Soil Moisture Estimation Using Air-Launched GPR Techniques

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1. Introduction & Theory

Near-surface soil water content is an important parameter in agricultural, geotechnical, and environmental applications, but is often difficult to measure over large areas. Recent investigations of ground penetrating radar (GPR) techniques suggest that these methods could provide high-resolution, cost-effective measurements of soil water content (Huisman *et al.* 2001).

This experiment investigates the efficacy of air-launched GPR techniques as a tool for estimating soil water content under variable soil conditions. Air-launched data were acquired using three GPR frequencies over layered soil profiles with different water contents and textures (Figure 1). These data were used to evaluate the accuracy of water content estimates from air-launched GPR and to determine the penetration depth of the air-launched GPR signal under differing soil conditions.

GPR methods can be used to estimate the dielectric constant (K) of soil , and several petrophysical relationships are available to estimate the soil water content based upon the dielectric constant. The dielectric constant is calculated using:

$$K = \left(\frac{1 + \frac{A_S}{A_M}}{1 - \frac{A_S}{A_M}} \right)^2 \qquad (1)$$

where A_S is the amplitude from the soil surface and A_m is the amplitude from a metal plate (Saarenketo and Scullion, 2000).

Figure 1: Multi-frequency GPR data were acquired after each new soil layer was added. This figure shows data acquisition with the 500 MHz antennas. GPR surveys were also acquired over a 1.5-m by 1.5-m steel plate placed in the tank to generate the maximum reflection amplitudes needed to calibrate the reflections from the soil surface.

2. Data Acquisition and Analysis

2.1. Data Acquisition

Data for this experiment were acquired under controlled climatic conditions in a large, non-conductive tank (Figure 1). Preliminary results have been compiled for the first three phases of this experiment, where soil water content and/or soil texture were varied for each phase. The first phase used a basal layer of saturated sand overlain by dry sand. A 15-cm thick layer of saturated sand was placed in the tank, and air-launched data were acquired over the sand with the 250-, 500-, and 1000-MHz antennas (Figure 1). After these surveys were completed, a large metal plate was placed in the tank, and air-launched data were collected above the plate. The plate was then removed, the basal layer was sealed, and a 6-cm layer of dry sand was added to the tank. Air-launched GPR data were acquired over this dry sand layer using all three GPR frequencies. Additional 3-cm layers of dry sand were incrementally placed in the tank, with GPR data acquisition after the addition of each layer, until the dry sand depth reached 30-cm. The height of the GPR antennas above the soil was measured at the beginning of each survey.

The second phase of the experiment was procedurally similar to the first phase, but a basal layer of dry sand was overlain by incremental layers of saturated sand. Also, the first saturated sand layer was 3-cm thick. The third phase of the experiment was similar to the second phase, but used an organic-rich sandy loam, where the basal layer was saturated and the overlying layers were dry.

2.2. Data Analysis for Air-Launched GPR

For each survey, the reflection from the air-ground interface was identified (Figure 2) and the amplitude of the reflection was determined. The amplitude values for all traces in a survey were averaged to reduce noise. The resulting average amplitude was used with (1) to estimate the dielectric constant (K). Then, Topp's equation (Topp *et al.*, 1980) was used to convert the dielectric constant to volumetric water content (θ_V):

$$\theta_v = -5.3\times10^{-2} + 2.92\times10^{-2}K - 5.5\times10^{-4}K^2 + 4.3\times10^{-6}K^3 \qquad (2)$$

