Three-Dimensional Water Content Estimation using Ground Penetrating Radar Groundwave Techniques

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1. Motivation

Accurate characterization of near-surface soil water content is important for optimizing crop yields, determining the scheduling and volumes of irrigation, and preventing groundwater degradation from agrochemicals leaching through the vadose zone. Characterizing the near-surface soil water content using conventional methods can be difficult, as this parameter is highly variable both spatially and temporally, and most methods obtain only a limited number of point measurements. Ground Penetrating Radar (GPR) groundwave techniques can be used to quickly obtain many water content measurements over a large area (Huisman *et al.*, 2001), but the efficacy of these techniques is limited by the uncertainty of the groundwave penetration depth. In this project, we seek to experimentally determine the penetration depth of the GPR groundwave as a function of GPR frequency, soil moisture, and soil texture.

2. Background

The GPR groundwave is a direct wave which travels between the transmitting and receiving antennas in the near subsurface (Figure 1). Currently, there is no general consensus for the penetration depth (z) of the groundwave (Du, 1996;Van Overmeeren *et al.*, 1997). This experiment investigates z using the electromagnetic groundwave velocity (v), where v can be estimated using the groundwave travel path (assumed to be the distance between the transmitting and receiving antennas) and the measured travel time of the groundwave between the antennas. Under low attenuation conditions, v is primarily dependent upon the soil water content, so we use saturated and dry soil to create layers with contrasting v.

