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Modelling the propagation of a radar signal through concrete as a low-pass filter

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Abstract

The knowledge of how a dispersive, dielectric medium such as concrete affects a propagating short electromagnetic pulse used in ground penetrating radar (GPR) is helpful both in the interpretation of radar results and in the prediction/modelling of expected radar measurements. Although there are a number of published results on the frequency-dependent, dielectric properties of media such as concrete and soils, the use of this information is still relatively small, primarily due the lack of a reliable method of applying these properties to propagating radar pulses. Modelling the dielectric medium as low-pass filter is one solution to this difficulty. In this paper the propagation of short pulses in concrete with known frequency-dependent properties is studied. The extent of how the pulses are attenuated and distorted is analysed and the implications on GPR applications are also discussed.

Keywords: Radar; Modelling; Propagation; Concrete; Low-pass; Filter; Signal processing; Dielectric properties; GPR; Antenna

1. Introduction

Ground penetrating radar (GPR), is a popular nondestructive testing tool for subsurface surveying and has been used in various fields such as civil engineering, geophysics, military, etc. This method relies on information obtained from GPR signals, which are in the form of short electromagnetic pulses emitted from a broadband antenna, propagated in the dielectric medium under study and reflected back to the antenna from any subsurface targets or interfaces. The amplitude of a pulse can be related to the type and size of the target detected as well as to the electrical conductivity of the medium involved. The delay time to detection of a reflected pulse can be related to the depth of the target or to the dielectric permittivity of the medium. Knowledge of the dielectric properties of the medium thus plays and important role in application of the GPR method since they can affect both the amplitude and the delay time of the propagating/reflecting pulse.

In a medium with frequency-dependent dielectric properties, i.e. a dispersive/conductive medium, the shape of GPR signals can become distorted because different frequency components in a pulse will travel at different speeds. It has been widely reported that the dielectric properties of concrete and soils [1,2] exhibit some frequency-dependent features, in particular when the moisture/water and salt/mineral contents are high. Thus, it is valuable to study how the dispersive/conductive medium will affect GPR signals. It should be stressed that both the amplitude and the shape of GPR signals are also strongly dependent on the distance of propagation from the antenna. Using the GPR method to study the effects of the medium dielectric properties upon propagating pulses will not be effective, since any changes to the amplitude or to the shape of a pulse could be due to the medium properties or to the antenna characteristics or to both. In addition, there is also a problem with the initial (breakthrough) pulse of many GPR systems, which is known to have a strong dependence upon the nature of the antenna–medium coupling interface [3]. As a result, the effects of medium dielectric properties upon a propagating pulse, which is solely based on the analysis of the initial and the reflected pulse as obtained from a GPR survey can be misleading.

In this paper the effects of the medium dielectric properties on a radar pulse is studied by assuming that

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the medium acts like a low-pass filter. The incident pulse comprises the input signal to the filter whilst the transmitted pulse acts as the output signal. Using this method, the effects of different moisture contents (MC) and of propagation distances on the pulse shape and amplitude can be studied. In addition the variation of the center frequency, f_c with propagation distance or depth can also be analysed. For pragmatic reasons GPR users often ignore the broadband nature of the GPR signal. Thus, even in the case where the medium exhibits strong frequency-dependent properties, only those values corresponding to the center frequency, f_c are used in any calculations or analyses. This paper discusses some of the implications when such approximations are made.

2. Filter basics

An electronic filter is used when the aim is to attenuate or remove unwanted frequency components in electrical signals or noise [4]. Analysis on how a filter transforms the input signal into the output signal can be carried out either in the time domain or in the frequency-domain. Thus if $f(t)$ is the input signal in the time domain and $g(t)$ is the output signal of a particular filter then

$$g(t) = f(t) * h(t) \tag{1}$$

where $h(t)$ is called the impulse response of the filter and $*$ indicates the convolution process between the two time functions. The corresponding frequency-domain relation in Eq. (1) can be written as

$$G(\omega) = F(\omega)H(\omega) \tag{2}$$

where $\omega = 2\pi f$ is the angular frequency in rad/s and f the frequency in Hz.

The frequency functions $G(\omega)$, $F(\omega)$ and $H(\omega)$ are the Fourier transforms of functions $g(t)$, $f(t)$ and $h(t)$, respectively, and are in general complex functions. In signal processing, the function $H(\omega)$ above is commonly called the transfer function or the response function of the filter. The shape of the amplitude spectrum $|H(\omega)|$ of the transfer function leads to the classification of the filter into several types, namely all-pass, low-pass, high-pass and band-pass filters. In general both the amplitude spectrum $|H(\omega)|$ and the phase spectrum $\phi(\omega)$ of the transfer function can have a significant effect on the shape of a pulse that passes through the filter. From Eq. (2) it can be shown that if both $F(\omega)$ and $H(\omega)$ are known, then $G(\omega)$ can be calculated and the output signal $g(t)$ can be obtained by carrying out an inverse Fourier transform on the function $G(\omega)$.

