Three-Dimensional Vadose Zone Characterization of a Wisconsin Orchard Using Electromagnetic Techniques

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1. Introduction

Characterizing the near-surface soil water content distribution is important for precision agriculture and groundwater remediation applications. Measuring soil water content over large areas is often difficult, as conventional point measurement and remote sensing techniques are often insufficient to characterize water content heterogeneity at the field scale. Ground penetrating radar (GPR) groundwaves are an electromagnetic geophysical technique that can be used to estimate water content quickly over large areas, and recent studies have indicated that the groundwave sampling depth is a function of antenna frequency (Grote et al., 2010). The objective of this research is to explore the potential of multi-frequency GPR groundwave data for characterizing the three-dimensional soil water content distribution at the field scale.

2. Background

GPR groundwaves are direct waves that travel in the shallow subsurface between the transmitting and receiving antennas (Figure 1, shown in blue). Groundwaves travel at the electromagnetic velocity of the near-surface soil. The soil velocity can be estimated by measuring the time needed for the groundwave to travel from the transmitting antenna to the receiving antenna and the distance between these antennas.The electromagnetic velocity is primarily dependent upon soil water content, so after the velocity is estimated, it can be converted to volumetric water content (VWC) using a petrophysical relationship.

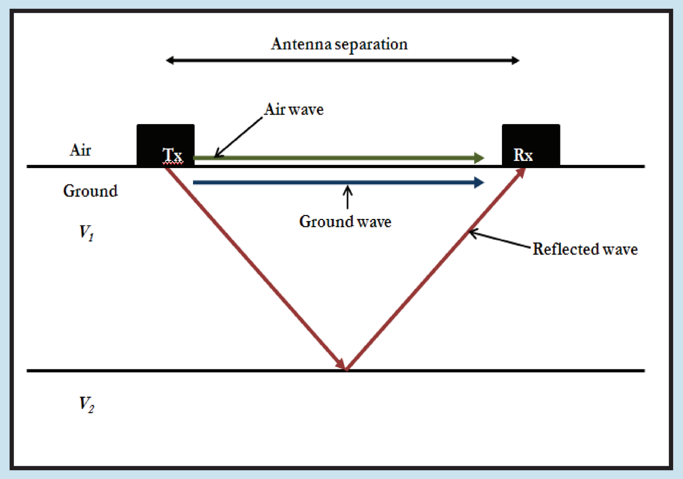

Figure 1: GPR groundwaves travel in the shallow subsurface directly between the GPR transmitter (TX) and receiver (RX).

3. Data Acquisition

GPR groundwave data were acquired in six rows over a gently sloping, 7-acre field site consisting primarily of sandy loam (Figure 2). GPR data were obtained using four antenna pairs with central frequencies of 100-, 250-, 500-, and 1000-MHz. Variable-offset surveys were acquired to determine an appropriate antenna separation for common-offset data and to aid with data interpretation. Common-offset data were then acquired using a sled system and a multi-channel adapter that allowed simultaneous data acquisition with multiple antenna pairs (Figure 3). In addition to the GPR data, vertical gravimetric water content and soil texture measurements were acquired in shallow boreholes at five locations; these measurements were used to estimate the VWC profile at each borehole location.

