TDR vs GRAVIMETRIC:
A Comparison of Soil Moisture Determination Methods

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ABSTRACT

This research is part of an on going project to study land-atmosphere processes that influence atmospheric circulation, for example, as used in numerical weather prediction. The purpose of the research is to calibrate an in situ method for measuring soil moisture content. Measuring soil moisture is important because the energy flux between the land and atmosphere occurs largely as evaporation from soil, transpiration from plants and condensation in the form of precipitation and dew. Our goal is to validate the in situ method as an effective monitor of variations in soil moisture. The following is a paper explaining the experiments I performed.

I. INTRODUCTION

Soil moisture is a key parameter regulating the flux of energy between the land and atmosphere. The research team lead by my mentor, Prof. A.W. England, is developing a system which will simultaneously measure land-atmosphere flux conditions and the microwave-frequency brightness of the ground. The goal of such measurements is to find ways to monitor land-atmosphere energy exchange with satellite microwave radiometers.

During the summer, the research team consisted of three graduate students, three undergraduates, and two high school students. The team was divided into three groups responsible for energy balance, radiometer and soil moisture equipment development and testing. In this report I will describe the work of the soil moisture group of which I was a part.

The way we calibrated this in situ method for soil moisture content was by comparing two methods simultaneously in the lab, those being the Time Domain Reflectometry (TDR) and the gravimetric methods. The TDR method is the most recently developed and the gravimetric has been used for many years now. The reason for the development of this new method is because the gravimetric method destroys the site at which the soil is taken and is much more labor intensive. The gravimetric method consists of taking cores of soil using a cylindrical tool, weighing the core, baking it to evaporate all of the moisture, then weighing it again. Taking the difference in weights, the water weight, and dividing it by the volume of the core gives you the volumetric water content. The TDR method consists of inserting two parallel rods, attached to one cable, into soil and examining an electromagnetic wave traveling in the rods reflected by the soil through a TDR cable tester. A personal computer (PC), hooked up to the TDR, is then used to convert the reflected signal to soil moisture content.

In the lab I ran two very similar experiments using different volumes of soils under the supervision and tutelage of Prof. England and John Galantowicz, a graduate student. The second experiment was done by learning from the errors in the first. Measurements were taken daily both gravimetrically and with the TDR.

II. EXPERIMENT 1

The first experiment was one in which we used three identical 10 liter containers (buckets) for the soil samples. The initial task I undertook was to learn how to operate the TDR. My job was to learn how to use the machine and teach everyone else in the group how to use it. I read the relevant literature having to do with previous experiments done with TDR cable testers. After learning how to use the machine I began my experiment. In each of the containers a drain was made and plugged up using Styrofoam (explanation to come). The containers were then weighed empty. I then collected soil at the Matthei Botanical Gardens where future experiments are to be conducted. In the lab I baked out the soil and deposited what I thought was an even amount into all three of the containers. The soil was packed in as tight as possible to simulate actual terrain. I kept track of how much soil I deposited by weighing the soil before baking, after baking (before depositing), and after depositing it. Each of the containers was flooded with water to moisten the baked soil, drained to make sure the moisture was homogeneous, then weighed again. One container was covered with plastic overnight each night, one was left alone, and the last had a grassy layer on top of the baked soil. The reason for the difference was to see if grass and other media affected the measurements. My first measurement was right after the containers were drained. I found the soil moisture content gravimetrically by weighing each of the wet soil containers separately and subtracting the weight of the dry soil from the wet soil, then dividing the water weight by the volume of soil in the container. Using the TDR was a bit more time consuming because the host PC was not linked to the TDR yet. For this reason I performed all functions on the TDR manually. I inserted three different sets of probes into each of the containers. I then connected the same cable to each of the probes one at a time. The TDR would display a wave-form that I used to determine soil moisture content. Figure 1 shows two typical wave-forms that the TDR would produce. Those two in particular are part of my second experiment showing a 32.3% moisture wave and a 16.5% moisture wave. I obtained all my measurements by using a number of equations sent to us by the TDR supplier company. The first equation being:

$$K=[(c*t)/(2*L)]^2 \quad (1)$$

where **c** is the velocity of an electromagnetic wave in free space ($3*10^8$ m/s), **t** is obtained from the wave form on the TDR screen using a maximum to minimum approach and multiplying it by 10^{-8}, and **L** is the depth the probes were inserted into the soil. Using the dielectric constant (**K**) the volumetric moisture content was then calculated by using the following equation:

