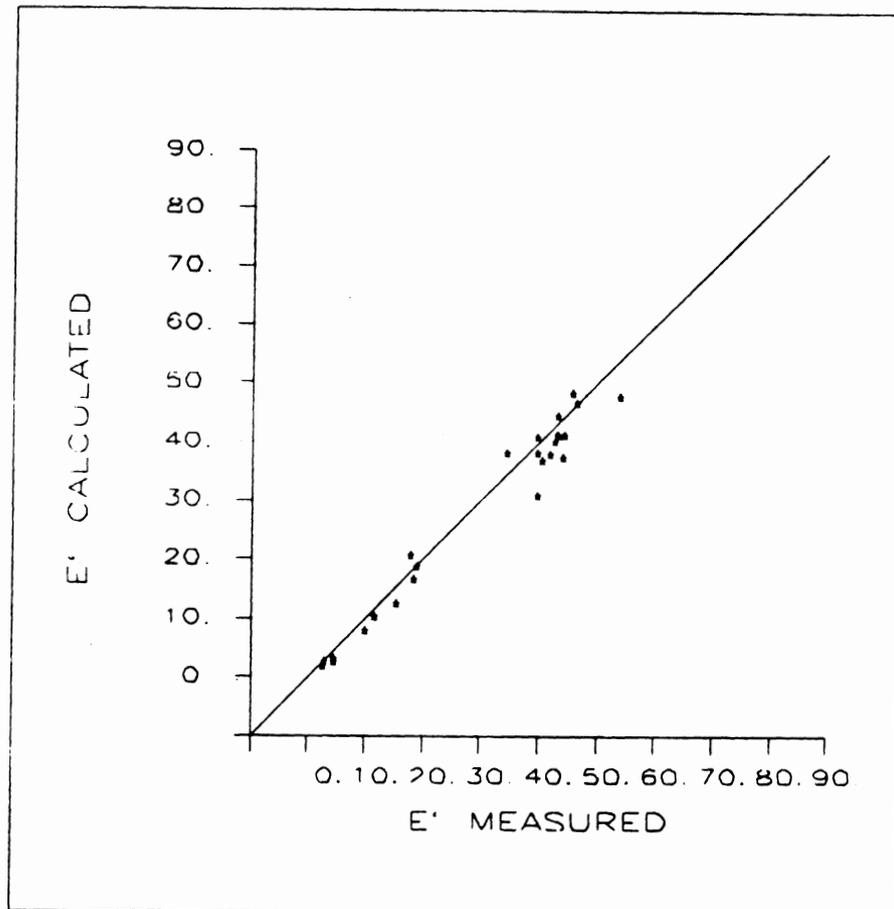


Figure 4.27(a). Evaluation of the thin-thick sample formula (refer to text) for the 0.141" probe at 8 GHz(real part).

8.0 GHz

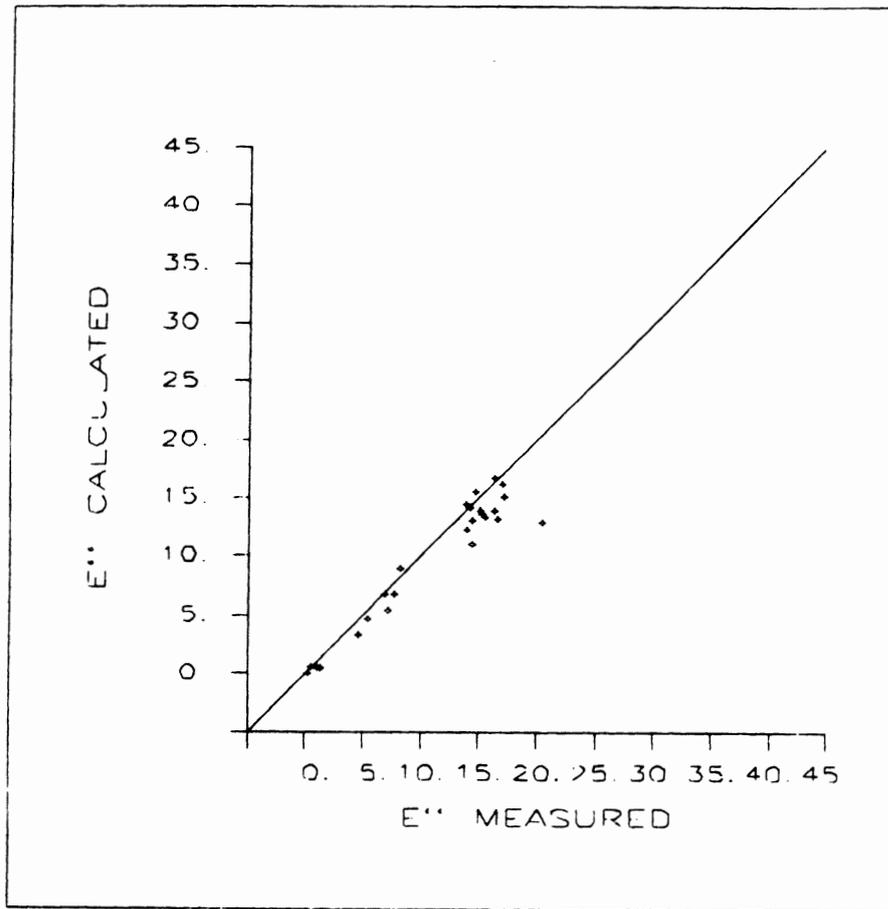


Figure 4.27(b). Evaluation of the thin-thick sample formula (refer to text) for the 0.141" probe at 8 GHz(imaginary part).

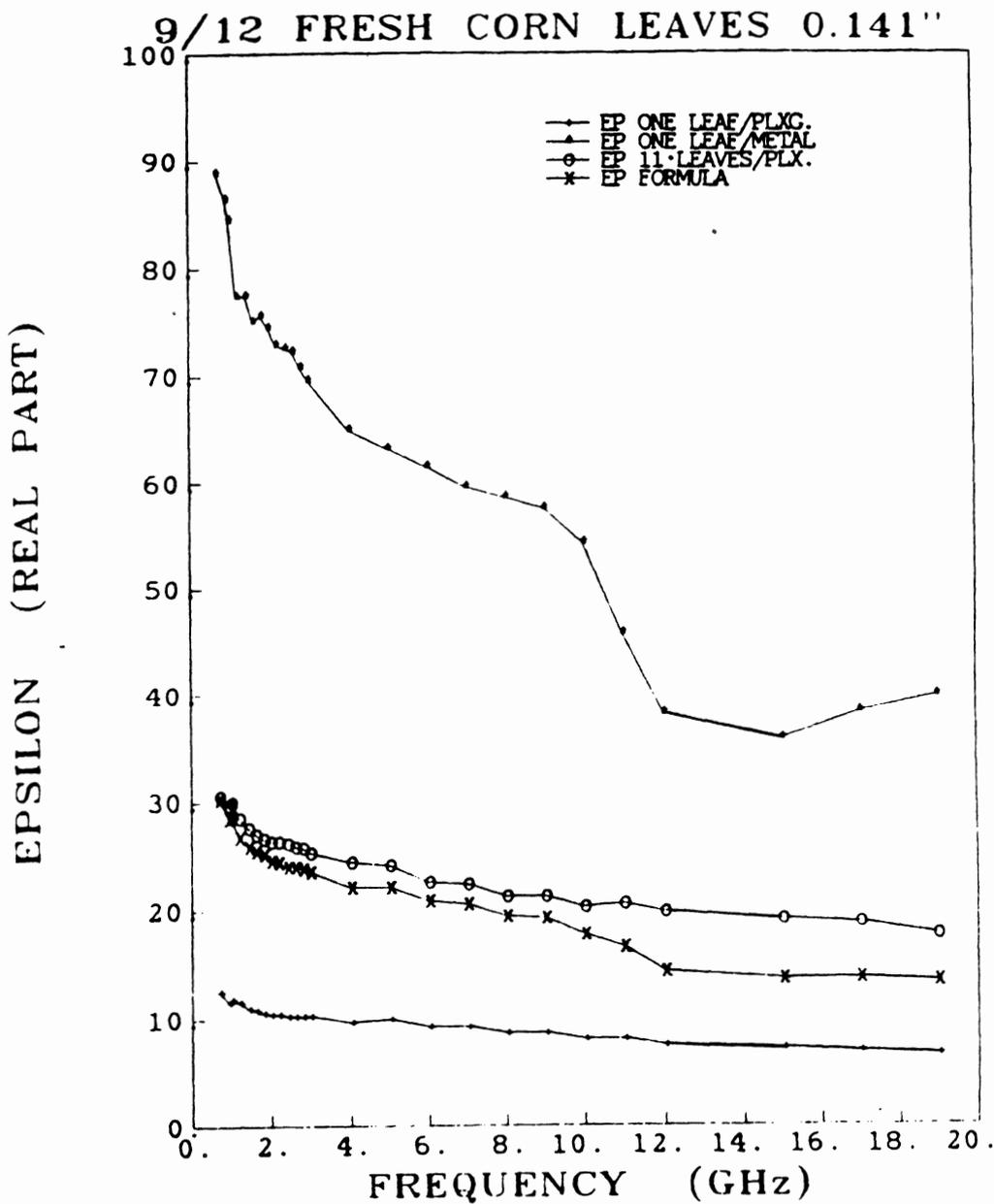


Figure 4.28(a). Spectra of measured one leaf/metal, one leaf/plexiglass, and thick stack/plexiglass along with the calculated values from the thin-thick formula (real parts). Above 11 GHz high-order modes propagation (upper curve) causes large errors.