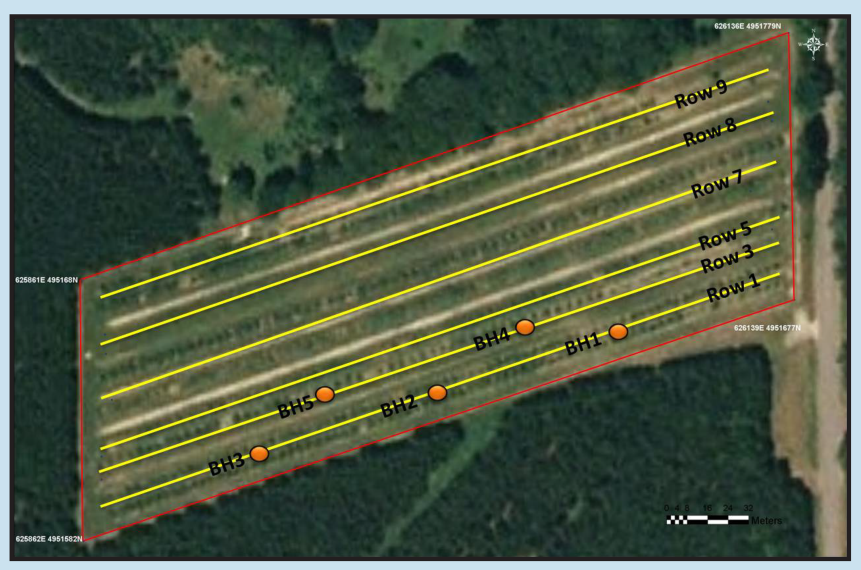

Figure 2: Common-offset GPR data were acquired in six traverses across the site.

Figure 3: Common-offset GPR data were acquired simultaneously for all frequencies using a sled system.

4. Data Analysis

For each GPR frequency, variable-offset surveys were used to identify the airwave and groundwave based upon their arrival times and velocities (Figure 4). Then, the arrival time of the airwave and groundwave at the antenna separation used in the common-offset data acquisition was noted. These arrival times (and the wavelet pattern observed in the variable-offset data) were used to identify the airwave and groundwave wavelets in the common-offset data. The arrival times for both the airwave and groundwave in the common-offset data were noted for each measurement (Figure 5), and these times were used to calculate the time needed for the groundwave to travel between antennas. The groundwave travel time was then used to calculate the groundwave velocity. Topp's equation (Topp et al., 1980) was used to convert the velocity measurements to VWC estimates.

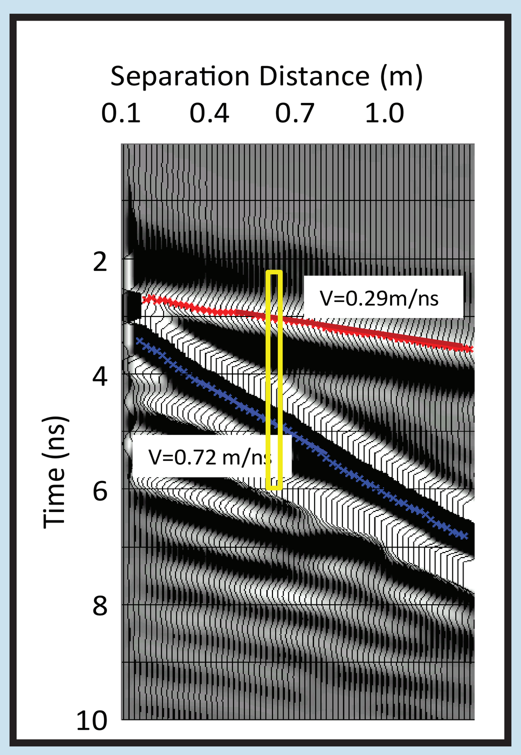

Figure 4. Variable offset data acquired with 250 MHz antennas. The box shows the separation distance between antennas at which the common-offset data were acquired.

