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6. AUTHOR(S)
James L. Kurtz, Jason Cowdery, Mary E. Collins

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Electronic Communications Laboratory
PO Box 140245
Gainesville, FL 32614-0245

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13. ABSTRACT ***(Maximum 200 Words)***
On September 23 and 24, 1997 tests were performed by the University of Florida on soils at Phillips Drop Zone in Yuma Proving Ground, Arizona. Soil Samples were also collected and additional tests were later made in the laboratory in order to characterize the soil properties. These tests were performed for the Army Research Laboratory. The objectives of this effort were primarily to characterize the soil conditions, particularly moisture and dielectric permittivity, in support of anticipated unexploded ordnance (UXO) related ground penetrating measurements.

Described in the report are details of the field and laboratory soil tests. the results of those tests, and results of soil modeling for Yuma soils. The field tests which are described include time doman reflectometer tests and the resulting data from those tests. The laboratory tests include characterization of the physical and chemical properties of the soils, including measured moisture content. Comparisons of field measured moisture to the laboratory measurements are made. Soil model results are presented which show the calculated dielectric permittivity, conductivity, attenuation, and surface reflection loss of representative Yuma soils for different moisture contents ranging from 0 to 10%. The model data can be used to estimate several fo the major attenuation effects encountered when trying to detect subsurface targets in the types of soils found in this area of Yuma.

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Additional Soil Evaluations at Yuma Proving Ground

James L. Kurtz
Jason Cowdery

Electronic Communications Laboraotry

Mary E. Collins
Environmental Pedology and Land Use Laboratory

December 15, 1997

University of Florida
Gainesville, Florida

Prepared for:
Army Research Laboratory
Contract DAAL01-95-K-0029

Electronic Communications Laboratory
P.O. Box 140245
Gainesville, FL 32614-0245
(904) 392-1705
(904) 392-7169 (fax)

University of Florida

Abstract

On September 23 and 24, 1997 tests were performed by the University of Florida on soils at Phillips Drop Zone in Yuma Proving Ground, Arizona. Soil samples were also collected and additional tests were later made in the laboratory in order to characterize the soil properties. These tests were performed for the Army Research Laboratory. The objectives of this effort were primarily to characterize the soil conditions, particularly moisture and dielectric permittivity, in support of anticipated unexploded ordnance (UXO) related ground penetrating radar measurements.

Described in the report are details of the field and laboratory soil tests, the results of those tests, and results of soil modeling for Yuma soils. The field tests which are described include time domain reflectometer tests and the resulting data from those tests. The laboratory tests include characterization of the physical and chemical properties of the soils, including measured moisture content. Comparisons of field measured moisture to the laboratory measurements are made. Soil model results are presented which show the calculated dielectric permittivity, conductivity, attenuation, and surface reflection loss of representative Yuma soils for different moisture contents ranging from 0 to 10%. The model data can be used to estimate several of the major attenuation effects encountered when trying to detect subsurface targets in the types of soils found in this area of Yuma.

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1.0 Introduction

This report describes work performed by the University of Florida for the Army Research Laboratory to further characterize soils at Yuma Proving Ground (YPG) for anticipated ground penetrating radar (GPR) measurements. The objectives of this effort were primarily to characterize the soil conditions, particularly moisture and dielectric permittivity, prior to anticipated unexploded ordnance (UXO) related ground penetrating radar measurements. Measurements of soil moisture and dielectric permittivity allow improved estimates of soil related GPR performance to be made; especially soil attenuation.

Several types of tests were performed on soils at Phillips Drop Zone on September 23 and 24, 1997 and subsequently in the laboratory, in order to characterize the soil conditions in the areas of interest. Time Domain Reflectometer (TDR) tests were made with probes inserted directly into the ground, soil visual inspections and tests were made in the field, and soil samples were collected for further laboratory testing at the University of Florida. The TDR makes a measurement of a pulse waveform input to parallel probes inserted into the soil. From the TDR measurements the effective velocity of the pulse in the soil is measured and, in turn, the soil dielectric constant (approximately the real dielectric permittivity) and volumetric moisture content can be calculated. The characteristics of the TDR pulse return also allow estimates of low frequency soil conductivity. Visual tests of the soil were also made in the field to compare the general soil conditions to previously sampled conditions [1]; i.e. to compare moisture. Soil samples were collected to make bulk density measurements, gravimetric moisture measurements, soil composition, dc conductivity, and other measurements upon return of the samples to the laboratory. Tests in the field were curtailed due to an impending hurricane (Nora) in the Yuma, Arizona area on the afternoon of September 24, 1997.

Previous work with YPG soils and results of soil modeling efforts are used here to estimate the complex dielectric permittivity of several Yuma soils having several different compositions and at different moisture contents; some of this work is in [1-3], the most recent work is in [4]. Prior modeling work has shown that the soil composition (sand and clay) can be used in a model to make reasonable estimates of dielectric permittivity after modifying the model to "fit" measured permittivity data for the Yuma soils. Such a modified model has been used here to make dielectric permittivity estimates for several Yuma soils with varying moisture content. The soil dielectric permittivity from the model is then used to make soil attenuation versus frequency estimates.

The TDR tests, soil tests, and soil collections described in this report were made in the cleared and natural areas of Phillips Drop Zone at YPG. Some of the existing target areas at Phillips Drop Zone are as described in previous reports [1-5], however, different targets have been added in several areas for the UXO related tests. For the soil tests described in this report, several positions in the mines area (including the M68 area), the boxes area (include the M42 area), and in the natural area were examined and tested. Further details of the soil test locations and soil collection depths will be provided in the report.

2.0 Time Domain Reflectometer Theory and Field Test Results

The Time Domain Reflectometer makes measurements of soil electromagnetic characteristics by applying a pulse waveform onto parallel metal probes inserted into the soil. From the TDR measurements the effective velocity of the pulse in the soil is measured and, in turn, the soil dielectric constant (approximately the real dielectric permittivity) and volumetric moisture content can be calculated. The characteristics of the TDR pulse return also allow estimates of low frequency soil conductivity.

TDR soil measurements require obtaining a time delay (distance) measurement and amplitude measurements at several points on the measured TDR trace. Figure 1 shows a typical TDR trace with the probes inserted into the ground as far as possible. After adjustment of the TDR settings, the trace will appear approximately as shown in Figure 1.

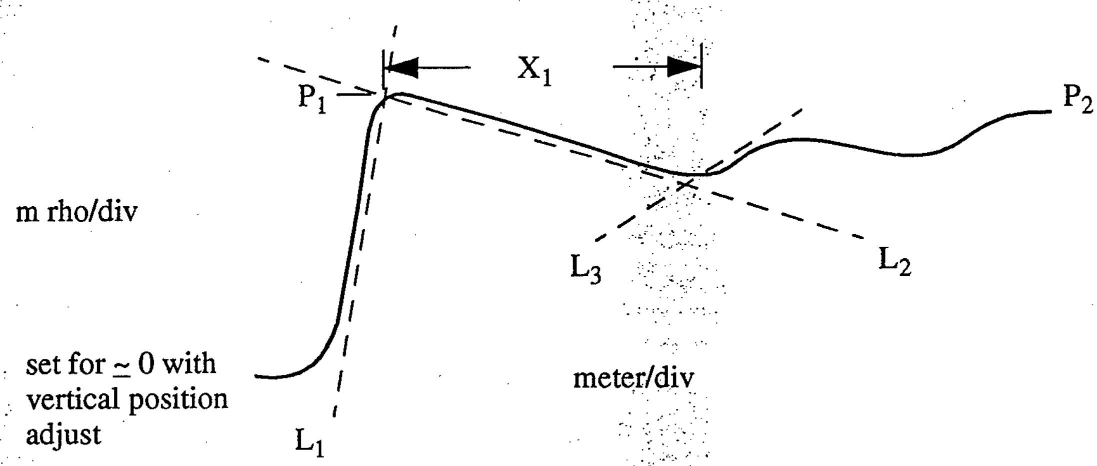

Figure 1. Example time domain reflectometer waveform.

The TDR trace, from left to right, represents the response from a cable matched to the TDR impedance (~50 ohms), followed by a region X_1, corresponding to the parallel probes in the ground (a mismatched condition), followed by responses related to multiple reflections. The points of interest on the trace and to be measured are:

1. The peak point P_1, corresponding to the first reflection.

2. the distance X_1, corresponding to the equivalent time of travel in the soil.

3. The approximate final value reflection P_2, measured at three to four times the distance X_1.

The first peak can be approximated by considering the intersection of a tangent line on the leading edge of the mismatch, L_1, and on the trailing edge, L_2. The distance X_1 can be measured by the difference of the horizontal distance corresponding to P_1 and the second inflection point, which marks the beginning of multiple reflection responses. This distance X_1 is the equivalent length of the parallel probes in the soil. The equivalent relative dielectric permittivity is approximately

$$\varepsilon_r = \left(\frac{x_1}{x_{ref}}\right)^2$$

where x_{ref} is the physical length of the probes (or the length measured by the TDR in air). Using the TDR, ε_r is usually an accurate (5-10% error) representation of the low frequency (<10 MHz) dielectric permittivity. Also, the value of ε_r is most accurate for low loss soils (low conductivity). In this case ε_r will approximate the real permittivity or dielectric constant.

The amplitude point P_2 is measured at a horizontal distance three to four times X_1 and represents the approximate final value of the reflections. The values of P_1 and P_2 are used to determine the conductivity from equations. An equation developed by Giese and Tiemann and reported in [6] has been shown to give an estimate of low frequency conductivity from the TDR; we refer to this conductivity as σ_{gt}. The equation uses the values of P_1 and P_2 and ε_r previously determined from the TDR. The conductivity obtained from the TDR, σ_{gt}, is usually at least twice the value measured by other low frequency measurements. There are other equations for calculation of thin layer conductivity from the TDR measurements which are given in [6]; we do an alternate calculation of thin layer conductivity σ_t as a check on σ_{gt} (although σ_t is not as accurate as σ_{gt}). From comparisons with swept frequency tests that have been performed on Yuma soils we have found that the TDR estimates of conductivity agree most closely at low frequencies (below ten megaHertz).

Volumetric soil moisture, m_v, may also be determined from the TDR measured dielectric permittivity by using an equation developed by Topp, et al [7]. Topp and others determined that the volumetric moisture in cm^3(water)/cm^3(soil) for many soils at varying moisture contents can be closely related to a functional relationship of the dielectric permittivity as obtained from the TDR. Appendix A of this report includes charts that can be used to find the volumetric moisture from the dielectric permittivity. To find volumetric moisture using the charts in Appendix, read the volumetric moisture on the vertical axis corresponding to the intersection of the curve and the real dielectric permittivity (or dielectric constant) on the horizontal axis.

2.1 TDR Measurement Results

The TDR was used at several areas of Phillips Drop Zone on September 23 and 24, 1997 to obtain estimates of dielectric permittivity (low frequency dielectric constant), conductivity, and volumetric moisture content. These measurements and the results are shown in Table 1. Refer to Section 3 for more details on the areas and soils sampled for laboratory tests.

Table 1: TDR Measurements YPG - Phillips Drop Zone 9/2397 and 9/24/97

Date	Run	Probe (prong)	Start [cm]	Stop [cm]	Δx [cm]	Location/position	ε_r calc	P_1	P_2	m_v [cm^3/cm^3]	σ_{gt} [mS/m]	σ_t [mS/m]
9/23/97	2	2	1.43	1.94	51	Near boom road, parallel to surface	2.890	0.45	0.70	0.0269	0.0752	0.0070
9/23/97	3	3	4.34	4.71	37	Near boom road, parallel to surface	3.423	0.35	0.75	0.0407	0.0100	0.0049
9/23/97	4	2	1.44	2.15	73	East side of shack	5.921	0.50	0.80	0.1015	0.0149	0.0072
9/23/97	Mines 1 position 1	2	1.42	2.08	66	1st mines location, and 1st position	4.840	0.50	0.75	0.0759	0.0178	0.0083
9/23/97	Mines 1 position 2	2	1.43	2.08	65	1st mines location, 2nd position	4.694	0.50	0.80	0.0724	0.0133	0.0064
9/23/97	Mines 1 position 2	3	4.36	4.73	37	1st mines location, 2nd position	3.423	0.34	0.85	0.0407	0.0054	0.0027
9/23/97	Mines 1 position 2	2	-	-	66	mines 1 2nd position	4.840	0.50	0.75	0.0759	0.0178	0.0083
9/23/97	Boxes 1	2			66	Boxes position 1	4.840	0.50	0.75	0.0758	0.0178	0.0083
9/23/97	Boxes 1	3			39	Boxes position 1	3.8025	0.35	0.85	0.0503	0.0059	0.0029
9/23/97	Boxes 2	3	4.36		37	Boxes position 2 M42	3.423	0.35	0.85	0.0407	0.0056	0.0028

Table 1: TDR Measurements YPG - Phillips Drop Zone 9/2397 and 9/24/97

Date	Run	Probe (prong)	Start [cm]	Stop [cm]	Δx [cm]	Location/position	ε_r calc	P_1	P_2	m_v [cm^3/ cm^3]	σ_{gt} [mS/m]	σ_t [mS/m]
9/23/97	Boxes 2	2	1.43		63	Boxes position 2 M42	4.410	0.50	0.75	0.0654	0.0170	0.0080
9/23/97	Mines area 3 position 1	3	4.35	4.72	37	Mines area 3 posi-tion 1 M68	3.423	0.35	0.85	0.0407	0.0056	0.0028
9/23/97	mines area 3 position 2	3		4.72	37	Mines area 3 posi-tion 1 M68	3.423	0.35	0.85	0.0407	0.0056	0.0028
9/23/97	mines area 3 position 2	2	1.42	2.08	66	Mines area 3 posi-tion 1 M68	4.840	0.50	0.75	0.0759	0.0178	0.0083
9/24/97	Natural position 1	2	1.43	2.08	65	Natural position 1	4.690	0.50	0.75	0.0724	0.0176	0.0082
9/24/97	Natural position 1	3	4.36	4.74	38	Natural position 1	3.610	.35-.4	0.85	0.0454	0.0057	0.0028
9/24/97	Natural position 1	3		4.73	37	Natural position 2	3.423	0.35	0.85	0.0407	0.0056	0.0028
9/24/97	Natural position 2	2	1.42	2.04	62	Natural position 2	4.200	0.51	0.82	0.0620	0.0115	0.0056

Table 1 shows the results obtained with the TDR on September 23 and 24, 1997 at Phillips Drop Zone. For these tests two types of probes were used, a two-prong parallel probe 30 cm in length, and a three-prong probe 20cm in length. The three-prong probe offers several potential advantages over the two-prong probe. First, the design of the three-prong probe approximates a coaxial line where the center probe acts as the center conductor of the coaxial line and the two outer conductors are the outer coaxial shield. This type of probe has been reported to give more accurate results than two-prong probes which are not as well matched to the 50 Ohm source impedance of the TDR [8]. However, the three-prong probes were received just prior to the September tests and previous test data with these probes had not been obtained by UF researchers. For this reason both types of probes were used for most of the tests to try to obtain a comparison.

In all of the results of Table 1 the time/distance locations in Figure 1 are measured from the TDR trace and the amplitude points P_1 and P_2 are measured. These points from the trace are then used to calculate dielectric constant, ε_r, volumetric moisture, m_v, and conductivity, σ_t and σ_{gt}. The dielectric constant is directly related to the distance measured; that is, the longer the apparent distance of the probe in the soil the larger the calculated dielectric constant. The volumetric moisture will increase with increasing dielectric constant since the moisture is calculated from the dielectric constant (a third order equation). The conductivity will also generally increase with increasing dielectric constant, but the calculation is mostly dependent on the terms P_1 and P_2. Dielectric constant and conductivity can be related to soil attenuation. Section 4 on Soil Modeling describes graphs given in Appendix B of several soils with different dielectric permittivity (complex dielectric permittivity and conductivity) versus frequency. Those graphs should be referred to in order to appreciate the significance of the TDR measured values on attenuation, recognizing that the TDR provides low frequency measurements of these parameters. The specific values of ε_r, m_v, σ_t, and σ_{gt} obtained will be discussed more below.

The first tests in Table 1 were made near the boom road and the test shack. The first two tests, using the two- and three-prong probes, were attempts to measure the soil near the surface by inserting the probes approximately parallel to the surface (actually at a slight angle to the surface) within the first three inches of soil. In both cases the dielectric constants were near 3, although the three-prong probe resulted in higher dielectric constant (this is important to note since most of the other measurements showed lower dielectric constant with the three-prong probe, as will be discussed). The volumetric moisture content measured between about 2.7% and 4.0% using the two- and three-prong probes, respectively. The test results in the soil sampling section show a minimum bulk density of about 1.7. Using this value of bulk density would result in a gravimetric moisture of 1.6% to 2.3%. This is somewhat lower than the laboratory measurements of gravimetric moisture for most soils, but no soil samples were actually taken from this specific area to allow comparison. The low frequency conductivity of the soil obtained from the TDR was between about 5 and 7 mS/m. The third test in Table 1 is with the two-prong probes inserted into the soil the full extent (30 cm). This test resulted in higher dielectric constant (5.9), higher m_v (10%), and higher σ_{gt} (7.2 mS/m) than the first two near-surface tests. These higher moisture results are reasonable considering this was a shaded area near the shack. An area near the inserted TDR probes was dug with a coring tool and found to be quite wet to the touch at 30 cm depth, which further substantiated the higher moisture readings. σ_{gt} obtained with the TDR is usually about twice the value measured by other low frequency measurements [6].

The other locations tested with the TDR and shown in Table 1 are potential GPR test areas for UXO related tests. The first area tested was the mines area and denoted Mines 1, position 1 and 2. Position 1 and 2 in each area correspond to a first position at the West-most location of the area and the second position further East, usually near the Eastern edge of the area, unless otherwise noted. As can be seen in Table 1 the two-prong probes in the Mines 1 area resulted in higher dielectric constant (about 4.7 compared to 3.4) at position 2. This result can be partially explained by two causes: 1) the two-prong probe is 10 cm longer and therefore averages the soil conditions deeper than the three-prong probe and, 2) the two- and three-prong probes can be expected to give slightly different readings. The second cause is believed to be minor in terms of measured dielectric constant, but further test comparisons of the two- and three-prong probes will need to be performed to verify similarities or differences in the probes. The volumetric moisture content measured at the positions in Mines 1 with the different probes varied from about 4% to 7.6% (again, the longer two-prong probes give the higher moisture content). For a bulk density of 1.7 (average for soils in this area) the calculated gravimetric moisture ranges from 2.36% to 4.47%.; the laboratory measured gravimetric moisture for these soils was 3.2 to 5.3%, which is close to the range calculated from the volumetric moisture content. Similarly, σ_{gt} varied from about 2.7 to 8.3 mS/m in the Mines 1 area, depending on the probes used and the position within this area, DC conductivity (measured in laboratory), was only 0.7 to 1.1 mS/m.

The next area tested with the TDR was the Boxes area at positions 1 and 2. Again, as can be seen in Table 1, the two-prong probes in the Boxes area resulted in higher dielectric constant, about 4.8 compared to 3.8, at position 1 and 4.4 to 3.4 at position 2. This result can be partially explained by the two causes cited above in the Mines 1 area. The volumetric moisture measured at the positions in Boxes with the different probes varied from about 4.1% to 7.6% (again, the longer two-prong probes give the higher moisture content). For a bulk density of 1.8 (about the average for soils in this area) the calculated gravimetric moisture would range from 2.3% to 4.2%.; the laboratory measured gravimetric moisture for these soils was 2.2% to 4.4%, which is very close to the range calculated from the volumetric moisture content. Similarly, σ_{gt} varied from about 2.8 to 8.3 mS/m in the Boxes area, depending on the probes used and the position within this area, DC conductivity (measured in laboratory), was only 0.7 to 1.4 mS/m.

The next area tested with the TDR was the Mines area 3 at positions 1 and 2. Again, as can be seen in Table 1, the two-prong probes in the Mines area 3 resulted in higher dielectric constant, about 4.8 compared to 3.4, at position 2. This result can be partially explained by the two causes cited above. The volumetric moisture measured at the positions in Mines area 3 with the different probes varied from about 4.1% to 7.6% (again, the longer two-prong probes give the higher moisture content). For a bulk density of 1.8 (about the average for soils in this area) the calculated gravimetric moisture would range from 2.5% to 4.2%.; the laboratory measured gravimetric moisture for these soils was 2.2% to 5.1%, which is again close to the range calculated from the volumetric moisture content. Similarly, σ_{gt} varied from about 2.8 to 8.3 mS/m in the Mines area 3, depending on the probes used and the position within this area, DC conductivity (measured in laboratory), was only 0.9 to 1.1 mS/m.

The last area tested with the TDR was the Natural area at positions 1 and 2. Again, as can be seen in Table 1, the two-prong probes in the Natural area resulted in higher dielectric constant, about 4.7 compared to 3.6, at position 1, and 4.2 compared to 3.4 at position 2. These results can be partially explained by the two causes cited above. The volumetric moisture measured at the positions in Natural area with the different probes varied from about 4.1% to 7.2% (again, the longer two-prong probes give the higher moisture content). For a bulk density of 1.8 (about the average for soils in this area) the calculated gravimetric moisture would range from 2.27% to 4.0%.; the laboratory measured gravimetric moisture for these soils was 2.6% to 6.3%, which is not as close as the comparisons to gravimetric moisture in the cleared area when compared to the range calculated from the volumetric moisture content (the highest gravimetric moisture was encountered in this area). Similarly, σ_{gt} varied from about 2.8 to 8.2 mS/m in the Mines area 3, depending on the probes used and the position within this area, DC conductivity (measured in laboratory), was only 0.9 to 1.3 mS/m.

Other observations can be made when analyzing and comparing the TDR and laboratory test data. The dielectric constant is very consistent for all of the measurements using the 3-prong probe; the ε_r range was 3.4 to 3.8 or 11.7% variation. For the 2-prong probe the ε_r range was 4.2 to 5.9 or 40% variation, not including the first measurement in the table for which the probes were probably not fully covered with soil. Also, the laboratory measured gravimetric moisture content was generally somewhat higher than the TDR results would indicate for most soils. This is especially true recognizing that the 3-prong probe extends to about 8" depth, which is the nearly the same depth from which all of the soils were sampled for lab tests (0-4" and 5-9"). If only the 3-prong TDR volumetric moisture data is used for comparisons to the laboratory gravimetric moisture, then the laboratory gravimetric moisture would have been a good bit higher than the TDR equivalent moisture (the volumetric moisture divided by the bulk density). That is, soils would have had an equivalent of about 2.1% gravimetric moisture (using only the 3-prong probe TDR data). If the gravimetric moisture as measured in the laboratory is averaged for all the sampled soils taken from 0-4" and 5-9" in depth, it is seen that the average from 0-4" is about 3.3% and the average from 5-9" is about 4.6%.; so the average gravimetric moisture at either depth is higher than the results from the TDR would indicate. The laboratory results indicate that the deeper soils retained slightly more moisture, on average, after return to the laboratory; this is discussed more in Section 3. The DC conductivity measured in the laboratory is consistently less that the TDR σ_{gt}, although the trend in conductivity values at each site are the same.

Possible explanations for differences in TDR measured/calculated moisture and laboratory measured moisture are:

1). Errors in volumetric moisture equation. The equation by Topp and Annan [7] for calculating volumetric moisture from TDR measured ε_r is not as accurate for low volumetric moisture (this is essentially a curve fit equation). For dielectric constant (real permittivity) less than about 2, the equation cannot be used at all. For dielectric constants between 2 and 5 there is significant error. At higher dielectric constants the error is usually less than 5%. Unfortunately, this is the best known equation at the present time.