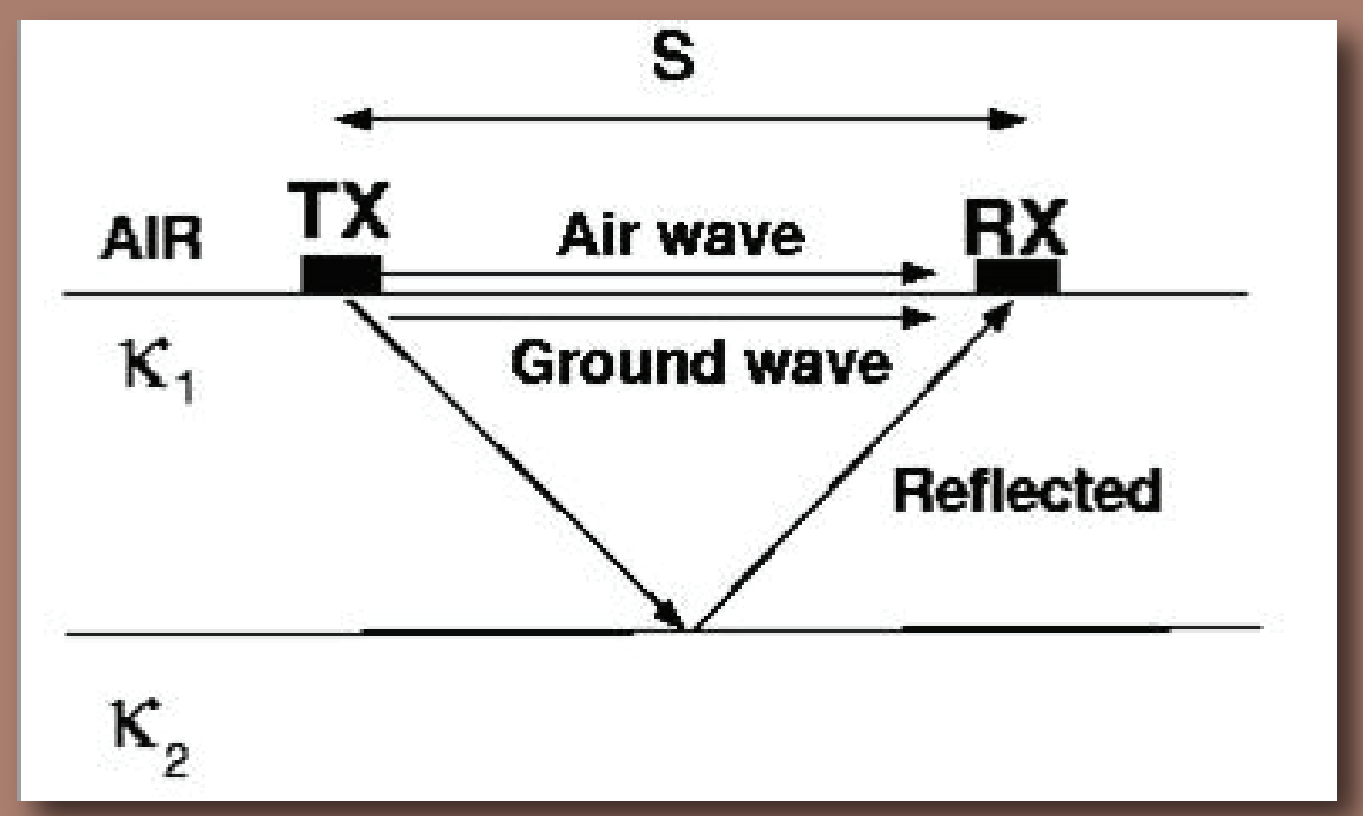

Figure 1: The GPR groundwave is a direct wave traveling in the near subsurface between the transmitting and receiving antennas.

3. Data Acquisition and Analysis

3.1. GPR Data Acquisition

This experiment investigates z using soil layers with contrasting v within a large, non-conductive, fiberglass tank (Figure 2). First, a layer of homogenously saturated sand (low v) was placed in the tank, and multi-frequency GPR data were acquired over this layer using antennas with central frequencies of 100-, 250-, 500-, and 1000-MHz. Three variable-offset surveys were acquired with each frequency; a common-midpoint survey was performed in the middle of the tank (Figure 2), and two wide angle reflection and refraction (WARR) surveys were collected, where each of the WARR surveys began at opposite ends of the tank. The saturated sand was then sealed, and 3-cm layers of dry sand (high v) were incrementally added to the tank. GPR data were acquired after each additional soil layer. The groundwave v was calculated for each GPR survey, and z was determined by noting the thickness of dry sand at which the velocity ceased to change with additional dry sand layers. This procedure was repeated using a basal layer of dry sand overlain by incremental layers of saturated sand to determine the penetration depth in saturated sand. Finally, the entire experiment was repeated using a basal layer of saturated loam overlain by dry loam and using a basal layer of dry loam overlain by saturated loam.

Figure 2: Common-midpoint surveys were performed in the middle of the tank for each GPR frequency. To avoid compaction of the soil, no one entered the tank after soil was added. The antennas were moved remotely using ropes.