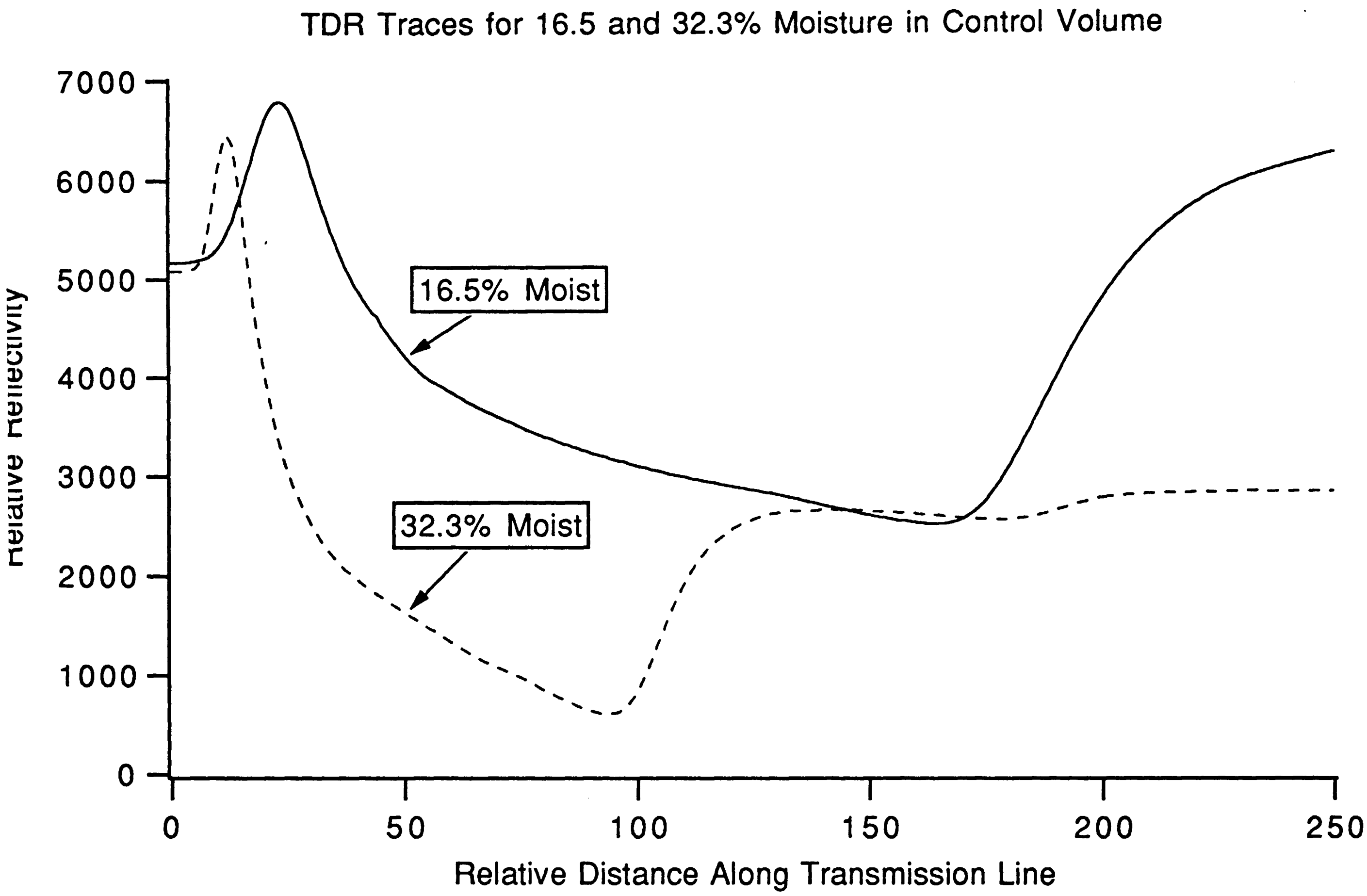
$$Vw= 4.3e^{-6} * K^3 - 5.5e^{-4} * K^2 + 2.92e^{-2} * K - 5.3e^{-2} \quad (2)$$

Again because the software for the host PC was not developed yet I calculated all soil moisture content manually. This was done on a daily basis for 13 days. During each of the days I would set the three containers outside in the sun to help the evaporation process.

ERRORS:

During and after the experiment we recognized a few errors in our procedures. This is a list of all the probable errors we could have avoided:

1. The weighing of the soil before and after it was baked was done by using 1000 mL beakers because we didn't have access to a scale that had enough capacity and was as precise as we needed it to be. We later bought a scale to fit our needs.