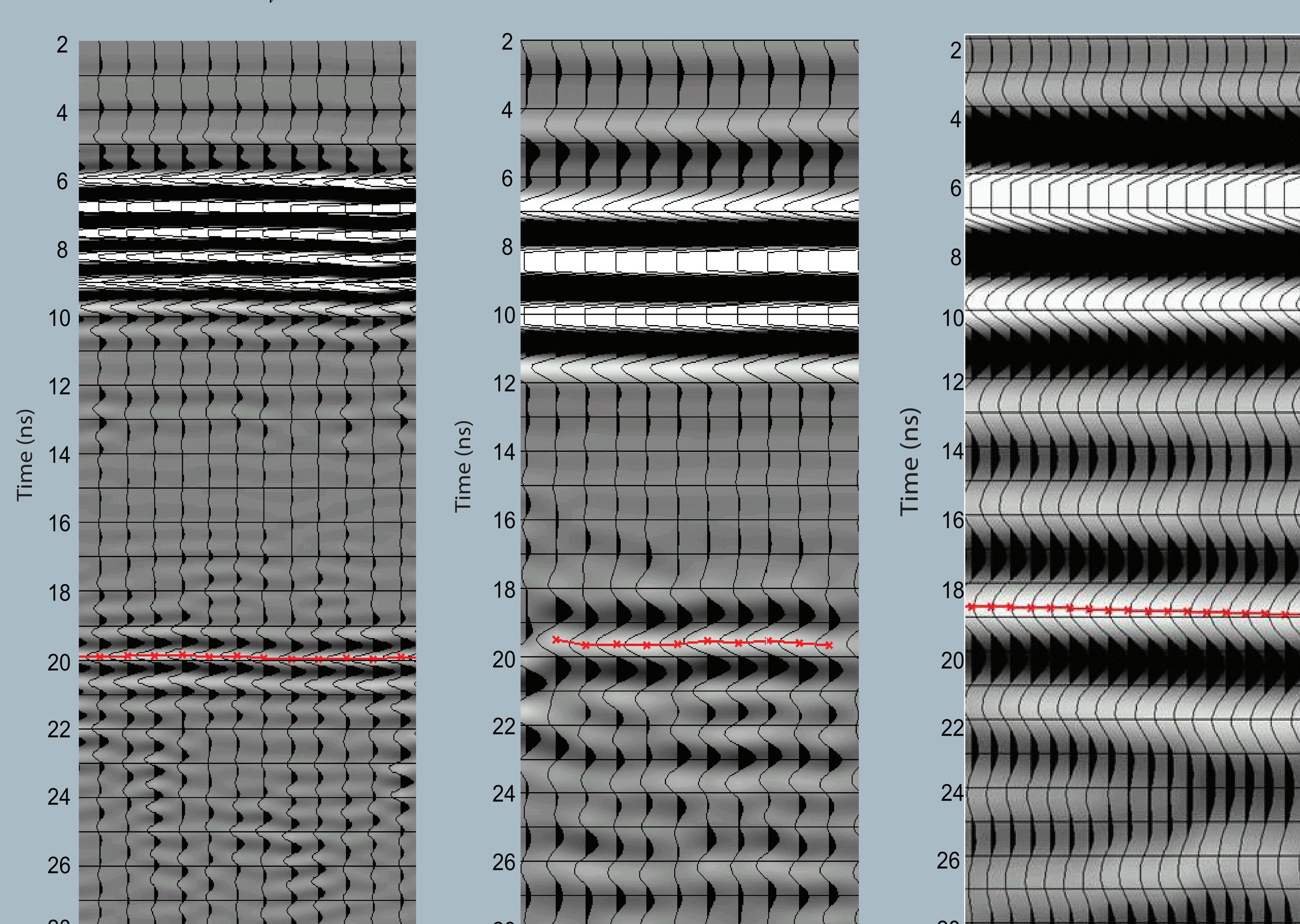

Figure 2a: 1000 MHz data acquired over saturated sand.

Figure 2b: 500 MHz data acquired over saturated sand.

Figure 2c: 250 MHz data acquired over saturated sand.

Figure 2: The largest trough of the first reflection event (reflection from the soil surface) was chosen for amplitude measurements. This trough is marked with red asterisks in the above figures.

3. Results

Comparison of volumetric water content estimates obtained from GPR amplitude data to water content estimates obtained through gravimetric sampling (Table 1) show that the GPR-derived estimates are reasonably accurate. Table 1 shows that the water content estimates from GPR data seemed to be more accurate for the saturated soils than for the dry soils. The accuracy was similar for each GPR frequency. Higher errors in water content estimation may be caused by variations in the height above the soil as the antennas are moved, possible tilting of the antennas, error in the metal calibration surveys, or inaccuracies produced by using a general petrophysical relationship rather than a soil-specific relationship.

Volumetric Water Content Estimates from Gravimetric Sampling and Air-launched GPR Techniques

	Dry sand (from dry sand overlying saturated sand)	Dry sand (from basal layer of dry sand)	Saturated sand (from saturated sand overlying dry sand)	Saturated sand (from basal layer of saturated sand)	Dry loam (from dry loam overlying saturated loam)	Saturated loam (from basal layer of saturated loam)	RMSE
Gravimetric Sampling	0.30%	0.30%	37%	35%	0.70%	43%	
250 MHz	1.80%	1%	37%	39%	6%	40%	3.1%
500 MHz	10%	6%	40%	40%	2%	42%	5.2%
1000 MHz	4%	7%	39%	41%	7%	42%	4.8%

Table 1: A comparison of volumetric water content estimates from air-launched GPR data and from gravimetric sampling show a RMSE in the GPR-based estimates of ~5%.