9/12 FRESH CORN LEAVES 0.141''

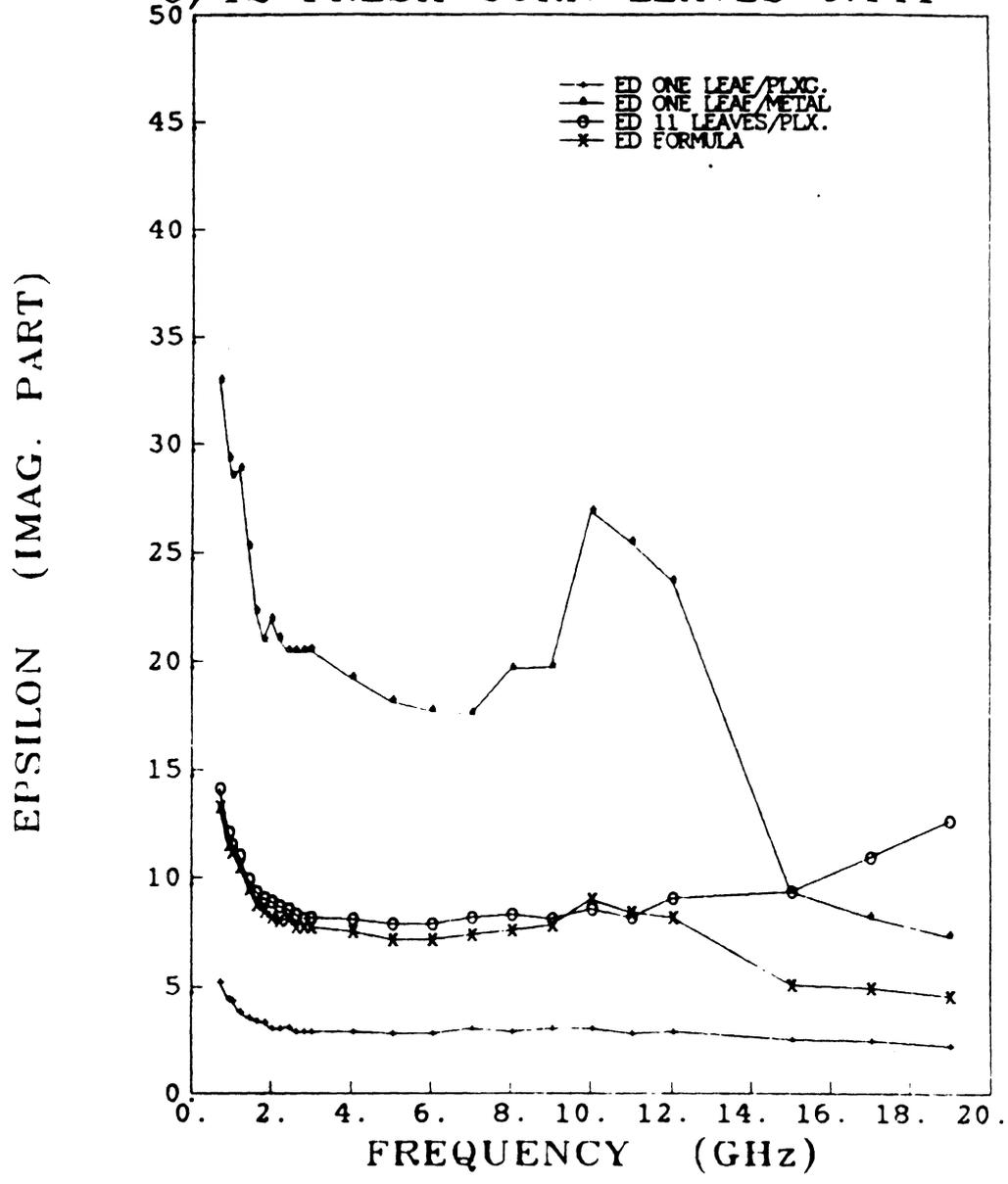


Figure 4.28(b). Spectra of measured one leaf/metal, one leaf/plexiglass, and thick stack/plexiglass along with the calculated values from the thin-thick formula (imaginary parts). Above 11 GHz high-order modes propagation (upper curve) causes large errors.

was tested for a wide frequency range, wide range of dielectric values, and for the .141" probe (Table 4.3). The results were found to be very satisfactory as shown in Table (4.3). Figures (4.24) to (4.27) show how well this approximate model works. Figures 4.28(a) and (b) show spectra of an example of these measurements for thin and thick samples against various backgrounds. The data above 11 GHz was plotted to show how high-order modes can propagate when we use a metal background and a very thin sample. To avoid this problem, however, we can use either a thicker sample or a background material other than metal.

f(GHz)	1	2	4	8
# points	24	25	25	25
ϵ' slope	1.0265	1.0078	1.0026	.9594
ϵ' intercept	-2.03	-1.2728	-1.0795	-.5036
ϵ' variance	15.03	11.51	8.90	7.81
ϵ' ρ	.9776	.9829	.9858	.9849
ϵ'' slope	1.0306	1.0351	.9834	.8726
ϵ'' intercept	-.0707	-.3509	-.2225	.2683
ϵ'' variance	4.38	1.70	1.43	2.34
ϵ'' ρ	.9610	.9684	.9660	.9601

Table (4.3): Evaluation of the thin-thick formula for the .141" probe.

4.4.4 Comparison to the Waveguide Transmission System

As was discussed earlier in Chapter 3, the transmission technique is, in general more accurate than the reflection technique. A comparison between both systems provides a useful confirmation of the validity of the probe-system accuracy. The choice of material was a problem since the sample requirements are different for the two techniques. Yellow cheese was finally selected because it is suitable for both systems. As shown in Fig. (4.29) the agreement is very good and the error is within the expected $\pm 5\%$ bounds. This evaluation test gave us confidence in our measurement techniques to go ahead and start measurements on vegetation samples.

4.5 Probe Usage and Limitations-Other Probe Configurations

The standard probes were found to have the following features and limitations:

1. Wide frequency band (.5 - 20 GHz for the .141" and .05 - 9 GHz for the .250").
2. Accurate to within $\pm 5\%$ for all values of ϵ' and to within $\pm 10\%$ for all values of ϵ'' except for low loss materials (because rounding error is ± 0.1).
3. The system is very suitable for temperature measurements.

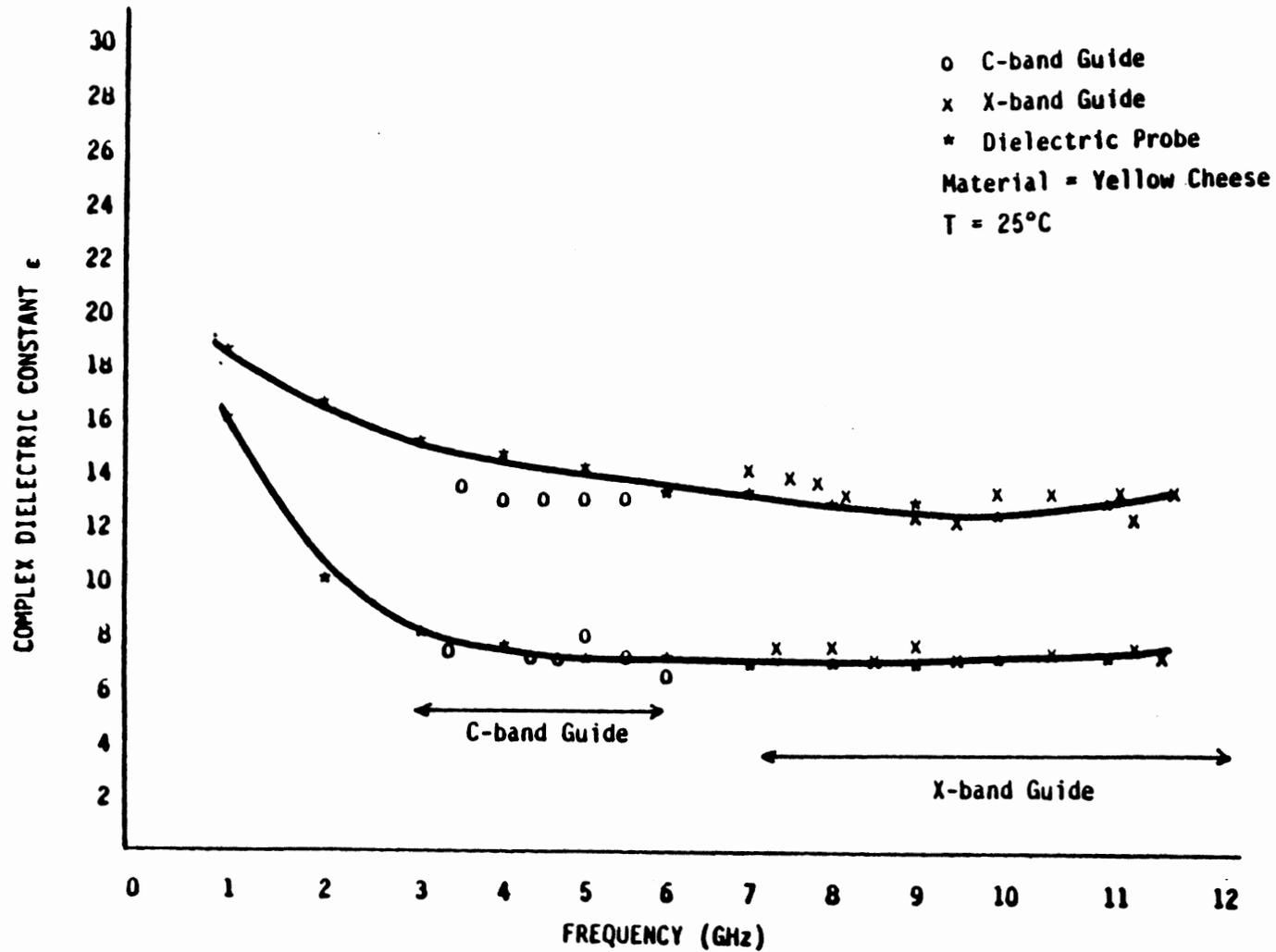


Figure 4.29. Comparison between the probe and the waveguide systems.