2). Change in soil moisture. It is possible that some soils absorbed moisture and others lost moisture before the laboratory tests were completed.

3). Differences in probes. At present we feel the three-prong probe dielectric constant is accurate to the depth of testing (20 cm or about 8"). We will attempt to resolve these differences with the two- and three-prong probes by testing the probes with solutions of known dielectric and conductivity (upon return of the TDR to the University of Florida from YPG).

3.0 Soil Sampling and Laboratory Test Results

3.1 Introduction

Ten soils were sampled in September, 1997 at the Yuma Proving Grounds (YPG). The soils were sampled in the same area at the YPG as the soils were sampled in 1995 [1](Collins et al., 1995). The soils were sampled to a depth of 9 inches. Duplicates were sampled for comparisons. The location, position, depth, and physical and chemical data are presented in Table 2. Physical properties analyzed include particle size < 2 mm (% sand, silt, and clay), particles > 2 mm (% gravel),% gravimetric moisture, and dry bulk density (g cm^{-3}). Chemical properties analyzed were pH (1:1 H_2O) and electrical conductivity (dS/m). The ranges and means of the soil properties for all samples, 0 to 4 inch depths, and 5 to 9 inch depths are given in Table 3. Correlation coefficients were calculated and are presented in Table 4.

3.2 Sampling Procedure

Sampling sites were selected and locations recorded. At each sampling site, the soil was sampled by incremental depth: 0 to 4 inches and 5 to 9 inches. The soil coring apparatus takes samples in thicknesses of 4 inches. The volume of the soil core was 228 cm^3. Knowing this volume allowed us to calculate the dry soil bulk density. The soil in the core was placed in a plastic bag, immediately sealed, and labeled. A second core was taken very close to the first core, at a distance of approximately two feet. This procedure was used throughout except in the Natural Area. In the Natural Area, the soil was sampled in a "gravelly" surface zone (samples 1-1 and 1-2) and in a "non-gravelly" surface zone (samples 2-1 and 2-2) (Figures 2 and 3). This was done to determine if the percentage of particles > 2 mm influenced the results.

Table 2: PHYSICAL AND CHEMICAL PROPERTIES OF SOILS SAMPLED IN 1997

Location	Position	Depth	%Moisture	%Gravel	%Sand	%Silt	%Clay	pH	EC ds/m	Dry BD
Mines 1 site 1	1	0-4"	3.7	16.2	92.2	5.2	2.6	8.7	0.07	1.64
Mines 1 site 1	1	0-4 duplicate	3.2	16.0	91.2	6.0	2.8	8.7	0.08	1.74
		Average	3.5	16.1	91.7	5.6	2.7	8.7	0.08	1.69
Mines 1 site 1	1	5-9"	5.3	18.4	88.2	8.3	3.5	8.8	0.11	1.63
Mines 1 site 1	1	5-9" dupli.	4.4	18.7	90.2	6.7	3.1	8.9	0.08	1.69
		Average	4.9	18.6	89.2	7.5	3.3	8.9	0.10	1.66
		0-9 Ave	4.2	17.3	90.5	6.6	3.0	8.8	0.09	1.68
Mines 1 site 1	2	0-4"	3.5	12.4	92.6	5.5	1.9	8.8	0.08	1.71
Mines 1 site 1	2	0-4" dupli.	3.8	11.2	92.4	5.9	1.7	8.8	0.09	1.77
		Average	3.7	11.8	92.5	5.7	1.8	8.8	0.09	1.74
Mines 1 site 1	2	5-9"	3.3	11.0	92.2	6.0	1.8	8.9	0.09	1.82
Mines 1 site 1	2	5-9" dupli.	3.7	20.3	91.2	6.2	2.6	8.8	0.09	1.85
		Average	3.5	15.7	91.7	6.1	2.2	8.9	0.09	1.83
		0-9 Ave	3.6	13.7	92.1	5.9	2.0	8.8	0.09	1.79
Mines Area 3	1	0-4"	2.4	9.2	94.2	3.7	2.1	8.8	0.08	1.82
Mines Area 3	1	0-4" dupli.	2.2	10.5	94.2	3.8	2.0	9.0	0.10	1.91
		Average	2.3	9.9	94.2	3.8	2.1	8.9	0.09	1.87
Mines Area 3	1	5-9"	5.1	6.8	87.8	7.3	4.9	8.9	0.11	1.71
Mines Area 3	1	5-9" dupl.	2.3	7.1	95.0	3.2	1.8	8.9	0.13	1.79
		Average	3.7	7.0	91.4	5.3	3.4	8.9	0.12	1.75
		0-9 Ave	3.0	8.4	92.8	4.5	2.7	8.9	0.11	1.81

Table 2: PHYSICAL AND CHEMICAL PROPERTIES OF SOILS SAMPLED IN 1997

Location	Position	Depth	%Moisture	%Gravel	%Sand	%Silt	%Clay	pH	EC ds/m	Dry BD
Mines Area 3	2	0-4"	2.2	7.0	94.8	3.2	2.0	8.8	0.11	1.82
Mines Area 3	2	0-4" dupl.	4.3	6.2	92.6	4.3	3.1	8.9	0.09	1.82
		Average	3.3	6.6	93.7	3.8	2.6	8.9	0.10	1.82
Mines Area 3	2	5-9"	4.6	9.1	89.4	6.7	3.9	8.8	0.12	1.79
Mines Area 3	2	5-9" dupl.	3.5	8.7	94.0	3.5	2.5	8.9	0.10	1.89
		Average	4.1	8.9	91.7	5.1	3.2	8.9	0.11	1.84
		0-9 Ave	3.7	7.8	92.7	4.4	2.9	8.9	0.11	1.83
Boxes site 1	1	0-4"	2.9	17.7	91.6	5.5	2.9	8.8	0.10	1.75
Boxes site 1	1	0-4" dupli.	2.6	13.8	92.4	4.7	2.9	8.8	0.10	1.76
		Average	2.8	15.8	92.0	5.1	2.9	8.8	0.10	1.76
Boxes site 1	1	5-9"	4.4	12.7	89.2	6.3	4.5	8.8	0.08	1.72
Boxes site 1	1	5-9" dupli.	4.4	11.3	92.0	5.6	2.4	8.9	0.09	1.51
		Average	4.4	12.0	90.6	6.0	3.5	8.9	0.09	1.62
		0-9 Ave	3.6	13.9	91.3	5.5	3.2	8.8	0.09	1.69
Boxes site 1	2	0-4"	2.2	13.1	94.0	4.5	1.5	8.8	0.09	1.82
Boxes site 1	2	0-4" dupli.	2.4	9.8	94.2	4.4	1.4	8.9	0.14	1.77
		Average	2.3	11.5	94.1	4.5	1.5	8.9	0.12	1.80
Boxes site 1	2	5-9"	4.2	10.1	92.8	5.2	2.0	8.9	0.07	1.86
Boxes site 1	2	5-9" dupli.	3.6	11.2	93.8	4.6	1.6	8.9	0.08	1.88
		Average	3.9	10.7	93.3	4.9	1.8	8.9	0.08	1.87
		0-9 Ave	3.1	11.1	93.7	4.7	1.6	8.9	0.10	1.83
Natural Area	1-1	0-4"	2.6	13.3	93.2	4.9	1.9	8.9	0.10	1.92
Natural Area	1-1	0-4" dupli.	4.1	12.7	93.0	4.9	2.1	8.9	0.09	1.84
		Average	3.4	13.0	93.1	4.9	2.0	8.9	0.10	1.88

Table 2: PHYSICAL AND CHEMICAL PROPERTIES OF SOILS SAMPLED IN 1997

Location	Position	Depth	%Moisture	%Gravel	%Sand	%Silt	%Clay	pH	EC ds/m	Dry BD
Natural Area	1-1	5-9"	6.3	8.0	82.4	12.4	5.2	8.8	0.08	1.64
Natural Area	1-1	5-9" dupli.	5.6	10.5	83.0	11.0	6.0	8.7	0.10	1.59
		Average	6.0	9.3	82.7	11.7	5.6	8.8	0.09	1.61
		0-9 Ave	4.7	11.1	87.9	8.3	3.8	8.8	0.09	1.75
Natural Area	1-2	0-4"	3.6	13.0	91.4	6.6	2.0	8.8	0.10	1.84
Natural Area	1-2	0-4" dupli.	4.6	6.4	91.4	6.4	2.2	8.9	0.10	1.82
		Average	4.1	9.7	91.4	6.5	2.1	8.9	0.10	1.83
Natural Area	1-2	5-9"	5.2	6.3	85.6	9.1	5.3	8.9	0.13	1.75
Natural Area	1-2	5-9" dupli.	4.7	19.1	87.6	7.8	4.6	8.8	0.07	1.71
		Average	5.0	12.7	86.6	8.5	5.0	8.9	0.10	1.73
		0-9 Ave	4.5	11.2	89.0	7.5	3.5	8.9	0.10	1.78
Natural Area	2-1	0-4"	3.7	4.7	90.6	7.2	2.2	8.8	0.08	1.86
Natural Area	2-1	0-4" dupli.	4.3	6.5	91.4	6.3	2.3	8.8	0.09	1.76
		Average	4.0	5.6	91.0	6.8	2.3	8.8	0.09	1.81
Natural Area	2-1	5-9"	4.4	1.7	90.2	7.6	2.2	8.8	0.08	1.79
Natural Area	2-1	5-9" dupli.	5.9	6.6	90.2	7.4	2.4	8.9	0.08	1.54
		Average	5.2	4.2	90.2	7.5	2.3	8.9	0.08	1.67
		0-9 Ave	4.6	4.9	90.6	7.1	2.3	8.8	0.08	1.74
Natural Area	2-2	0-4"	3.6	4.4	89.8	7.6	2.6	8.8	0.10	1.84
Natural Area	2-2	0-4" dupli.	4.3	5.4	90.6	6.5	2.9	8.8	0.09	1.83
		Average	4.0	4.9	90.2	7.1	2.8	8.8	0.10	1.84
Natural Area	2-2	5-9"	5.3	3.9	90.4	6.8	2.8	8.9	0.12	1.72
Natural Area	2-2	5-9" dupli.	4.6	1.7	90.0	7.0	3.0	8.7	0.09	1.70
		Average	5.0	2.8	90.2	6.9	2.9	8.8	0.11	1.71
		0-9 Ave	4.5	3.9	90.2	7.0	2.8	8.8	0.10	1.77

Table 3: Ranges and means of soil properties - 1997 samples

Parameter	Range	Mean
% Moisture (all samples)	2.2 - 6.3	3.9
% Moisture (0-4 inch depth)	2.2 - 4.6	3.3
% Moisture (5-9 inch depth)	2.3 - 6.3	4.6
% Gravel (all samples)	1.7 - 20.3	10.3
% Gravel (0-4 inch depth)	4.4 - 17.7	10.5
% Gravel (5-9 inch depth)	1.7 - 20.3	10.2
% Sand (all samples)	82.4 - 95.0	91.0
% Sand (0-4 inch depth)	89.9 - 94.8	92.3
% Sand (5-9 inch depth)	82.4 - 95.0	89.8
% Silt (all samples)	3.2 - 12.4	6.2
% Silt (0-4 inch depth)	3.2 - 7.6	5.4
% Silt (5-9 inch depth)	3.2 - 12.4	6.9
% Clay (all samples)	1.4 - 6.0	2.8
% Clay (0-4 inch depth)	1.4 - 3.1	2.3
% Clay (5-9 inch depth)	1.6 - 6.0	3.3
pH (all samples)	8.7 - 9.0	8.8
pH (0-4 inch depth)	8.7 - 9.0	8.8
pH (5-9 inch depth)	8.7 - 8.9	8.8
EC (all samples)	0.07 - 0.14	0.10
EC (0-4 inch depth)	0.07 - 0.14	0.10
EC (5-9 inch depth)	0.07 - 0.13	0.10
Bulk density (all samples)	1.51 - 1.91	1.77
Bulk density (0-4 inch layer)	1.64 - 1.91	1.80
Bulk density (5-9 inch layer)	1.51 - 1.89	1.73

Figure 2. Natural Area sampled with a gravelly surface. Soils were sampled in this area.

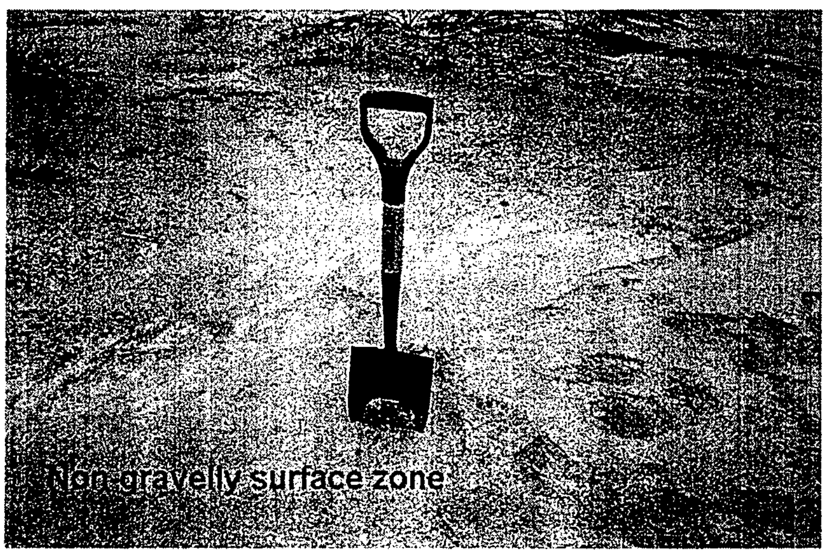

Figure 3. Natural Area with little gravels in the surface. Soils were sampled in this area.

3.3 Laboratory Methods

All samples were analyzed in the Environmental Pedology Laboratory in the Soil and Water Science Department at the University of Florida in Gainesville using standard methods [9](Soil Survey Staff, 1996). Percent gravimetric moisture was determined by immediately weighing the soils when the samples arrived at the laboratory, and then oven-drying and weighing the samples. The difference in weight is the gravimetric moisture content. The oven-dry samples were used to determine % gravel, sand, silt, clay, pH, EC and dry bulk density.

Percent gravel (> 2 mm) and% sand (2 mm to 0.05 mm) were determined by sieving. Percent silt (0.05 mm to 0.002 mm) and % clay (< 0.002 mm) were determined using the pipette method in which the silt and clay content are based on the differences in the settling times of the different size particles. The pH measurements were made with a glass electrode using a soil-water ratio of 1:1. After completing the pH measurement, electrical conductivity (EC) determinations were made on the same 1:1 soil-water mixtures. Dry bulk density was calculated based on the oven-dry weight of a known volume of soil.

3.4 Results and Discussion

The soils sampled at the YPG are classified as Aridisols. Aridisols are located mostly in desert regions, develop under sparse vegetation, and have a surface layer that is low in organic matter. The soils cannot be classified any further in "Soil Taxonomy" because of the shallow depth observations and samples that were taken. In the previous study [1] (Collins, 1995), most of the soils were Calcids. These are Aridisols with a high content of extractable calcium.

3.4.1 Physical Soil PropertiesCharacteristics

Gravimetric moisture content of the soils ranged from 2.2 to 6.3%. The overall average moisture content of the soils sampled was 3.9%. The highest moisture content was in the 5-9 inch layer in the Natural Area 1-1, and the lowest moisture content was in the 0-4 inch layer of the Mines sites 1 and 2, and the Boxes site 2. The average moisture content of the 0-4 inch layer and the 5-9 inch of all the samples was 3.3% and 4.6%, respectively. Thus, the soils increased in moisture content in the 5-9 inch depth at many of the sites, and were considerably higher in moisture content (Figure 4) than the samples collected and analyzed in 1995.

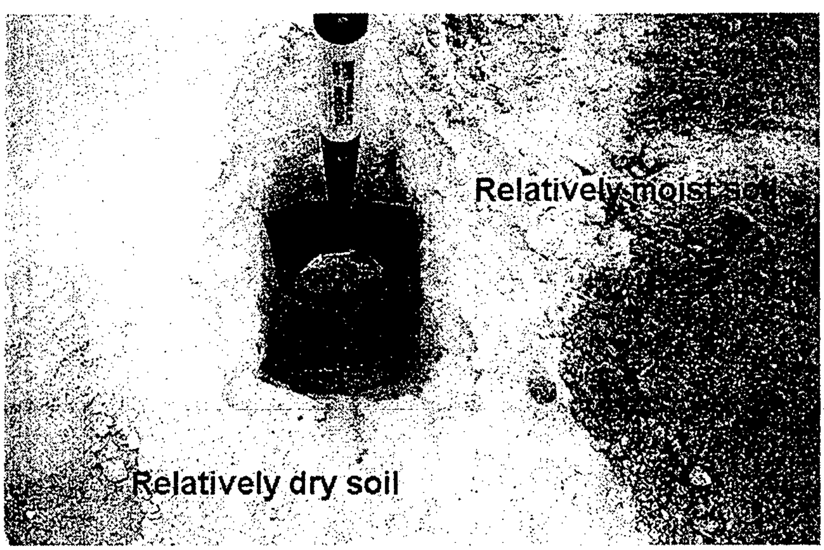

Figure 4. Dry and wet soils. - The soil was dry near the surface (0-4 inches) and relatively moist with depth (5-9 inches).

The soils' particle size were dominated by sands. The average sand percentage was 91.0. The highest sand content was 95.0% at Mines Area 3 sites (Figure 5). Lowest amount was 82.4% in Natural Area 1-1. Clay content ranged from 1.4 to 6.0% with an average of 2.8. The lowest clay contents were for the soils at the Boxes Site 1; highest amounts were in the Natural Area 1-1. Silt content had a wide range, 3.2 to 12.4%. The average silt percentage was 6.2. Gravels or particles > 2mm in size averaged 10.3% but varied from 1.7 to 20.3%. The soils in the Natural Areas were sampled according to gravels on the surface (Figures 2 and 3). This area has not been disturbed, hence the name Natural Area (Figure 6). The average gravel content in the gravelly surface zone was 11.4%, while in the nongravelly surface zone it was 4.4%.

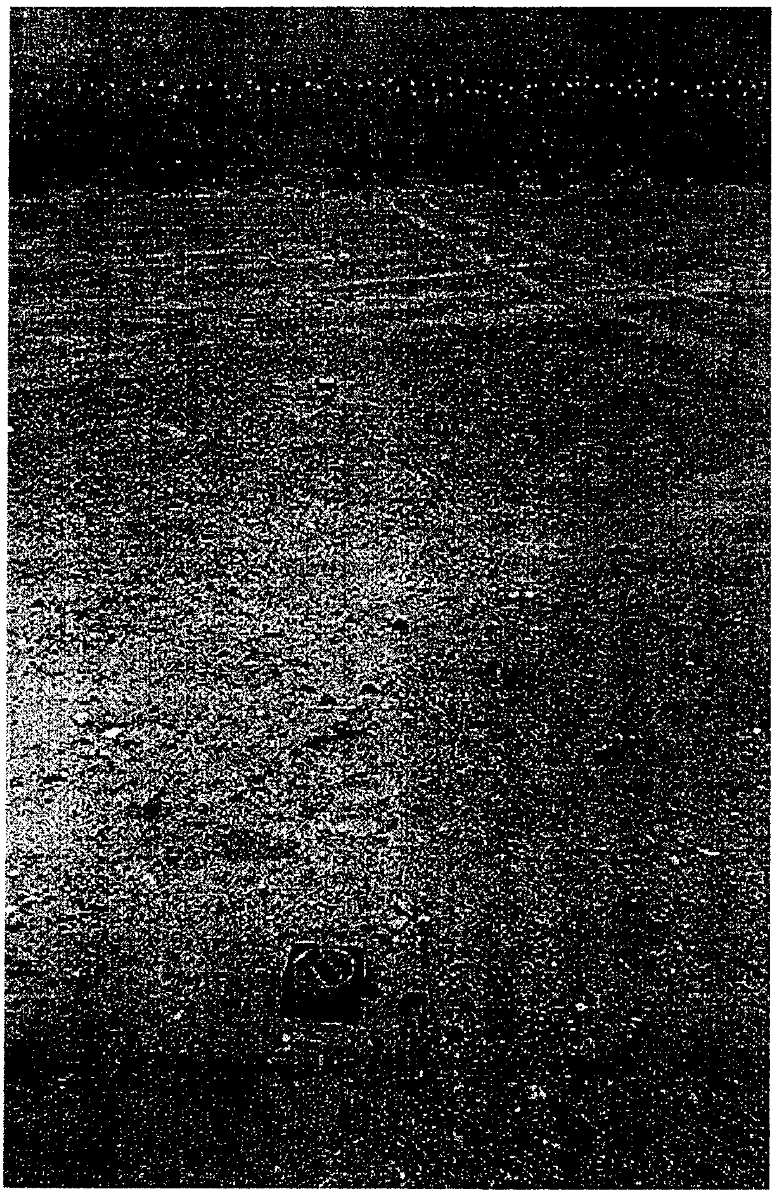

Figure 5. High sand content soils. The high sand content in these soils can be seen in this photo showing where the soils were sampled in the Mines.

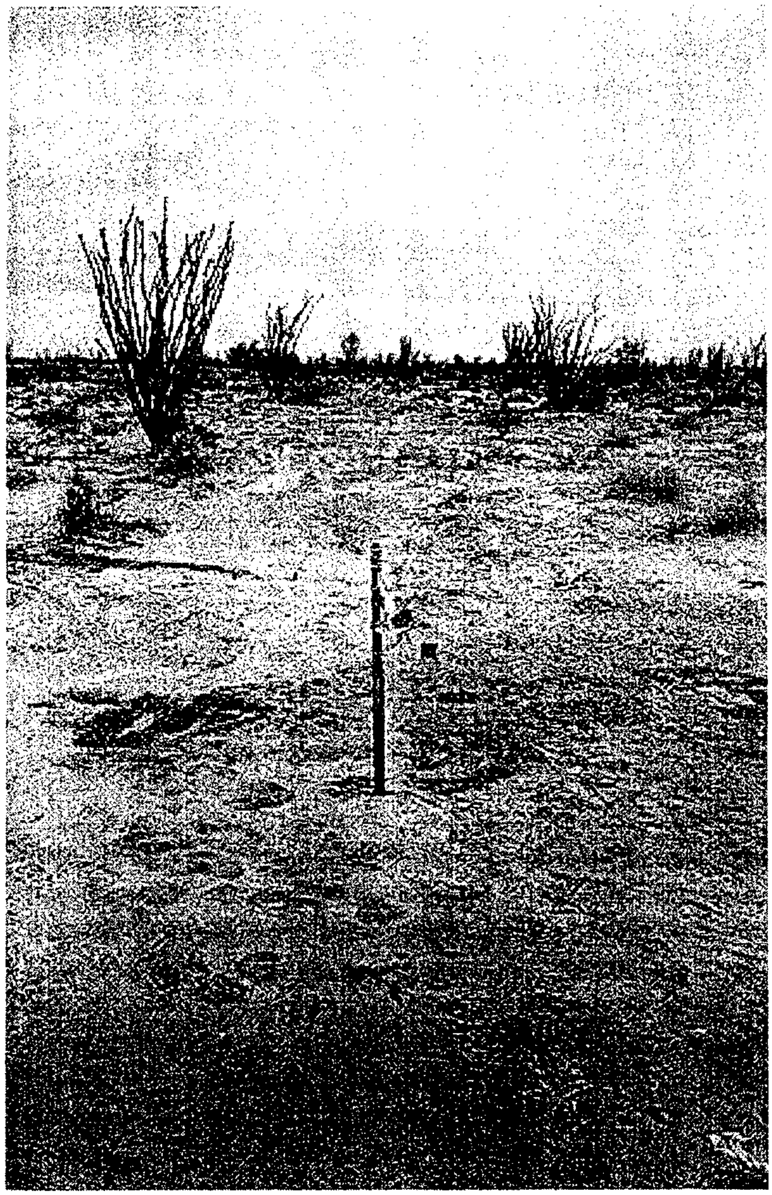

Figure 6. The Natural Area where soils were sampled.