TDR Traces for 16.5 and 32.3% Moisture in Control Volume
Relative Reflectivity
7000
6000
5000
4000
3000
2000
1000
0
16.5% Moist
32.3% Moist
0
50
100
150
200
250
Relative Distance Along Transmission Line

2. Because the containers were not deep enough for the probes (30cm) to be submerged completely I had to measure the depth of each of the probes using a ruler.
3. We didn't know if the soil was homogeneously moist. In the covered container some of the dew on the plastic could have dripped back onto the top of the soil. In the uncovered one the top was being exposed to sun as well as to air conditioning inside the lab which might have made the top much drier.
4. The probes in each of the containers were moved around too much. Each of the containers had to be weighed without the cable attached, then the cable had to be connected to use the TDR, then again disconnected to set outside. The probes had widened the holes in which they were in by the end of the experiment.
5. The last error was in obtaining the **t** value for equation 1. I used my eyes to estimate the maximum and minimum in the wave formation. I tried to be as consistent as possible but this error could be corrected.

These errors were corrected in our second experiment.

III. EXPERIMENT II

In this experiment only one controlled volume was used. The container was made from a 6 inch diameter PVC pipe. The pipe was long enough for the rod to be completely submerged in soil. A thick plastic material was used as the bottom of the container which was sealed up by silicon. A drain was also installed into this control volume. Again I deposited baked soil into the container, packing it in tightly. I flooded it with water and let it drain. I ran the same experiment as the first with a few differences. One was that each night the container was covered, a paper towel was placed under the plastic to absorb all the moisture evaporating from the soil. The second difference is probably the most significant, that being that the software was ready to be used so the value of **t** in equation 1 would be much more precisely known. John Galantowicz wrote the code for the PC. Now my job was much simpler because the computer calculated everything for me with the push of a button. One major benefit from the code was that a much more precise way of determining **t** was used. John wrote the code so the computer would use the method I used (max/min) to obtain **t** and display the soil moisture on the PC screen, but he also wrote code that would use a more sophisticated scheme to determine t, which consisted of finding the slopes in the curves and also displaying that soil moisture on the PC screen. So within the program was another test on which method of finding **t** was more precise.

ERRORS:

A few errors still existed in our second experiment but we corrected what we could from our first experiment. I believe the only error that still existed from our first was the moving of the rods for the same reasons, but not much could be done about that in the type of experiments we ran. A new error did come up, which was that the probes had to be completely submerged every time a measurement was to be taken. The cable would pull the probes back up if they were not completely submerged.

IV. RESULTS

EXPERIMENT #1

Even with all the errors, experiment one showed that both the gravimetric and TDR techniques were compatible. Figure 2 shows the daily decline for all three containers showing both TDR and gravimetric measurements. Figure 3 shows the same thing in 3-D to see the comparison better. Figure 4 shows plots of the gravimetric method vs. the TDR method for all three containers. As you can see the 45 degree line is what the plot should look like, the reason being that there should be a ratio of 1:1 for the measurements. Taking into account the errors, these results are very promising. Our lowest correlation coefficient was .967. Figure 5 and table 2 were taken from Topp et al., 1984. These show a much more disperse area of points. Comparing this to our findings shows that our experiment was valid and quite useful.

EXPERIMENT #2

From this second experiment we see that the TDR and gravimetric methods are almost identical, with a correlation