4. The system is very suitable for measuring liquid or semi-liquid materials but is difficult to use with solid materials.
5. The probe is suitable for non-destructive and *in-vivo* measurements.

Other Probe Configurations

For standard cables, the ratio $\frac{r_1}{r_2} \approx .3$ and is kept constant in order to maintain Z_0 constant (refer to Fig. 4.2). In order to build an "optimum" probe, it may be necessary to change this ratio to increase the probe sensitivity over a particular frequency band and a given range of ϵ . The cut-off frequency of the first higher-order mode is proportional to $(r_2 - r_1)$ while the sensitivity is proportional to the probe tip area, i.e. to $\pi(r_1^2 - r_2^2)$. Thus we have two major objectives with opposing requirements:

1. To avoid moding $(r_2 - r_1)$ should be small.
2. To increase the sensitivity, $\pi(r_1^2 - r_2^2)$ should be large which means $(r_2 - r_1)$ should be large too.

Preferrably, the ratio $(\frac{r_1}{r_2})$ should be kept constant in order to keep the cable characteristic impedance matched to the probe tip.

Chapter 5

Measurement Results

This chapter presents the experimental results obtained using the open-ended coaxial probe system. Gravimetric moisture content M_g was used in this chapter, instead of the volumetric moisture content M_v , because it is a directly measurable quantity, while M_v is dependent on vegetation density. Vegetation density is very hard to measure, especially for leaves, and the density data measured in this study represents an approximate estimate at best. For the most part, the dielectric data presented in this report will be the actual measurements derived from the probe measurements. In some cases, however, the measured variation of ϵ as a function of moisture will be presented in the form of plots based on regression equations generated using actual data. This is done for the purpose of making presentations clearer in cases where multiple plots are included in a given figure. It should be noted that these regressions provide excellent fits to the data and probably describe the moisture dependence of ϵ better than the actual data. The data presented in this chapter is a subset of that presented in Appendix A. The primary purpose of this chapter is to acquaint the reader with

the observed dielectric behavior. Interpretation and modeling of the data are the subjects of Chapter 6.

5.1 Plant Type, Part, and Location

1. *Plant type*

Plant types (species) vary depending on the following parameters: (a) density, (b) salinity, (c) bound water content, and (d) how the vegetation material shrinks when it dries out. Salinity and bound water effects are more dominant at low frequency, while density effects are more obvious at low moisture levels. Figure 5.1 shows a comparison between corn (*Zea Mays*) leaves and soybean leaves at 1 GHz. Corn leaves have, in general, higher values of ϵ' and ϵ'' than soybean leaves. The difference can be attributed either to measurement errors in the dielectric constant and moisture content or to physical and physiological differences. Figure 5.2 shows another comparison between corn stalks and black spruce tree trunk to test the effects of plant type on high density plant parts. The tree samples were measured at moistures less than 40% (gravimetric). Corn stalks have a lower ϵ for dry samples, which can be attributed to density effects.

2. *Plant part*

In order to illustrate the differences between plant parts, we will test two different parts from the same species. Corn leaves and corn stalks are compared at 1 GHz in Fig. 5.3. These two plant parts show comparable

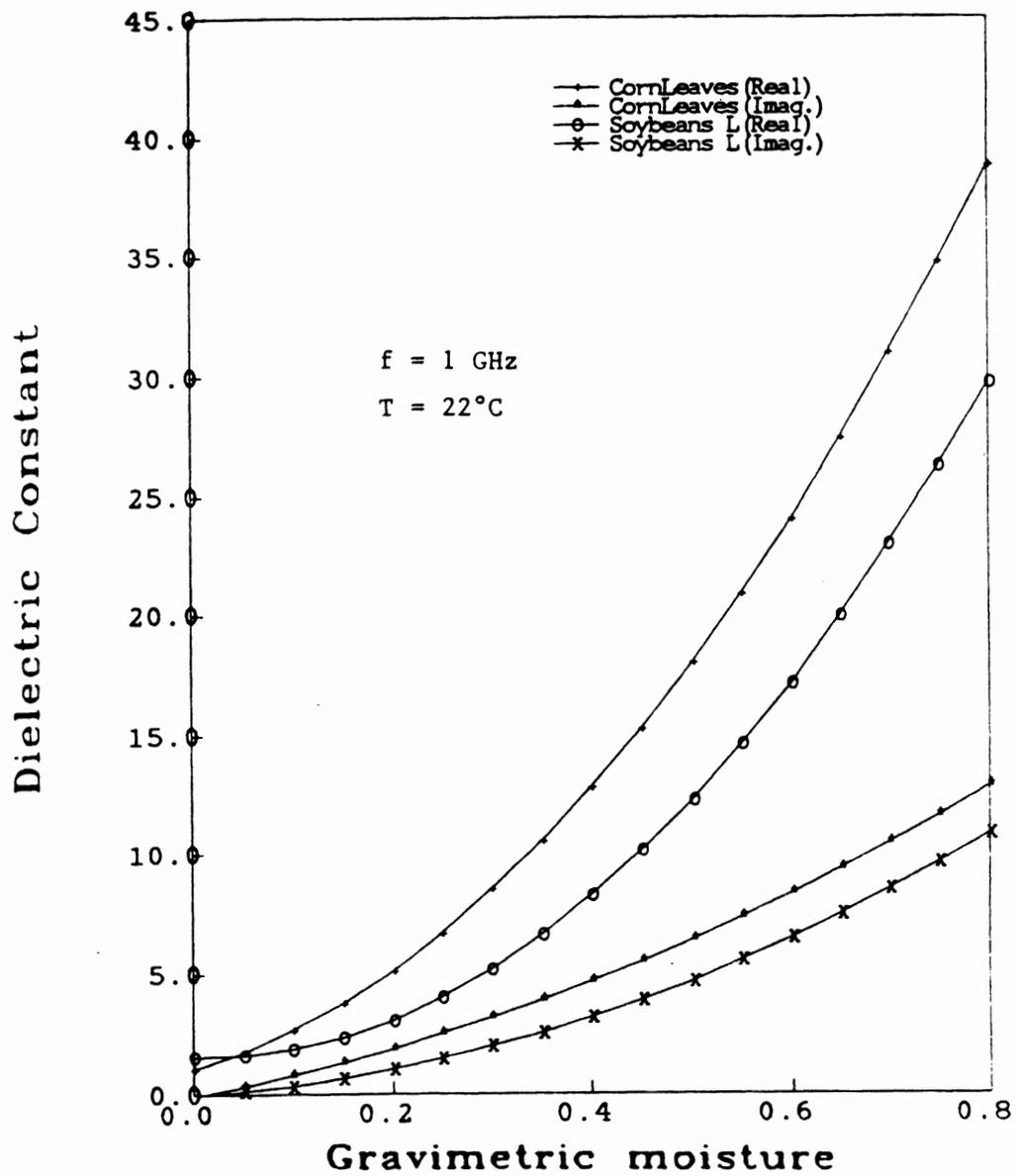


Figure 5.1. Comparison between corn leaves and soybeans leaves. Curves were fitted to measured data using a second order polynomial fit.