Dry bulk densities (Db_d) (weight of dry soil/volume of soil) were determined.The Db_d includes particles > 2 mm. ranged from 1.91 g cm^{-3} in the 0-4 inch depth at the Mines Area 3 to 1.51 g cm^{-3} in the duplicate sample of the 5-9 inch depth at the Boxes site 1. The average Db_d of all the samples was 1.77 g cm^{-3}. The average Db_d of the 0-4 inch layer was higher than the average Db_d of the 5-9 inch layer (1.80 and 1.73 g cm^{-3}), respectively.

3.4.2 Chemical Soil Properties

Electrical conductivities (EC) were low (average was 0.10 dS/m) indicating that the soil system was saturated with calcium. EC values ranged from 0.07 to 0.14 ds/m. EC values were uniformly low across the entire sampling depth and region. In contrast, the pH values were uniformly high. The average pH was 8.8 with a range of 8.7-9.0

3.4.3 Statistical Correlations

Simple correlations were calculated for the properties analyzed to determine if relationships exist. The data were stratified into 0-4 inch, 5-9 inch and 0-9 inch increments. Correlation coefficients are presented in Table 4.

The highest positive correlation coefficients were between % moisture and % silt with coefficients of 0.82, 0.88 and 0.92 at the 0-4, 5-9, and 0-9 inch depths, respectively. In most soils, clay and moisture contents are more closely related than silt and moisture contents. In these soils though, the silt contents were higher than the clay contents, and this may account for the higher correlations between silt and moisture than clay and moisture contents. The correlation of % moisture and clay were quite high at the 5-9 inch depth (0.64), but were much lower in the 0-4 inch depth (0.26). This relationship is probably because the 0-4 inch depth dries more quickly following rainfall than the 5-9 inch depth, regardless of the clay content in the 0-4 inch depth. Percent moisture and % sand had a high negative correlation as would be expected as the larger sand-size particles have a much lower water-holding capacity than silt or clay.

Smaller negative correlations were calculated between % moisture and gravel as well as % moisture and pH, and % moisture and EC. The larger gravel-size particles obviously have less effect on the water-holding capacity of the soils than the sand, silt, or clay-size particles. A relatively high negative correlation (-0.75) was calculated between % moisture and dry bulk density at the 5-9 inch depth. In this depth range, compared to the 0-4 inch depth, the % moisture increased while the dry bulk density decreased. Also in the 5-9 inch depth, % sand and dry bulk density were positively correlated (0.65) while % silt and % clay and dry bulk density were negatively correlated (-0.65 and -0.55, respectively).

Table 4: Correlation Coefficients of Soil Propertie

	%Moisture	%Gravel	%Sand	%Silt	%Clay	pH	EC dS/m	Dry BD
0-4" Depth								
%Moisture	1							
%Gravel	-0.392796499	1						
%Sand	-0.804116347	0.231907898	1					
%Silt	0.826518795	-0.273872457	-0.943912653	1				
%Clay	0.262268785	0.014851818	-0.540118754	0.231936297	1			
pH	-0.353376746	-0.266508877	0.583644127	-0.477004101	-0.503603267	1		
EC ds/m	-0.41475371	-0.131476243	0.380186146	-0.307344082	-0.336653843	0.556858818	1	
Dry BD	-0.054174768	-0.545378785	0.222414191	-0.155209992	-0.259622694	0.876034165	0.403488654	1
5-9" Depth								
%Moisture	1							
%Gravel	-0.217750246	1						
%Sand	-0.84320823	-0.04450419	1					
%Silt	0.886876517	0.016072445	-0.968888677	1				
%Clay	0.642064571	0.086881894	-0.904384525	0.770636421	1			
pH	-0.782632854	0.16826277	0.783463675	-0.819841417	-0.60380712	1		
EC ds/m	-0.198242283	-0.197900279	-0.003912677	-0.155821794	0.278732687	0.045501576	1	
Dry BD	-0.752496447	0.069472118	0.6507585	-0.650723679	-0.553689161	0.553458301	0.102737086	1
0-9" Depth								
%Moisture	1							
%Gravel	-0.205144792	1						
%Sand	-0.898695138	-0.026417128	1					
%Silt	0.926927396	-0.029403176	-0.950726914	1				
%Clay	0.552070428	0.13105971	-0.7778588	0.544696596	1			
pH	-0.63319381	-0.251500211	0.520449123	-0.568533741	-0.255385573	1		
EC ds/m	-0.336913831	-0.371132694	0.236151209	-0.423440867	0.219535676	0.6040808	1	
Dry BD	-0.431478809	-0.456380663	0.51277512	-0.473025376	-0.42822559	0.728155515	0.635185234	1

4.0 Soil Modeling and Modeling Results

Previous work has been carried out at the University of Florida to develop improved soil models to predict the electromagnetic (EM) characteristics of soils; this work is mainly describe in [4]. but also in [2,3, and 5]. The soil models that have been developed can be used to calculate soil permittivity versus frequency for different soil moisture content. These types of models are important because much of the measured and compiled data that exists on soils pertains to the physical and chemical characteristics of the soil, but little data is usually measured on soil EM characteristics. When EM data is available, it is often limited to low frequency measurements of conductivity and/or dielectric constant, such as the data obtained from the TDR. While this data is of value, more detailed knowledge of soil EM characteristics over frequency is necessary to determine GPR performance, since most GPRs of interest operate over ultra-wideband frequency ranges. A second factor driving the need for models is that soil permittivity varies considerably with moisture and soil EM data for varying moisture is not readily available for most soils.

It is desirable to develop soil EM models which use more commonly known and measured soil properties. The models that have been developed estimate dielectric permittivity from typically available soil properties such as moisture (by weight or volume), soil texture (percent sand, silt, and clay), the soil bulk and specific density. A previous report [1] further describes these and other physical/chemical properties which may significantly affect soil EM characteristics. This report is based on prior University of Florida soils modeling studies [2-5] and other work [10-13].

4.1 Soil Models

A relatively simple model for prediction of soil dielectric permittivity at varying moisture levels was developed by Wang and Schmugge and is found in [14]. The model equations are based on measurements of soil samples which are cited in [14] and taken from several sources listed in that paper. The Wang-Schmugge model was used to estimate the dielectric permittivity of Yuma, Arizona soils for which measured data were available; those results are described in [4]. For certain Yuma soil samples the results were good, but in general, the model does not accurately relate changes in soil composition and moisture changes to the measured soil EM data. These results, in part, led to consideration of the Ulaby/Dobson soil model which is further discussed in this report; this model better utilizes changes in soil composition and moisture to more accurately predict the dielectric permittivity of soil-water mixtures.

The paper by Hallikainen, Dobson, Ulaby, et al. [10 and 11] introduces two soil models for estimating the complex relative dielectric permittivity of soil mixtures at various moisture levels. The authors refer to the models as the four-component and semiempirical model, respectively. Each model has relative merits when considering the accuracy of the model and the availability of measurable properties as inputs. The theory of these models is fundamental to most recent soil modeling efforts to determine soil EM properties. A paper by Peplinski, Ulaby, and Dobson [13] further examines the model proposed in [10-11] but at lower frequencies (<1 GHz). Henceforth, the semiempirical model in [10 and 11] and [13] will be referred to collectively as the Ulaby/Dobson model, as these author's names are cited in both papers.

4.2 Model Parameters

Before describing the model and some results obtained with the model, a review of some of soil terminology and relevant model parameters used will be presented.

The porosity V_p of a soil mixture is defined as follows:

$$V_p = 1 - \rho_b/\rho_s \tag{1}$$

where ρ_b is the bulk density of the soil and ρ_s is the specific density of the soil. These soil properties usually can be estimated or measured. The bulk density was measured for the soils collected at Yuma in September 1997 and reported in the Soil Sampling Results section of this report. The specific density is fairly constant for soils of a given type; for Yuma soils ρ_s is taken to be about 2.6.

Volumetric moisture content, has already been discussed in the TDR section, and is an important quantity affecting soil EM properties. Computation of m_v can be performed as follows:

$$m_v = \rho_b\,(W_w/W_s) \quad cm^3/cm^3 \tag{2}$$

where W_w and W_s are the weight of water in a soil sample and the weight of the dry soil in that sample, respectively. The term W_w/W_s is referred to as gravimetric moisture, m_g.

A term used in the soil model is the dielectric permittivity (real part) of soil, ε_s. Empirical fitting of soil data yields the following equation for ε_s:

$$\varepsilon_s = (1.01 + 0.44\rho_s)^2 - 0.062 \tag{3}$$

An increase in soil moisture content generally causes a corresponding increase in total dielectric permittivity of a soil mixture. Temperature of the soil-water mixture can also affect the dielectric constant. The Debye equation provides estimates for the real and imaginary parts of the dielectric constant of water as a function of frequency, based upon a relaxation model of water and an effective or net conductivity of the water. Assuming a Debye-type relaxation model, the complex permittivity of free water is as follows:

$$\varepsilon'_{fw} = \varepsilon_{w\infty} + \frac{\varepsilon_{w0} - \varepsilon_{w\infty}}{1 + (2\pi f\tau_w)^2} \tag{4}$$

$$\varepsilon''_{fw} = \frac{2\pi f\tau_w(\varepsilon_{w0} - \varepsilon_{w\infty})}{1 + (2\pi f\tau_w)^2} + \frac{\sigma_{mv}}{2\pi\varepsilon_0 f} \tag{5}$$

In equations (4-5), ε'_{fw} and ε''_{fw} are the real and imaginary relative permittivities, respectively, of free water, ε_{woo} is the high-frequency limit of ε_w, ε_{w0} is the static dielectric constant of water, f is the frequency in Hz, τ_w is the relaxation time of water which is dependent upon the approximated salinity of free water $S_{mv} = 0.64\sigma_{mv}$, σ_{mv} is the effective conductivity of water in S/m, and ε_0 is the permittivity of free space, 8.854e-12 F/m.

4.3 Semiempirical Model

The semiempirical model given in [13] and which is used in this report requires fewer measured parameters than other models and is therefore more convenient to use. The model has been tested and compared to measured data for Yuma soils in the 0.3 - 1.3 GHz frequency range. The Ulaby/Dobson model as described in [13] was used with adjustments to better match the soil EM characteristics in this frequency range. The adjusted model is used in this report to make comparisons with EM data collected on soils from the Yuma site. The particular soils tested and compared to the model were collected earlier [1], but the soils came from the Phillips Drop Zone area.

The seimiempirical model 13] provides an expression for the complex relative permittivity of a soil mixture in the form $\varepsilon'_m - j\varepsilon''_m$ as follows:

$$\varepsilon'_m = \left[1 + \frac{\rho_b}{\rho_s}(\varepsilon_s^{\alpha} - 1) + m_v^{\beta'} \cdot \varepsilon'^{\alpha}_{fw} - m_v\right]^{1/\alpha} \tag{6}$$

$$\varepsilon''_m = [m_v^{\beta''} \cdot \varepsilon''^{\alpha}_{fw}]^{1/\alpha} \tag{7}$$

where ρ_b, ρ_s, m_v, ε_{fw}, and ε_s are as previously defined and α, β', and β'' are constants chosen to best approximate the dielectric permittivity with equations (9-10). At high moistures, one must multiply the result given by equation (9) by 1.15 and subtract 0.68, resulting in a linearly adjusted equation for ε'_m at high moisture levels. Note that $\alpha = 0.65$ is an empirically defined constant. Also found empirically were β' and β''; given the mass fractions of sand S and clay C, β' and β'' are determined by the following equations:

$$\beta' = 1.2748 - 0.519S - 0.152C \tag{8}$$

$$\beta'' = 1.33797 - 0.603S - 0.166C \tag{9}$$

Equations (4-5) for the complex permittivity of free water are used in the semiempirical model with a modification of the imaginary component as follows:

$$\varepsilon''_{fw} = \frac{2\pi f\tau_w(\varepsilon_{w0} - \varepsilon_{w\infty})}{1 + (2\pi f\tau_w)^2} + \frac{\sigma_{eff}}{2\pi\varepsilon_0 f} \cdot \frac{\rho_s - \rho_b}{\rho_s m_v} \tag{10}$$

where the terms in (13) are the same as in (8) except for the effective conductivity σ_{eff}, which replaces σ_{mv}. In this model σ_{eff} is found empirically as follows:

$$\sigma_{eff} = 0.0467 + 0.2204\rho_b - 0.4111S + 0.6614C \tag{11}$$

As described in [4], comparisons between measured and predicted EM characteristics using the original Ulaby/Dobson model showed that changes in sand content overwhelm corresponding changes in soil moisture and/or clay content. Results of a sensitivity analysis were used to make adjustments in the parameters of the semiempirical model. Refinement of the parameters resulted in the following updated equations for β', β'', and σ_{eff}:

$$\beta' = 1.10 - 0.050S - 0.15C \tag{12}$$

$$\beta'' = 0.98 - 0.14S - 0.10C \tag{13}$$

$$\sigma_{eff} = -0.040 + 0.204\rho_b - 0.23S + 0.10C \tag{14}$$

These equations β', β'', and σ_{eff} are used for the current calculations.

4.4 Comparisons of Semiempirical Model to Yuma Data

The Ulaby/Dobson semiempirical model was used to estimate the dielectric properties of Yuma soil samples from several locations over a range of relatively low moisture levels (up to 10% by weight). Although Yuma soil EM measurements were recorded over the frequency range of 30 MHz to 1.3 GHz, the Ulaby/Dobson model is designed for use in the 0.3-1.3 GHz range. Plots relating measured and predicted permittivities exhibit a drastic overshoot in modeled conductivity at frequencies below 50 MHz and some error below 75 MHz. Since the model does not accurately predict the dielectric properties of soils at frequencies below 50 MHz well, the following analysis was performed at frequencies above 50 MHz.

For the modeling, six different soils with textures representative of most of the soils encountered at Phillips Drop Zone were used; these soils are listed in Table 5. The gravimetric moisture of the soil as originally tested at the University of Florida is also shown in Table 5, as m_g. This moisture is used as a comparison point to match the model predicted EM data to the measured EM data. Other physical/chemical properties of these soils is shown in other reports [1-5]. In the following analysis the modified Ulaby/Dobson model is used to calculate the complex dielectric permittivity of the soil-water mixtures for gravimetric moisture of 1-10%. The reason for using these particular soils is that the texture (per cent sand and clay) covers the range of most soils at YPG Phillips Drop Zone, the soils' texture is similar to those collected in September 1997, and the model matches the EM data for these soils fairly well. The results of the model calculations are shown in Appendix B.

Table 5: Composition of Samples Measured by Ulaby/DobsonUlaby/Dobson

Soil sample	Location	Sand (%)	Clay (%)	Gravimetric Moisture (%)
Sample YA141	Natural area site 14	85.4	2.6	1.70
Sample YA2	Boxes area B1	86.2	2.4	1.57
Sample YA6	Boxes area B1	88.6	2.6	2.43
Sample YA32	Clones Area Cc	89.6	2.8	2.68
Sample YA67	Wires and Pipes D9a	91.2	2.7	0.49
Sample YA74	Wires and Pipes D9a	95.2	1.1	1.28

Soil Attenuation

Of interest in radar applications is the attenuation of a signal through the soil medium. In order to find normalized attenuation in dB/m, one must first calculate the attenuation factor α given the real and imaginary soil permittivity ε' and ε'', respectively, as well as the permittivity and permeability of free space, ε_0 and μ_0. Calculation of α is as follows:

$$\alpha = \omega \times \sqrt{0.5 \times \mu_0(\varepsilon_0(\varepsilon''))} \times \sqrt{\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1} \qquad (15)$$

Determination of one-way attenuation in dB/m follows directly from (18):

$$\text{attenuation} = 20.0 \log(e^{\alpha}) \qquad (16)$$

Discussion of Model Results

Shown in Appendix B are plots of the complex dielectric permittivity versus frequency for the soils in Table 5. calculated using the modified Dobson/Ulaby model of equations 6 and 7 with the required parameters. The conductivity is calculated at $\omega\ \varepsilon''_m$ and plotted versus frequency. Also shown in Appendix B is a plot of the one-way attenuation for each soil versus frequency calculated using equation 15 and 16. Each plot is calculated for ten values of gravimetric moisture, usually ranging from 1-10% (or in the case of YA 67 from 0.5% to 9.5%). Shown in each plot, as a solid line, is the measured value of the dielectric permittivity data at one gravimetric moisture which was used to match to the model. There is a significant variance of the measured data (and terms calculated from the measured data), versus frequency. The reason for this variance is, in part, related to the measuring instrument and measurement technique (the soil sample is only brought into surface contact with a measuring probe). One result of the variance in the measured data is that the modeled data only matches the measured data over a range of frequencies, since the model results in smooth curves, essentially fitting the data. To improve the utility of the model data, a set of tables follows the graphs in Appendix B. A table for each soil lists the real permittivity, imaginary permittivity, conductivity, attenuation, and surface reflection at ten moistures and seven frequencies (the table entries are calculated by averaging the graphical data within about 25MHz of the listed frequency). All calculations assume normal incidence of the EM wave. Each group of plots the data in the corresponding table is briefly described below. In all cases below when comparing the measured data and the model data, the comparison is made at the reference gravimetric moisture, unless otherwise specified (i. e., the data to which the model was matched).

The data for soil YA141 show the typical tendencies of the model as compared to the measured data. The model estimates the real dielectric permittivity as nearly constant over the calculated frequency range. The measured data increases as frequency decreases. The measured data at m_g = 1.7% is slightly higher than the calculated data falling between 2 and 3% at high frequencies and mostly between 3 and 4% at lower frequencies. The lowest calculated real permittivity for this soil, near 1% moisture, is about 2.99; the highest calculated real permittivity at 10% moisture, near 1.1GHz, is about 6.4. The calculated imaginary permittivity generally matches the shape of the measured imaginary dielectric permittivity and the calculated values are somewhat higher than the measured values at frequencies above about 75 MHz. The lowest imaginary permittivity for this soil, near 1% moisture, is about 0.15 near 1.1 GHz; the highest imaginary permittivity at 10% moisture, near 75MHz, is about 1.15. The measured and calculated conductivity, which are directly related to the imaginary permittivity, show that the measured curve lies between the calculated curves for moisture contents between about 1% and 2% (over most of the frequency range). The lowest modeled conductivity for this soil, near 1% moisture, is about 2.4 mS/m; the highest conductivity at 10% moisture, near 1.1GHz, is about 31.4 mS/m. The attenuation plot is similar in shape to the conductivity. The lowest attenuation for this soil, near 1% moisture, is about 4.4 dB/m near 75 MHz; the highest attenuation, near 1.1GHz, is about 41.7dB/m. The lowest surface reflection loss, near 75 MHz, is about 7.2dB at 10% moisture; the highest reflection loss for this soil, near 1% moisture, is about 11.5 dB at 1.1GHz.

The data for soil YA2 again show the typical tendencies of the model. That is, the model estimates the real dielectric permittivity as nearly constant over the calculated frequency range and the measured data increases as frequency decreases. The measured data at m_g = 1.57% is slightly higher than the calculated data falling between 1 and 2% at high frequencies and mostly between 2 and 3% at lower frequencies. The lowest calculated real permittivity for this soil, near 1% moisture, is about 2.99; the highest calculated real permittivity at 10% moisture, near 1.1GHz, is about 6.4. The calculated imaginary permittivity generally matches the shape of the measured imaginary dielectric permittivity and, in this case, the calculated and measured values are closely matched at frequencies above about 75 MHz. The lowest imaginary permittivity for this soil, near 1% moisture, is about 0.15 near 1.1 GHz; the highest imaginary permittivity at 10% moisture, near 75MHz, is about 1.36. The measured and calculated conductivity, which are directly related to the imaginary permittivity, show that the measured curve lies between the calculated curve for moisture contents between about 1% and 4%. The lowest modeled conductivity for this soil, near 1% moisture, is about 2.5 mS/m; the highest conductivity at 10% moisture, near 1.1GHz, is about

32.2 mS/m. The attenuation plot is similar in shape to the conductivity. The lowest attenuation for this soil, near 1% moisture, is about 4.6 dB/m near 75 MHz; the highest attenuation, near 1.1GHz, is about 41.6dB/m. The lowest reflection loss, near 75 MHz, is about 7.2dB at 10% moisture; the highest reflection loss for this soil, near 1% moisture, is about 11.2 dB at 1.1GHz.

The data for soil YA6 shows similar tendencies to the model data for soil YA2. That is, the model estimates the real dielectric permittivity as nearly constant over the calculated frequency range. The measured data increases as frequency decreases. The measured data at $m_g = 2.43\%$ is slightly lower than the calculated data falling between 1 and 2% at high frequencies and falls mostly between 2 and 3% at lower frequencies. The lowest calculated real permittivity for this soil, near 1% moisture, is about 2.99; the highest calculated real permittivity at 10% moisture, near 1.1GHz, is about 6.4. The calculated imaginary permittivity generally matches the shape of the measured imaginary dielectric permittivity and, in this case, the calculated and measured values are closely matched at frequencies above about 75 MHz The lowest imaginary permittivity for this soil, near 1% moisture, is about 0.13 near 1.1 GHz; the highest imaginary permittivity at 10% moisture, near 75MHz, is about 1.13. The measured and calculated conductivity, which are directly related to the imaginary permittivity, show that the measured curve lies between the calculated curve for moisture contents between about 1% and 3%. The lowest conductivity for this soil, near 1% moisture, is about 2. mS/m; the highest conductivity at 10% moisture, near 1.1GHz, is about 29.1 mS/m. The attenuation plot is similar in shape to the conductivity. The lowest attenuation for this soil, near 1% moisture, is about 3.9 dB/m near 75 MHz; the highest attenuation, near 1.1GHz, is about 37.6dB/m. The lowest reflection loss, near 75 MHz, is about 7.2dB at 10% moisture; the highest reflection loss for this soil, near 1% moisture, is about 11.3 dB at 1.1GHz.

The data for soil YA32 shows similar tendencies to the model data for soil YA2 and YA67 below. That is, the model estimates the real dielectric permittivity as nearly constant over the calculated frequency range. The measured data increases as frequency decreases. The measured data at $m_g = 2.68\%$ is slightly lower than the calculated data falling below 1% at higher frequencies and between 1 and 2% at lower frequencies. The lowest calculated real permittivity for this soil, near 1% moisture, is about 2.99; the highest calculated real permittivity at 10% moisture, near 1.1GHz, is about 6.4. The calculated imaginary permittivity generally matches the shape of the measured imaginary dielectric permittivity and, in this case, the calculated and measured values are closely matched at frequencies above about 75 MHz, although the imaginary permittivity falls below the calculated permittivity. The lowest imaginary permittivity for this soil, near 1% moisture, is about 0.12 near 1.1 GHz; the highest imaginary permittivity at 10% moisture, near 75MHz, is about 1.07. The measured and calculated conductivity, which are directly related to the imaginary permittivity, show that the measured curve lies between the calculated curve for moisture contents between about 1% and 3%. The lowest modeled conductivity for this soil, near 1% moisture, is about 2. mS/m; the highest conductivity at 10% moisture, near 1.1GHz, is about 29.1 mS/m. The attenuation plot is similar in shape to the conductivity. The lowest attenuation for this soil, near 1% moisture, is about 3.9 dB/m near 75 MHz; the highest attenuation, near 1.1GHz, is about 28.5dB/m. The lowest reflection loss, near 75 MHz, is about 7.2dB at 10% moisture; the highest reflection loss for this soil, near 1% moisture, is about 11.5 dB at 1.1GHz.