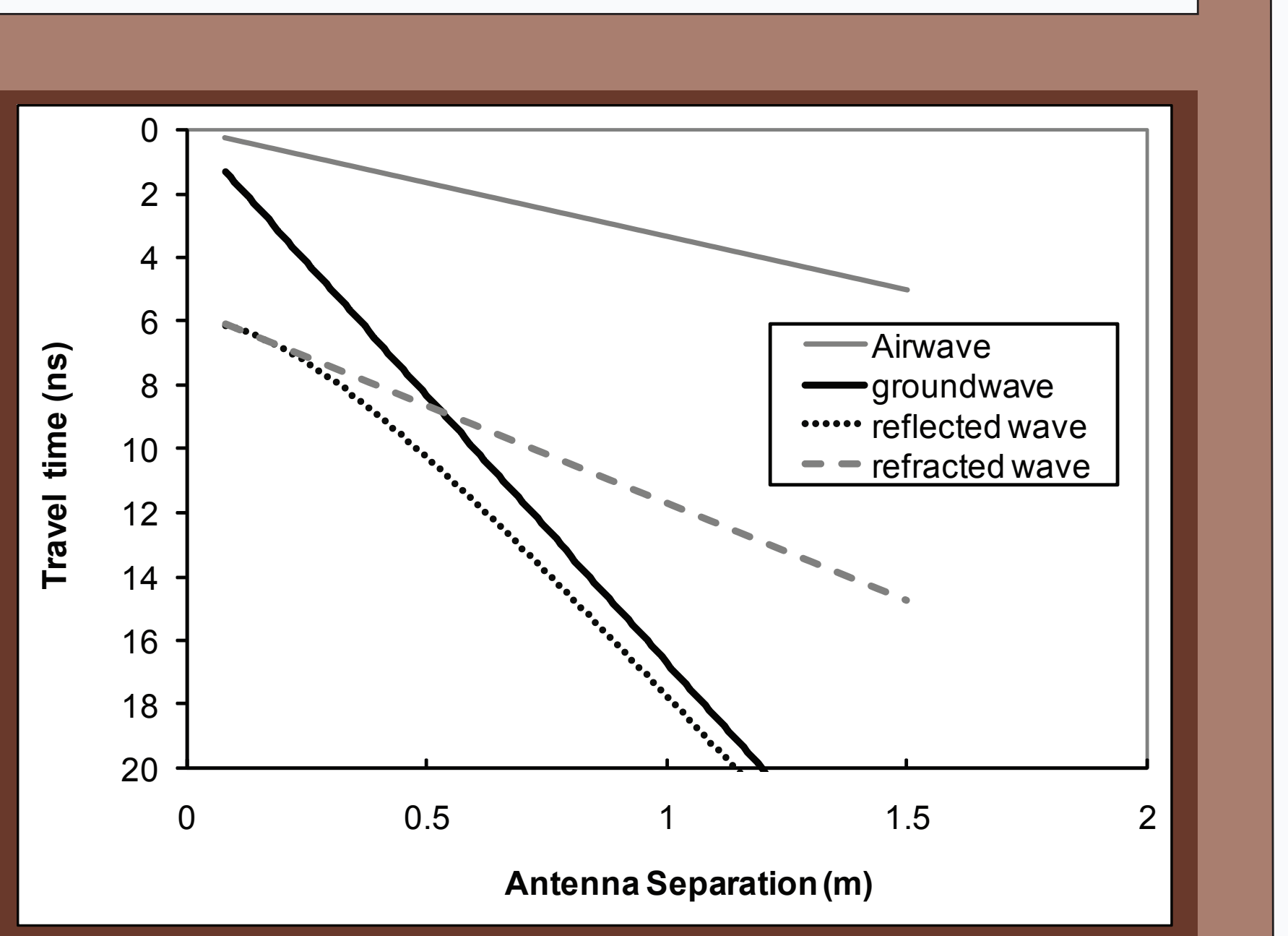

Figure 3: When the surficial soil layer is thin, the groundwave may experience interference with the reflected or refracted waves. This figure shows a 9-cm layer of saturated sand overlying a basal layer of dry sand. The groundwave v must be determined from the initial portion of the groundwave wavelet (early travel times) to avoid interference from the reflected and refracted waves.

3.2. Data Analysis and Interpretation

Careful identification of the groundwave was the most critical aspect of data interpretation. Due to the layered nature of the experiment, reflections and refractions were sometimes observed along with the groundwave. Figure 3 shows how these waves will arrive when a thin layer of saturated sand overlies a basal layer of dry sand. When the overlying saturated sand layer is thin, the groundwave v must be determined in the early-time portion of the groundwave event, before superposition with the reflected or refracted wave begins. At very early times, superposition with the airwave can also potentially interfere with obtaining a valid groundwave v. Identifying a valid portion of the groundwave from which to calculate v was the first step in data interpretation.

After the groundwave was identified, a portion of the groundwave wavelet was chosen to calculate v. Although modeling studies sometimes show the groundwave as a single negative-amplitude event, our data show the groundwave to be a modified Ricker wavelet with multiple peaks (positive amplitudes, shown as black in Figure 4) and troughs (negative amplitudes, shown as white) centered around a high-amplitude trough. For variable-offset surveys, any of these peaks or troughs will provide the same groundwave v, provided that there is no interference from other waves (Figure 4h). For some surveys, superposition with portions of the airwave, refraction, or reflection wavelet interfered with the portions of the groundwave wavelet (Figures 4b - 4d). In these circumstances, a portion of the groundwave wavelet that did not appear to be influenced by superposition with another wavelet was used to calculate v. The groundwave v was calculated for each of the three variable-offset surveys acquired for each layer, and these values were averaged to obtain a single v estimate per frequency for each layer.