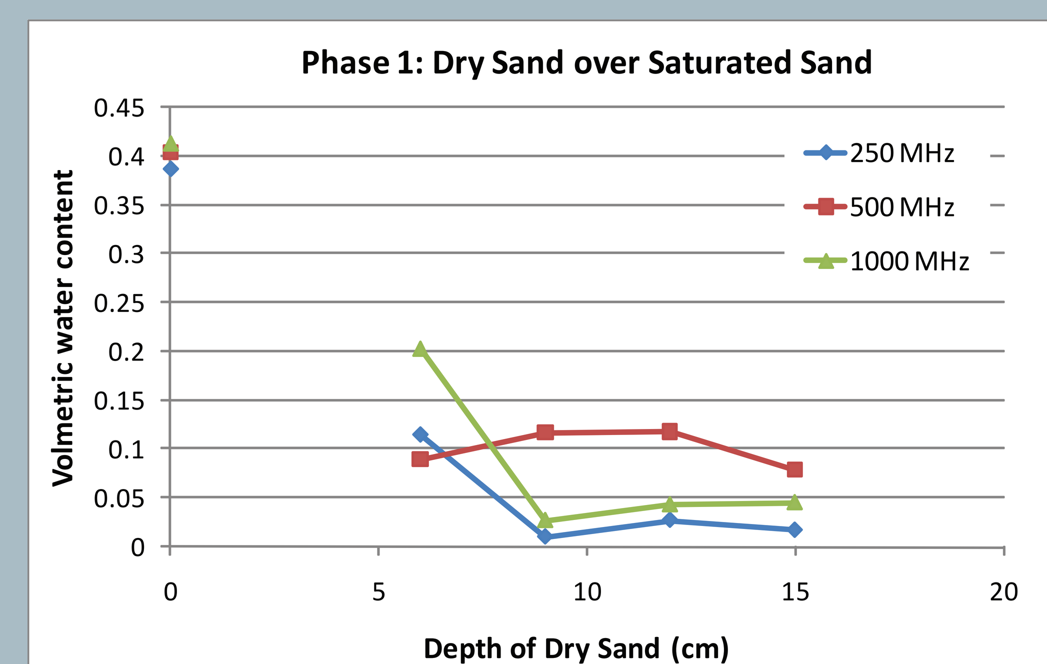

Figure 3: The penetration depth of air-launched GPR reflections in dry sand is between 6 and 9 cm.

The penetration depth of air-launched GPR reflections can be estimated by noting how the calculated water content changes as additional overlying soil layers are placed in the tank. When the overlying soil layer is thin, the GPR reflection may penetrate through the overlying soil into the underlying basal layer, and the resulting water content estimate will be different from that of either the basal or the overlying layer. Figures 3, 4, and 5 show the water contents calculated using air-launched data for each of the three phases of this experiment. These graphs show similar trends throughout each phase, where the initial water content corresponds to that of the basal layer, while the next one to two surveys show water contents in between those of the basal layer and the overlying soil. After the air-launch penetration depth has been reached, the water contents remain approximately constant at the value of the overlying soil layer. Figures 3, 4, and 5 show that the penetration depth does not appear to be frequency dependent. For dry sand (Figure 3), the penetration depth is between 6 and 9 cm. For saturated sand (Figure 4) and for dry loam (Figure 5), the penetration depth is slightly less, between 3 and 6 cm. These results suggest that the penetration depth may be moderately sensitive to soil moisture and texture and that the penetration depth of air-launched GPR data is similar to that of satellite-based remote sensing data, which has a penetration depth of 5 cm or less (Jackson *et al.*, 1996).