The data for soil YA67 shows similar tendencies to the model data for soil YA32 (and is also similar to YA74 that follows). That is, the model estimates the real dielectric permittivity as nearly constant over the calculated frequency range. The measured data increases as frequency decreases. The model data in the graphs is calculated for m_g = 0.5 to 9.5% moisture in this case. The measured data at m_g = 0.49% is slightly lower than the calculated data falling below 0.5% at higher frequencies and between 0.5 and 1.5% at lower frequencies. The lowest calculated real permittivity for this soil, near 0.5% moisture, is about 2.99; the highest calculated real permittivity at 9.5% moisture, near 1.1GHz, is about 6.3. The calculated imaginary permittivity generally matches the shape of the measured imaginary dielectric permittivity and, in this case, the calculated and measured values are closely matched at frequencies above about 75 MHz; although the imaginary permittivity falls below the calculated permittivity. The lowest imaginary permittivity for this soil, near 1% moisture, is about 0.11 near 1.1 GHz; the highest imaginary permittivity at 10% moisture, near 75MHz, is about 0.97. The measured and calculated conductivity, which are directly related to the imaginary permittivity, show that the measured curve lies mostly below the calculated curve for a moisture content of 0.5%. The lowest modeled conductivity for this soil, near 1% moisture, is about 1.8. mS/m; the highest conductivity at 10% moisture, near 1.1GHz, is about 27.2 mS/m. The attenuation plot is similar in shape to the conductivity. The lowest attenuation for this soil, near 1% moisture, is about 3.4 dB/m near 75 MHz; the highest attenuation, near 1.1GHz, is about 35.2dB/m. The lowest reflection loss, near 75 MHz, is about 7.2dB at 10% moisture; the highest reflection loss for this soil, near 1% moisture, is about 11.5 dB at 1.1GHz.

The data for soil YA74 shows similar tendencies to the model data for soil YA67. That is, the model estimates the real dielectric permittivity as nearly constant over the calculated frequency range. The measured data increases as frequency decreases. The measured data at m_g =1.28% is somewhat lower than the calculated data falling below 1% at all frequencies. For this reason we can expect the modeled real permittivity to be high for this soil. The lowest calculated real permittivity for this soil, near 1% moisture, is about 2.99; the highest calculated real permittivity at 10% moisture, is about 6.41 at this frequency. The calculated imaginary permittivity generally matches the shape of the measured imaginary dielectric permittivity and, in this case, the calculated and measured values are closely matched at frequencies above about 75 MHz, although the measured imaginary permittivity falls below the calculated permittivity. The lowest imaginary permittivity for this soil, near 1% moisture, is about 0.08 near 1.1 GHz; the highest imaginary permittivity at 10% moisture, near 75MHz, is about 0.67. The measured and calculated conductivity, which are directly related to the imaginary permittivity, show that the measured curve lies mostly below the calculated curve for a moisture content of 1%. The lowest modeled conductivity for this soil, near 1% moisture, is about 1.2. mS/m; the highest conductivity at 10% moisture, near 1.1GHz, is about 23.4 mS/m. The attenuation plot is similar in shape to the conductivity. The lowest attenuation for this soil, near 1% moisture, is about 2.3 dB/m near 75 MHz; the highest attenuation, near 1.1GHz, is about 30.2dB/m. The lowest reflection loss, near 75 MHz, is about 7.2dB at 10% moisture; the highest reflection loss for this soil, near 1% moisture, is about 11.5 dB at 1.1GHz.

The last set of curves in Appendix B compares modeled data for YA141 and YA74 which are the soils with the highest and the lowest sand content, respectively. Following the graphs are the tables which summarize the data for each soil at seven frequencies.

Utility of Model Data

The model data in Appendix B can be used to make certain performance estimates for ground penetrating radar. For example, if the soil texture and moisture content is known then the graph or table with the closest soil texture (to one under consideration) can be used to estimate permittivity, conductivity, attenuation loss, and reflectivity loss. The moisture can be estimated with the TDR; as noted above, accuracy improves if the moisture is above several per cent.

An alternative use of the Appendix B data is to use the soil with closest match to the TDR permittivity and moisture data at the lowest calculated frequency, then estimate the parameters at other moisture content or frequencies from the graphs or tables. Since modeled real permittivity has the largest errors, matching the imaginary permittivity or conductivity may be more accurate. As an example, the Mines Area 3 TDR readings indicated real permittivity of about 3., m_v of 4.1% (m_g of about 2.1%), and σ_{gt} of 2.8 mS/m. This would match closely with the data for soil YA32 or YA6; that is, at 2% m_g the conductivity is 2.43 and 2.5 mS/m for these two soils respectively. It would be reasonable to use the model data for these soils for the soil in the Mines Area 3.

Estimates of GPR signal attenuation due to surface loss and through-the-soil loss can be made from the graphs or tables in Appendix B. The estimates can be made by esitmaing the surface loss and through-the-soil loss at mid-frequency from the graphs or tables. By multiplying the attenuation [dB/m] by the depth of the target and doubling that loss the two-way soil loss is obtained. This loss is added to the surface loss to obtain to total loss due to these two factors. Dispersion effects and target loss will generally increase the actual attenuation of the GPR signal. If the GPR transmit spectrum is known, that spectrum can be multiplied times the attenuation and reflection curves to obtain the resultant return signal in the frequency domain. The ratio of the equivalent receive energy to the transmit energy can then be calcuated to estimate the GPR signal loss. This is a more involved calculation, but potentially more accurate.

5.0 Summary

This report describes work performed by the University of Florida for the Army Research Laboratory to further characterize soils at Yuma Proving Ground. The soils at selected UXO test sites at Phillips Drop Zone were collected in September 1997 and both field tests and laboratory tests were performed.

The current efforts concentrated on better determining the near-surface (< 9") properties of the soils and YPG during the late September 1997 tests. Time domain reflectometry tests of dielectric constant, moisture, and conductivity indicated that the soils contained more moisture, on average, that was present during previous tests. Field tests were performed to allow a later determination of bulk density of the soils, which had not previously been measured by the University of Florida at YPG. Laboratory tests on the soils were performed to measure or calculate gravimetric moisture, particle size (% sand, % clay, % silt, and % gravel), dry bulk density, pH and DC electrical conductivity. Comparisons of the laboratory tests to field TDR tests confirmed the higher moisture (compared to previous tests).

Previously developed soil models were used with six representative Yuma soils to calculate dielectric permittivity, conductivity, soil attenuation, and surface reflection loss versus frequency from 50 MHz to 1.3 GHz, with varying moisture content. The model data is compared to the measured data and presented in graphs and tables for gravimetric moisture contents ranging from 0 to 10%. The model results can be used to estimate soil attenuation and surface loss for a ground penetrating radar operating in this frequency range at YPG. Other loss factors (i.e., dispersion and target loss) are not considered in this report.

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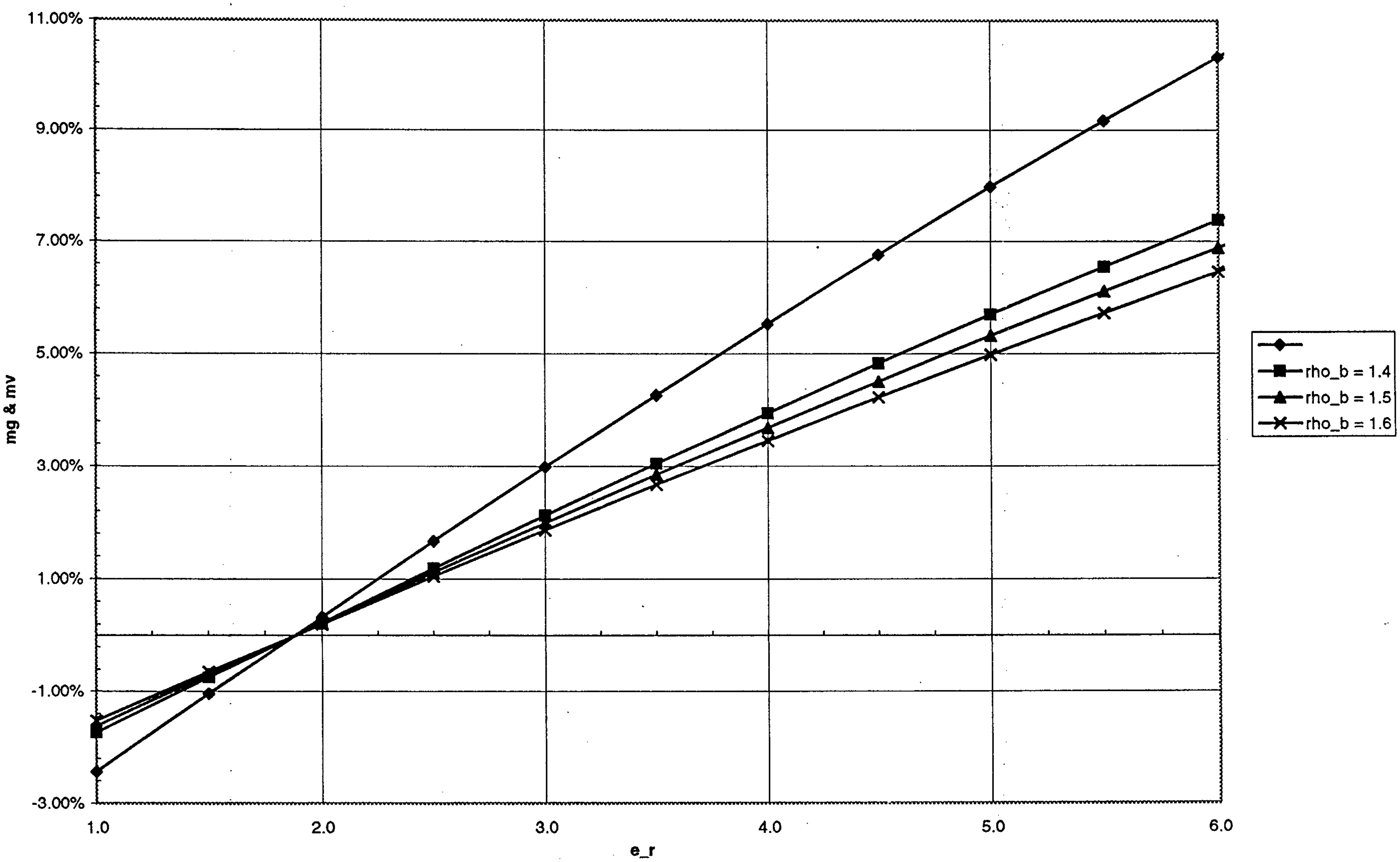
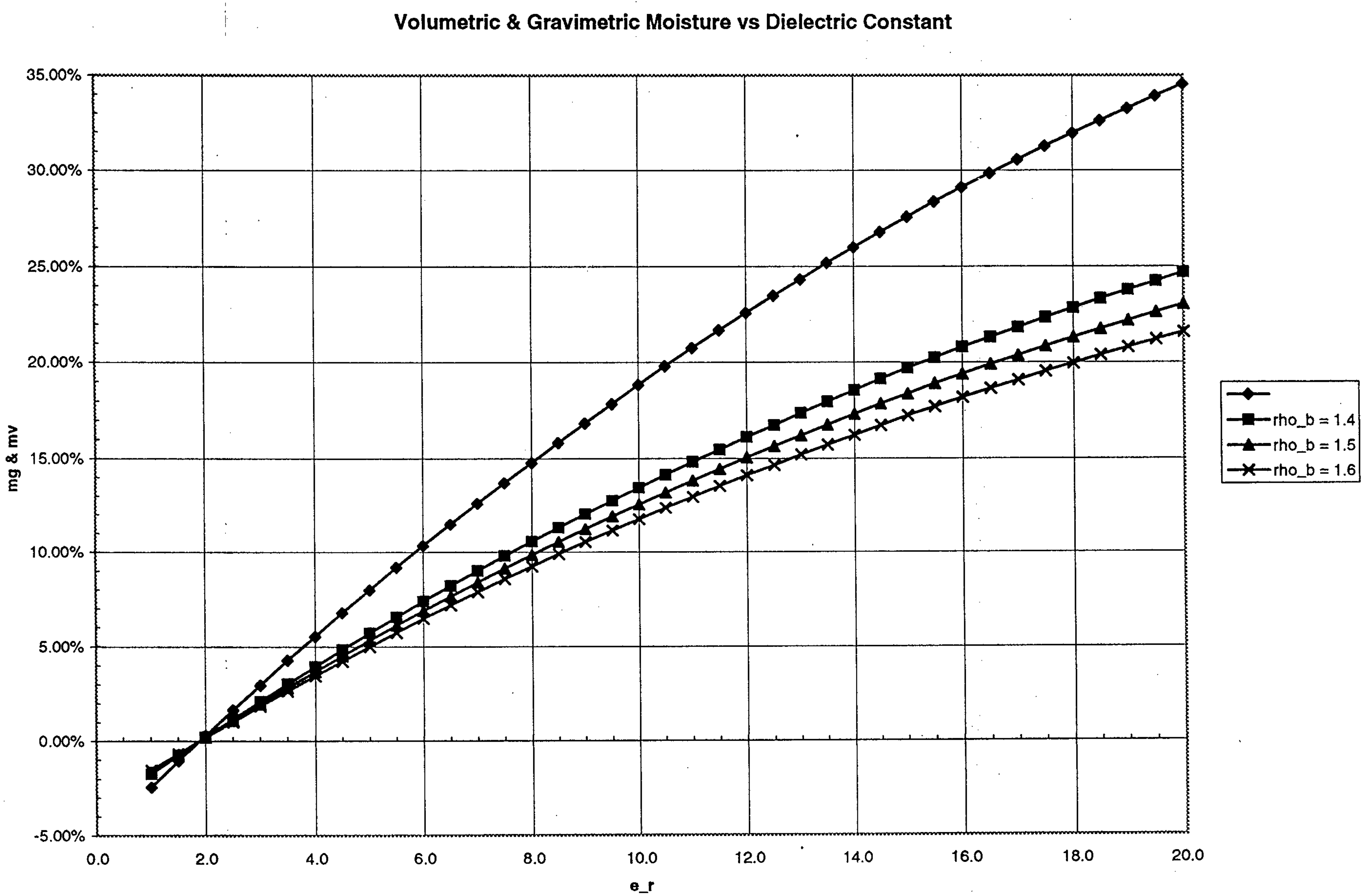
Appendix A. Volumetric and gravimetric moisture versus dielectric constant as measured with the time domain reflectometer.

Note:
Gravimetric moisture is plotted as the volumetric moisture (top curve for high moisture content) divided by the bulk density for three bulk density values, 1.4, 1.5, and 1.6.

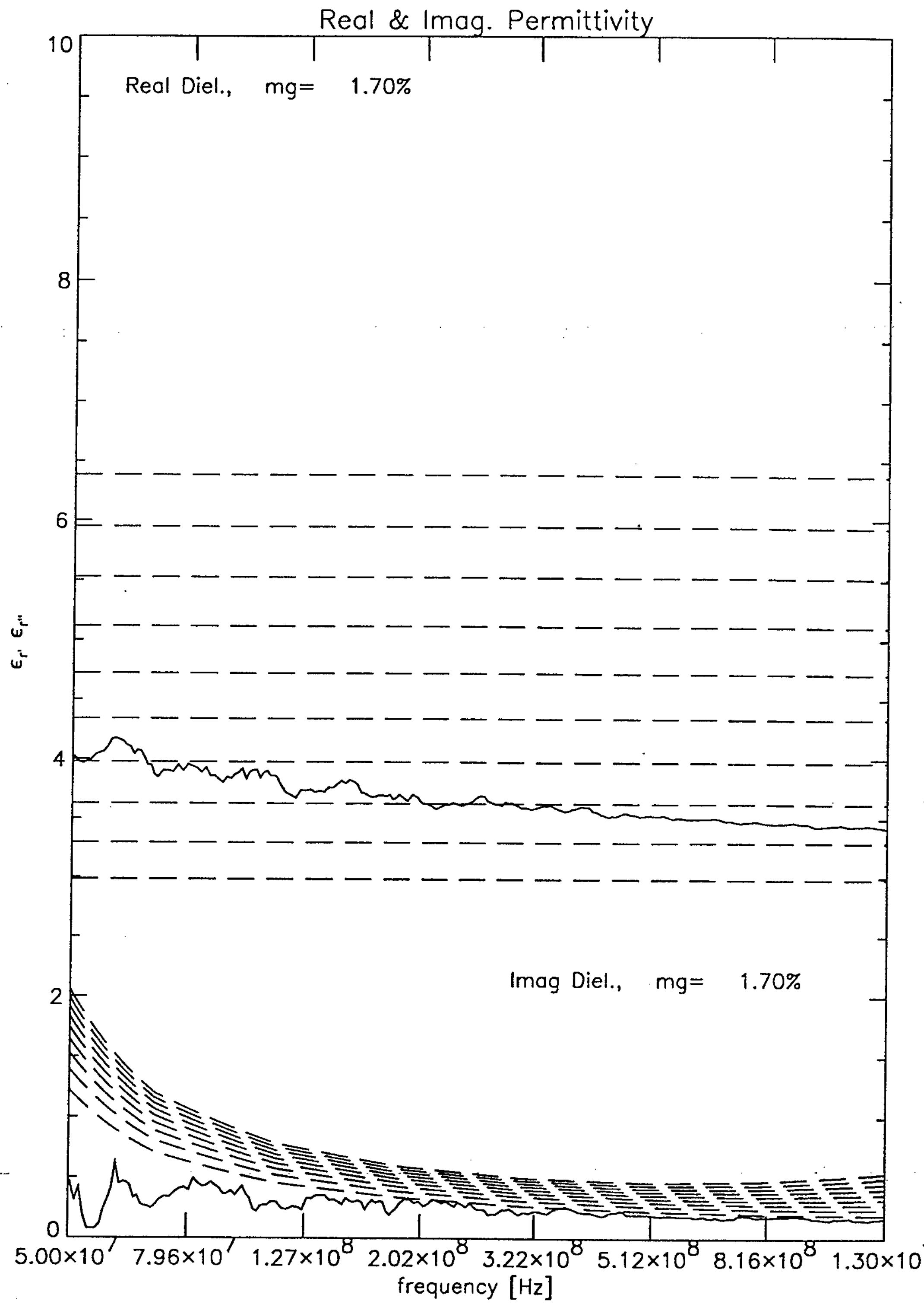
Volumetric & Gravimetric Moisture vs Dielectric Constant



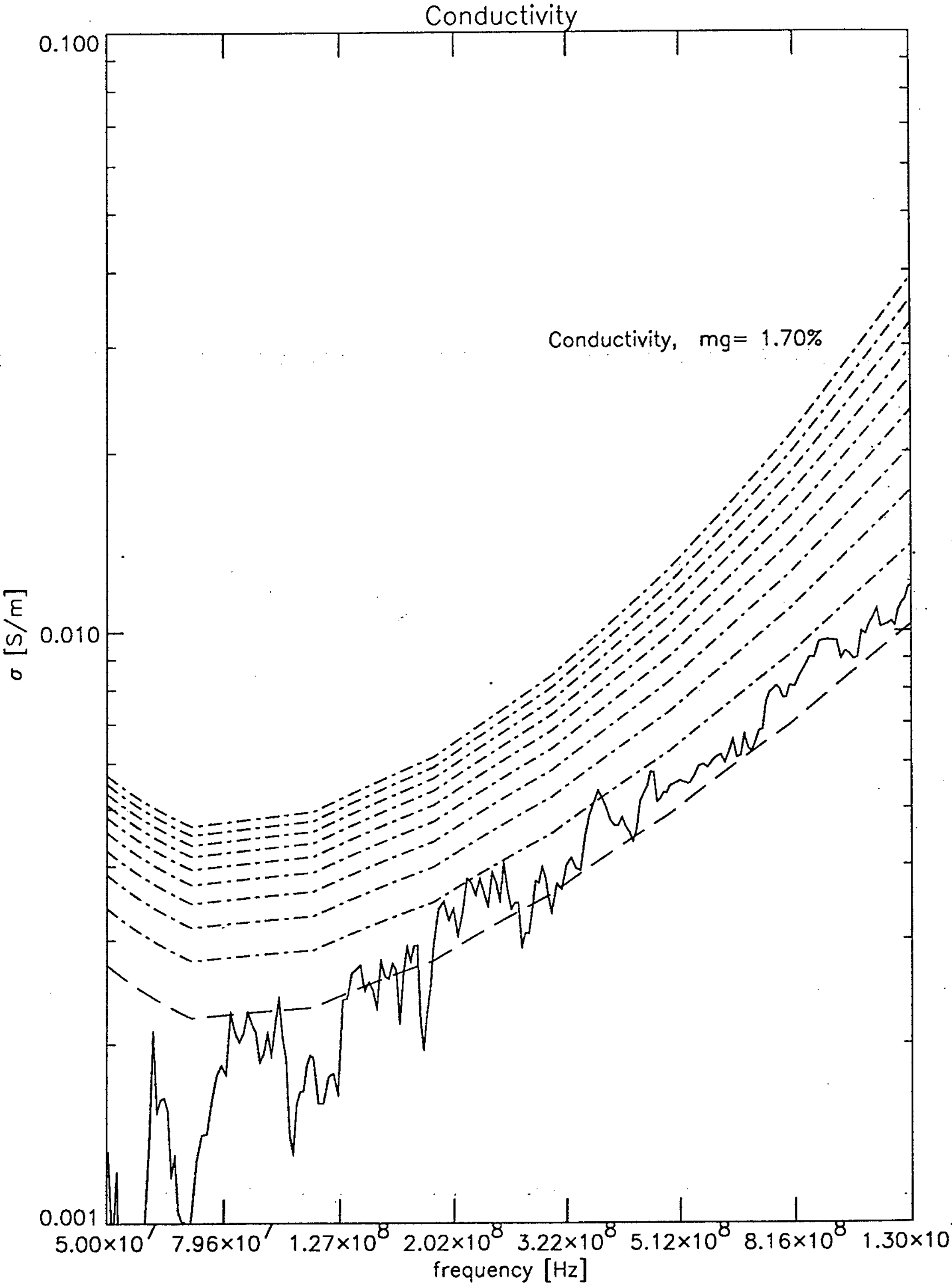


Volumetric & Gravimetric Moisture vs Dielectric Constant
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
-5.00%
mg & mv
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
e_r
rho_b = 1.4
rho_b = 1.5
rho_b = 1.6

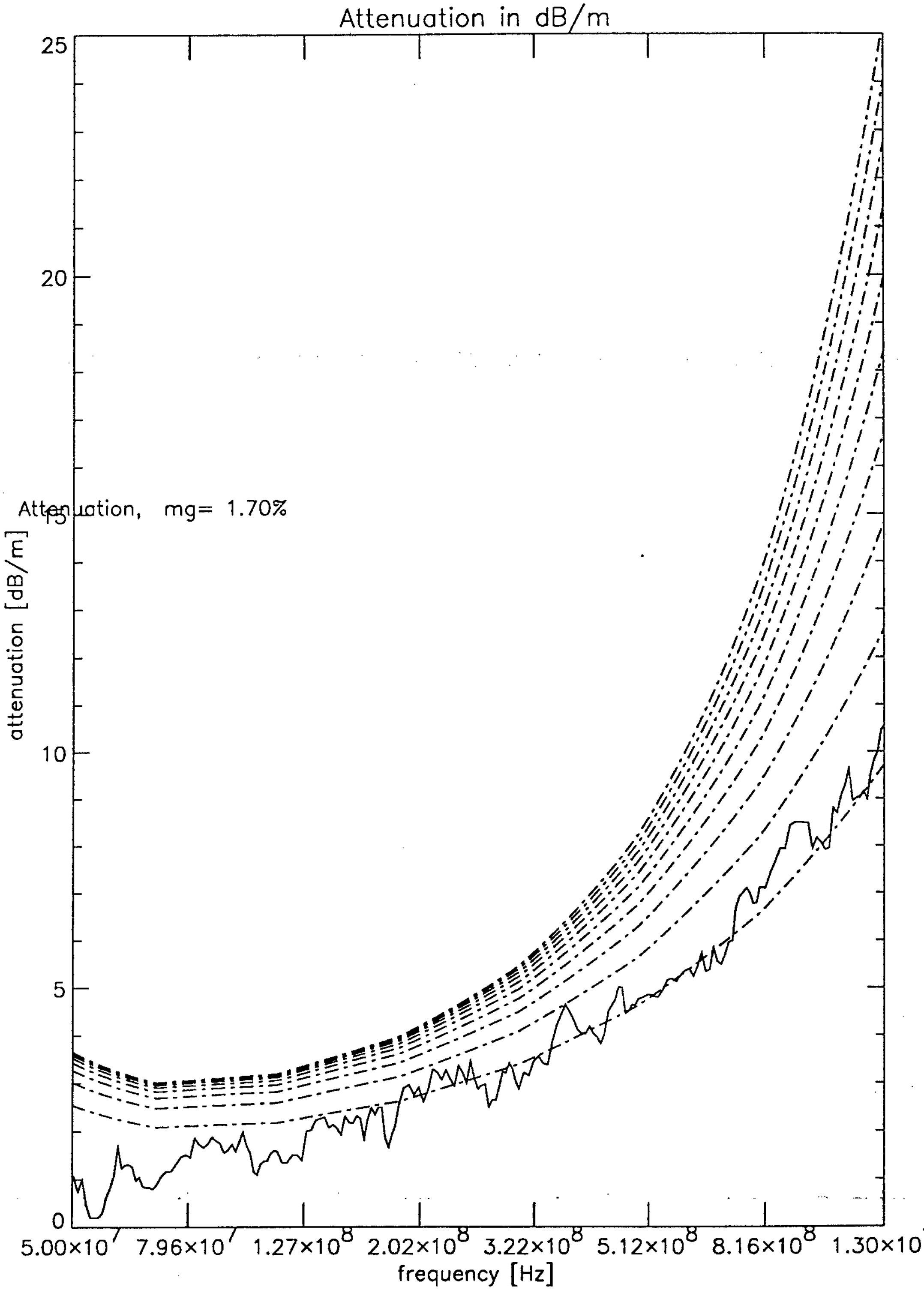
Appendix B. Graphs and tables of modelled dielectric permittivity, conductivity, attenuation, and surface reflection loss for selected soils at Yuma Proving Ground.