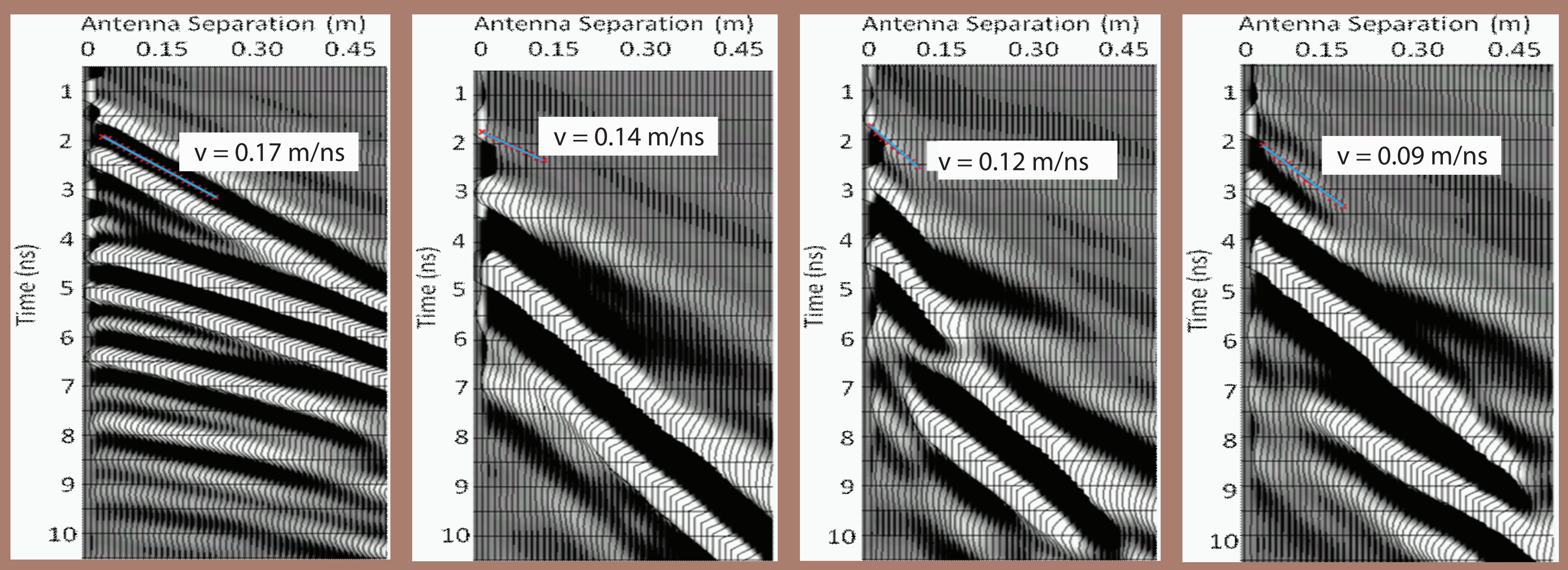

Figure 4a: Dry sand

Figure 4b: 3-cm of saturated sand overlying dry sand

Figure 4c: 6-cm of saturated sand overlying dry sand

Figure 4d: 9-cm of saturated sand overlying dry sand

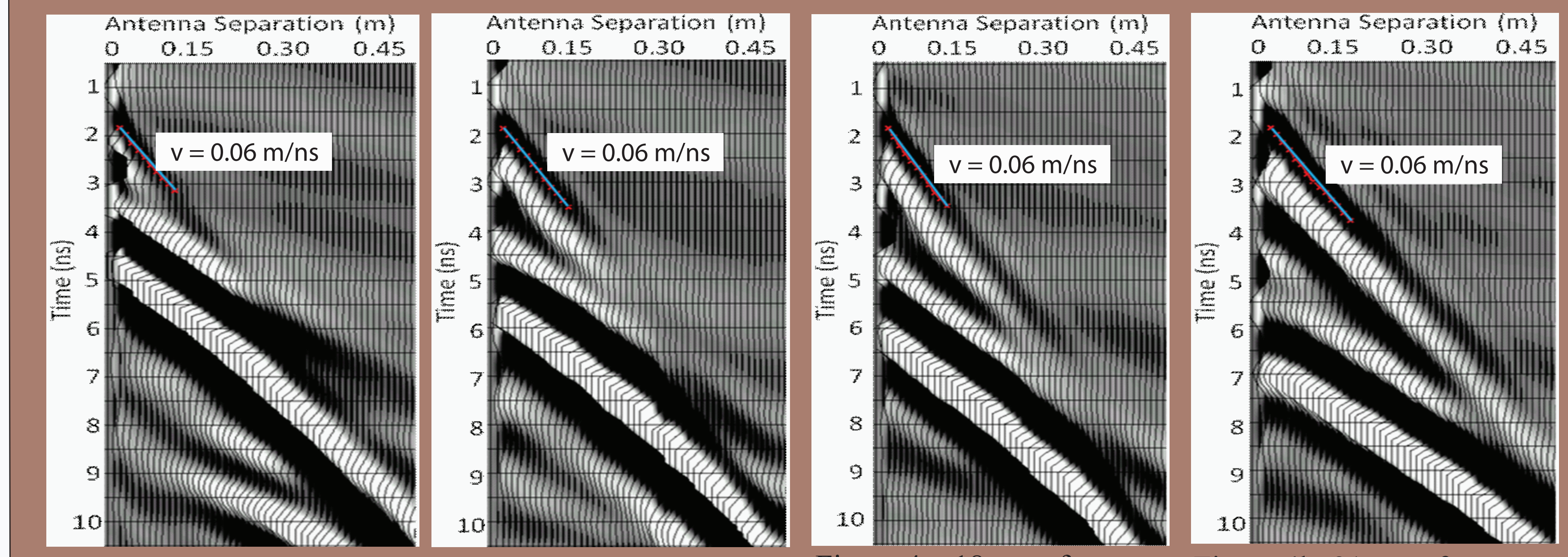

Figure 4e: 12-cm of saturated sand overlying dry sand

Figure 4f: 15-cm of saturated sand overlying dry sand

Figure 4g: 18-cm of saturated sand overlying dry sand

Figure 4h: 21-cm of saturated sand overlying dry sand

Figure 4: Common-midpoint surveys acquired with 1000 MHz antennas as 3-cm layers of saturated sand are incrementally added to a basal layer of dry sand. The groundwave velocity decreases as additional saturated sand layers are added. The velocity values derived from these surveys are also shown in Figure 6.

4. Experimental Results

The groundwave penetration depth (z) can be estimated by observing the depth of overlying soil where v ceases to change with additional soil layers. Figure 5 shows v measurements in dry sand overlying saturated sand; the z for each frequency is given in Table 1. These results show that z is frequency dependent, with lower frequencies having greater z. Figure 6 and Table 1 show similar results from saturated sand overlying dry sand; these results suggest that soil water content does not greatly influence z. Only preliminary results for the 500-MHz and 1000-MHz antennas are available from the third experiment, in which dry loam overlies saturated loam, but these two frequencies seem to have penetration depths similar to those observed in sand (Figure 7 and Table 1). These results indicate that soil texture does not greatly influence z, although additional data are necessary to confirm this. The results produced thus far show that GPR groundwave methods may become a valuable field tool for soil water content estimation, since multi-frequency groundwave data could be used to quickly create vertical water content profiles over large areas, and preliminary results suggest that calibrations for soil texture or moisture are probably unnecessary.

MHz	Dry Sand (cm)	Wet Sand (cm)	Dry Loam (cm)	Wet Loam (cm)
1000	12	12	12	15
500	21	~21	~24	24
250	27	30		
100	42			

Table 1: Penetration depth values for each frequency in sand and loam. The penetration depth does not appear to be highly dependent upon soil texture or moisture.