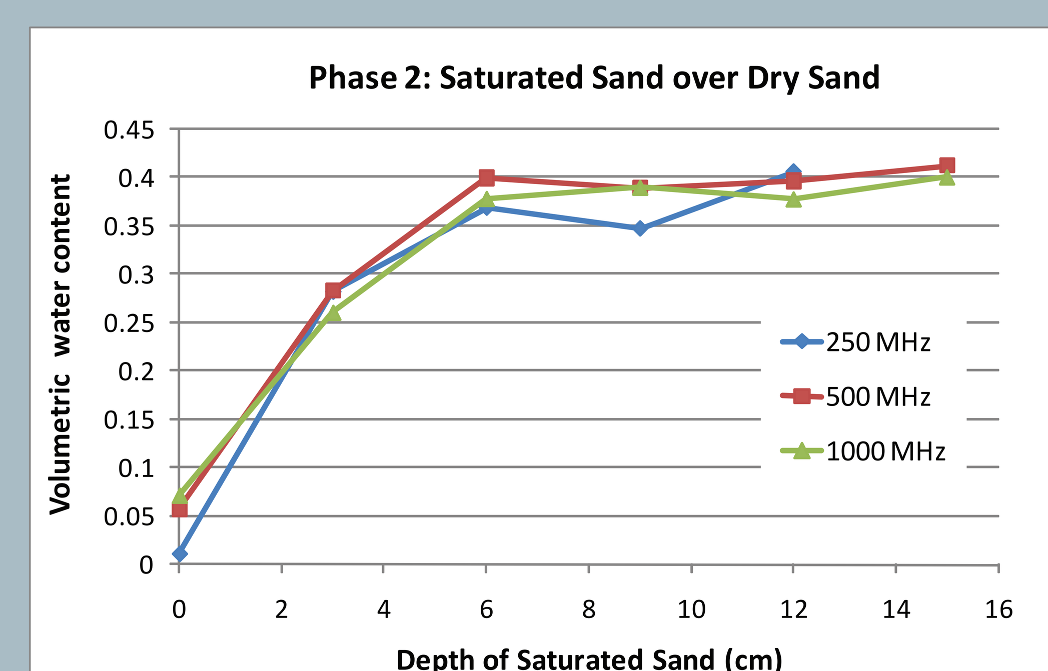

Figure 4: The penetration depth of air-launched GPR reflections in saturated sand is between 3 and 6 cm.

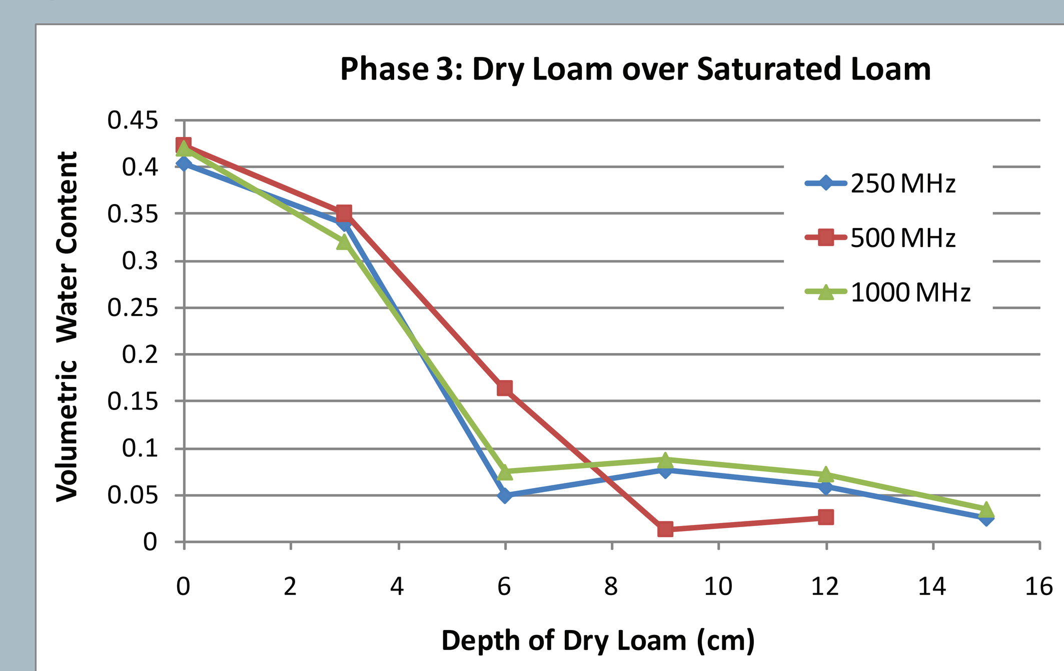

Figure 5: The penetration depth of air-launched GPR reflections in dry loam is between 3 and 6 cm.

4. Acknowledgements

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5. References

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