3. Concrete as a low-pass filter

The effect of a dispersive medium on a propagating pulse can be described in term of its frequency-dependent propagation factor $\mathrm{PF}(\omega)$, which is commonly written as:

$$\mathrm{PF}(\omega) = \mathrm{e}^{-\gamma(\omega)z} = \mathrm{e}^{-(\alpha(\omega)+\mathrm{j}\beta(\omega))z} \tag{3}$$

where $\gamma(\omega)$, $\alpha(\omega)$, and $\beta(\omega)$ are the frequency-dependent propagation constant, the frequency-dependent attenuation coefficient and the phase constant, respectively, and z is the propagation distance. A dispersive medium can also be characterised by its frequency-dependent dielectric properties that are commonly represented by the complex, relative permittivity

$$\varepsilon_r^*(\omega) = \varepsilon_r'(\omega) - \mathrm{j}\varepsilon_r''(\omega) \tag{4}$$

where $\varepsilon_r'(\omega)$ and $\varepsilon_r''(\omega)$ are the real and the imaginary parts of the complex permittivity. The propagation constant and the complex permittivity of the medium is related through the following equation:

$$\gamma(\omega) = \mathrm{j}\left(\frac{c}{\omega z}\right)\sqrt{\varepsilon_r^*(\omega)} \tag{5}$$

In modelling concrete as a low-pass filter, the propagation factor $\mathrm{PF}(\omega)$ of the concrete plays the role of the transfer function $H(\omega)$ of the filter. Thus the effect of a dispersive medium with a propagation constant $\gamma(\omega)$ on a pulse travelling for a distance z can be modelled as a signal passing through a filter with a transfer function $H(\omega)$. Similarly if the frequency-dependent attenuation coefficient $\alpha(\omega)$, the phase constant $\beta(\omega)$ and the travelled distance z are known, the amplitude and the phase spectra of the transfer function $H(\omega)$ can be written as:

$$|H(\omega)| = \mathrm{e}^{-\alpha(\omega)z} \tag{6a}$$

$$\phi(\omega) = -\beta(\omega)z \tag{6b}$$

The complex frequency-dependent, relative permittivities of a concrete specimen with MC by volume of 6.2 and 9.3%, are shown in Fig. 1. These experimental results were obtained from transmission line studies of moisture conditioned concrete specimens [4].

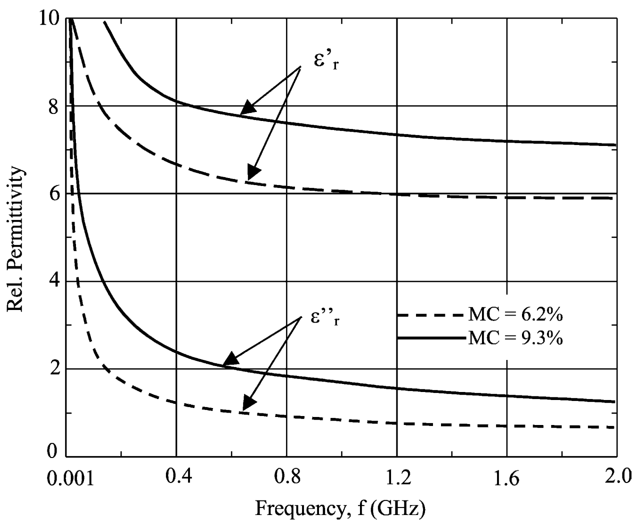

Fig. 1. Dielectric properties of concrete: MC = 6.2 and 9.3%.

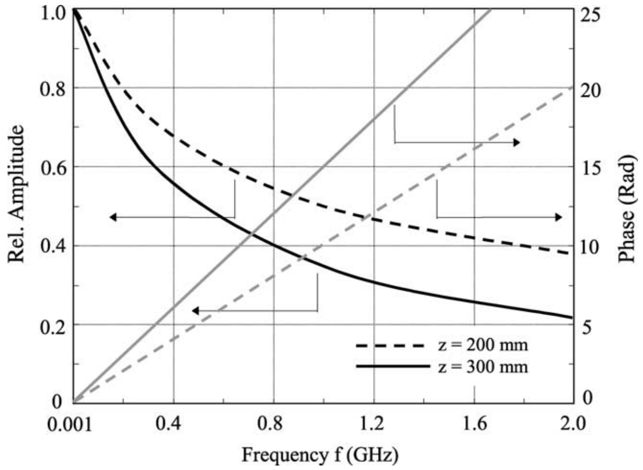

Fig. 2. Transfer functions of the LP filters for 200 and 300 mm travel distances.

