Characterization of ground-penetrating radar (GPR) response in a variety of Earth materials under different moisture conditions

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ABSTRACT

As part of a study using GPR to quantitatively determine Volumetric Moisture Content (VMC) spatially for hillslope hydrology and water leak detection applications, a series of controlled laboratory experiments were conducted to investigate material-specific GPR response to different VMC conditions. Using a specially developed GPR-soil hydrology test facility, six materials were tested with incremented moisture from dry to saturation. A number of directly derived GPR trace parameters acquired using Reflection Profiling Mode were used to develop and test VMC-GPR relationships to enable GPR measurement of soil moisture and to determine the effect of different material properties on hydraulic characteristics and how this is manifested in GPR response. Data was analysed in both the time and frequency domains as a depth-average and at specific depths beneath the subsurface. The most consistent parameter investigated used was the mean instantaneous amplitude. A strong textural dependence related to how the water interacted with the host material suggests that individual models can be combined to form a moisture response model for GPR based on the particle size distribution of a material. This only works for well-structured materials and where there is a relatively simple subsurface structure and where other system interference is low.

Keywords: Instantaneous Amplitude, Ground Penetrating Radar, Subsurface Moisture.

1. INTRODUCTION

Subsurface moisture is an important variable for many environmental investigations and can vary significantly in both space and time. Soil moisture is particularly important in determining the hydrological response of a hillslope because it influences processes such as runoff and subsurface flow. Subsurface moisture can also be found in urban environments, particularly in locations of mains water leakage. Despite this, existing techniques for measuring moisture, such as the gravimetric method, Time Domain Reflectometry and the Neutron Moderation Method are often limited by the fact that they are invasive, provide point measurements, are time consuming and require soil-specific calibration. One method that has the potential to overcome all of these limitations is ground penetrating radar (GPR). This research project aims to use GPR to quantitatively determine Volumetric Moisture Content (VMC) at different depths beneath the surface and in a spatially distributed sense for hillslope hydrology and water leak detection applications.

1.1 GPR and subsurface-moisture estimation

GPR has the potential for rapid soil-moisture assessment. However, very little research has attempted to use GPR as an in situ water detector in spite of the fact that it has long been recognized that the propagation velocity of radar waves is largely determined by soil-water content due to its impact on dielectric constant. In order to use GPR to assess VMC, a choice is required concerning which characteristics of a GPR response can be used. A qualitative level of analysis is based on visual analysis by expert estimation. Five basic methods of data visualization are commonly used in GPR and Geophysics: raw traces in the time domain (which can be presented as a single trace, a transect, or 3-D grid), their amplitude spectra in the frequency domain, and three complex attributes (Instantaneous Amplitude, Instantaneous Phase and Instantaneous Frequency) obtained by Hilbert transform. These visualizations, although revealing much about the nature of the GPR response to changing subsurface conditions, do not enable any quantitative VMC estimate to be achieved.

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Traditionally, Common Mid-point Surveys (CMPs) are conducted to determine the velocity of an electromagnetic wave through a given material. Since velocity depends on the dielectric constant of a material, dielectric constant can be calculated from the two way travel time (TWTT). From velocity, VMC is usually derived using the empirical Topp et al. (1980) polynomial equation. The velocity has also been used to measure soil water content during an infiltration experiment using borehole GPR although this is of limited use in most field applications. Research has also focused on developing more direct, potentially more robust and less time-consuming radar techniques using other GPR-derived parameters such as signal amplitude, or amplitude spectra in the frequency domain to determine VMC. In this research the emphasis is on obtaining estimates of VMC accurately and efficiently. This necessitates direct methods using data acquired in reflection profiling mode, minimal data processing, and the potential for real time results. An initial investigation into the GPR response to a variety of Earth materials under different moisture conditions was conducted in which statistical signal characteristics were derived using each of the five basic data visualizations. Testing these statistical methods for specific materials under strictly controlled conditions involves special experimental consideration when using GPR.