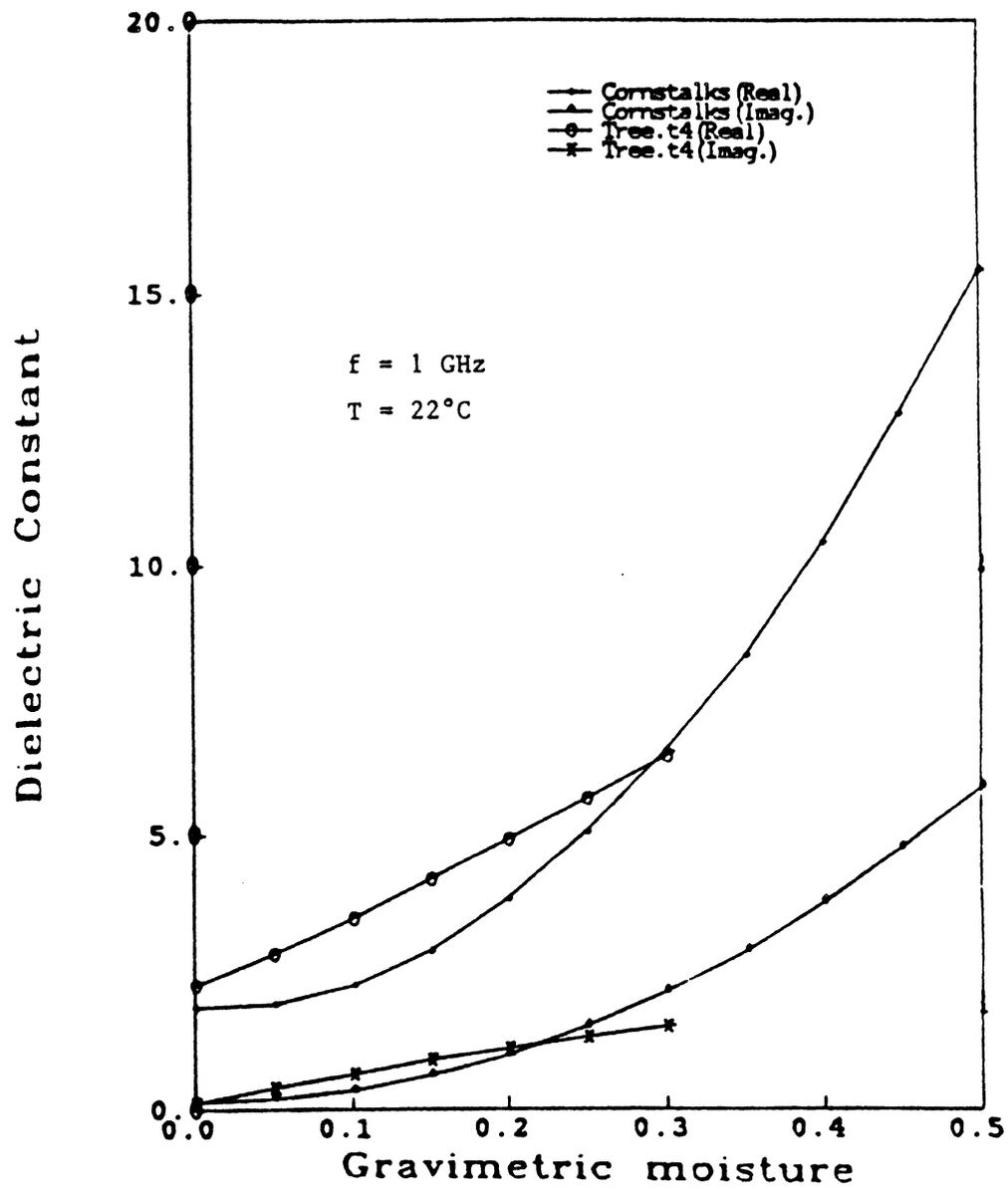


Figure 5.2. Comparison between corn stalks(measured on the inside part) and tree trunk (Black-Spruce). Curves were fitted to measured data using a second order polynomial fit.

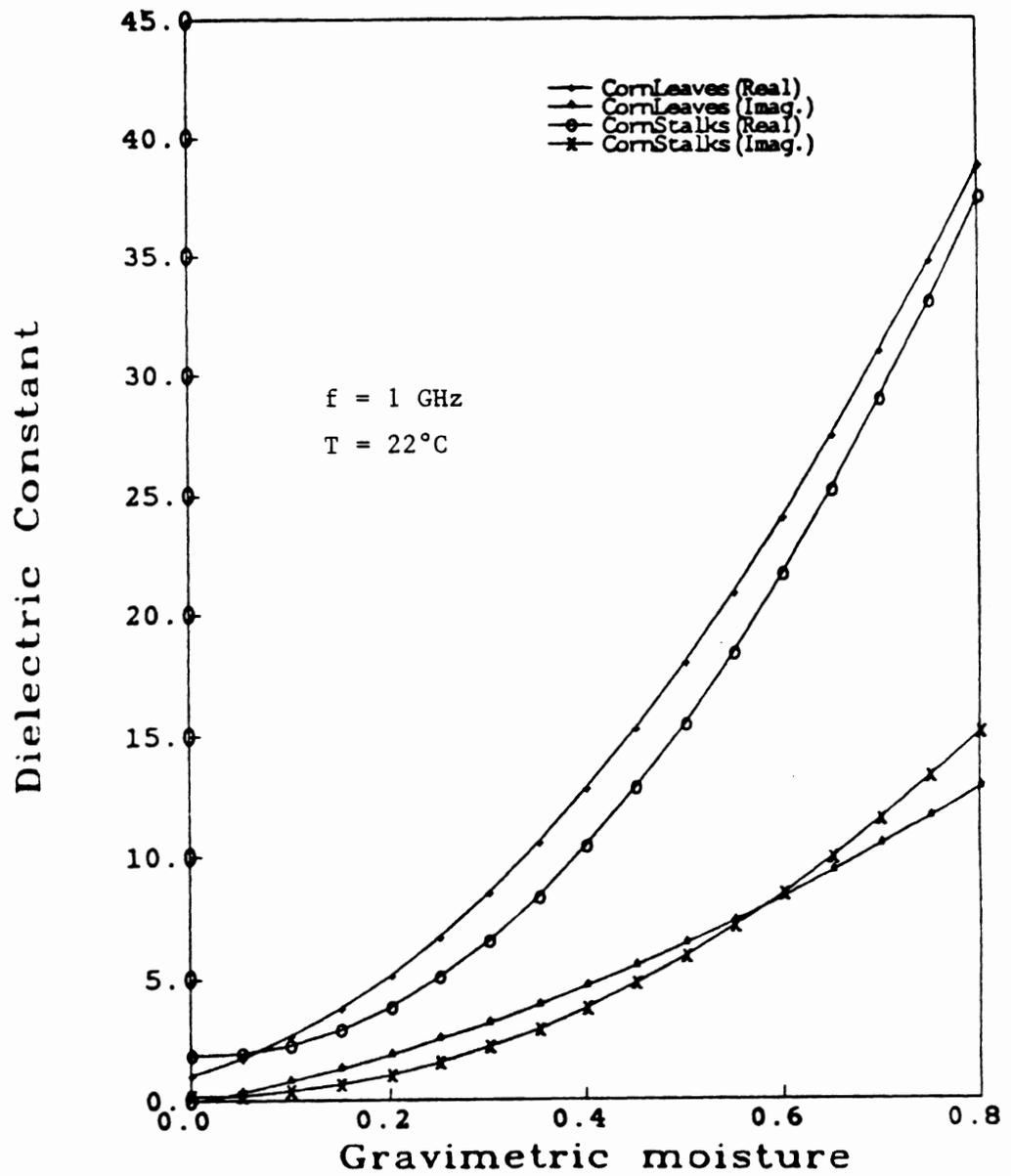


Figure 5.3. Comparison between corn leaves and corn stalks. Curves were fitted to measured data using a second order polynomial fit.

trends and magnitudes for both ϵ' and ϵ'' in spite of the fact that their densities are different.

3. *Part location*

It was observed that plants have a moisture distribution profile, especially tall plants like corn. Figure 5.4 shows the dependence of ϵ' , ϵ'' , and M_v on height (above the ground) for a corn stalk of a fresh plant. The measured dielectric constant varies quite significantly as a function of height while the measured volumetric moisture exhibits a weaker dependence. This behavior may be explained by the fact that when the probe is used to measure the dielectric of a corn stalk from the outside sheath, it actually measures ϵ of the sheath (leaf) material surrounding the stalk, and not the stalk itself (because the fringing field of the probe has an effective penetration depth of only few millimeters). The moisture determination, however, is performed for the stalk including the sheath and the inside. Hence, Fig. 5.4 should not be considered quantitatively and the general trend only matters here.

5.2 Frequency Dependence

Figures 5.5 and 5.6 show the frequency behavior of the dielectric constant of corn leaves at different volumetric moisture levels. The trends in these two figures can be compared to those of saline liquid water (refer to Fig. 2.1) and to those of bound water (refer to Fig. 5.18). The low frequency behavior of ϵ'' is similar to those exhibited by both saline and bound water. At high

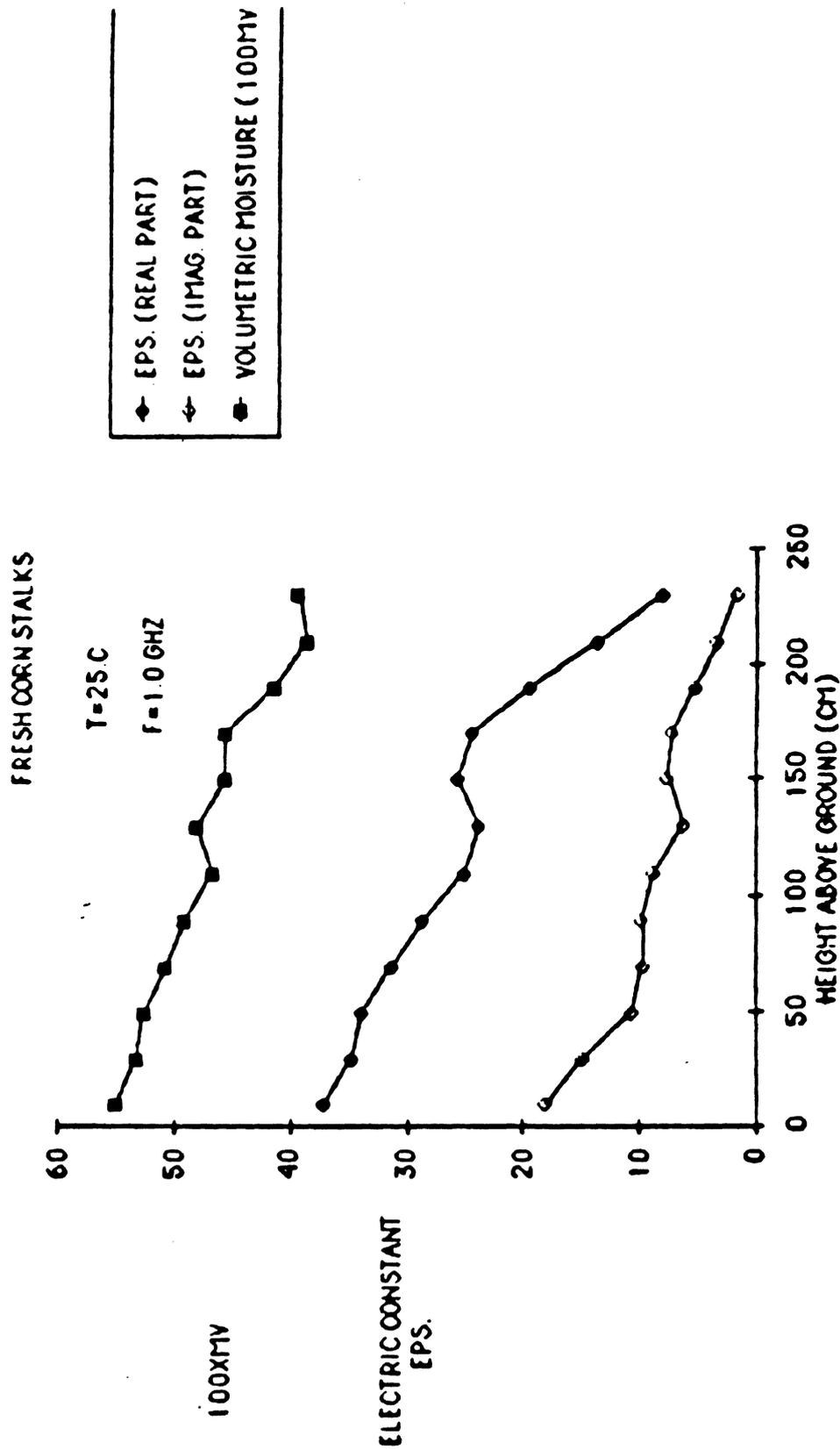


Figure 5.4. Measured dielectric constant and calculated volumetric moisture for fresh corn stalks as a function of height above the ground (cm).