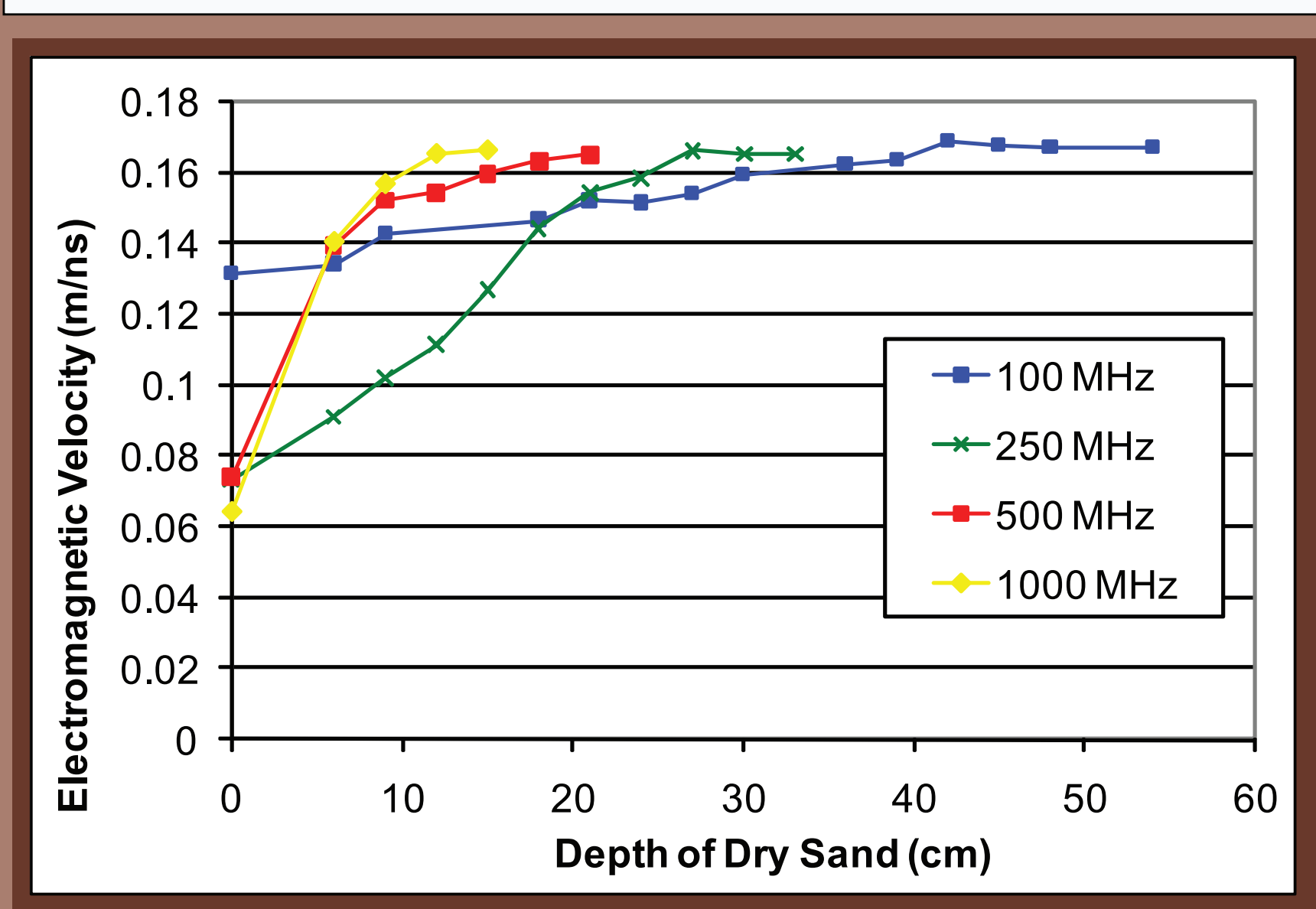

Figure 5: The groundwave velocity increases with each additional layer of dry sand until the depth of penetration is reached.