2. METHODS AND MATERIALS

For deriving relationships between moist soils and dielectric constant it is possible to simplify the problem by considering only pure sand, or pure clay, mixed with air and water. The approach adopted here is to test and characterize the GPR response after each successive water addition to a given material using the GPR in reflection profiling mode and to relate the quantitative measurements of the signal to independent estimates of VMC. To perform tests of radar response to a variety of Earth materials two laboratory test facilities were constructed. The large test facility (LTF) is described elsewhere. The Small Test Facility (STF) (Figure 1) consists of a plastic container 0.45m wide, 0.60m long, and 0.60m deep, surrounded by gravel (M1, see Table 1) and placed in the centre of the LTF. The STF was designed to allow water in at the surface as evenly distributed infiltration and to drain out through a tap into a tipping bucket to measure drainage. Drainage was assisted by a waterproof concrete base which sloped towards the outlet and reduced the depth of material to 0.58m. Moisture measurements were made by seven ThetaProbes (Delta T Devices Ltd.), at the depths indicated on Figure 1, and connected to a DataTakker 500 datalogger, logging every two minutes. These observed moisture measurements will be used for developing relationships with derivable GPR signal characteristics and to provide validation data to VMC estimations made using the GPR.

2.1 Experimental Details

Six experimental runs were performed using six separate materials (M1-M6) placed inside the STF, Table 1 summarises the main physical and dielectric properties for each of the six materials. Median particle diameter (D50) was estimated by reading off the cumulative frequency particle distribution (Figure 2) for the fine earth component (0-2mm) derived using the wet sieving technique and sedigraph analysis, and demonstrates a decrease in D50 between M1 and M6. M1 is a gravel material with 100% over 2mm and is therefore excluded from Figure 2. M2-M5 are dominantly sands with either a low gravel content (M2 and M3) or a low silt content (M4 and M5) in addition to the sand content. M2 is a coarse sand with 98% greater than 1mm and is a very well-sorted material. M4 and M5 are both fine-grained sands in which 100% of the particles are smaller than 1mm. The major difference is that for M4 only 53% is less than 0.25mm whilst for M5 97% is. M3 is a mixed sand which represents an intermediate between the coarse and fine sands. Whereas the coarse and fine sands tend to be grouped in one or two classes, M3 is more complex with a dominance between 0.25-0.5mm and then 0.5-1mm but with 15% greater than 1mm. M6 is the most complex material with a large clay component and large fine sand component. Hydraulic conductivity, measured using a MiniDisk Infiltrometer (Decagon), decreases with decreasing D50. These data must be used with caution because of the small number of samples (just five, but only one for M1 and M4) and also due to poor contact between the infiltrometer membrane and the materials with more gravel.

Water was added in five litre increments from dry to saturation every 25 minutes, although for M6 saturation was never achieved and its low hydraulic conductivity meant that water took much longer to infiltrate and redistribute which required longer separation times. The average VMC for each experiment is shown in Figure 3 and indicates a linear rise in VMC with each water increment. Small differences in porosity and distribution result in the limited VMC variability shown in Figure 3. To obtain the ThetaProbe derived estimates of VMC, the ThetaProbes were calibrated for each experimental material using the method outlined in the ThetaProbe manual. The calibrated equations were compared with gravimetric estimations for 10 samples of each material. The VMC estimate by ThetaProbe is accurate (maximum mean absolute
deviation of 0.034 m³/m³ until 0.25 m³/m³ after which there is greater scatter in the results and a tendency to overestimate the VMC by as much as 0.12 m³/m³ for the coarse materials. This is due to fewer data at higher VMCs and the effect of poor contact between the material and the ThetaProbe rods (for M1 and M6 especially).

Porosity estimates were obtained by saturating a 500 ml sample of material and measuring the VMC using a calibrated ThetaProbe. VMC at saturation generally decreases with D₅₀, although there is little difference for M4 and M5. M3 has the lowest porosity which is a result of the mix of particle sizes. M6 porosity is higher than that of M3 due to a higher proportion of large particles including stones which reduce the effective volume which can be occupied by water. Differences in texture, porosity and hydraulic conductivity can be expected to produce variable moisture distributions after a constant period of time for each material. This distribution can be approximated using the ThetaProbes.

Figure 1: Schematic of experimental configuration using the Small Test Facility.

Figure 2: Cumulative Frequency Distribution (%) for the fine earth fraction (0-2mm) for each of the Experimental Materials.

Figure 3: Average VMC for the wetting runs for M1-M6.

Figure 4: Average VMC for the drying runs for M1-M6.