Figure 2. EXP. #1--SOIL MOISTURE

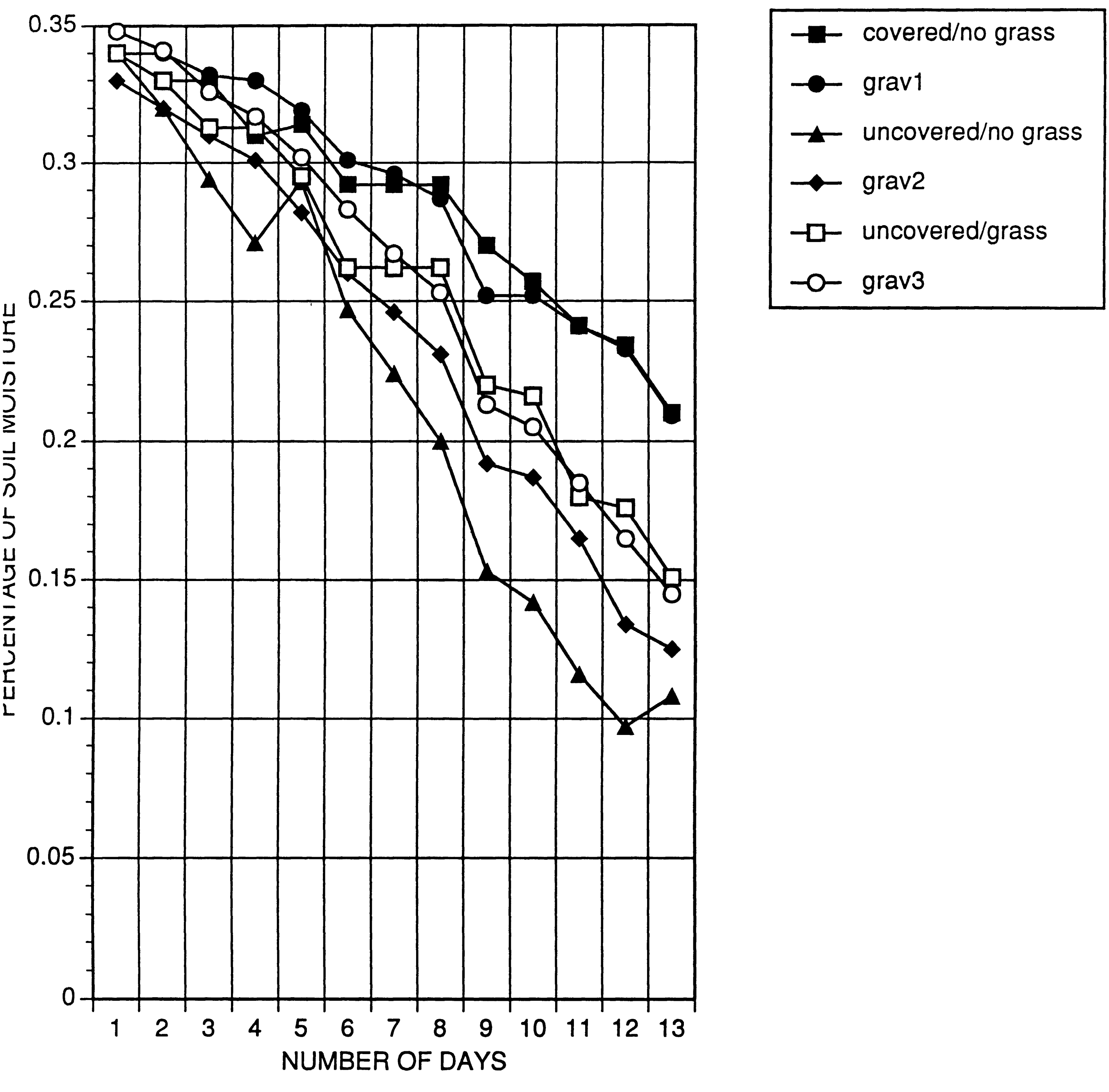
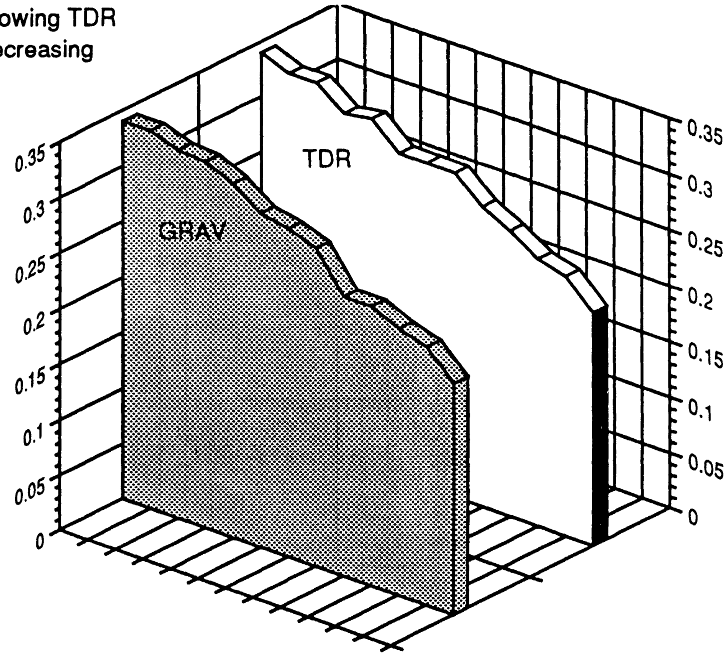
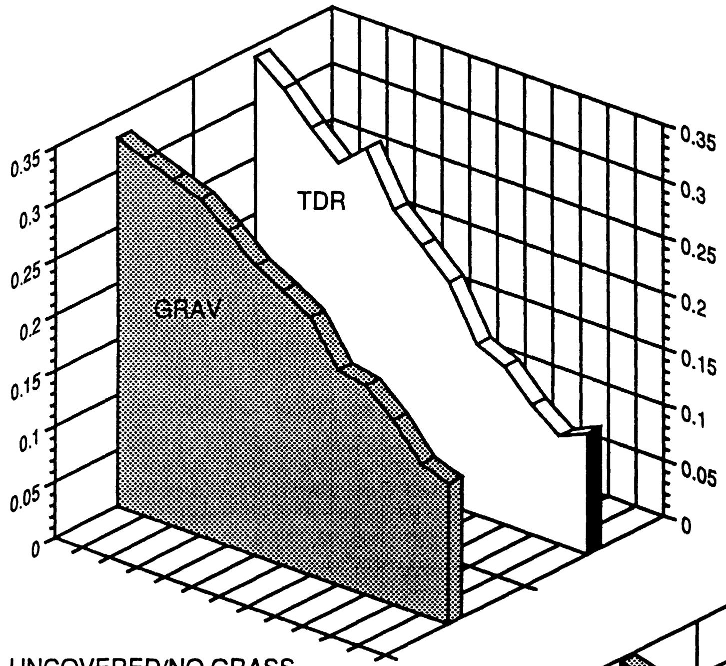