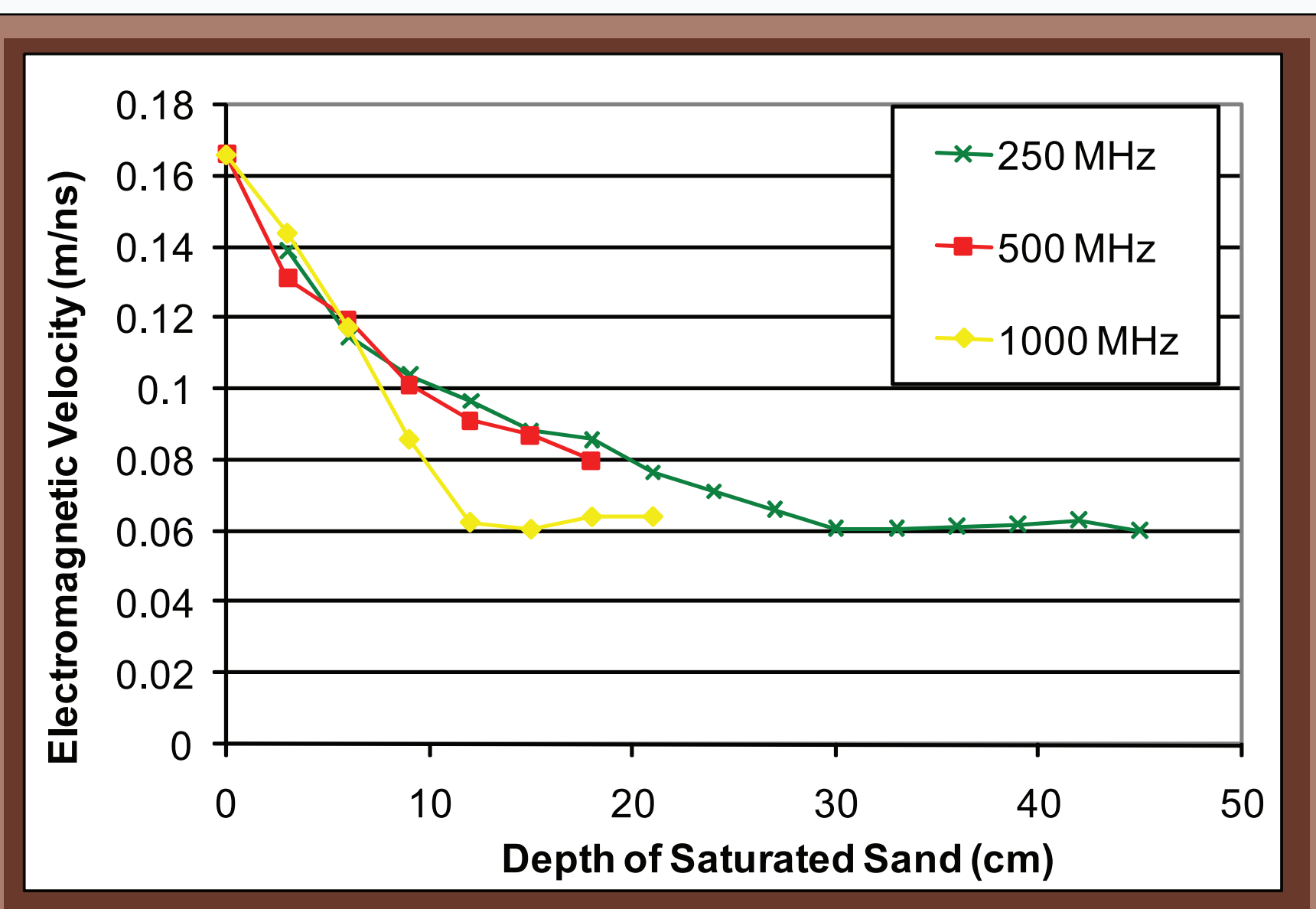

Figure 6: The groundwave velocity decreases with each additional layer of saturated sand until the depth of penetration is reached.