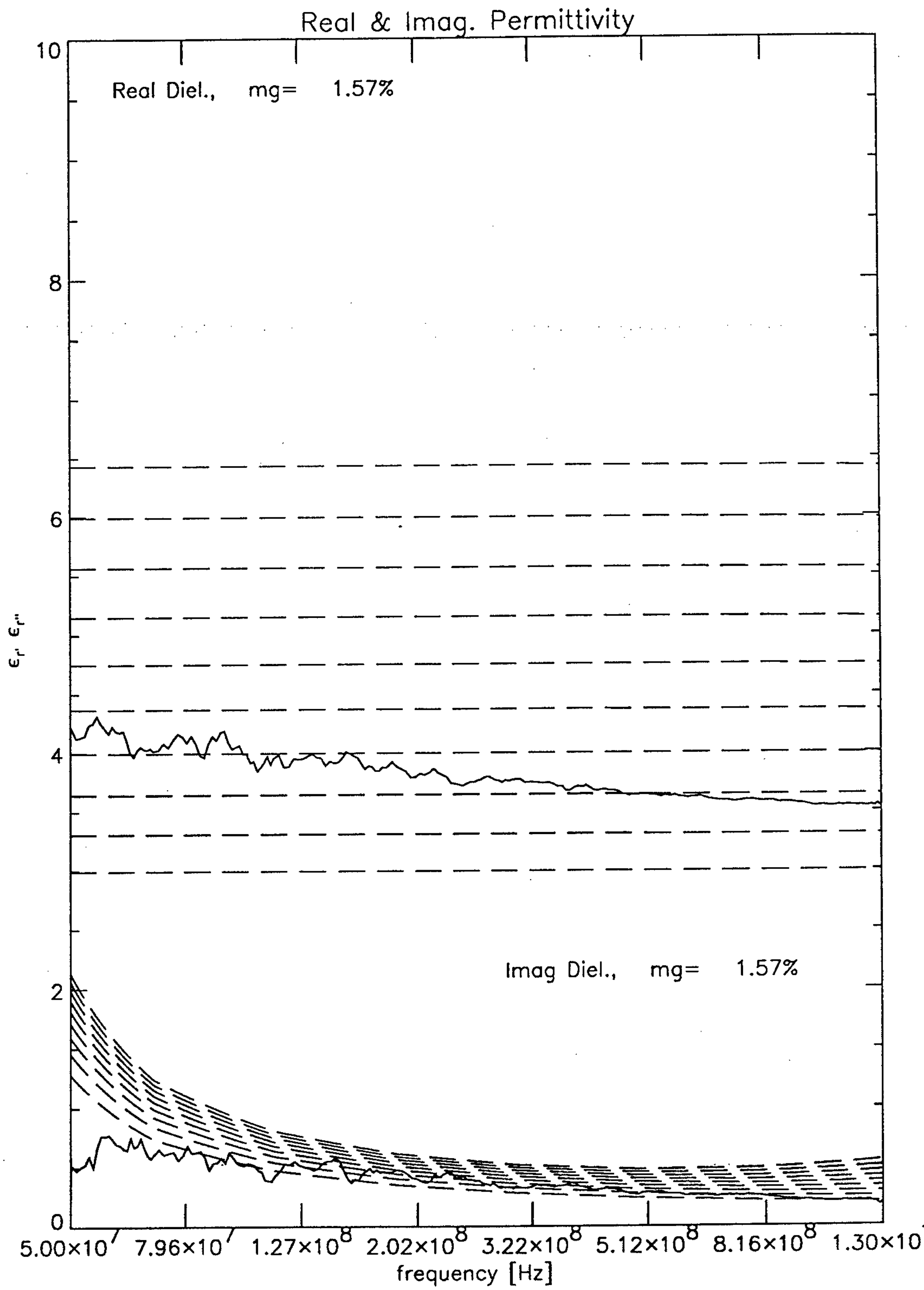
Sample 14 YA141, mg = 1.70, %Clay = 2.6, %Sand = 85.4
(sweep for mg = 1 -> 10)



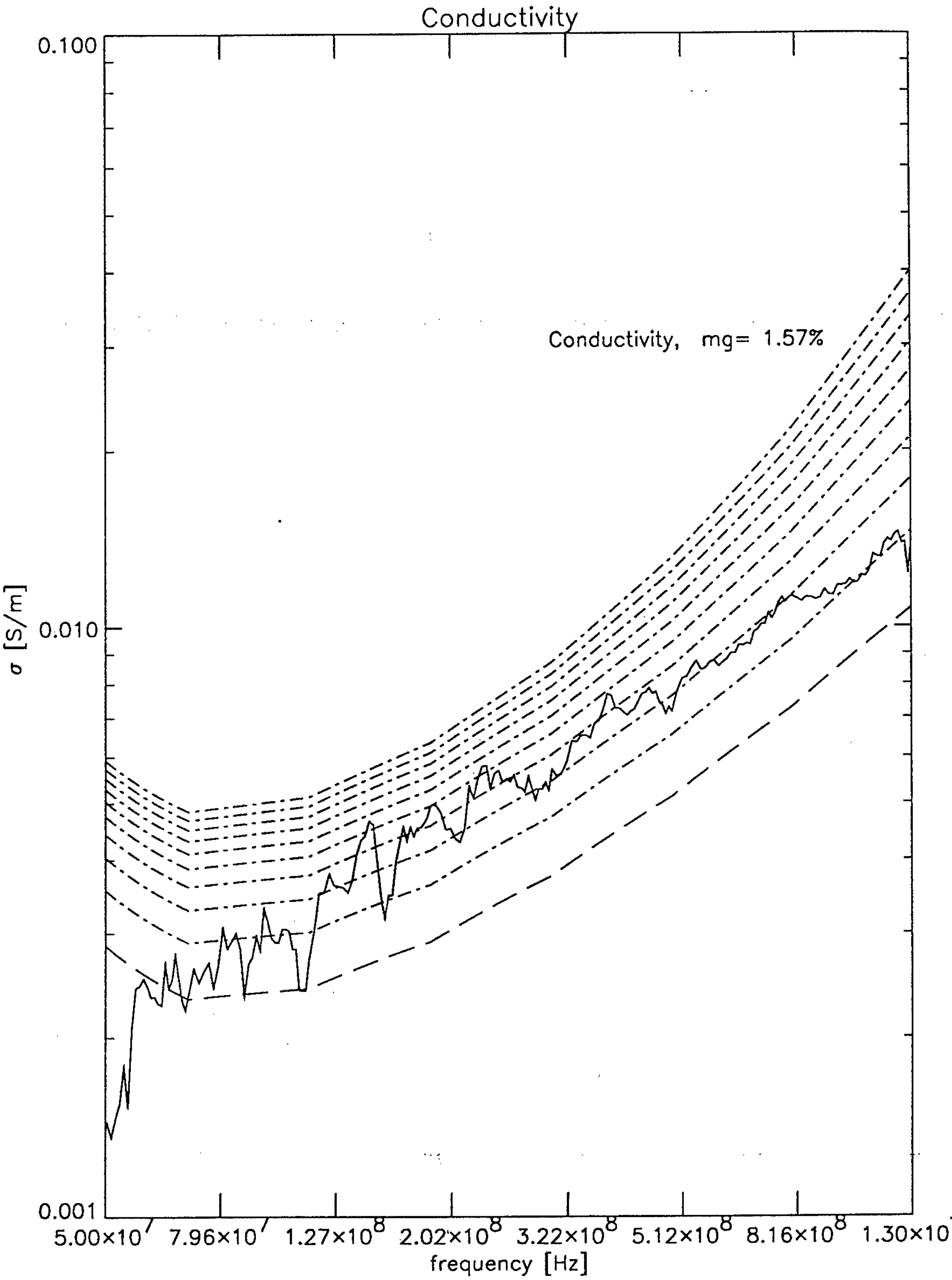
Sample 14 YA141, mg = 1.70, %Clay = 2.6, %Sand = 85.4
(sweep for mg = 1 -> 10)



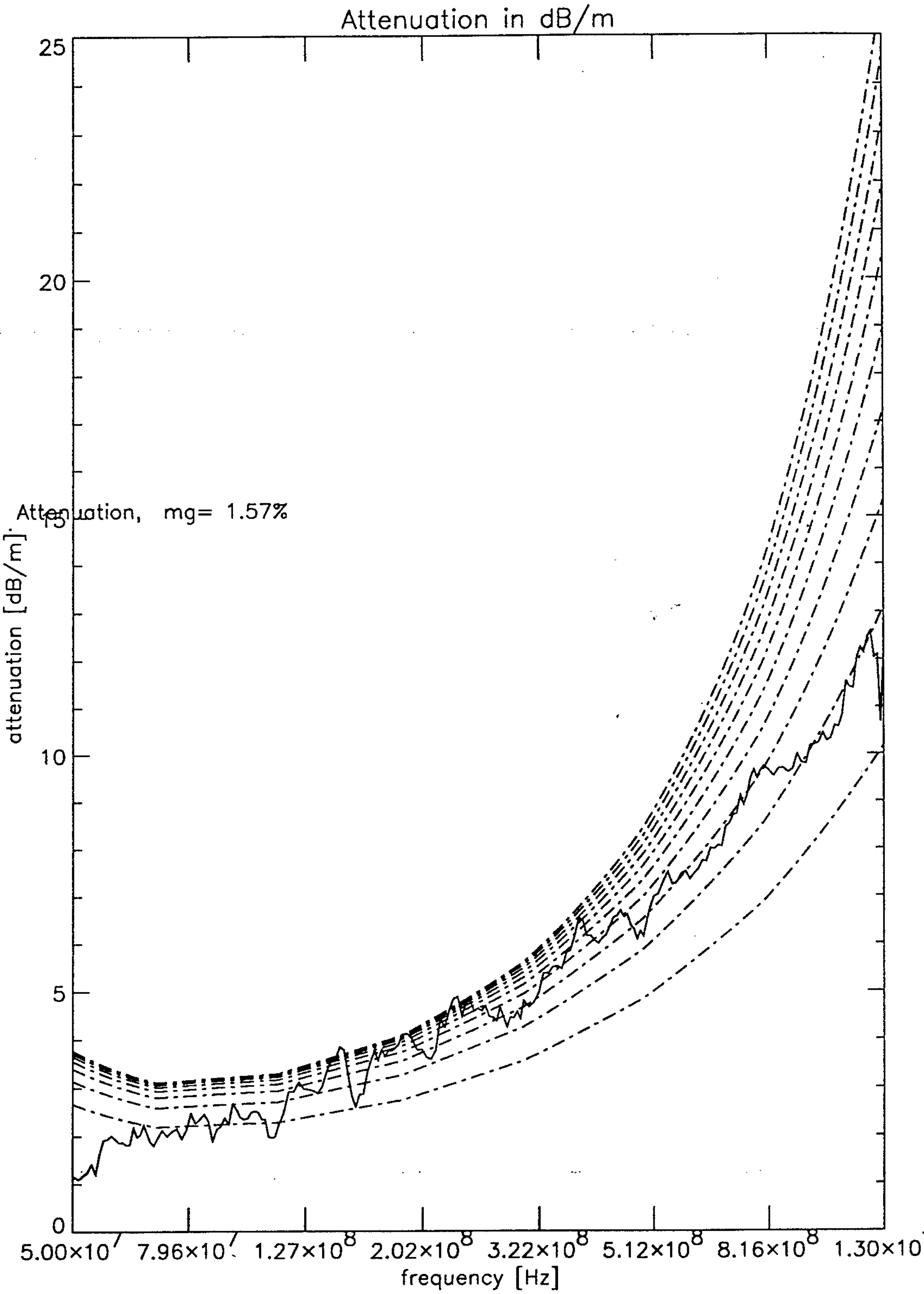
Sample 14 YA141, mg = 1.70, %Clay = 2.6, %Sand = 85.4
(sweep for mg = 1 -> 10)



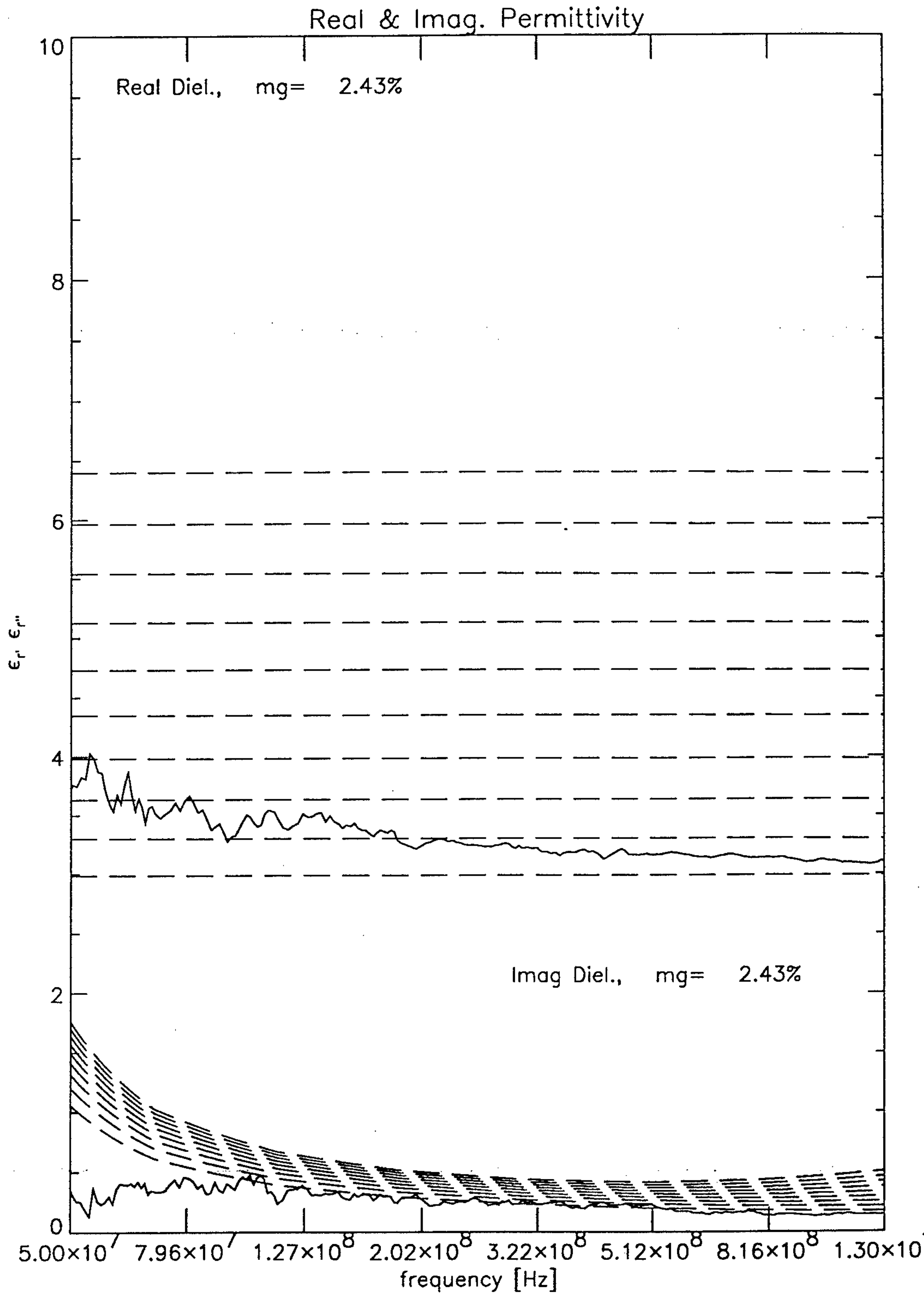
Sample B1 YA2, mg = 1.57, %Clay = 5.4, %Sand = 86.2
(sweep for mg = 1 -> 10)



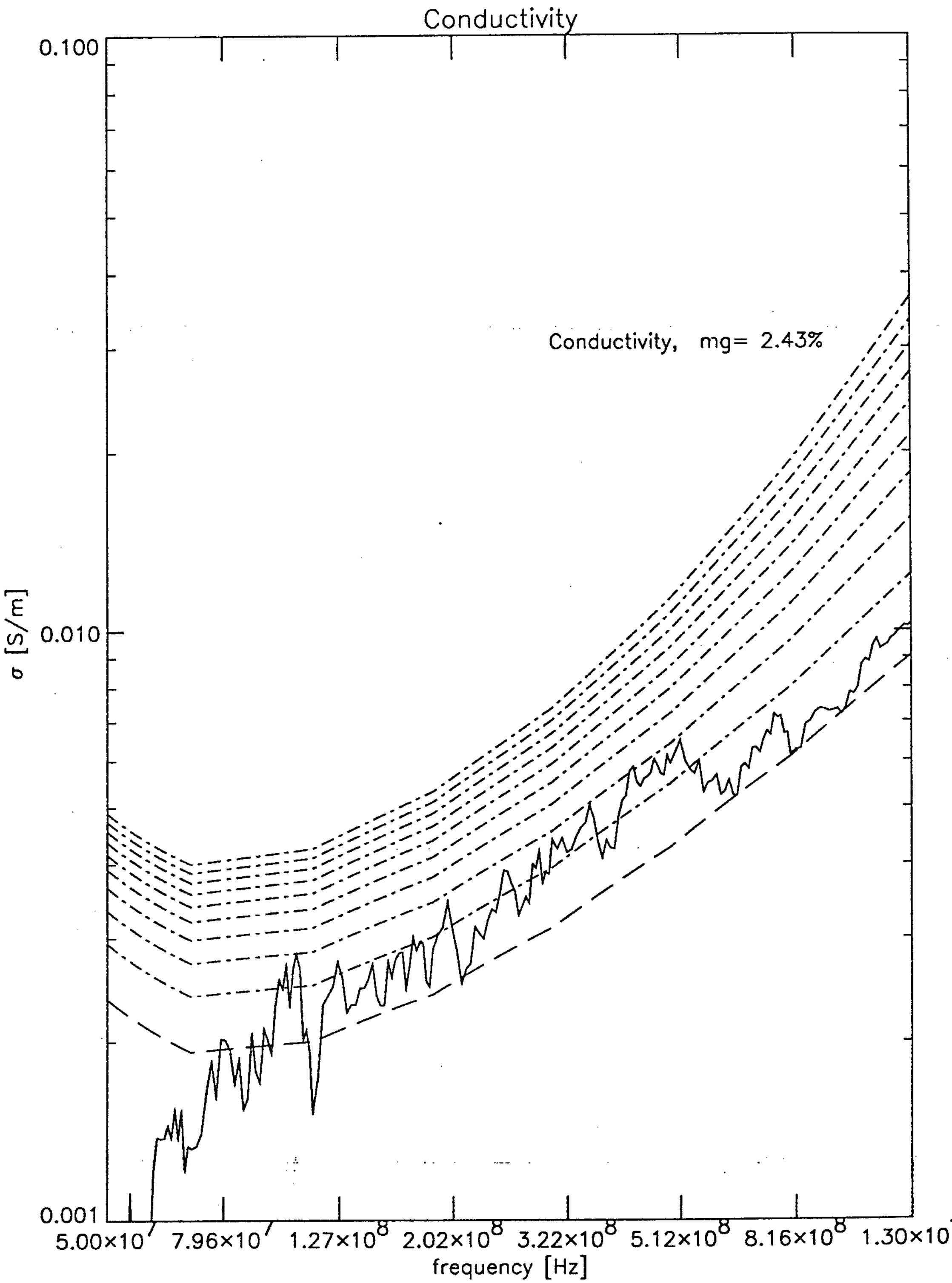
Sample B1 YA2, mg = 1.57, %Clay = 5.4, %Sand = 86.2
(sweep for mg = 1 -> 10)