Figure 3. EX. #1-- 3D Graphs showing TDR and GRAVIMETRIC values of decreasing soil moisture



COVERED/NO GRASS



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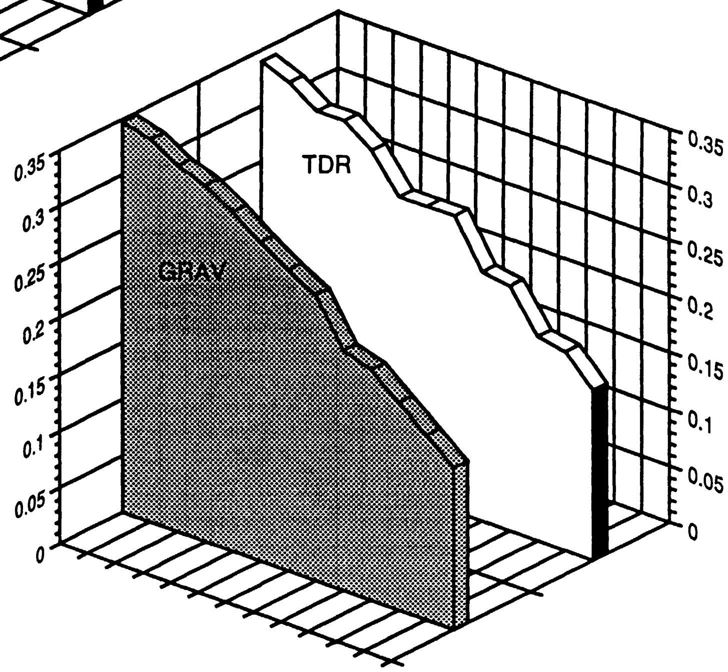