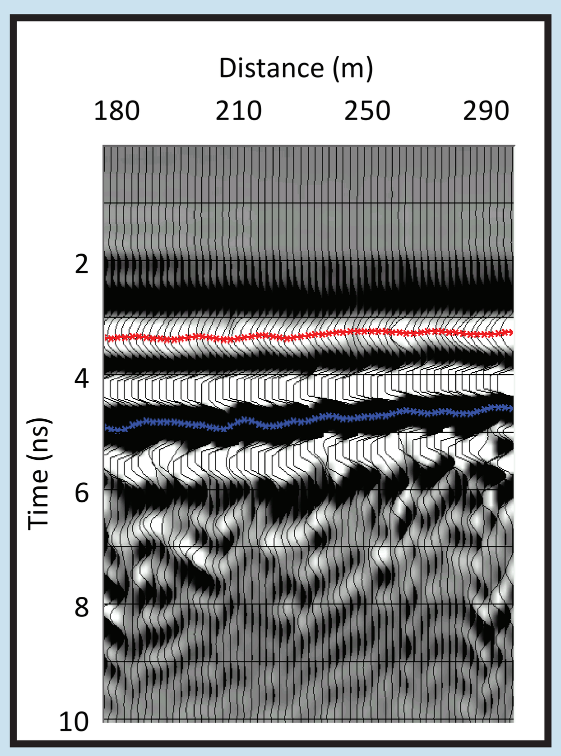

Figure 5: Common-offset 250 MHz data acquired along Row 1. Variations in the groundwave travel time indicate changes in soil moisture.

5. Results

Figures 6a – 6d show the VWC estimated from GPR data for each frequency. These plots show that different GPR frequencies produce different average water contents, but the distribution of water content across the field is similar for all frequencies. Modeling and laboratory experiments predict that higher frequencies will have shallower sampling depths, so the 1000 MHz antennas are probably sampling the shallowest soil, while the 100 MHz antennas sample deeper soils (Table 1). At this site, the shallow soil is the wettest, has the least variation in VWC, and has the least correlation with the VWC patterns observed in the other frequencies, suggesting that the recent precipitation has not yet been vertically redistributed. The other three frequencies show much more similar VWC distributions and have similar average water contents; these similarities are probably indicative of vertical redistribution of water in the deeper, less-organic rich soils.

Table 1: Average VWC and sampling depth for each frequency.

Frequency (MHz)	1000	500	250	100
Average VWC across field	0.41	0.35	0.34	0.34
Predicted sampling depth (cm)	6.9	11.2	14.2	21.1

GPR data acquired near the boreholes were compared to the estimated VWC profiles in these boreholes. Figures 7a-c shows the VWC estimated from gravimetric water content (GWC) samples acquired in three boreholes and VWC estimated from the nearest GPR measurements. To better compare the VWC from GPR and gravimetric measurements, the GPR measurements are plotted at the sampling depth predicted by laboratory and modeling studies (Table 1, from Grote et al. 2010). These plots show that GPR and gravimetric techniques generally provide similar water content values, although significant variations are observed at a few locations. The difference between the gravimetric and GPR estimates of VWC could be caused by differences in sampling depths (the GPR sampling depths may not be accurate for this soil type) or by differences in location (the boreholes were installed a few feet away from the GPR traverse).

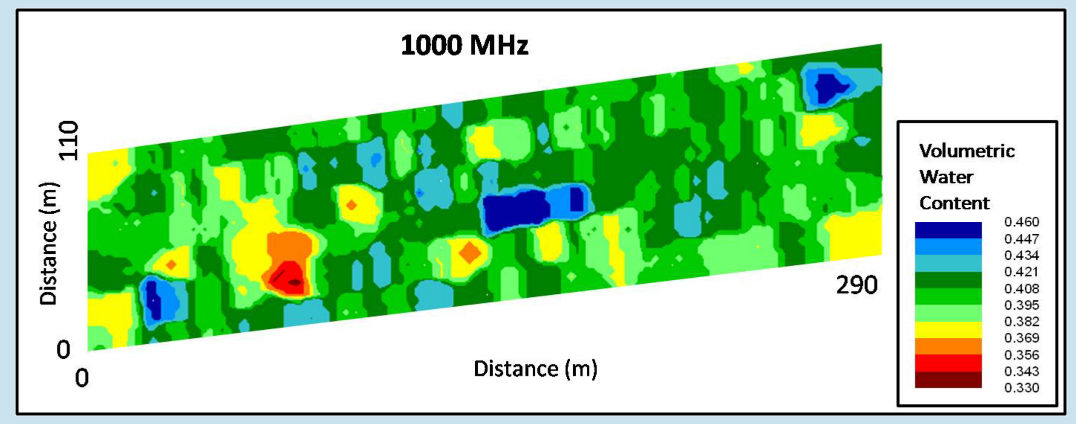

Figure 6a: VWC from 1000 MHz GPR.