NEW CORN LEAVES VS. FREQUENCY

10/15/1985

0.141" NGP
P=400.0 GMS

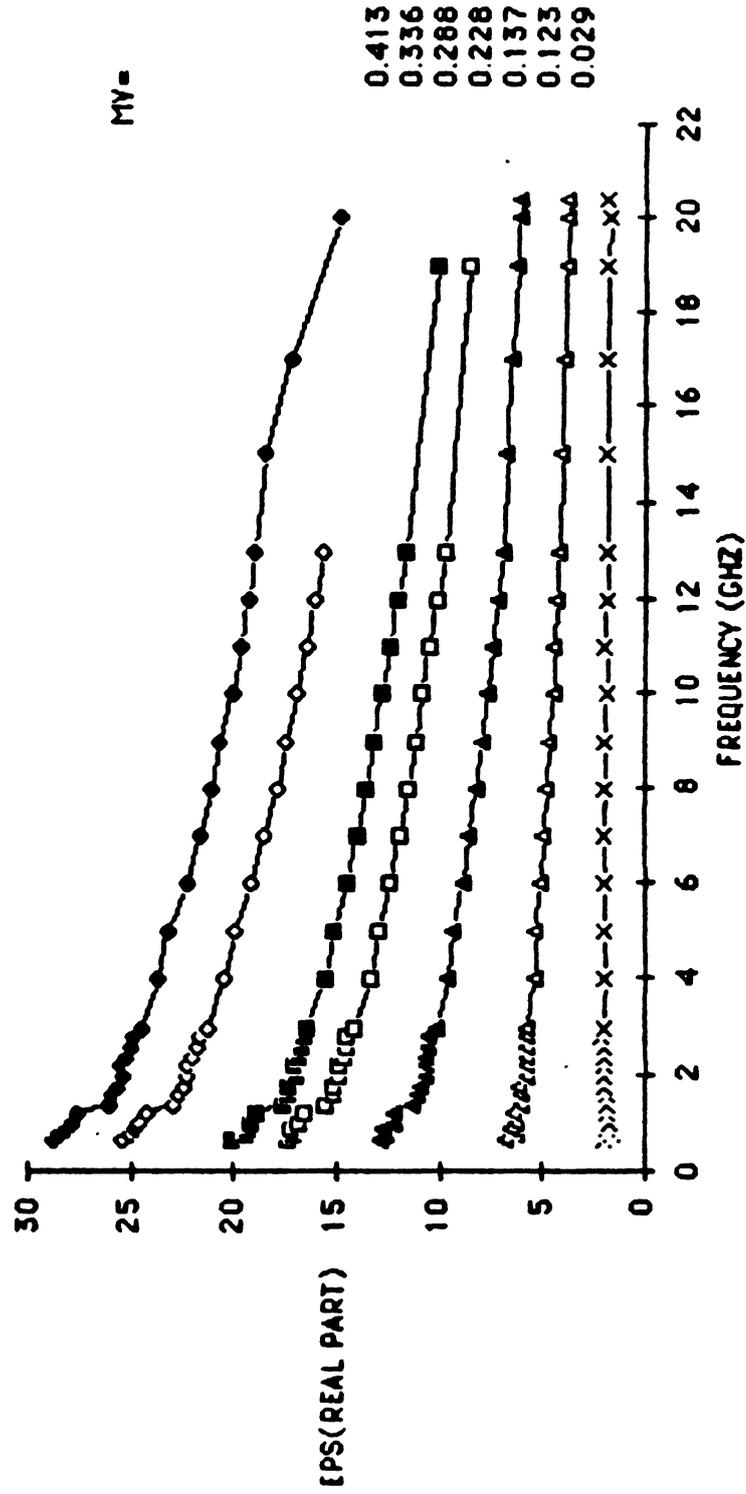


Figure 5.5. Measured spectra of the dielectric constant of corn leaves with volumetric moisture M_v as parameter (real parts).

0.141° NOP
P=400.0 GMS

NEW CORN LEAVES VS FREQUENCY

10/15/1985

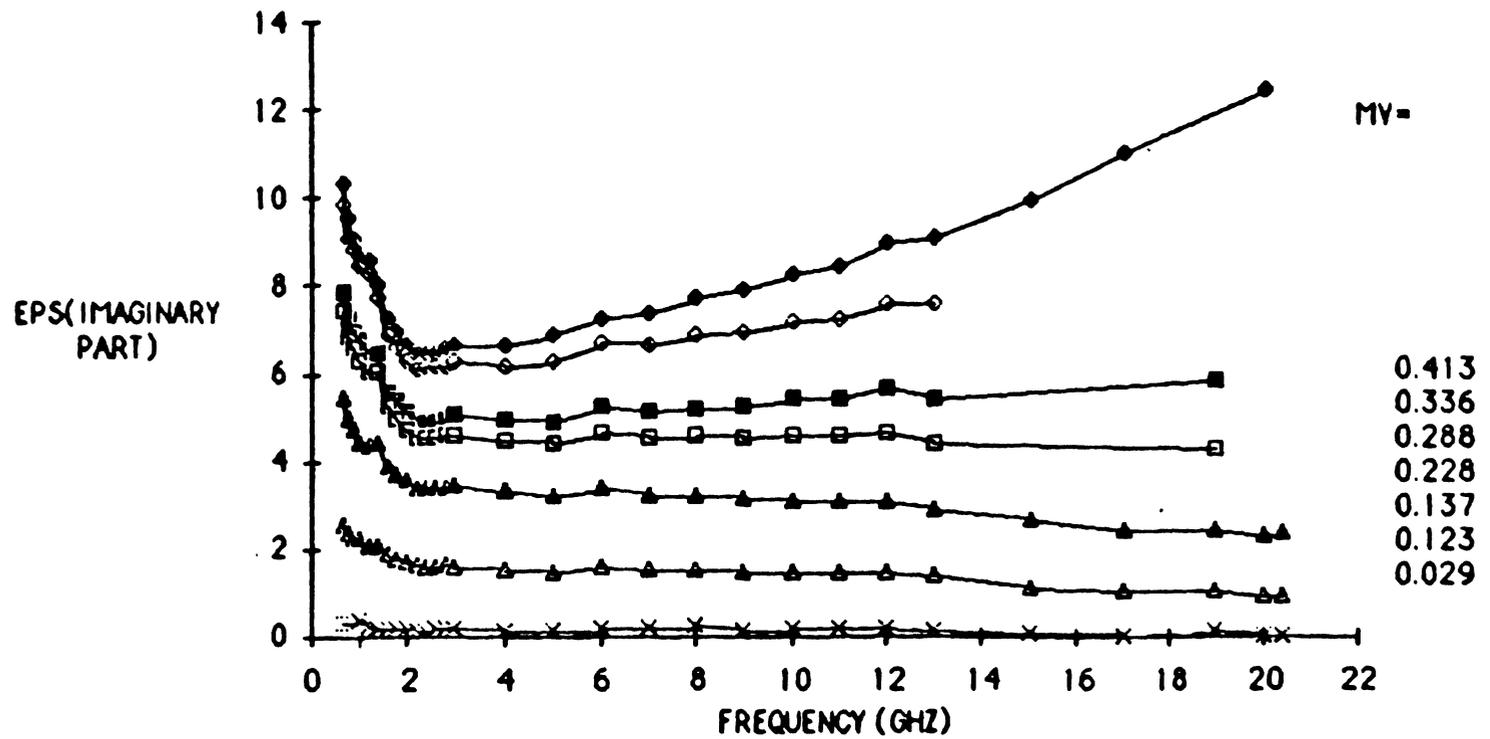


Figure 5.6. Measured spectra of the dielectric constant of corn leaves with volumetric moisture M_v as parameter (imaginary parts).

frequencies , however, ϵ'' increases with f because of the free water component. For the medium to low moisture samples ($M_v \leq .2$), ϵ'' does not increase with increasing f , but stays rather constant or decreases slowly with f . This behavior is attributed to bound-water domination at low moisture levels (because the bound relaxation frequency is below .2 GHz and its Cole-Cole shape factor is .5, ϵ'' exhibits a very slowly varying dependence on f for $f > 2$ GHz, as illustrated in Fig. 5.18). The dielectric loss factor ϵ'' has a minimum around 2 GHz and this minimum becomes less sharp with decreasing moisture content. This minimum separates the low frequency region (where losses are dominated by conductivity and bound water) from the high frequency region (where losses are dominated by free water relaxation with $f_0 = 18$ GHz at room temperature). At $f \leq 3$ GHz, the permittivity ϵ' decreases with increasing frequency at a rate comparable to that observed for bound water. This is discerned from a comparison of Fig. 5.5 with Fig. 5.18. Similar frequency behavior were observed for other vegetation types and parts (refer to Appendix A). Figure 5.7 shows plots for Crassulaceae Echeveria (which has succulent leaves) on an expanded scale covering the .2-2 GHz range. This material has a relatively low salinity (the measured salinity of the extracted liquid was 4 parts per thousands). The real part is almost constant indicating that there is no relaxation process in this frequency range, which means that the bound water content is negligible and the dielectric loss is dominated by ionic conductivity.