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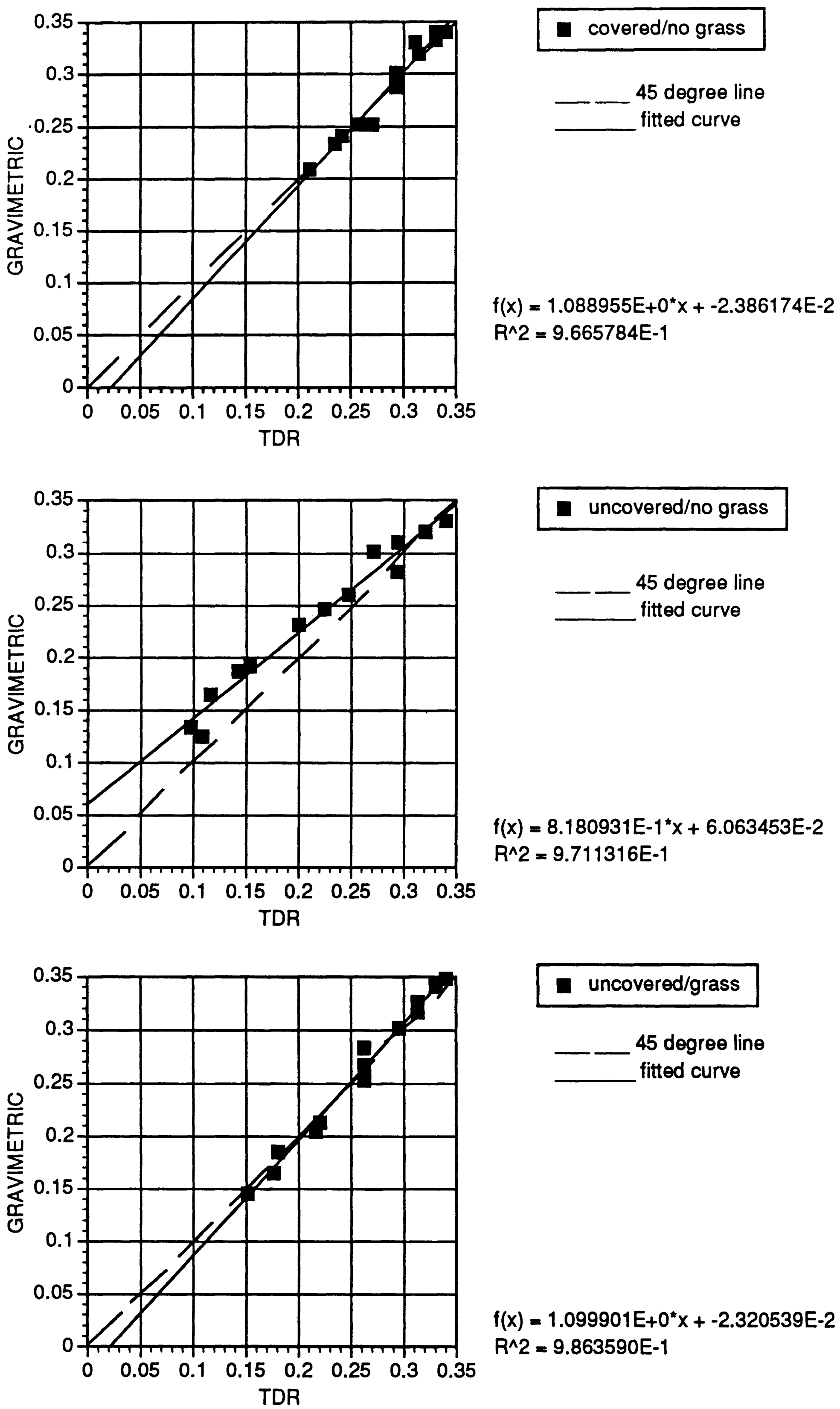
Figure 4. EX.#1 TDR vs GRAVIMETRIC
with correlation coefficient value and formula



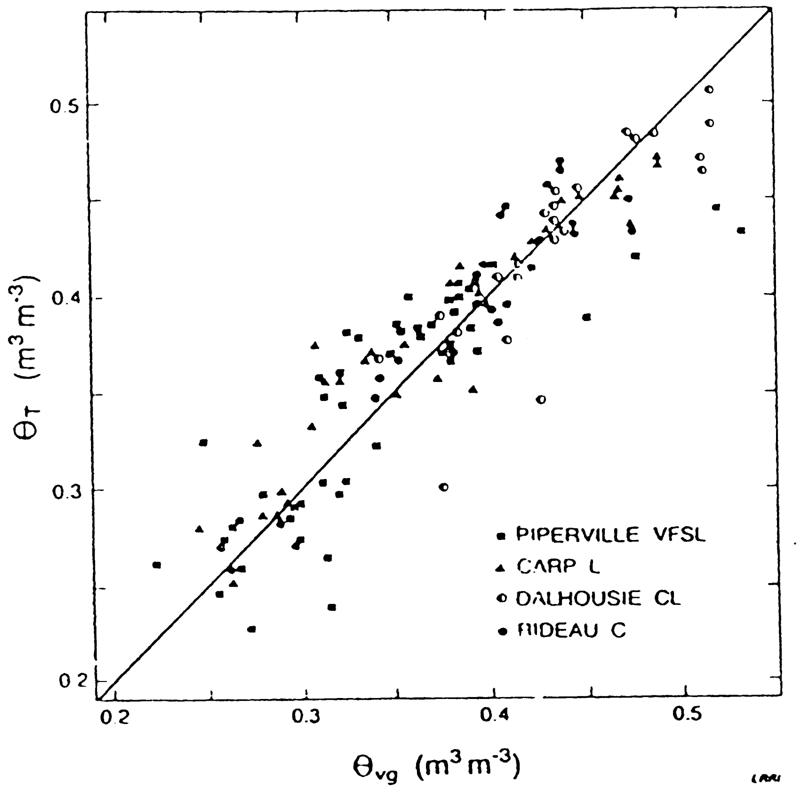


Fig. 5. TDR measured water content (θ_T) vs. gravimetric water content (θ_{vg}) for data from soil pits in the four soil associations.