To minimise the effects of moisture distribution, radar profiles were taken 20 minutes after each successive increment of added water, allowing the water to fully infiltrate into the facility. All radar data were collected using a bistatic Sensors and Software PulseEKKO 1000A GPR system, a time window of 30ns, a sampling interval of 50ps, with 32 stacks (32 traces averaged to produce one during profiling) and an antenna frequency of 900 MHz and consisted of 20 traces which were then averaged to provide a trace for each water addition and each material. After completion of the wetting runs for each material, the tap was opened and water allowed to drain until no more water would come out. Drainage times lasted between 1-15 hours depending on the hydraulic conductivity of the material. Figure 6 indicates that for the coarse materials (M1 and M2) drainage is very rapid due to their high hydraulic conductivities and almost all of the added water drains. For the materials with lower hydraulic conductivities drainage takes much longer and a large amount of added water is retained in
the material. Furthermore, the finer grained materials retain more moisture throughout the STF profile. No drainage occurred for M6 and therefore average VMC remained constant although it did redistribute. For these runs the GPR was left recording traces every 30 seconds. These data were used to test the relationships developed using the wetting runs and involved two stages. First, processing the GPR data in order to analyze it. Second, deriving a statistic with which to characterize the GPR signal response.

<table>
<thead>
<tr>
<th>Material / Experiment</th>
<th>D$_{50}$ (mm)</th>
<th>Porosity (m$^3$/m$^3$)</th>
<th>Hydraulic Conductivity (mm/hr$^{-1}$)</th>
<th>Dielectric Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>M1</td>
<td>10</td>
<td>0.470</td>
<td>76.00</td>
<td>0.00</td>
</tr>
<tr>
<td>M2</td>
<td>1.49</td>
<td>0.405</td>
<td>1032.83</td>
<td>308.44</td>
</tr>
<tr>
<td>M3</td>
<td>0.440</td>
<td>0.281</td>
<td>801.00</td>
<td>479.42</td>
</tr>
<tr>
<td>M4</td>
<td>0.240</td>
<td>0.350</td>
<td>47.33</td>
<td>0.00</td>
</tr>
<tr>
<td>M5</td>
<td>0.175</td>
<td>0.389</td>
<td>380.5</td>
<td>521.87</td>
</tr>
<tr>
<td>M6</td>
<td>0.055</td>
<td>0.337</td>
<td>31.67</td>
<td>26.87</td>
</tr>
</tbody>
</table>

Table 1: Summary of material and dielectric properties for each of the experimental materials. Note that the hydraulic conductivities are preliminary results from only five samples. Dielectric constant measured using ThetaProbe for 100 samples. Porosity derived using ThetaProbe values at saturation for each experimental run. D$_{50}$ derived from 30 samples of each material.

From the ThetaProbe calibration procedure dielectric constant can be calculated for each material. Dry dielectric constant was obtained from 100 samples of each material. The results (Table 1) suggest an increase in dielectric constant with decreased particle size. M1 is anomalous due to poor contact in the gravel, whilst M3 and M6 have higher dielectric constants, perhaps due to their higher proportion of small particle sizes. Variability is greatest in M1 and M6. These differences in dielectric constant can be expected to produce changes in GPR response between materials.

2.2 Analysis of GPR Data

Processing of the radar data was kept to a minimum in order to preserve the original amplitude values and therefore the potential impact of the subsurface moisture on the signal. Thus the analysis of the GPR data comprised six stages:

- Processing of the original time-domain data to produce the raw data for each of the other four basic visualizations.
- Export traces from PulseEKKO 4.2 software to Microsoft Excel for further manipulation.
- The analysis start time is approximated as timezero (defined as the direct air arrival and represents the first energy of arrival$^{13}$) minus the air-wave travel time (0.567ns at 900MHz for PulseEKKO 1000A).
- The analysis end time corresponds to the base reflection of the STF and was determined by adding theoretical TWTTs to the start time. TWTTs were calculated from the dielectric constant distribution based on the seven ThetaProbes and assuming a vertically incident plane wave as in simple synthetic radargram analyses$^4$. Calculation of reflection coefficients then enabled the end time to be objectively determined as the zero-crossing prior to a peak of sign indicated by the reflection coefficient that is closest in time to the theortical travel times. Because changing VMC affects TWTTs, the analysis end time was adjusted to accommodate this variation based on subsequent ThetaProbe TWTT estimations.
- The selected statistic is then calculated for all data between the start and end times.
- A relationship is then developed by plotting the observed ThetaProbe VMC against the value of each statistic for each material.