11/12/85G

SK #18

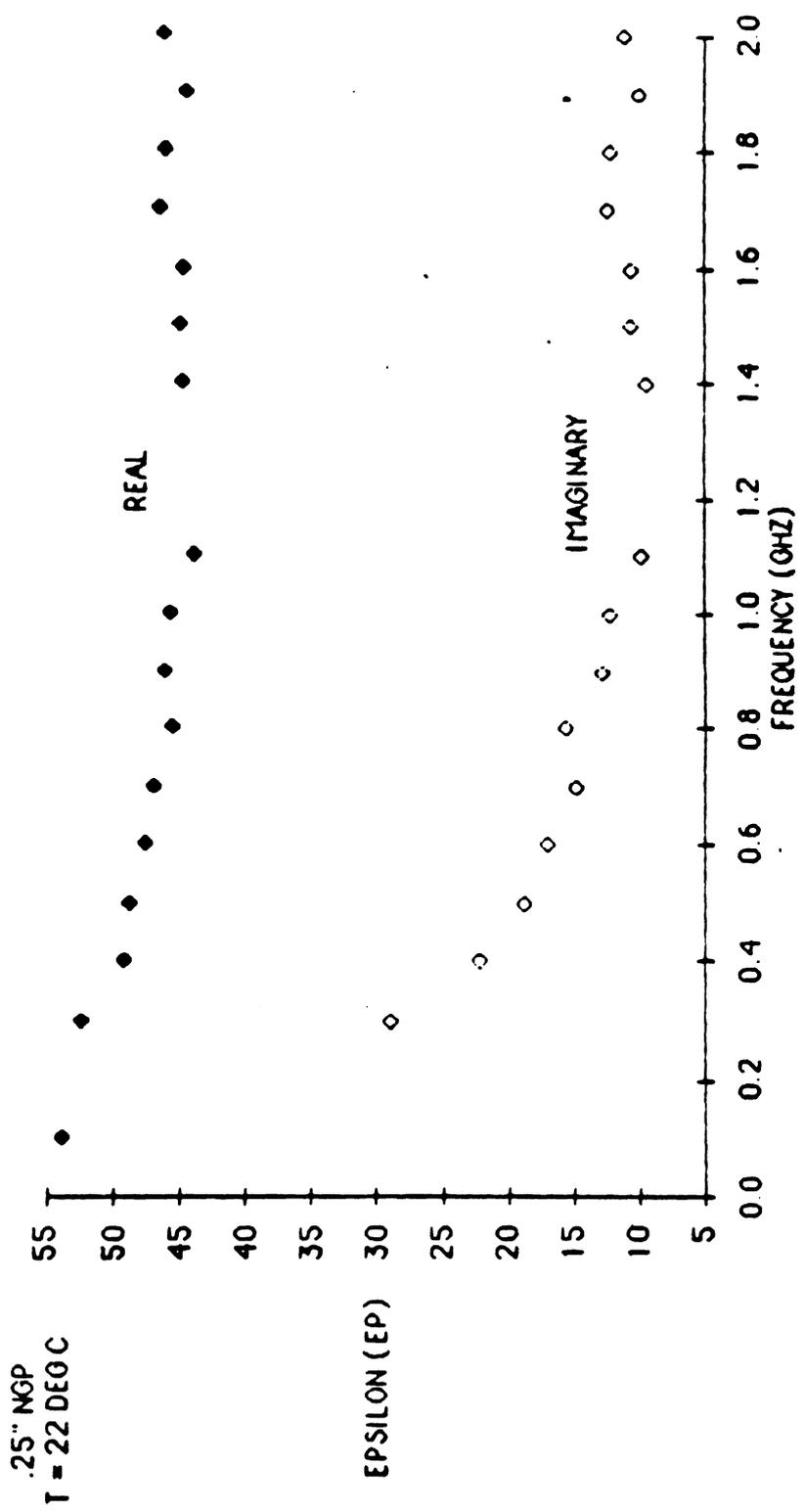


Figure 5.7. Measured spectra of the dielectric constant (real and imaginary parts) at the low frequency band (.1-2 GHz) for Crassulaceae Echeveria leaves.

5.3 Water Content Dependence

Since the main constituent of a plant is liquid water, its dielectric properties are driven by the dielectric properties of liquid water. Liquid water exists in plant tissues in two forms: free and bound. In addition, the free water component usually has a certain amount of dissolved salts, which leads to an ionic conductivity term. It was generally found that ϵ' and ϵ'' are both monotonically increasing functions of water content. Figure 5.8(a) shows the dielectric constant for corn leaves versus M_g at 1, 4, and 17 GHz. As expected, ϵ' increases steadily with increasing M_g and decreases steadily with increasing f . On the other hand, ϵ'' increases steadily with M_g and has a peculiar frequency response: at low moisture levels, $\epsilon''(1 \text{ GHz}) \geq \epsilon''(4 \text{ GHz}) \geq \epsilon''(17 \text{ GHz})$, while at high moisture levels, $\epsilon''(17 \text{ GHz}) \geq \epsilon''(1 \text{ GHz}) \geq \epsilon''(4 \text{ GHz})$. The reason we choose to report dielectric data as a function of gravimetric moisture rather than volumetric moisture is, as discussed earlier, because M_v is not a measurable quantity and it depends on the assumption we make about the dry vegetation density and the manner by which plants lose water (i.e., whether or not they shrink). In some cases, ϵ' was observed to decrease with increasing moisture content at very high moisture contents. An example of this behavior is shown in Fig. 5.8(b). No explanation is available at present for this unexpected behavior.

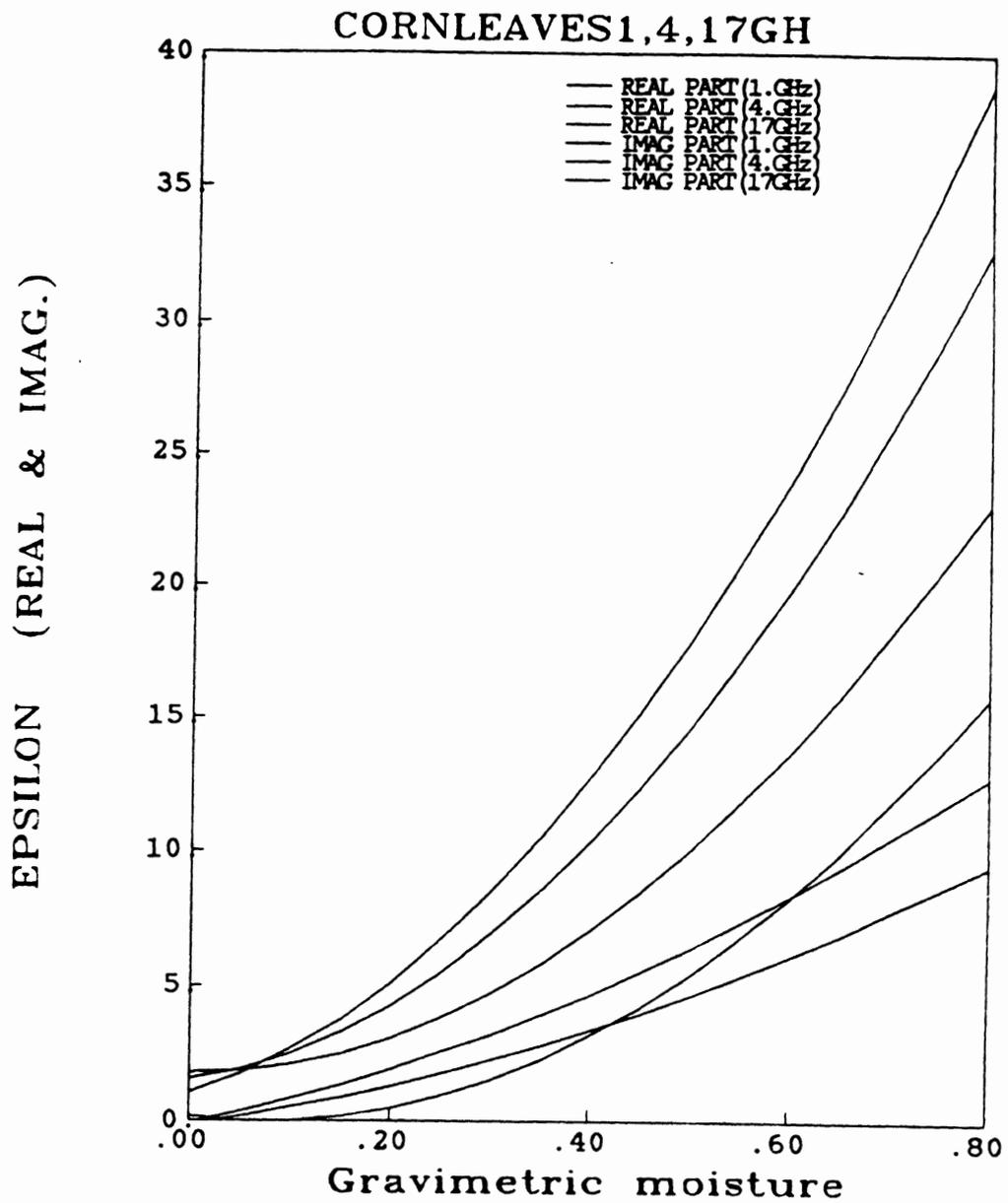


Figure 5.8(a). Measured dielectric constant of corn leaves at 1, 4, and 17 GHz, respectively, with frequency as parameter.