Table 2. Parameter estimates and correlation for the functional relationship between θ_T and θ_{vg} (The relationship had the form $\theta_T = A + B\theta_{vg}$)

Soil and location	n	A intercept	B slope	Correl coeff
Soil pits-all soils	135	0.0[illegible]6	0.904	0.917
Both mid-slope and flat	175	0.0[illegible]	0.974	0.975
0–50 mm for both midslope and flat	35	−0.0[illegible]6	0.964	0.978
All other depths	140	0.012	0.971	0.985

coefficient of .990. Again a few errors here and there threw the measurements off a bit, but over all it was a very promising experiment. Figure 6 shows a 3-D picture of the decline in soil moisture. As you can see in the graph the experiment lasted 21 days. Figure 7 again shows a plot of the gravimetric vs. TDR measurements.

V. DISCUSSION

From these experiments we found that the methods were compatible, as we expected, and the TDR system would be much more beneficial because it can also be multiplexed, that meaning it can be connected to 10 or more sets of cables and probes to receive 10 different signals, as we already did in the lab. Another reason being that the system can be automated to where measurements can be taken for a long period of time, which is one of the goals of the research. A few more experiments are still to come, one in which the multiplexed system is tested out in the field again being compared to the gravimetric method in a similar fashion as the first two previous experiments.

Figure 6. EXP. #2-- 3D graphs showing TDR and Gravimetric values of decreasing soil moisture