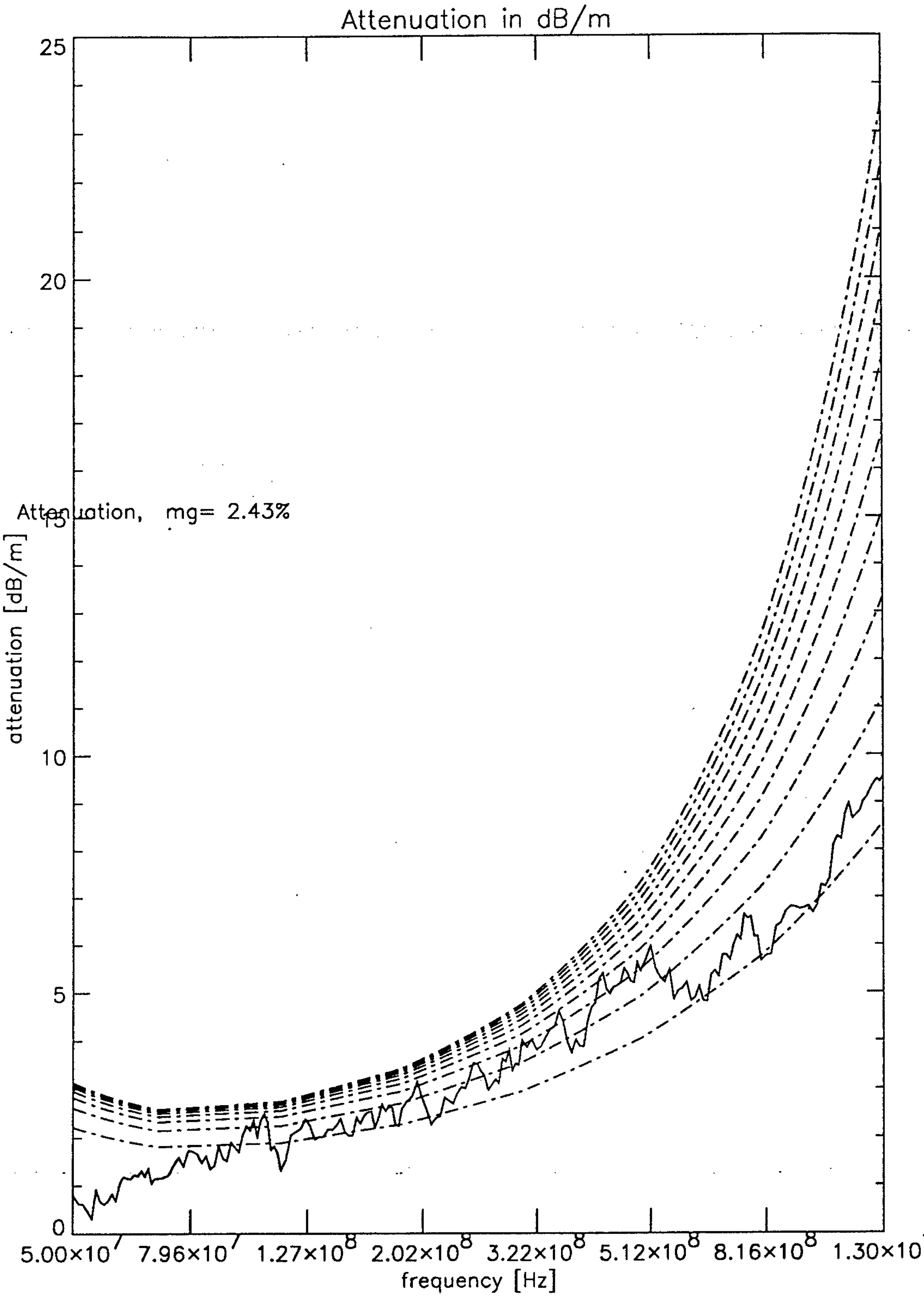
Sample B1 YA2, mg = 1.57, %Clay = 5.4, %Sand = 86.2
(sweep for mg = 1 -> 10)



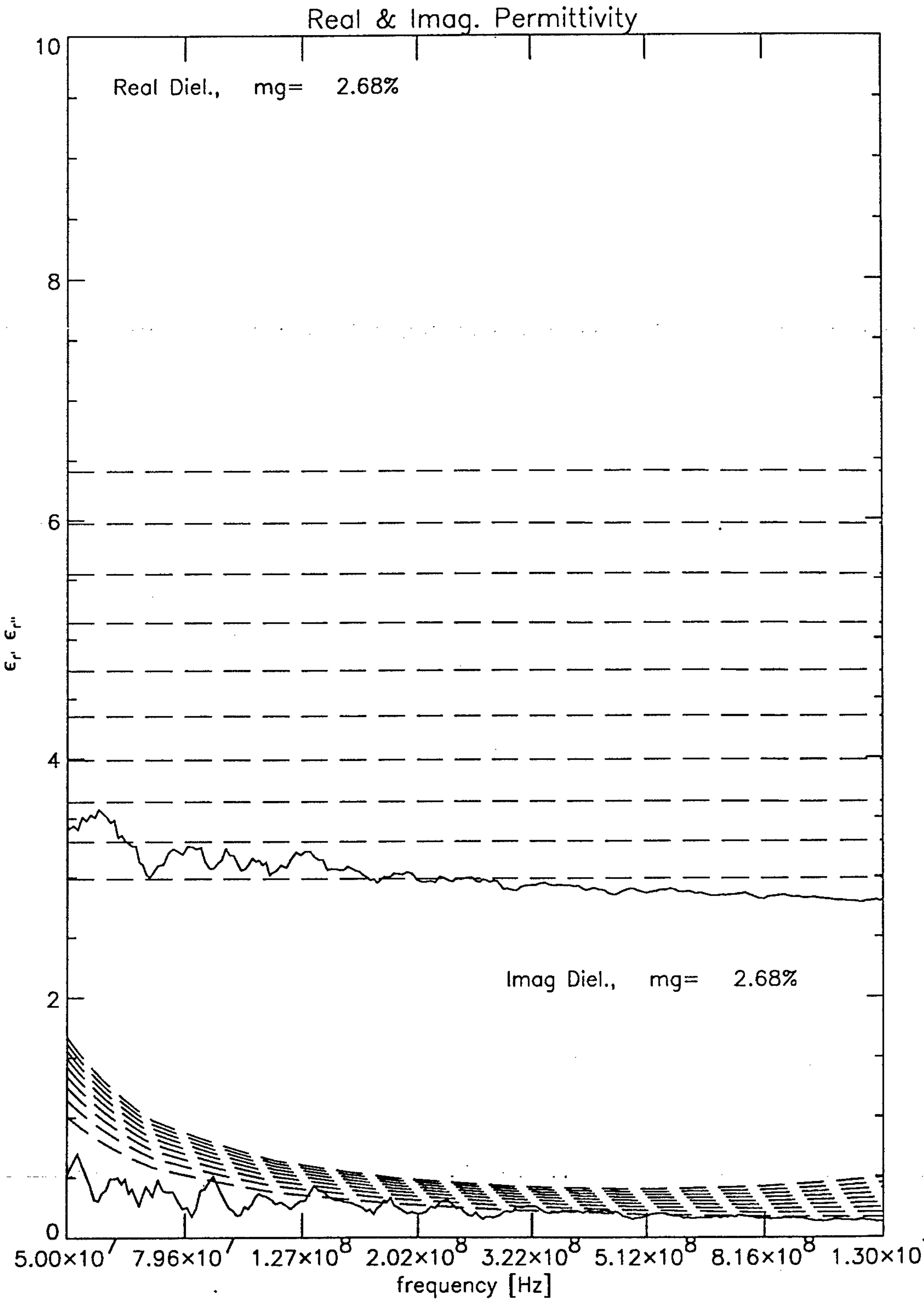
Sample B1 YA6, mg = 2.43, %Clay = 2.6, %Sand = 88.6
(sweep for mg = 1 -> 10)



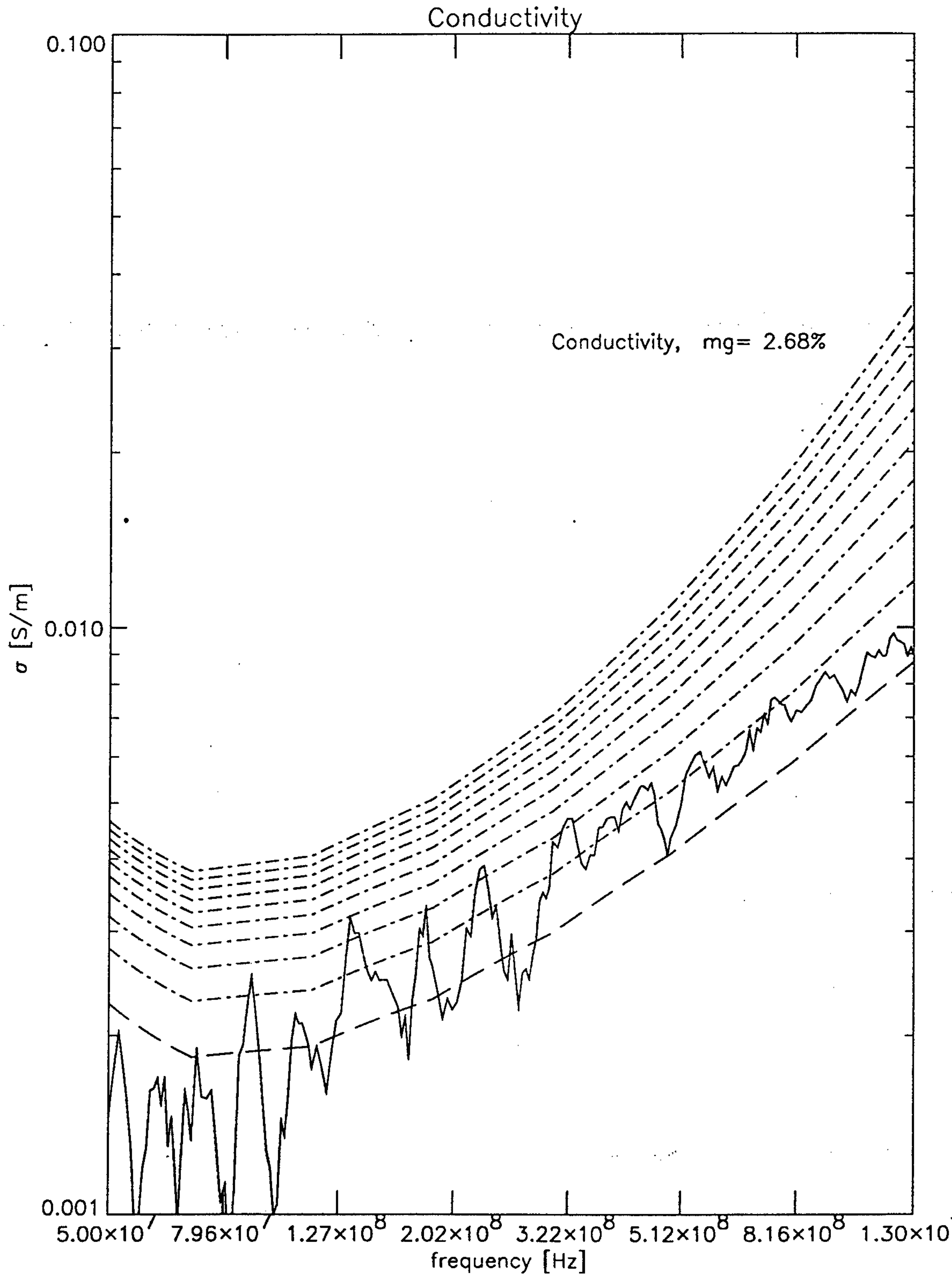
Sample B1 YA6, mg = 2.43, %Clay = 2.6, %Sand = 88.6
(sweep for mg = 1 -> 10)



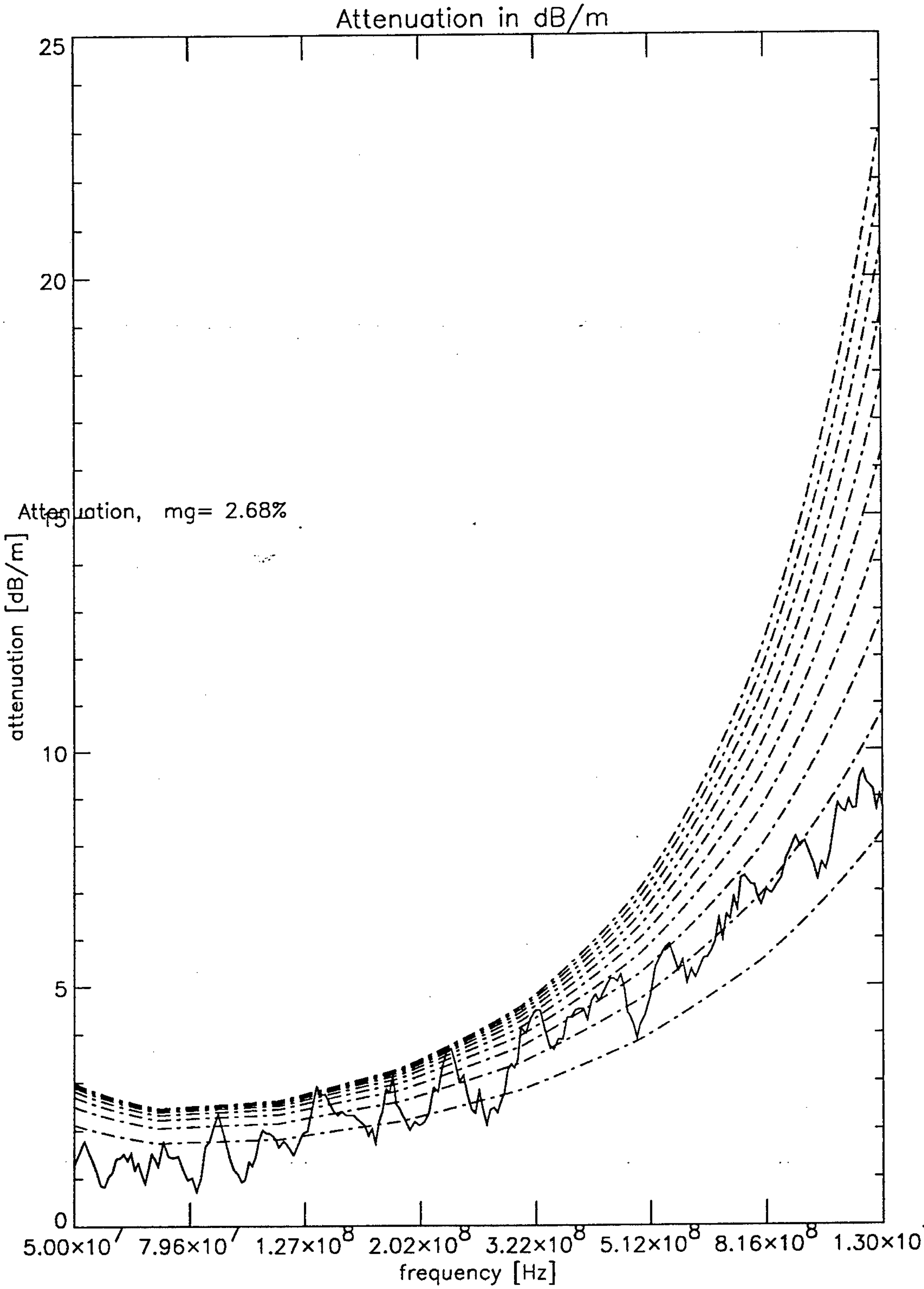
Sample B1 YA6, mg = 2.43, %Clay = 2.6, %Sand = 88.6
(sweep for mg = 1 -> 10)



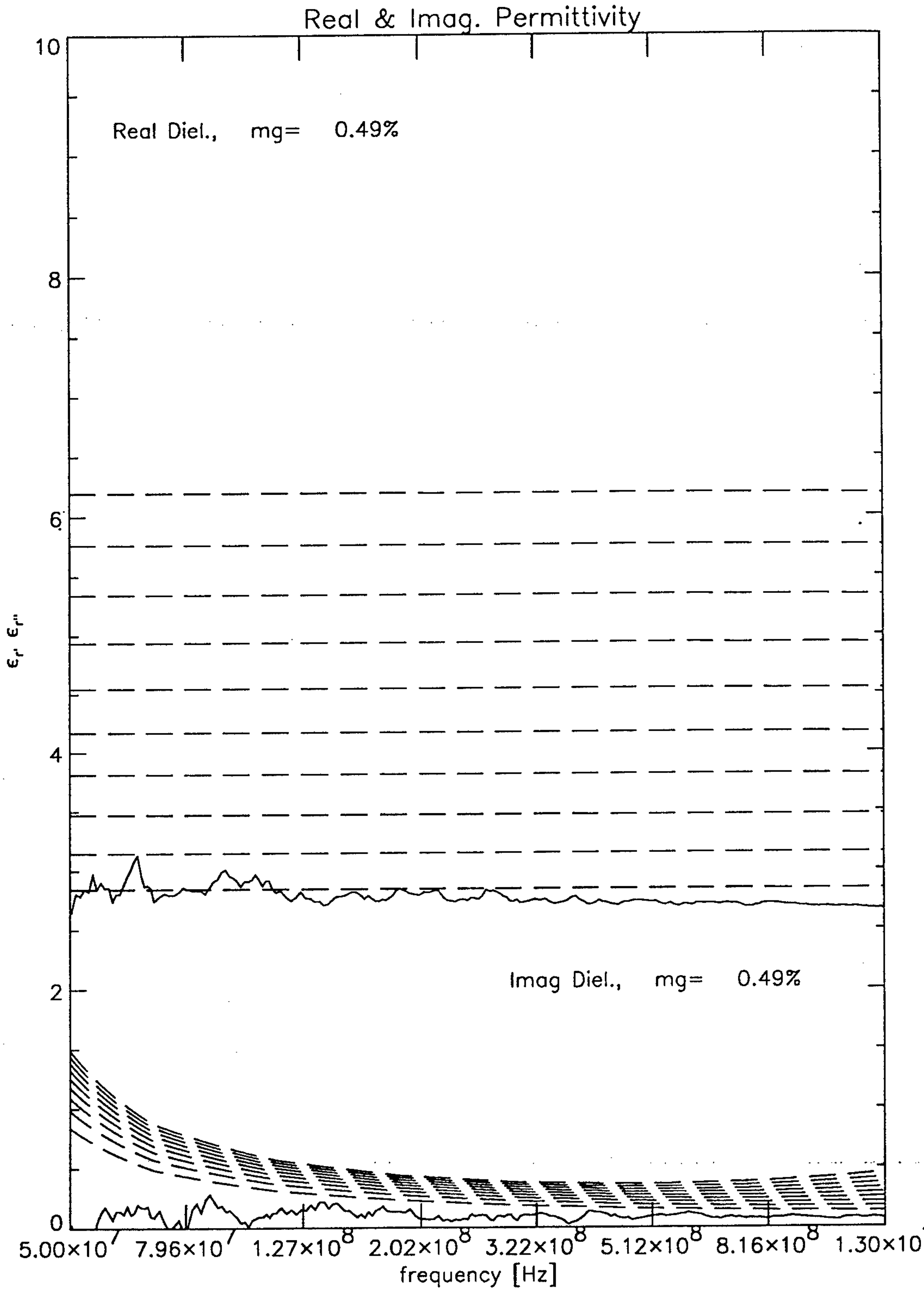
Sample Cc YA32, mg = 2.68, %Clay = 2.8, %Sand = 89.6
(sweep for mg = 1 -> 10)



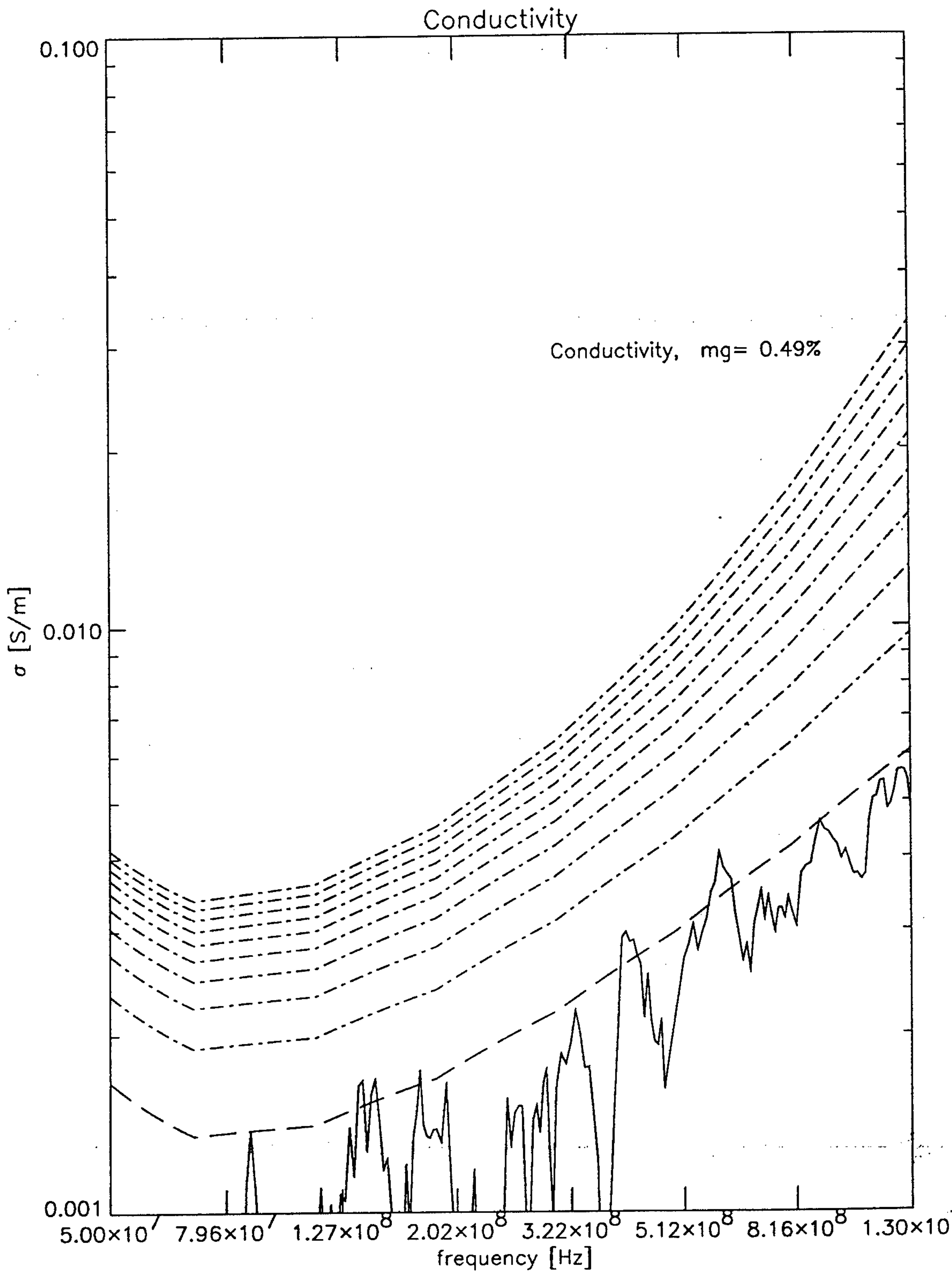
Sample Cc YA32, mg = 2.68, %Clay = 2.8, %Sand = 89.6
(sweep for mg = 1 -> 10)