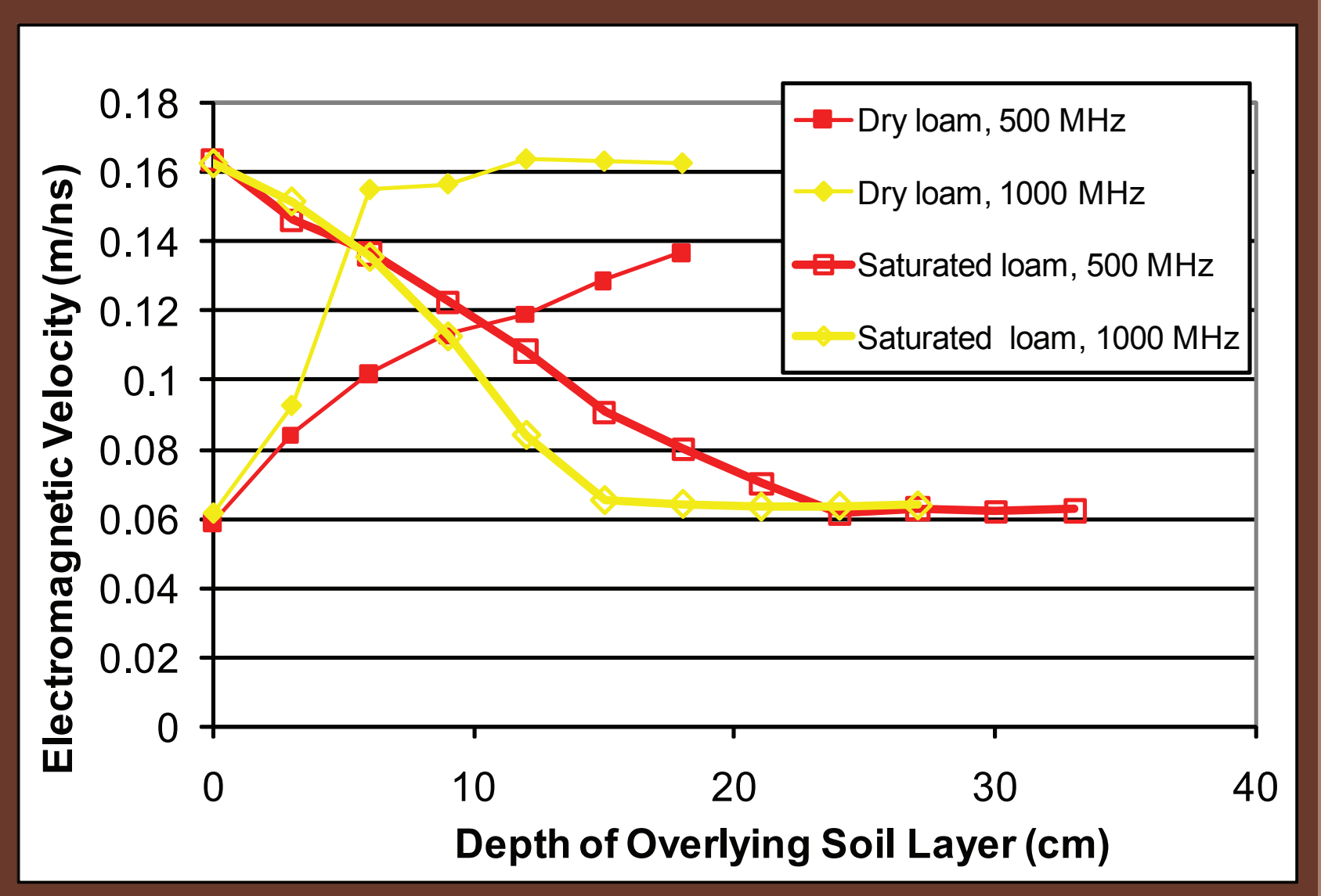

Figure 7: Comparison of 500- and 1000-MHz data acquired over dry loam and saturated loam. Water content does not appear to greatly influence groundwave penetration depth in this soil.

5. Acknowledgements

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6. References

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