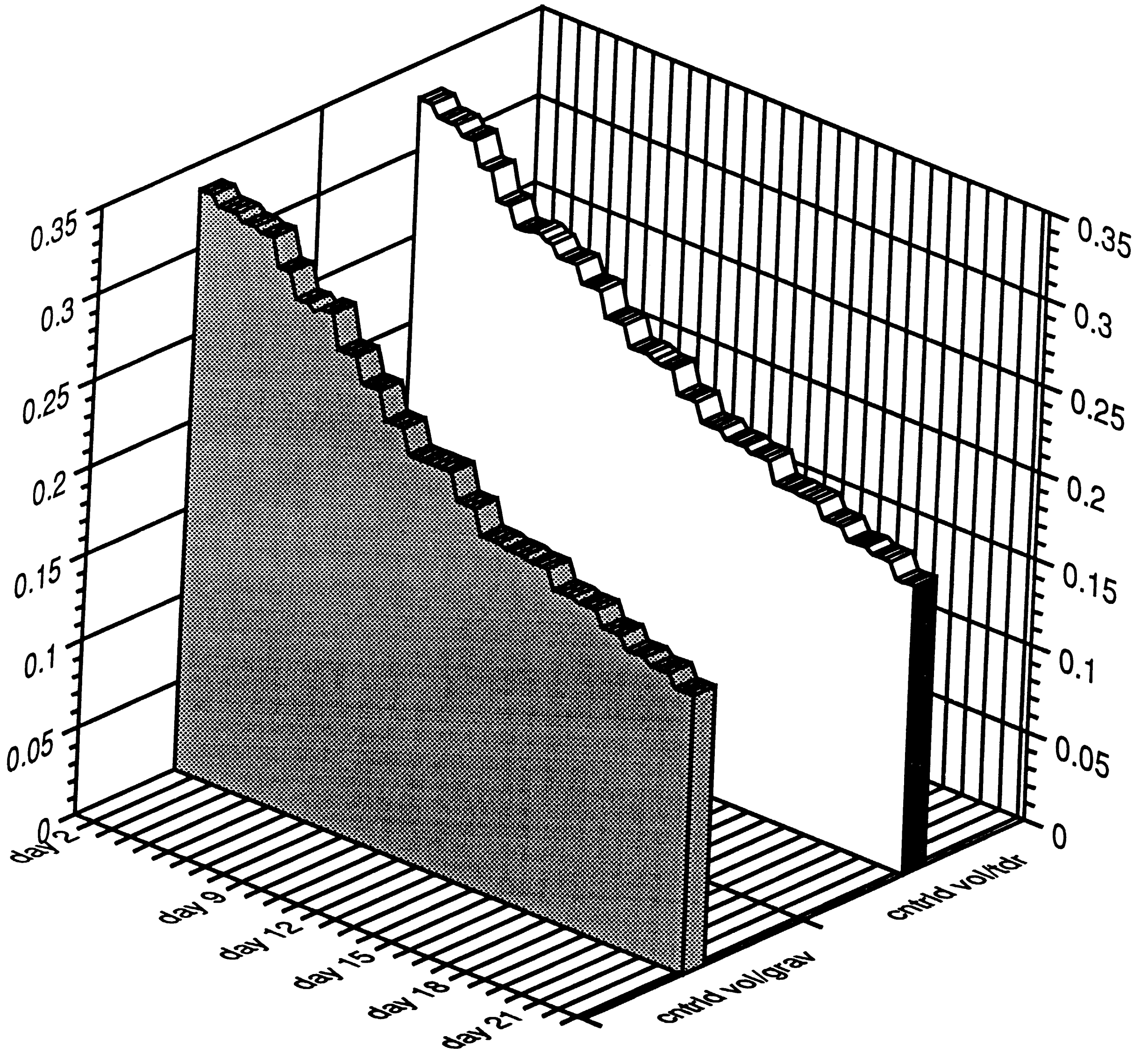
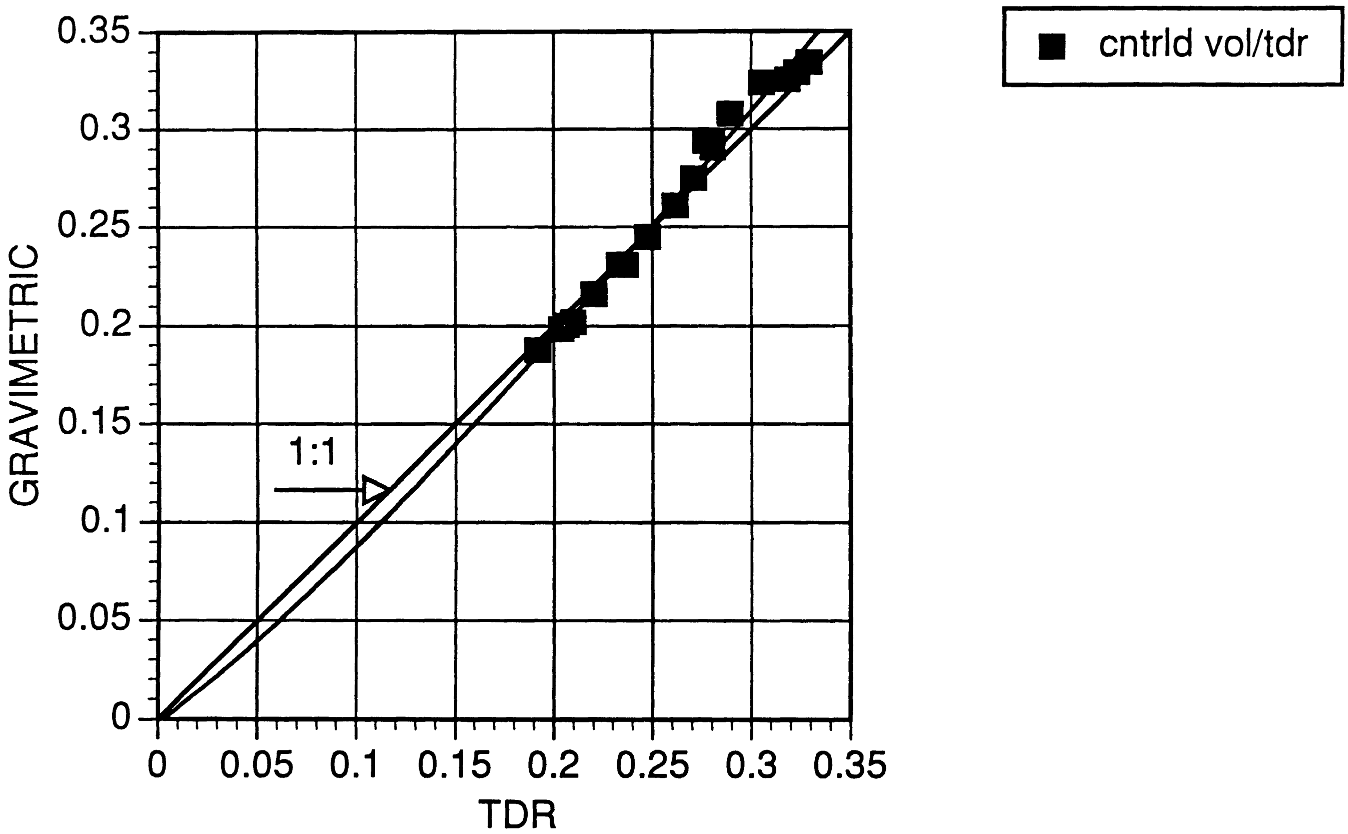


Figure 7. EXP #2-- TDR vs. GRAVIMETRIC plot with correlation coefficient value and formula



f(x) = 1.230185E+0 * (x^1.146645E+0)

R^2 = 9.897965E-1

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