SOYBEANS #8
REALS
1/17/66G

.141" NGP
T=22 DEG

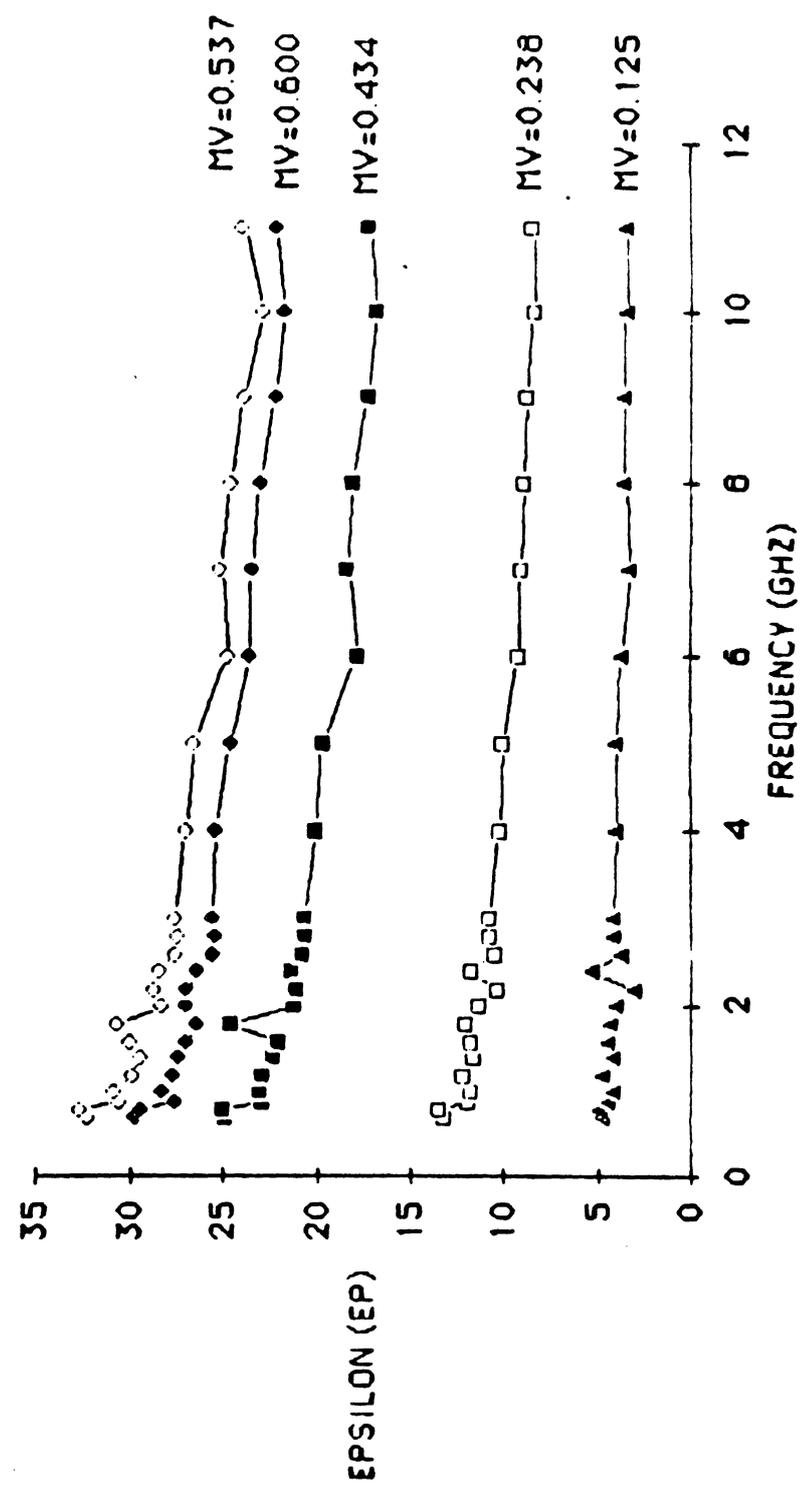


Figure 5.8(b). Measured spectra of the dielectric constant of soybeans leaves with volumetric moisture M_v as parameter (real parts).

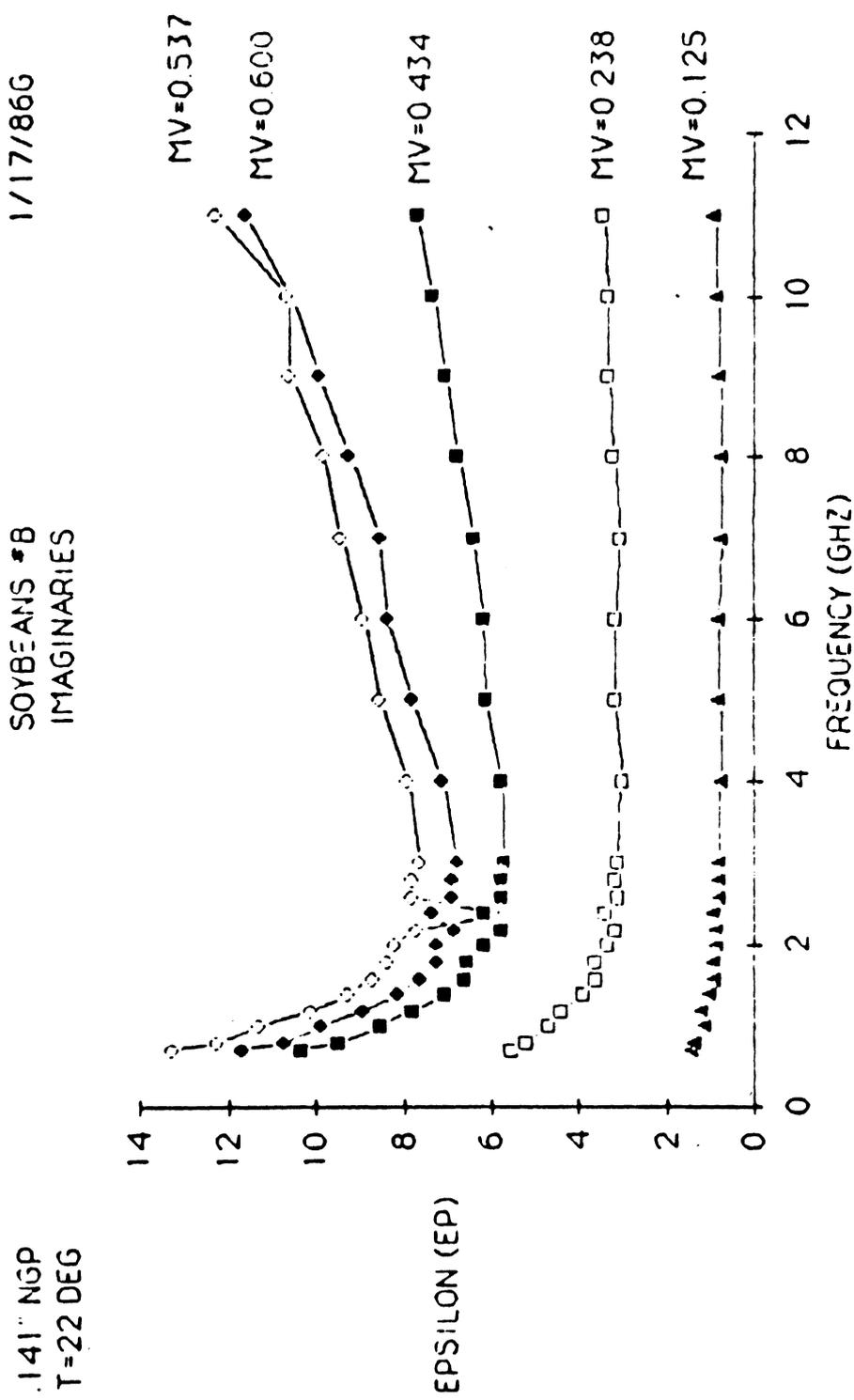


Figure 5.8(c). Measured spectra of the dielectric constant of soybeans leaves with volumetric moisture M_v as parameter (imaginary parts).

5.4 Salinity Effects

The equivalent *NaCl* salinity, in parts per thousand, is defined as the number of grams of *NaCl* dissolved in one kilogram of distilled water. The imaginary part of the dielectric constant, ϵ'' , can be expressed as:

$$\epsilon'' = \epsilon_c'' + \epsilon_b'' + \epsilon_f'' \quad (5.1)$$

where the subscripts c, b, and f denote the conductivity, bound, and free water terms, respectively. Below 1 GHz, ϵ_c'' and ϵ_b'' are, in general, much larger than ϵ_f'' , while above 4 GHz, ϵ_f'' is the dominant factor. We can summarize the loss mechanisms as follows:

1. conductivity term

$$\epsilon_c'' = \frac{\sigma_{eff}}{\omega \epsilon_0} = \frac{\sigma_e}{f} \quad (5.2)$$

where σ_{eff} is the effective conductivity in *Siemens/m* and σ_e ($\sigma_e = \sigma_{eff}/2\pi\epsilon_0$) is in *sec⁻¹*.