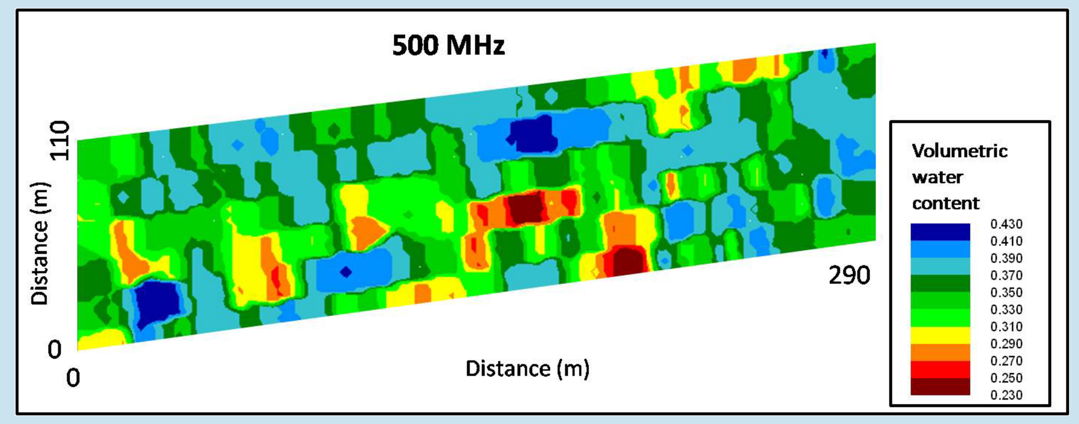

Figure 6b: VWC from 500 MHz GPR.

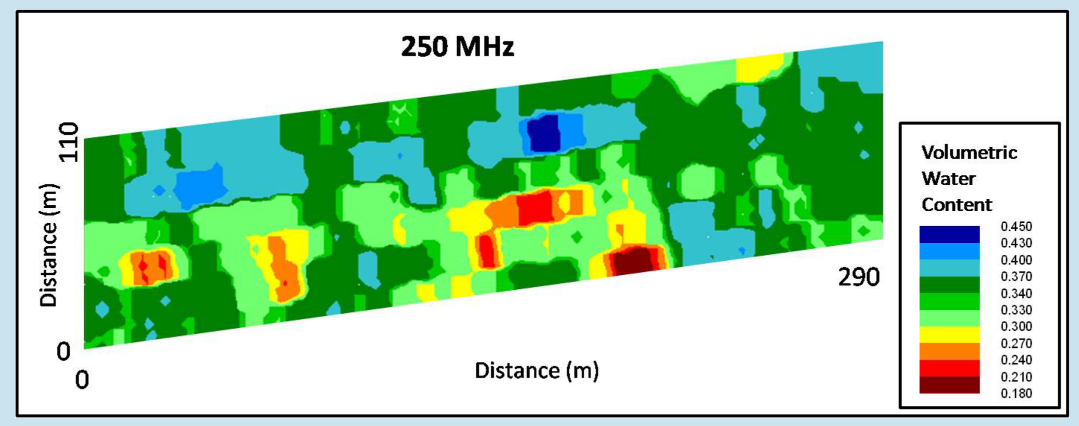

Figure 6c: VWC from 250 MHz GPR.