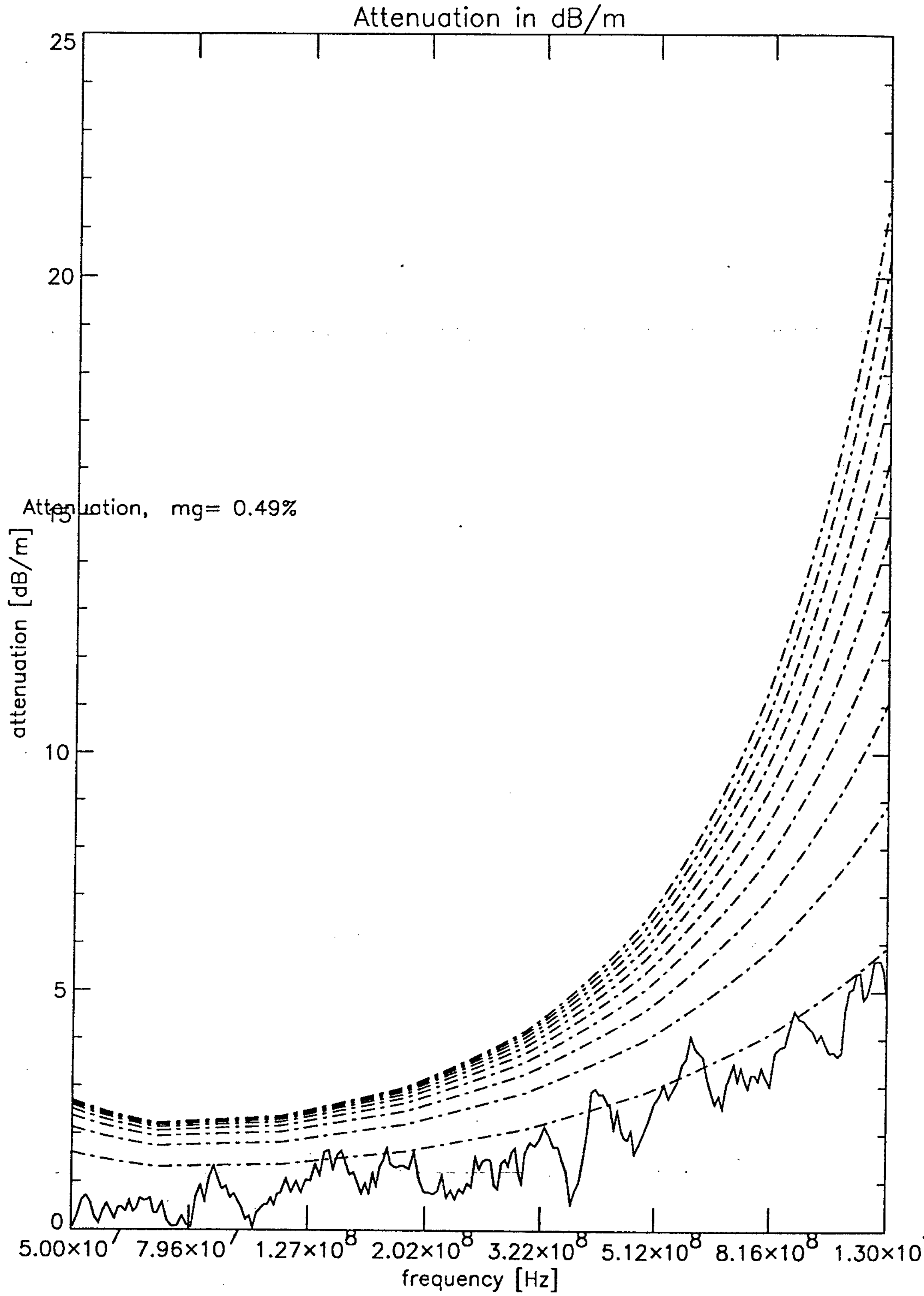
Sample Cc YA32, mg = 2.68, %Clay = 2.8, %Sand = 89.6
(sweep for mg = 1 -> 10)



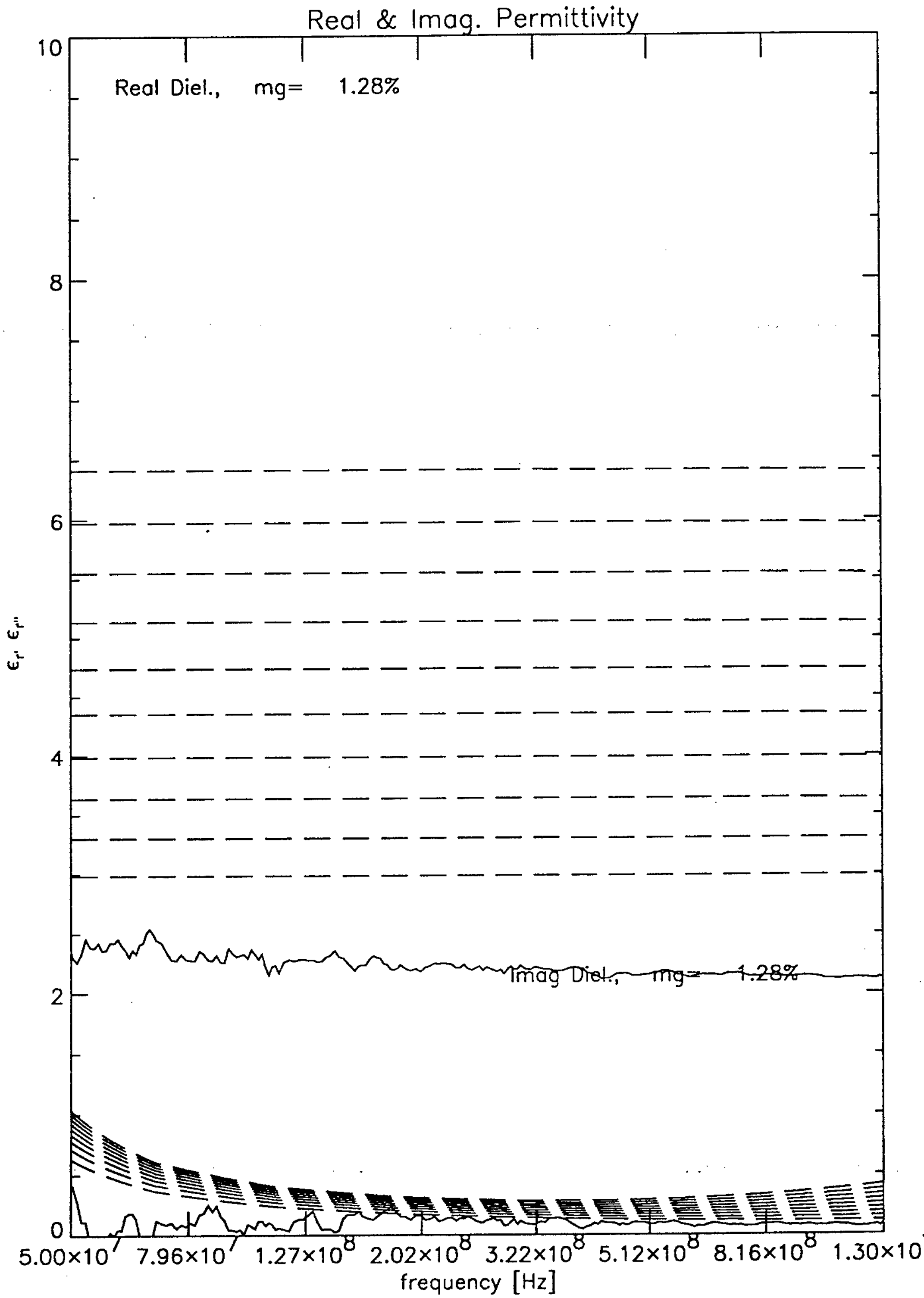
Sample D9a YA67, mg = 0.49, %Clay = 2.7, %Sand = 91.2
(sweep for mg = 0.5 -> 9.5)



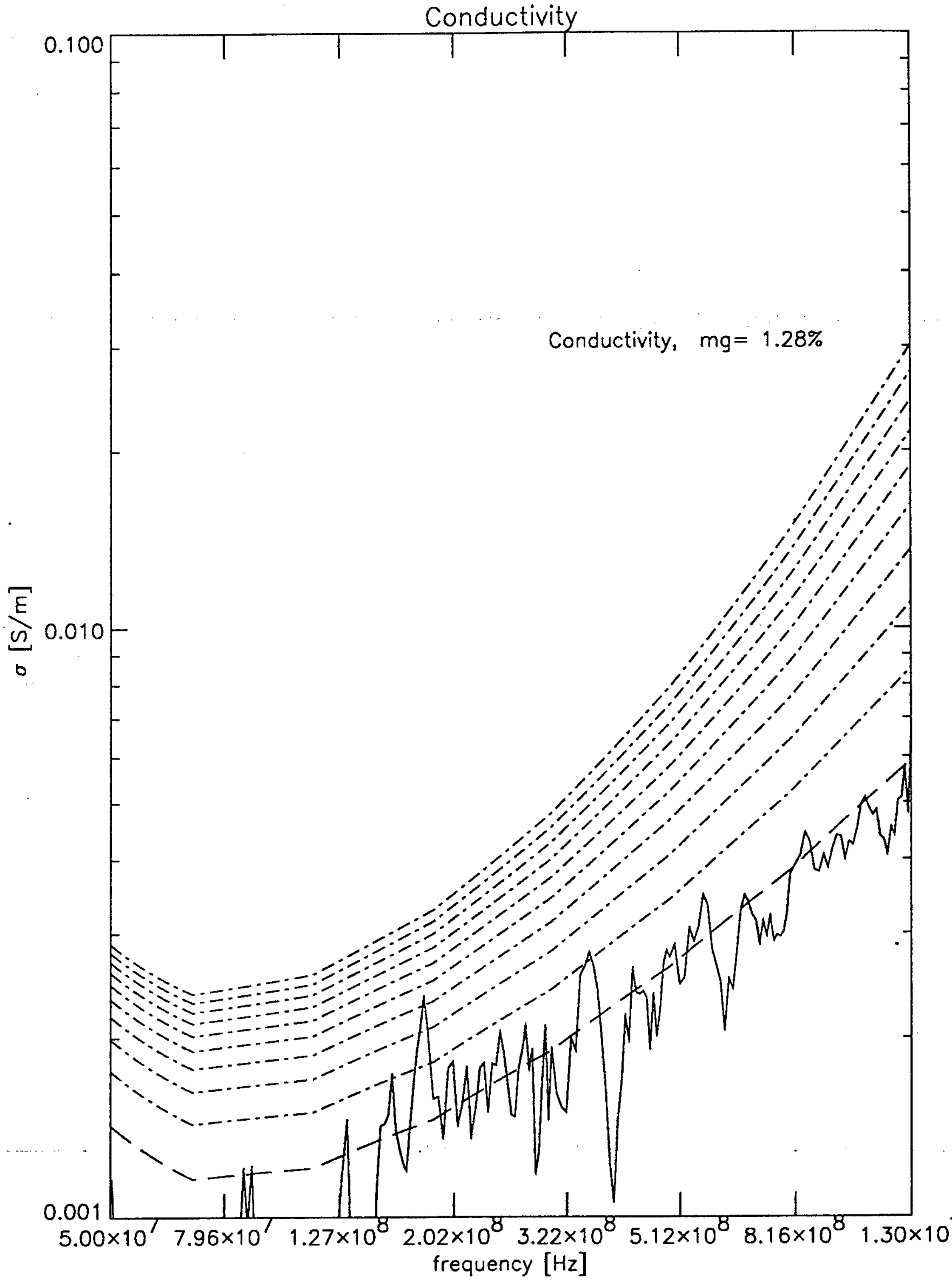
Sample D9a YA67, mg = 0.49, %Clay = 2.7, %Sand = 91.2
(sweep for mg = 0.5 -> 9.5)



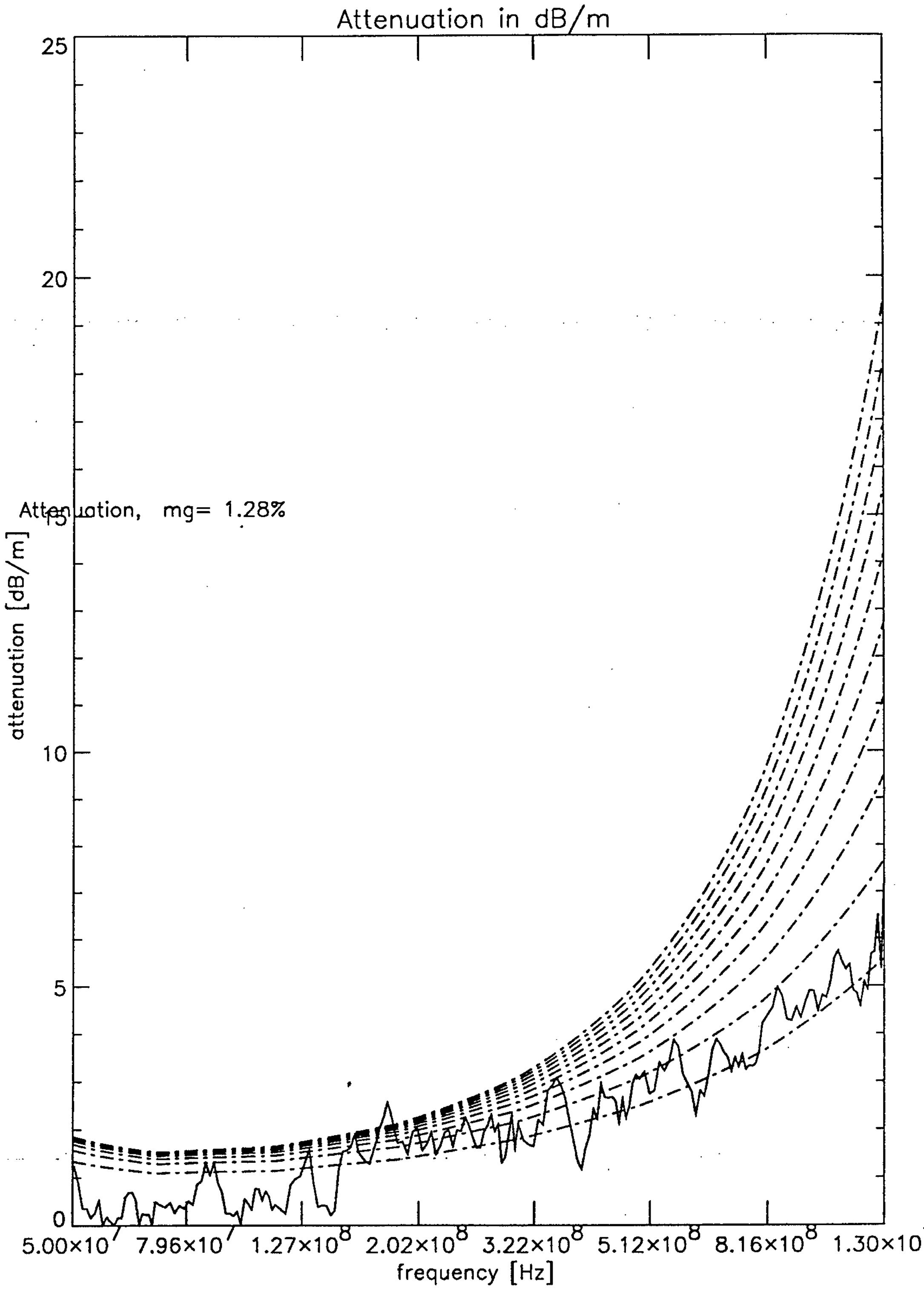
Sample D9a YA67, mg = 0.49, %Clay = 2.7, %Sand = 91.2
(sweep for mg = 0.5 -> 9.5)



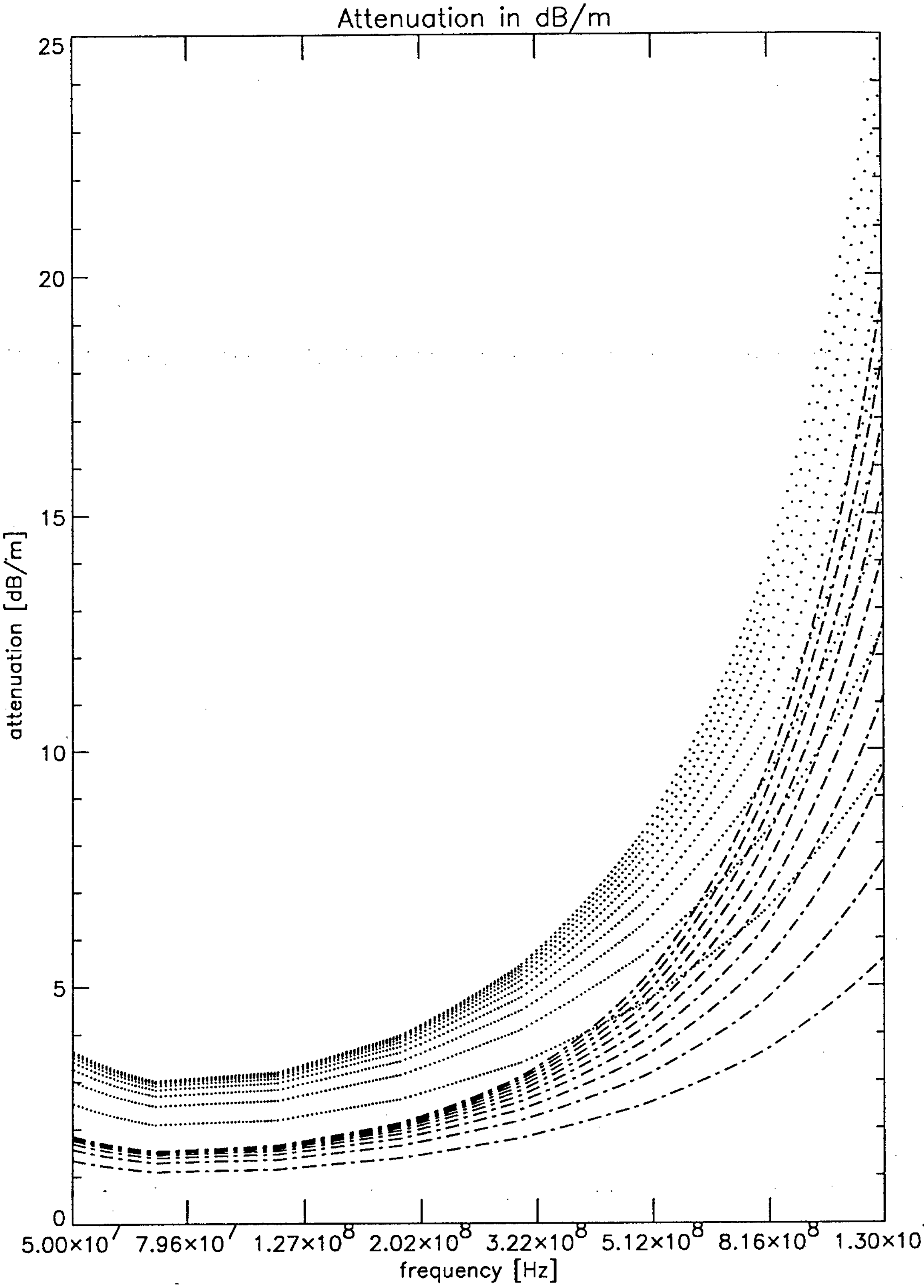
Sample D9a YA74, mg = 1.28, %Clay = 1.1, %Sand = 95.2
(sweep for mg = 1 -> 10)



Sample D9a YA74, mg = 1.28, %Clay = 1.1, %Sand = 95.2
(sweep for mg = 1 -> 10)



Sample D9a YA74, mg = 1.28, %Clay = 1.1, %Sand = 95.2
(sweep for mg = 1 -> 10)



Sample D9a YA74, mg = 1.28, %Clay = 1.1, %Sand = 95.2 => dotted line.
Sample 14 YA141, mg = 1.70, %Clay = 2.6, %Sand = 85 => dashed line.
(sweep for mg = 1 -> 10)

Table B-1 Average soil parameters for soil area YA141

Soil Area	%Sand	%Clay	%mg observed
YA141, 14	85.40	2.60	1.70

f (MHz.)	74.47	149.76	301.83	501.35	696.36	899.20	1099.60
Moisture = 1.							
e_r'	2.99	2.99	2.99	2.99	2.99	2.99	2.99
e_r''	0.62	0.31	0.22	0.18	0.16	0.15	0.15
cond (mS/m)	2.35	2.56	3.57	5.05	6.40	7.64	8.99
atten (dB/m)	4.43	4.84	6.76	9.55	12.12	14.47	17.02
REFdB (dB)	11.30	11.43	11.45	11.46	11.46	11.47	11.47
Moisture = 2.							
e_r'	3.30	3.30	3.30	3.30	3.30	3.30	3.29
e_r''	0.78	0.39	0.27	0.23	0.21	0.20	0.20
cond (mS/m)	2.94	3.21	4.52	6.48	8.34	10.10	12.06
atten (dB/m)	5.26	5.78	8.13	11.68	15.03	18.20	21.74
REFdB (dB)	10.57	10.71	10.74	10.75	10.75	10.75	10.75
Moisture = 3.							
e_r'	3.63	3.63	3.63	3.63	3.63	3.63	3.62
e_r''	0.89	0.44	0.31	0.27	0.25	0.24	0.24
cond (mS/m)	3.35	3.68	5.21	7.59	9.90	12.14	14.69
atten (dB/m)	5.71	6.30	8.95	13.03	17.00	20.85	25.23
REFdB (dB)	9.94	10.09	10.11	10.12	10.12	10.12	10.12
Moisture = 4.							
e_r'	3.98	3.98	3.97	3.97	3.97	3.97	3.97
e_r''	0.98	0.49	0.35	0.30	0.29	0.28	0.28
cond (mS/m)	3.68	4.05	5.79	8.55	11.29	14.01	17.15
atten (dB/m)	5.99	6.63	9.50	14.02	18.52	22.99	28.14
REFdB (dB)	9.40	9.53	9.56	9.56	9.57	9.57	9.57
Moisture = 5.							
e_r'	4.34	4.34	4.34	4.34	4.34	4.34	4.34
e_r''	1.05	0.53	0.38	0.33	0.32	0.32	0.32
cond (mS/m)	3.96	4.37	6.30	9.43	12.60	15.80	19.54
atten (dB/m)	6.16	6.85	9.89	14.80	19.78	24.81	30.69
REFdB (dB)	8.93	9.05	9.07	9.07	9.07	9.08	9.08
Moisture = 6.							
e_r'	4.72	4.72	4.72	4.72	4.72	4.72	4.71
e_r''	1.11	0.56	0.41	0.36	0.35	0.35	0.36
cond (mS/m)	4.20	4.66	6.77	10.25	13.86	17.55	21.91
atten (dB/m)	6.28	7.00	10.19	15.43	20.86	26.43	32.99
REFdB (dB)	8.50	8.61	8.63	8.63	8.63	8.64	8.64

Moisture = 7.							
e_r'	5.12	5.11	5.11	5.11	5.11	5.11	5.11
e_r''	1.17	0.59	0.43	0.39	0.38	0.39	0.40
cond (mS/m)	4.42	4.91	7.21	11.04	15.08	19.27	24.27
atten (dB/m)	6.34	7.10	10.42	15.97	21.81	27.88	35.11
REFdB (dB)	8.12	8.22	8.23	8.24	8.24	8.24	8.24
Moisture = 8.							
e_r'	5.52	5.52	5.52	5.52	5.52	5.52	5.52
e_r''	1.22	0.62	0.46	0.41	0.41	0.42	0.44
cond (mS/m)	4.61	5.15	7.62	11.81	16.29	20.99	26.63
atten (dB/m)	6.38	7.16	10.60	16.44	22.67	29.22	37.08
REFdB (dB)	7.78	7.86	7.88	7.88	7.88	7.88	7.89
Moisture = 9.							
e_r'	5.95	5.95	5.95	5.95	5.94	5.94	5.94
e_r''	1.27	0.65	0.48	0.44	0.44	0.45	0.47
cond (mS/m)	4.80	5.38	8.01	12.56	17.49	22.71	29.01
atten (dB/m)	6.40	7.20	10.74	16.85	23.45	30.46	38.93
REFdB (dB)	7.47	7.54	7.55	7.56	7.56	7.56	7.56
Moisture = 10.							
e_r'	6.38	6.38	6.38	6.38	6.38	6.38	6.37
e_r''	1.32	0.67	0.51	0.47	0.47	0.49	0.51
cond (mS/m)	4.97	5.59	8.39	13.30	18.67	24.42	31.41
atten (dB/m)	6.40	7.23	10.85	17.22	24.18	31.63	40.68
REFdB (dB)	7.18	7.25	7.26	7.26	7.26	7.26	7.27