2.3 Analysis Techniques

This research has investigated a large number of potential means of characterizing the GPR response in a variety of Earth materials under different moisture conditions. Some results using visual, velocity and time- and frequency-domain amplitude methods have been presented previously$^{10}$. This paper reports on more recent results obtained using the
experimental configuration outlined above and concentrates solely on derivable signal characteristics. A preliminary analysis (using only M2 and M4) indicated that the top 10 statistical methods that provided the best relationship fit for each material considered were the Trace Amplitude Variance (TAV), Mean Instantaneous Amplitude (MIA), the Coefficient of Variation for Instantaneous Amplitude (CVIA), the Mean Trace Amplitude (MTA), Amplitude Spectra Median (ASME), Median Instantaneous Amplitude (MEIA), Amplitude Spectra Mean (ASM), Amplitude Spectra Variance (ASV), Amplitude Spectra Maximum (ASMAX), and the Median Trace Amplitude (META). A further analysis using all six materials will be briefly discussed. Then a method will be selected and tested within the context of developing VMC estimation relationships and, combined with visual analysis, for characterising the GPR response in a variety of Earth materials under different moisture conditions. Finally, consideration is made of the potential limitations of the developed relationships.

3. RESULTS AND DISCUSSION

3.1 Selection of a statistical signal characteristic

MIA was selected as a method for characterising GPR response and estimating VMC owing to its ease of determination (compared to amplitude spectra, for example, which involves more processing) and the strength of the initial relationships. Of the three best methods (TAV, MIA, CVIA), MIA produces the most consistently strong relationships for each material. This is indicated by summing the Coefficient of Determination for each material relationship in which MIA produces the highest value (5.555 compared to 5.524 for TAV, 5.233 for CVIA). There is a notable difference between these three methods and MTA due to the limited number of significant relationships for this method (summed \( R^2 \) is only 2.757). Because MTA is sensitive to the sign of the amplitude values it only produces significant relationships for two materials. This sensitivity arises from the location of dielectric gradients and therefore depends on where the subsurface is wet or dry. Signal characteristics such as maximum, minimum, and range are too sensitive to extreme values. They are particularly affected by signal clipping which pervaded all experimental traces reported here due to close transmitter and receiver antenna proximities and good ground-coupling. Other methods, such as the instantaneous frequency and instantaneous phase, produce no significant relationships.

The instantaneous amplitude outlines the envelope of the trace and is independent of phase so that it may have its maximum at points other than the peaks and troughs of the real trace, especially where an event is the composite of several reflections. The envelope amplitude is associated with the reflection strength of the signal with a large value of envelope amplitude usually indicating major changes in subsurface layers and is an interpretational tool that describes waveform shape. Consequently, unlike the raw trace amplitude, it is insensitive to the sign of reflection events and use of its mean (MIA) makes it even less sensitive to extreme values. MIA is a method that takes into consideration the nature and changes of the entire GPR response; in particular, changes in the number of reflection events and their magnitude and duration. It therefore encompasses all possible sources of change that may arise from variation in subsurface moisture including any attenuation impacts.

3.2 Characterization of GPR Response

The results of the MIA-VMC analysis for each experiment are shown in Figure 5 and summarised in Table 2. As VMC decreases, MIA increases offering the potential to estimate VMC using MIA. The form of the best-fit relationship varies for each material. Coarse material relationships are linear (M1 and M2) whilst for complex or finer materials (M3, M4, and M6) the relationships are non-linear. The exception to this is M5 which, due to anomalous responses at low VMCs, has a linear best-fit. The reasons for this variable GPR response are related to the material, the effect of the material properties on the VMC and its distribution, the response of the GPR to VMC and moisture distribution, and the characteristics of a GPR trace itself.

3.2.1 Nature of the MIA-VMC relationship

Variability in response is expected to be different for different materials due to the ways in which moisture is interacts with the host material. The most dramatic changes in dielectric properties take place in a very narrow moisture range at which the particle surface forces can no longer control all the water molecules and free water starts to appear. The proportion of...
bound water should be higher in finer-grained materials resulting in a delay in the timing of the appearance of free water due to the increased surface area upon which bound water can occur. In contrast to bound water in which the water molecules are unable to turn in an electric field at frequencies near 1GHz, free water molecules can turn freely producing a much higher dielectric constant. A rapid rise in dielectric constant will occur at this point, and this would be expected to produce an increase in the returned trace amplitude value. In a layered material the effect of moisture is to increase values of the dielectric coefficients between layers resulting in a stronger reflection. However, the results presented above indicate declining amplitude values rather than rising ones, although there is a more rapid decrease in MIA over lower VMC values. This particularly occurs for M6 in which an increased delay in the appearance of free water is expected. This suggests that another process dominates the relationship.