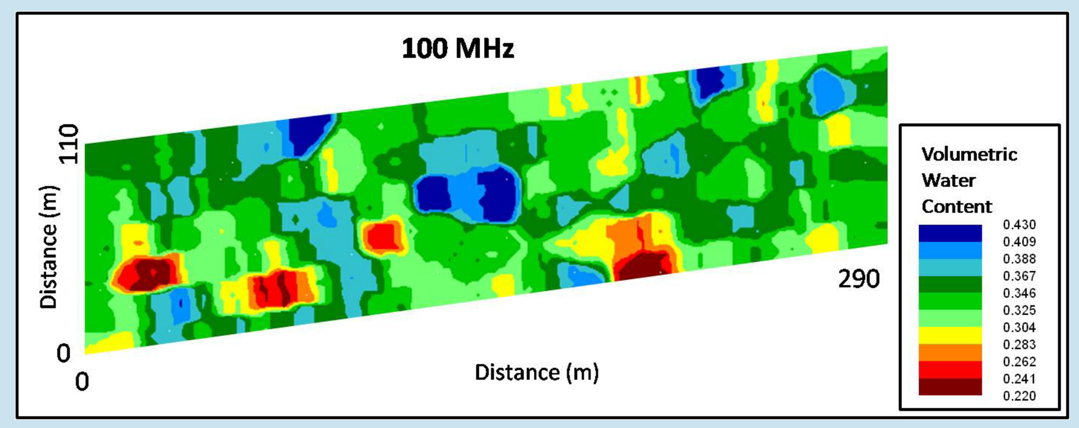

Figure 6d: VWC from 100 MHz GPR.

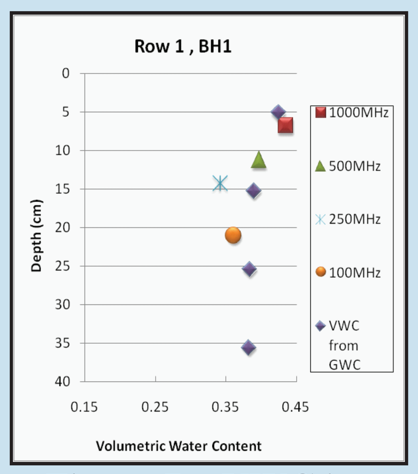

Figure 7a: VWC in borehole 1.

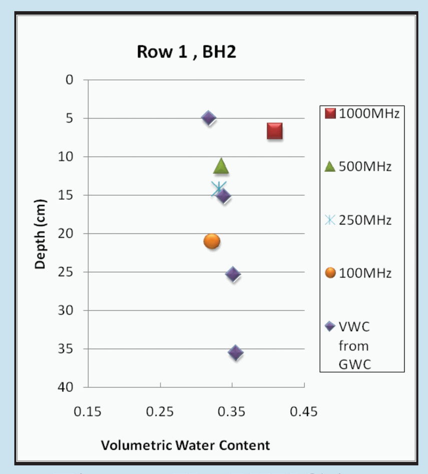

Figure 7b: VWC in borehole 2.

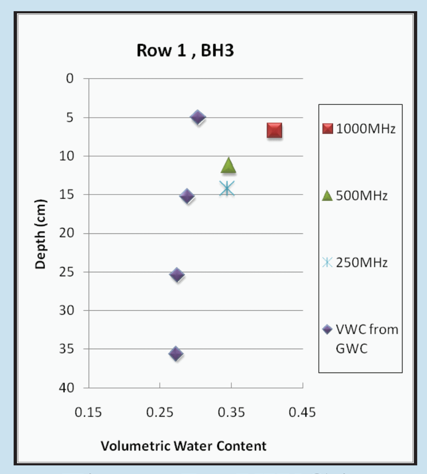

Figure 7c: VWC in borehole 3.

6. Conclusions

The results from this experiment show that multi-frequency GPR groundwave data can be used to determine the three-dimensional soil water content distribution. Data from different frequencies show similar water content distributions, while the absolute water content varies between frequencies. Comparison of VWC from GPR and from gravimetric samples shows similar results, although some differences are evident for the lower GPR frequencies; these differences may be caused by different sampling depths and slightly different lateral sampling locations.

7. Acknowledgments

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8. References

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Grote, K., T. Crist, and C. Nickel (2010), Experimental estimation of the GPR groundwave sampling depth, in revision for Water Resources Research.

Topp, G.C., J.L. Davis, and A.P. Annan (1980), Electromagnetic determination of soil water content: measurements in coaxial transmission lines, Water Resour. Res., 16(3), 574-582.