2. bound water term (refer to Sec. 5.5)

$$\epsilon_b'' = \frac{(\epsilon_{sb} - \epsilon_{\infty b}) \sqrt{\frac{f}{2f_{0b}}}}{(1 + \sqrt{\frac{f}{2f_{0b}}})^2 + (\frac{f}{2f_{0b}})} \quad (5.3)$$

where ϵ_{sb} and $\epsilon_{\infty b}$ are the static and optical limits for the bound water dielectric constant and f_{0b} is the resonance frequency (the spread relaxation parameter α was assumed to be .5).

3. *free water term*

$$\epsilon_f'' = \frac{(\epsilon_{sf} - \epsilon_{\infty f})\left(\frac{f}{f_{0f}}\right)}{1 + \left(\frac{f}{f_{0f}}\right)^2} \quad (5.4)$$

where ϵ_{sf} , $\epsilon_{\infty f}$, and f_{0f} are, as defined earlier, the relaxation parameters for free water.

At frequencies in the 1 GHz range, these terms can be approximated as:

1. $\epsilon_c'' \simeq \frac{C}{f}$,
2. $\epsilon_b'' \simeq \frac{B}{\sqrt{f}}$ ($f \gg f_{0b}$), and
3. $\epsilon_f'' \simeq F\sqrt{f}$ ($f \ll f_{0f}$),

where C , B , and F are constants. This approximate approach helps in studying and understanding the low frequency behavior of ϵ'' qualitatively. Unfortunately, both ϵ_c'' and ϵ_b'' terms decrease steadily with increasing frequency, although ϵ_b'' decreases more slowly than does ϵ_c'' , which makes it difficult to separate the contribution of these two terms. In order to resolve this problem, we extracted fluids from different plant parts at different moistures and measured their dielectric constant. Table 5.1 shows the measured salinity of included liquids for corn leaves and stalks that had been growing at different heights locations on the corn plant.

moisture	fresh plant			one day		two days	
location	part	$P(\text{tons})$	$S(\text{ppt})$	$P(\text{tons})$	$S(\text{ppt})$	$P(\text{tons})$	$S(\text{ppt})$
upper	leaves	20	6	20	11	25	20
upper	stalks	10	4	20	8	12	6
middle	leaves	15	6	20	14	25	29
	stalks	5	5.5	7	7	5	7
		10	5	17	7.5	12	8
lower	leaves	10	6	20	23	25	29
lower	stalks	3	5.5	5	7	5	6
		6	5.5	10	7	10	6
		8	6.5				

Table 5.1: Measured salinity of liquids extracted from corn plants at different pressures (in tons per unit area) and at different plant heights.

The data in Table 5.1 was obtained for three different corn plants from the same canopy. The first was measured while still fresh, the second and the third were measured one and two days later, respectively. Each plant was divided into three parts: upper, middle, and lower sections. Then, liquids from leaves and stalks, in each section, were extracted and measured separately and the

extraction pressure was recorded in tons per unit area. A modified hydraulic press was used to squeeze the juices out of the plant parts. The gravimetric moisture of different sections were measured and the estimated averages of $S(ppt)$ and M_g are given in Table 5.2:

leaves		stalks	
M_g	$S(ppt)$ by measuring ϵ	M_g	$S(ppt)$ by measuring ϵ
.351	29	.669	6
.396	29	.674	4
.521	23	.691	8
.525	20	.733	5
.605	11	.739	7.5
.624	14	.742	7
.646	6	.757	6
.657	6	.779	6
.675	6	.789	7

Table 5.2 Salinity and gravimetric moisture for corn leaves and stalks.

The following observations are offered:

1. It is very difficult to extract liquids from relatively dry leaves ($M_g \leq .3$).
2. Salinity increases with decreasing moisture content, which indicates an increase in concentration of ions with moisture loss.
3. The smallest reported M_g was .35 for corn leaves, while that for corn stalks was .67.

Figure 5.9 shows the measured salinity (in parts per thousands) of corn leaves as a function of volumetric moisture (assuming $\rho_{DV}=.33$); the maximum measured salinity is around 30 ppt, while the lowest is about 5 ppt. A best fit line for this set of data is shown also; a linear equation relating S to M_g is given by:

$$S = 37 - 46M_g \dots \dots \dots (\text{ppt}), \quad (5.5)$$

or,

$$\sigma_{eff} = 57 - 71M_g \dots \dots \dots (\text{m Siemens/cm}), \quad (5.6)$$

or

$$\sigma_e = 103 - 130 M_g \dots \dots \dots (\text{as defined in Eq.(5.2)}) \quad (5.7)$$

Because of the limited range of M_g for stalks, it was not possible to adequately relate S to M_g for stalks.

The previous three equations should be taken only as approximate estimates of S , σ_{eff} , and σ_e because the variability among different species is quite large. Furthermore, large differences in salinity were observed among samples of the same species depending on the stage of growth and geographic location. As

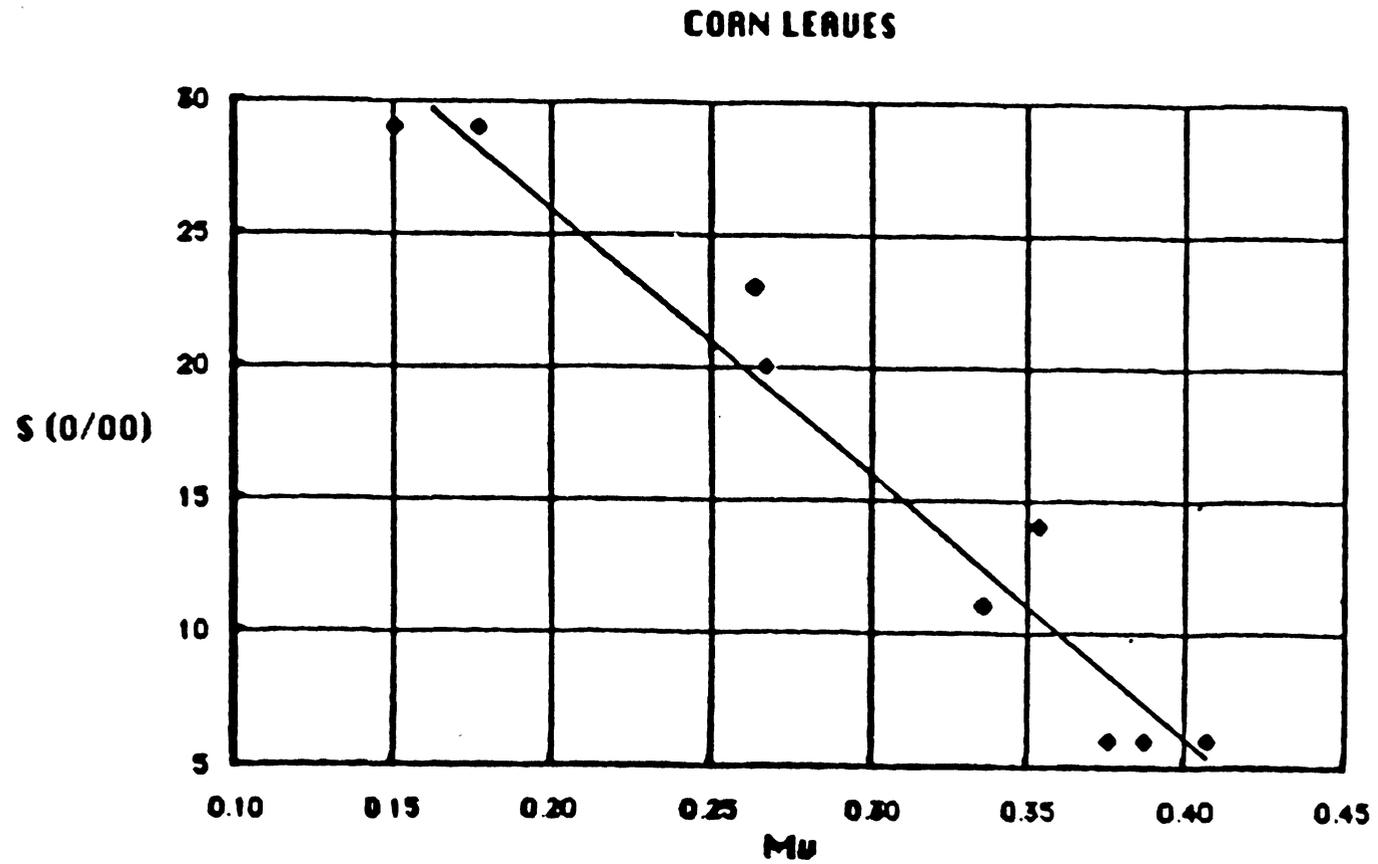


Figure 5.9. Measured salinity in (ppt) for extracted fluids from corn leaves at different volumetric moisture levels, plants were excised and naturally dried.

an example of this variability, the measured salinities of extracted liquids from fresh corn leaves (Ulaby and Jedlicka, 1984) grown near Lawrence, Kansas, were measured to be about 12 *ppt*. As shown in Table 5.1, the measured salinities of fresh corn leaves grown near Ann Arbor, Michigan, were measured to be about 6 *ppt*. This large difference can not be attributed to measurement errors or equipment calibration alone. A comparison between different measurements on corn leaves grown in Kansas (1984) and in Michigan (1985) is given in Table 5.3 (both measured using the same technique, the open-ended coaxial line probe system).

where	when	M_g	$f(\text{GHz})$	ϵ'	ϵ''	$\tan(\delta)$
Kansas	1984	.736	1	33.8	17	.50
		.653	1	30	15	.50
Michigan	1985	.835	1	46	18.5	.4
		.645	1	27	9	.33

Table 5.3: Comparison between measured corn leaves grown in Kansas and Michigan.

Another experiment was conducted in Michigan (December, 1985) on corn leaves and stalks (grown at the University of Michigan Botanical Gardens). The dielectric constant of corn leaves and corn stalks was measured as a function of