Table B-2 Average soil parameters for soil area YA2

Soil Area	%Sand	%Clay	%mg observed
YA2, B1	86.20	5.40	1.57

f (MHz.)	74.47	149.76	301.83	501.35	696.36	899.20	1099.60
Moisture = 1.							
e_r'	2.99	2.99	2.99	2.99	2.99	2.99	2.99
e_r''	0.66	0.32	0.23	0.19	0.17	0.16	0.15
cond (mS/m)	2.47	2.69	3.75	5.29	6.71	8.01	9.42
atten (dB/m)	4.64	5.08	7.08	10.01	12.69	15.15	17.82
REFdB (dB)	11.27	11.41	11.44	11.44	11.45	11.45	11.45
Moisture = 2.							
e_r'	3.31	3.31	3.31	3.31	3.31	3.31	3.31
e_r''	0.82	0.41	0.28	0.24	0.22	0.21	0.21
cond (mS/m)	3.07	3.36	4.72	6.77	8.70	10.54	12.57
atten (dB/m)	5.48	6.03	8.48	12.17	15.65	18.95	22.61
REFdB (dB)	10.53	10.69	10.71	10.72	10.72	10.73	10.73
Moisture = 3.							
e_r'	3.64	3.64	3.64	3.64	3.64	3.64	3.64
e_r''	0.93	0.46	0.33	0.28	0.26	0.25	0.25
cond (mS/m)	3.49	3.83	5.43	7.90	10.29	12.62	15.25
atten (dB/m)	5.94	6.55	9.30	13.53	17.64	21.62	26.14
REFdB (dB)	9.90	10.05	10.08	10.09	10.09	10.09	10.09
Moisture = 4.							
e_r'	4.00	4.00	4.00	4.00	4.00	3.99	3.99
e_r''	1.02	0.51	0.36	0.31	0.30	0.29	0.29
cond (mS/m)	3.83	4.21	6.02	8.88	11.71	14.52	17.76
atten (dB/m)	6.21	6.88	9.85	14.52	19.16	23.77	29.06
REFdB (dB)	9.36	9.50	9.52	9.53	9.53	9.54	9.54
Moisture = 5.							
e_r'	4.37	4.37	4.37	4.37	4.36	4.36	4.36
e_r''	1.09	0.55	0.40	0.34	0.33	0.33	0.33
cond (mS/m)	4.11	4.54	6.54	9.77	13.05	16.34	20.19
atten (dB/m)	6.38	7.10	10.24	15.29	20.42	25.59	31.62
REFdB (dB)	8.88	9.01	9.03	9.04	9.04	9.04	9.04
Moisture = 6.							
e_r'	4.75	4.75	4.75	4.75	4.75	4.75	4.74
e_r''	1.16	0.58	0.42	0.37	0.36	0.36	0.37
cond (mS/m)	4.36	4.83	7.02	10.61	14.32	18.12	22.59
atten (dB/m)	6.49	7.24	10.53	15.92	21.49	27.19	33.92
REFdB (dB)	8.46	8.57	8.59	8.60	8.60	8.60	8.60

Moisture = 7.							
e_r'	5.15	5.15	5.15	5.15	5.15	5.15	5.14
e_r''	1.21	0.62	0.45	0.40	0.39	0.40	0.41
cond (mS/m)	4.58	5.09	7.46	11.42	15.57	19.87	24.99
atten (dB/m)	6.55	7.33	10.75	16.45	22.44	28.64	36.03
REFdB (dB)	8.08	8.18	8.20	8.20	8.21	8.21	8.21
Moisture = 8.							
e_r'	5.56	5.56	5.56	5.56	5.56	5.56	5.56
e_r''	1.27	0.64	0.48	0.43	0.42	0.43	0.45
cond (mS/m)	4.78	5.34	7.88	12.19	16.79	21.61	27.38
atten (dB/m)	6.59	7.39	10.92	16.91	23.28	29.97	37.99
REFdB (dB)	7.74	7.83	7.84	7.85	7.85	7.85	7.85
Moisture = 9.							
e_r'	5.99	5.99	5.99	5.99	5.99	5.98	5.98
e_r''	1.32	0.67	0.50	0.45	0.45	0.47	0.49
cond (mS/m)	4.97	5.56	8.28	12.95	18.00	23.34	29.79
atten (dB/m)	6.60	7.43	11.06	17.31	24.06	31.20	39.83
REFdB (dB)	7.43	7.51	7.52	7.53	7.53	7.53	7.53
Moisture = 10.							
e_r'	6.43	6.43	6.43	6.43	6.43	6.42	6.42
e_r''	1.36	0.70	0.52	0.48	0.48	0.50	0.53
cond (mS/m)	5.14	5.78	8.66	13.70	19.21	25.08	32.22
atten (dB/m)	6.59	7.44	11.16	17.67	24.77	32.36	41.57
REFdB (dB)	7.15	7.22	7.23	7.23	7.23	7.23	7.24

Table B-3 Average soil parameters for soil area YA6

Soil Area	%Sand	%Clay	%mg observed
YA6, B1	88.60	2.60	2.43

f (MHz.)	74.47	149.76	301.83	501.35	696.36	899.20	1099.60
Moisture = 1.							
e_r'	2.99	2.99	2.99	2.99	2.99	2.99	2.99
e_r''	0.54	0.27	0.19	0.15	0.14	0.13	0.13
cond (mS/m)	2.04	2.22	3.11	4.40	5.60	6.71	7.91
atten (dB/m)	3.85	4.21	5.88	8.33	10.60	12.69	14.98
REFdB (dB)	11.34	11.44	11.45	11.46	11.46	11.46	11.46
Moisture = 2.							
e_r'	3.30	3.30	3.30	3.30	3.30	3.30	3.30
e_r''	0.67	0.34	0.24	0.20	0.18	0.18	0.17
cond (mS/m)	2.54	2.78	3.92	5.66	7.32	8.91	10.69
atten (dB/m)	4.55	5.00	7.06	10.19	13.18	16.04	19.26
REFdB (dB)	10.61	10.72	10.74	10.74	10.74	10.75	10.75
Moisture = 3.							
e_r'	3.63	3.63	3.63	3.63	3.63	3.63	3.63
e_r''	0.77	0.38	0.27	0.23	0.22	0.22	0.21
cond (mS/m)	2.89	3.17	4.52	6.64	8.72	10.77	13.12
atten (dB/m)	4.93	5.44	7.76	11.39	14.97	18.49	22.52
REFdB (dB)	9.98	10.09	10.11	10.11	10.11	10.12	10.12
Moisture = 4.							
e_r'	3.98	3.98	3.98	3.98	3.98	3.98	3.98
e_r''	0.84	0.42	0.30	0.26	0.25	0.25	0.25
cond (mS/m)	3.16	3.49	5.03	7.50	9.99	12.50	15.42
atten (dB/m)	5.16	5.72	8.24	12.29	16.38	20.49	25.29
REFdB (dB)	9.44	9.54	9.55	9.56	9.56	9.56	9.56
Moisture = 5.							
e_r'	4.35	4.35	4.35	4.35	4.35	4.35	4.34
e_r''	0.90	0.46	0.33	0.29	0.28	0.28	0.29
cond (mS/m)	3.40	3.77	5.48	8.29	11.20	14.17	17.69
atten (dB/m)	5.30	5.90	8.59	13.00	17.56	22.24	27.75
REFdB (dB)	8.95	9.04	9.06	9.06	9.07	9.07	9.07
Moisture = 6.							
e_r'	4.73	4.73	4.73	4.73	4.73	4.73	4.72
e_r''	0.96	0.48	0.36	0.32	0.31	0.32	0.33
cond (mS/m)	3.60	4.01	5.89	9.04	12.36	15.82	19.94
atten (dB/m)	5.39	6.03	8.85	13.60	18.60	23.80	30.00
REFdB (dB)	8.53	8.61	8.62	8.62	8.63	8.63	8.63

Moisture = 7.							
e_r'	5.13	5.13	5.13	5.13	5.12	5.12	5.12
e_r''	1.00	0.51	0.38	0.34	0.34	0.35	0.36
cond (mS/m)	3.79	4.23	6.27	9.77	13.51	17.46	22.20
atten (dB/m)	5.44	6.11	9.06	14.11	19.52	25.22	32.08
REFdB (dB)	8.14	8.22	8.23	8.23	8.23	8.23	8.23
Moisture = 8.							
e_r'	5.54	5.54	5.54	5.54	5.53	5.53	5.53
e_r''	1.05	0.54	0.40	0.37	0.37	0.38	0.40
cond (mS/m)	3.95	4.44	6.64	10.47	14.65	19.09	24.48
atten (dB/m)	5.47	6.17	9.23	14.56	20.36	26.54	34.04
REFdB (dB)	7.80	7.86	7.87	7.87	7.87	7.88	7.88
Moisture = 9.							
e_r'	5.96	5.96	5.96	5.96	5.96	5.96	5.95
e_r''	1.09	0.56	0.42	0.39	0.40	0.41	0.44
cond (mS/m)	4.11	4.63	6.99	11.17	15.78	20.73	26.78
atten (dB/m)	5.48	6.20	9.36	14.96	21.14	27.78	35.89
REFdB (dB)	7.48	7.54	7.55	7.55	7.55	7.55	7.55
Moisture = 10.							
e_r'	6.40	6.40	6.40	6.40	6.40	6.39	6.39
e_r''	1.13	0.58	0.44	0.42	0.43	0.45	0.48
cond (mS/m)	4.25	4.81	7.33	11.86	16.90	22.38	29.10
atten (dB/m)	5.48	6.22	9.48	15.33	21.86	28.95	37.64
REFdB (dB)	7.20	7.24	7.25	7.25	7.26	7.26	7.26

Table B-4 Average soil parameters for soil area YA32

Soil Area	%Sand	%Clay	%mg observed
YA32, Cc	89.60	2.80	2.68

f (MHz.)	74.47	149.76	301.83	501.35	696.36	899.20	1099.60
Moisture = 1.							
e_r'	2.99	2.99	2.99	2.99	2.99	2.99	2.99
e_r''	0.52	0.26	0.18	0.15	0.14	0.13	0.12
cond (mS/m)	1.95	2.13	2.97	4.22	5.37	6.44	7.61
atten (dB/m)	3.68	4.03	5.63	7.99	10.17	12.19	14.40
REFdB (dB)	11.35	11.44	11.45	11.46	11.46	11.46	11.46
Moisture = 2.							
e_r'	3.30	3.30	3.30	3.30	3.30	3.30	3.30
e_r''	0.64	0.32	0.23	0.19	0.18	0.17	0.17
cond (mS/m)	2.43	2.66	3.75	5.42	7.03	8.57	10.31
atten (dB/m)	4.35	4.78	6.75	9.76	12.65	15.43	18.55
REFdB (dB)	10.61	10.72	10.73	10.74	10.74	10.74	10.74
Moisture = 3.							
e_r'	3.64	3.64	3.64	3.64	3.63	3.63	3.63
e_r''	0.73	0.37	0.26	0.22	0.21	0.21	0.21
cond (mS/m)	2.76	3.03	4.33	6.37	8.39	10.38	12.67
atten (dB/m)	4.70	5.20	7.42	10.92	14.39	17.81	21.75
REFdB (dB)	9.99	10.09	10.10	10.11	10.11	10.11	10.11
Moisture = 4.							
e_r'	3.99	3.99	3.99	3.99	3.98	3.98	3.98
e_r''	0.80	0.40	0.29	0.25	0.24	0.24	0.24
cond (mS/m)	3.02	3.34	4.81	7.20	9.62	12.07	14.94
atten (dB/m)	4.92	5.46	7.88	11.79	15.77	19.79	24.48
REFdB (dB)	9.44	9.53	9.55	9.55	9.55	9.55	9.56
Moisture = 5.							
e_r'	4.35	4.35	4.35	4.35	4.35	4.35	4.35
e_r''	0.86	0.43	0.32	0.28	0.27	0.27	0.28
cond (mS/m)	3.24	3.60	5.24	7.97	10.80	13.72	17.17
atten (dB/m)	5.05	5.63	8.22	12.49	16.93	21.51	26.92
REFdB (dB)	8.96	9.04	9.05	9.06	9.06	9.06	9.06
Moisture = 6.							
e_r'	4.74	4.74	4.74	4.73	4.73	4.73	4.73
e_r''	0.91	0.46	0.34	0.30	0.30	0.31	0.32
cond (mS/m)	3.43	3.83	5.64	8.70	11.94	15.33	19.39
atten (dB/m)	5.14	5.75	8.47	13.07	17.95	23.05	29.16
REFdB (dB)	8.53	8.60	8.62	8.62	8.62	8.62	8.62

Moisture = 7.							
e_r'	5.13	5.13	5.13	5.13	5.13	5.13	5.13
e_r''	0.96	0.49	0.36	0.33	0.33	0.34	0.35
cond (mS/m)	3.61	4.04	6.01	9.41	13.07	16.95	21.62
atten (dB/m)	5.19	5.83	8.68	13.58	18.87	24.47	31.23
REFdB (dB)	8.15	8.21	8.22	8.22	8.23	8.23	8.23
Moisture = 8.							
e_r'	5.54	5.54	5.54	5.54	5.54	5.54	5.54
e_r''	1.00	0.51	0.38	0.35	0.36	0.37	0.39
cond (mS/m)	3.77	4.24	6.36	10.10	14.18	18.56	23.88
atten (dB/m)	5.21	5.88	8.84	14.03	19.71	25.79	33.19
REFdB (dB)	7.80	7.86	7.87	7.87	7.87	7.87	7.87
Moisture = 9.							
e_r'	5.97	5.97	5.97	5.97	5.97	5.96	5.96
e_r''	1.04	0.53	0.40	0.38	0.39	0.40	0.43
cond (mS/m)	3.91	4.42	6.70	10.78	15.30	20.18	26.15
atten (dB/m)	5.22	5.91	8.97	14.43	20.48	27.02	35.03
REFdB (dB)	7.48	7.53	7.54	7.54	7.55	7.55	7.55
Moisture = 10.							
e_r'	6.41	6.41	6.41	6.41	6.40	6.40	6.40
e_r''	1.07	0.55	0.42	0.40	0.41	0.44	0.47
cond (mS/m)	4.05	4.59	7.03	11.45	16.41	21.81	28.46
atten (dB/m)	5.21	5.93	9.08	14.79	21.20	28.19	36.79
REFdB (dB)	7.20	7.24	7.25	7.25	7.25	7.25	7.25

Table B-5 Average soil parameters for soil area YA67

Soil Area	%Sand	%Clay	%mg observed
YA67, D9a	91.20	2.70	0.49

f (MHz.)	74.47	149.76	301.83	501.35	696.36	899.20	1099.60
Moisture = 1.							
e_r'	2.99	2.99	2.99	2.99	2.99	2.99	2.99
e_r''	0.47	0.23	0.16	0.14	0.12	0.12	0.11
cond (mS/m)	1.78	1.94	2.71	3.86	4.93	5.92	7.00
atten (dB/m)	3.36	3.67	5.13	7.30	9.32	11.19	13.25
REFdB (dB)	11.36	11.44	11.45	11.46	11.46	11.46	11.46
Moisture = 2.							
e_r'	3.30	3.30	3.30	3.30	3.30	3.30	3.30
e_r''	0.59	0.29	0.21	0.17	0.16	0.16	0.16
cond (mS/m)	2.21	2.42	3.42	4.97	6.46	7.91	9.55
atten (dB/m)	3.95	4.35	6.16	8.94	11.63	14.24	17.18
REFdB (dB)	10.63	10.72	10.73	10.74	10.74	10.74	10.74
Moisture = 3.							
e_r'	3.64	3.64	3.64	3.64	3.64	3.64	3.64
e_r''	0.66	0.33	0.24	0.20	0.20	0.19	0.19
cond (mS/m)	2.50	2.76	3.95	5.85	7.74	9.63	11.81
atten (dB/m)	4.27	4.72	6.77	10.03	13.28	16.52	20.26
REFdB (dB)	10.01	10.09	10.10	10.11	10.11	10.11	10.11
Moisture = 4.							
e_r'	3.99	3.99	3.99	3.99	3.99	3.99	3.99
e_r''	0.73	0.37	0.27	0.23	0.23	0.22	0.23
cond (mS/m)	2.74	3.03	4.40	6.62	8.91	11.25	13.99
atten (dB/m)	4.47	4.96	7.20	10.85	14.60	18.43	22.92
REFdB (dB)	9.46	9.53	9.55	9.55	9.55	9.55	9.55
Moisture = 5.							
e_r'	4.36	4.36	4.36	4.36	4.36	4.35	4.35
e_r''	0.78	0.39	0.29	0.26	0.25	0.26	0.26
cond (mS/m)	2.94	3.27	4.79	7.35	10.04	12.83	16.15
atten (dB/m)	4.59	5.12	7.51	11.52	15.73	20.11	25.32
REFdB (dB)	8.97	9.04	9.05	9.06	9.06	9.06	9.06
Moisture = 6.							
e_r'	4.74	4.74	4.74	4.74	4.74	4.74	4.73
e_r''	0.83	0.42	0.31	0.28	0.28	0.29	0.30
cond (mS/m)	3.11	3.48	5.16	8.04	11.13	14.39	18.32
atten (dB/m)	4.66	5.23	7.75	12.08	16.73	21.63	27.53
REFdB (dB)	8.54	8.60	8.61	8.62	8.62	8.62	8.62

Moisture = 7.							
e_r'	5.14	5.14	5.14	5.14	5.14	5.13	5.13
e_r''	0.87	0.44	0.33	0.31	0.31	0.32	0.34
cond (mS/m)	3.27	3.67	5.51	8.72	12.22	15.96	20.50
atten (dB/m)	4.70	5.30	7.95	12.58	17.64	23.04	29.60
REFdB (dB)	8.16	8.21	8.22	8.22	8.22	8.22	8.22
Moisture = 8.							
e_r'	5.55	5.55	5.55	5.55	5.55	5.54	5.54
e_r''	0.90	0.47	0.35	0.33	0.34	0.35	0.37
cond (mS/m)	3.41	3.85	5.84	9.38	13.30	17.53	22.71
atten (dB/m)	4.72	5.35	8.11	13.02	18.47	24.35	31.55
REFdB (dB)	7.81	7.86	7.86	7.87	7.87	7.87	7.87
Moisture = 9.							
e_r'	5.98	5.98	5.98	5.97	5.97	5.97	5.97
e_r''	0.94	0.49	0.37	0.35	0.36	0.38	0.41
cond (mS/m)	3.54	4.02	6.16	10.03	14.38	19.11	24.94
atten (dB/m)	4.73	5.38	8.24	13.42	19.24	25.59	33.40
REFdB (dB)	7.49	7.53	7.54	7.54	7.54	7.54	7.54
Moisture = 10.							
e_r'	6.42	6.42	6.42	6.41	6.41	6.41	6.41
e_r''	0.97	0.50	0.39	0.37	0.39	0.41	0.44
cond (mS/m)	3.67	4.18	6.47	10.67	15.46	20.71	27.21
atten (dB/m)	4.72	5.40	8.35	13.78	19.96	26.76	35.16
REFdB (dB)	7.20	7.24	7.24	7.25	7.25	7.25	7.25

Table B-6 Average soil parameters for soil area YA74

Soil Area	%Sand	%Clay	%mg observed
YA74, D9a	95.20	1.10	1.28

f (MHz.)	74.47	149.76	301.83	501.35	696.36	899.20	1099.60
Moisture = 1.							
e_r'	2.99	2.99	2.99	2.99	2.99	2.99	2.99
e_r''	0.33	0.16	0.11	0.10	0.09	0.09	0.08
cond (mS/m)	1.23	1.35	1.89	2.72	3.51	4.25	5.08
atten (dB/m)	2.33	2.55	3.58	5.15	6.64	8.05	9.62
REFdB (dB)	11.42	11.45	11.46	11.46	11.46	11.46	11.46
Moisture = 2.							
e_r'	3.30	3.30	3.30	3.30	3.30	3.30	3.30
e_r''	0.40	0.20	0.14	0.12	0.12	0.12	0.12
cond (mS/m)	1.52	1.68	2.40	3.55	4.70	5.84	7.16
atten (dB/m)	2.73	3.02	4.32	6.39	8.46	10.52	12.90
REFdB (dB)	10.69	10.74	10.74	10.74	10.75	10.75	10.75
Moisture = 3.							
e_r'	3.64	3.64	3.64	3.64	3.64	3.63	3.63
e_r''	0.46	0.23	0.17	0.15	0.14	0.15	0.15
cond (mS/m)	1.72	1.91	2.79	4.23	5.74	7.28	9.11
atten (dB/m)	2.95	3.28	4.78	7.26	9.85	12.50	15.64
REFdB (dB)	10.06	10.10	10.11	10.11	10.11	10.11	10.12
Moisture = 4.							
e_r'	3.99	3.99	3.99	3.99	3.99	3.99	3.98
e_r''	0.50	0.25	0.19	0.17	0.17	0.17	0.18
cond (mS/m)	1.88	2.11	3.12	4.86	6.72	8.69	11.05
atten (dB/m)	3.08	3.45	5.11	7.96	11.02	14.24	18.11
REFdB (dB)	9.51	9.55	9.55	9.56	9.56	9.56	9.56
Moisture = 5.							
e_r'	4.35	4.35	4.35	4.35	4.35	4.35	4.35
e_r''	0.54	0.27	0.21	0.19	0.19	0.20	0.21
cond (mS/m)	2.02	2.27	3.43	5.46	7.69	10.09	13.01
atten (dB/m)	3.16	3.57	5.37	8.56	12.06	15.82	20.40
REFdB (dB)	9.02	9.06	9.06	9.06	9.06	9.06	9.07
Moisture = 6.							
e_r'	4.74	4.74	4.74	4.74	4.74	4.73	4.73
e_r''	0.57	0.29	0.22	0.21	0.22	0.23	0.25
cond (mS/m)	2.14	2.43	3.71	6.04	8.65	11.50	15.00
atten (dB/m)	3.21	3.65	5.58	9.08	13.01	17.29	22.56
REFdB (dB)	8.59	8.62	8.62	8.62	8.62	8.62	8.63

Moisture = 7.							
e_r'	5.14	5.14	5.13	5.13	5.13	5.13	5.13
e_r''	0.60	0.31	0.24	0.23	0.24	0.26	0.28
cond (mS/m)	2.25	2.57	3.99	6.62	9.62	12.93	17.03
atten (dB/m)	3.24	3.71	5.76	9.55	13.89	18.67	24.60
REFdB (dB)	8.20	8.22	8.23	8.23	8.23	8.23	8.23
Moisture = 8.							
e_r'	5.55	5.55	5.55	5.55	5.54	5.54	5.54
e_r''	0.62	0.33	0.26	0.25	0.27	0.29	0.31
cond (mS/m)	2.34	2.70	4.25	7.19	10.59	14.38	19.10
atten (dB/m)	3.25	3.75	5.91	9.98	14.71	19.98	26.54
REFdB (dB)	7.84	7.87	7.87	7.87	7.87	7.87	7.87
Moisture = 9.							
e_r'	5.97	5.97	5.97	5.97	5.97	5.97	5.96
e_r''	0.65	0.34	0.27	0.27	0.29	0.32	0.35
cond (mS/m)	2.44	2.82	4.51	7.76	11.57	15.85	21.21
atten (dB/m)	3.26	3.78	6.04	10.39	15.49	21.22	28.41
REFdB (dB)	7.52	7.54	7.55	7.55	7.55	7.55	7.55
Moisture = 10.							
e_r'	6.41	6.41	6.41	6.41	6.41	6.40	6.40
e_r''	0.67	0.35	0.29	0.29	0.32	0.35	0.38
cond (mS/m)	2.52	2.94	4.76	8.33	12.56	17.34	23.36
atten (dB/m)	3.25	3.80	6.15	10.76	16.23	22.41	30.20
REFdB (dB)	7.23	7.25	7.25	7.25	7.25	7.25	7.25