<table>
<thead>
<tr>
<th>Material</th>
<th>Form</th>
<th>Parameter 1</th>
<th>Parameter 2</th>
<th>R²</th>
<th>R²t</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Linear</td>
<td>0.5873</td>
<td>-2.13E-05</td>
<td>0.8524</td>
<td>0.8524</td>
<td>-6.7972</td>
<td>0.0001</td>
</tr>
<tr>
<td>M2</td>
<td>Linear</td>
<td>0.5171</td>
<td>-1.76E-05</td>
<td>0.9556</td>
<td>0.9556</td>
<td>-12.2682</td>
<td>5.48E-06</td>
</tr>
<tr>
<td>M3</td>
<td>Logarithmic</td>
<td>-0.3073</td>
<td>3.1909</td>
<td>0.9576</td>
<td>0.9525</td>
<td>-10.0083</td>
<td>0.0002</td>
</tr>
<tr>
<td>M4</td>
<td>Exponential</td>
<td>4.4802</td>
<td>-0.0002</td>
<td>0.9401</td>
<td>0.8367</td>
<td>-5.9885</td>
<td>0.0005</td>
</tr>
<tr>
<td>M5</td>
<td>Linear</td>
<td>0.6354</td>
<td>-1.96E-05</td>
<td>0.8901</td>
<td>0.8901</td>
<td>-7.5293</td>
<td>0.0001</td>
</tr>
<tr>
<td>M6</td>
<td>Exponential</td>
<td>0.6177</td>
<td>-0.0001</td>
<td>0.9592</td>
<td>0.8930</td>
<td>-7.6448</td>
<td>0.0001</td>
</tr>
<tr>
<td>Overall</td>
<td>Exponential</td>
<td>0.6535</td>
<td>-0.0001</td>
<td>0.5124</td>
<td>0.5082</td>
<td>-7.2593</td>
<td>2.12E-09</td>
</tr>
</tbody>
</table>

Table 2: Summary of Best-Fit Relationships for MIA for each material. Significance results are for the linear relationships at p < 0.05. Parameter 1 is the intercept for linear relationships and a constant for non-linear ones. Parameter 2 is the slope for linear relationships and the logarithm or exponent for non-linear ones.

3.2.2 GPR Signal Attenuation

It is proposed that the MIA value decreases because the VMC increases signal attenuation. This reduces later-time wavelet magnitudes and thus MIA. The rate of MIA decline will be especially high when a material produces significant attenuation of the GPR signal when dry. Figures 6 and 7 compare the dry raw amplitude traces for each of the materials. All are similar except for small deviations in event timing due to changes in the dry dielectric constant. M6 is an exception because apart from the first event, which is a combination of the transmitted pulse and the ground-wave, all of the other reflection events are of reduced magnitude. The initial stages of wetting act to increase the attenuation and consequently the decline in MIA is rapid compared to the other materials and explains the anomalous position of M6 on Figure 5. At a VMC of about 0.2m³/m³ there is little change in the GPR response and MIA remains constant. This biases the relationship towards an exponential form. The other materials do not attenuate the GPR signal when dry and therefore have higher initial MIA values, demonstrate no tendency towards a constant MIA value after a certain VMC, and show a more linear trend as a
consequence of moisture induced attenuation. This effect is enhanced by the increasing analysis time window used to derive MIA for each water increment. This time window increment was necessary to ensure that the depth from which the MIA estimate is derived is kept constant. In the absence of a priori data on changing dielectric conditions the actual time window cannot be properly known. Thus a constant time window may be used. This was applied to the M6 relationship using the maximum time window required at saturation (approximately 16.8ns) and produces a weaker relationship ($R^2 = 0.5541$):

$$VMC = 2.4953e^{-0.0004MIA}$$

This occurs mainly because of increased scatter in the results and the fact that the relationship uses too much data beyond the facility limits for the drier runs. Extending the time window beyond the depth of interest reduces the MIA value because of the decline in amplitudes with travel time (due to spreading and scattering losses) and any signal attenuation that may occur. If the method is to be applied to a greater depth three considerations must be made. Attenuation will prevent application to depths greater than about 0.6m in a material such as M6 when VMC exceeds a certain threshold. As long as the depth of investigation can be achieved the decline in amplitudes with increased travel time will need correcting for. The more variable the moisture in the subsurface, the greater the error in the VMC estimation when the original relationship is used if a constant time window is being used. There are a number of other aspects of the GPR response and the MIA-VMC relationships that are not explained simply by moisture induced attenuation by itself. In particular, the behaviour of the dry and saturated responses and the apparent non-linear behaviour of the GPR-VMC estimation for some materials. These issues will now be considered.

### 3.2.3 Dry and saturated material

Excluded from the relationships are the data from the dry and saturated cases which produce anomalous results as illustrated in Table 3. The dry values fit the trend more closely than the saturated values producing MIA values very close to the response from the first water addition. The saturated MIA values are higher than those at VMCs just below saturation. In otherwords, the dry and saturated MIA values oppose the trend. Figures 9 to 11 demonstrate that while dry and saturated traces are almost identical between materials, after the first moisture addition the GPR traces become very different. This occurs because at intermediate moisture conditions a three-phase system consisting of air, water and material exists, whilst at the moisture extremes only a two-phase system exists. The two-phase systems produce an homogeneous environment whilst the three-phase system can potentially consist of variable distributions of the three components. Thus in the two-phase system the only sources of trace variation are changes in signal propagation velocity or magnitude differences induced by attenuation; both of which depend upon the nature of the material and its effect on porosity. However, the apparent variation in hydraulic conductivity and porosity indicate that different moisture conditions would exist for each material. In particular, an inhomogeneous distribution of VMC may produce reflection events that are inconsistent with the trend of VMC with MIA.

### 3.2.4 Moisture distribution

Figures 10 and 11 demonstrate that upon the addition of water the raw GPR traces for each material are very different. This is a direct consequence of the location of the water relative to the GPR signal. In the case of water rising through the profile a positive wavelet would occur earlier in time each time water was added. The magnitude of the reflection would depend upon the dielectric contrast between the dry and wet interface while attenuation would reduce amplitudes below this reflection. At the same time the direct arrivals would be relatively unchanged. Therefore, for coarse materials with high hydraulic conductivity, the linear decline in amplitude values is affected through decreasing amplitudes after the dry-wet interface. At later average VMC values, the water table will be near enough to the surface to interfere with the direct arrivals and the ground-wave will begin to occur at later times. This alters the amplitude distribution further, but the process is still dominated by the decreasing amplitudes after the interface reflection. Where the material hydraulic conductivity is low, moisture movement proceeds slowly down through the profile. While the moisture is in a narrow near-surface layer, strongly negative direct arrivals are interfered with by strong positive wet-dry interface events producing superposition of wavelets; dramatically altering the early-time waveform and also produces high magnitude signal ringing (as shown by M4 on Figure 11). High MIA values occur which are maintained until the wet-dry interface reflection no longer interferes with the direct arrivals. By this stage attenuation acts to decrease all amplitudes below this event. It is this variable behaviour that results in the anomalous behaviour of M5 at low moisture contents.
The positive wavelet at the start of the M3-M6 traces indicates moisture in a narrow near-surface layer which is followed by deeper, drier material. The lack of interference with the transmitted pulse in M1 and M2 indicates moisture that is able to move away from the near surface. This interpretation is confirmed by comparing the moisture distributions of two materials. Figures 12 and 13 demonstrate that for materials with high hydraulic conductivity (e.g. M2) water is distributed as a rising water table, whilst for the other materials (e.g. M4) a more or less complex wetting front descends through the profile. M4 is particularly complex since a dry zone results in between two wet zones. This can be expected to produce a very complex GPR response. The distribution of moisture, as well as its VMC, is therefore important in determining GPR response.

3.2.5 The role of the Direct Arrivals

The presence of the transmitted pulse and the ground-wave may be expected to bias any statistics derived from the GPR signal by producing a non-stationary time-series. Recent research and analysis shows that the received GPR signal possesses distinguished non-stationary characteristics. It is common practice to remove the direct arrivals from GPR data. However, the nonstationary components may be of more interest than the stationary residuals and it is this that forms the basis of this research. Whilst the ground-wave changes in timing and magnitude depending on the material through which it propagates, the transmitted pulse provides a constant component of the GPR trace against which all other amplitude variations can be compared. The statistical relationships developed above work well because the moisture-induced variation in amplitude is assessed relative to a wavelet that is generally known or identifiable. Because the transmitted pulse is of high magnitude, the effect of variability in trace response at later times is minimized. Removal of the transmitted pulse would increase the statistical contributions of noise and interference. Furthermore, common processing to restore amplitudes to the magnitude of the transmitted pulse would generally render estimation of VMC useless by removing the attenuation effect. The results above do however demonstrate that the transmitted pulse can suffer interference. For example, in the dry situation it is combined with the ground-wave and in the saturated case, the interaction of the signal with near-surface moisture produces a positive wavelet superposed upon the negative transmitted pulse. This complicates the removal of the transmitted pulse in environments where near surface moisture is highly variable and may render the MIA-VMC method inappropriate.
Fortunately, the disturbance of the transmitted pulse in these experiments produces an envelope amplitude that retains a similar magnitude and temporal duration as an undisturbed pulse.

![Figure 10](image1) ![Figure 11](image2)  
**Figure 10:** Mean Raw Amplitude Traces for M1-M3 after first water addition.  
**Figure 11:** Mean Raw Amplitude Traces for M4-M6 after first water addition.

![Figure 12](image3) ![Figure 13](image4)  
**Figure 12:** Idealized moisture distribution for each water addition for M2.  
**Figure 13:** Idealized moisture distribution for each water addition for M4.

3.2.6 Summary

The relationship between MIA and VMC appears to demonstrate a GPR response to a variety of Earth materials under variable moisture conditions in which the VMC attenuates the radar signal in a near-linear way. There is a textural dependence which is expressed through the effect of material properties on the distribution of moisture. This produces apparent non-linear responses due to variable reflection patterns. As a consequence, although a MIA-VMC relationship exists over an average material depth of about 0.6m, this can be distorted by variability in moisture distribution. Furthermore, if a material attenuates the signal under dry conditions, the rate of MIA decline will be more rapid and may eventually reach a point where MIA can decline no further. These two aspects suggest that site-specific calibration will be necessary for application of the technique and that the relationships should be tested to assess accuracy and repeatability.
A number of statistical methods for deriving estimates of near-surface VMC using GPR data were investigated. Of these the mean instantaneous amplitude effectively and reliably estimates VMC. Relationships were developed and tested on a variety of Earth materials. Under conditions of variable moisture distribution the insensitivity of MIA to the sign of the reflection event enables it to estimate VMC accurately. Textural dependence is exhibited by the resulting relationships through its...
impact on moisture distribution. MIA effectively measures attenuation patterns that result from changing subsurface conditions. Initial testing of these relationships confirms that variable moisture distributions can introduce variability into the results and in combination with an inappropriate non-linear relationship can produce very poor results. Otherwise, maximum error is 0.07m$^3$/m$^3$; which is only marginally worse than uncalibrated ThetaProbes. The testing also indicates that the model is limited to intermediate VMCs (not dry and saturated conditions) and should be used with caution when applying to areas of high or low VMC. Such problems, mean that there is still a need for site-specific calibration. Further work is required to extend the analysis depth, clarify the ambiguity of the relationships for different materials, assess the potential for using a combination relationship that accounts for the effect of texture on the potential field response, and to investigate the additional effects of other sources of signal attenuation.

**Figure 14**: Observed VMC plotted against Predicted VMC for each material experiment estimated using the Material Specific Equations. Fitted logarithmic line shows the overall trend in all data. Fitted linear line shows overall trend after removing saturated data and M4 results.

**Figure 15**: Plot of Standardized Residuals for each material experiment based on Material Specific Equations.

**Figure 16**: Observed VMC plotted against Predicted VMC for each material experiment estimated using the Material Specific Equations except for M4 in which the next best-fit linear equation is used to estimate VMC. Fitted line shows the overall trend in all data.

**Figure 17**: Plot of Standardized Residuals for each material experiment based on Material Specific Equations except for M4 in which the next best-fit linear equation was used to estimate VMC.

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