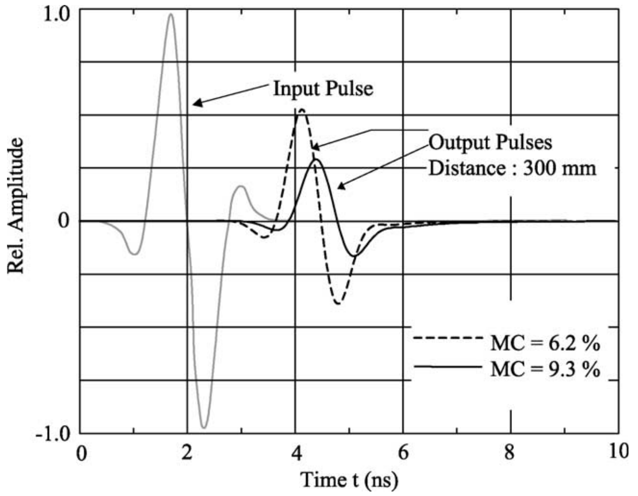

Fig. 3. Modelling of input and output signals of low-pass filters.

It can be seen from Fig. 1 that there is a relatively, strong frequency dependence in the low frequency range. The transfer function $H(\omega)$ for the filter generated using the permittivity in Fig. 1 and a propagation distance z of 200 mm, the length of the specimen used in this study, is shown in Fig. 2. From the shape of the amplitude spectrum, $|H(\omega)|$ it is clear that the high frequency components of the GPR signals will be strongly attenuated compared to the low frequency components and this is one of the characteristics of a low-pass filter. The phase spectrum, $\phi(\omega)$ on the other hand shows a linear dependence with respect to frequency, f.

4. Results and discussions

4.1. Validation of filter model

In order to study how a 300 mm thick concrete specimen affects a GPR signal, an input pulse with center frequency, f_c of 650 MHz is chosen as the input to the low-pass filter, with a transfer function as shown in Fig. 2 can be generated. The pulse represents a typical GPR signal generated by a 900 MHz antenna, directly coupled to concrete surface [5]. The output of this filter can then be compared to that of the filter generated from concrete with a different MC of 9.3%. The input and the output signals of the two filters are shown in Fig. 3.

Fig. 3 indicates how the concrete dielectric property is predicted to affect the amplitude, delay time and the shape of the input pulse using the low-pass filter transfer function.

To verify that this modelling is realistic, the following analyses can be carried out.

I. The electromagnetic wave speed, v in concrete is approximately given by the following equation

$$v = \frac{c}{\sqrt{\varepsilon_r'}}, \tag{7a}$$

where $c = 300$ mm/ns is the wave speed in air and ε_r' is the real part of the complex dielectric permittivity of the concrete given in Eq. (4). For a propagation distance z, the delay time, τ in nanosecond (ns) can be calculated using:

$$\tau = \frac{z}{v} = \frac{z\sqrt{\varepsilon_r'}}{c}. \tag{7b}$$

The value of the dielectric permittivity, ε_r' can be obtained from Fig. 1 which at frequency 650 MHz and MC of 6.2% is about 6.3. For a propagation distance $z = 300$ mm, the time delay τ calculated from Eq. (7b) is about 2.5 ns which is compared well with the delay time between the input and output pulses in Fig. 3, obtained by comparing the zero-crossing points of the respective pulses.

II. The attenuation of the pulse amplitude can be analysed if the attenuation coefficient, α at frequency of 650 MHz is known. From Eqs. (3)–(5) the attenuation coefficient, α can be written as follows

$$\alpha = \left(\frac{\omega}{c}\right)\left[\left(\frac{\varepsilon_r'}{2}\right)\left(\sqrt{1+\left(\frac{\varepsilon_r''}{\varepsilon_r'}\right)^2}-1\right)\right]^{1/2} \tag{8}$$

Substituting the estimated values for the real, ε_r' and imaginary, ε_r' parts of the permittivity at frequency 650 MHz in Fig. 1 into Eq. (8) gives an estimate of the attenuation coefficient α of 2.7 Np/m. For a propagation distance $z = 300$ mm, the attenuation of the pulse can be calculated using Eq. (6a) and is evaluated as 0.44.

This compares well with a value of the ratio of the peak-to-peak amplitude of the output pulse to that of the input pulse. From Fig. 3, this is evaluated as 0.47.

From these two comparisons it can be seen that the output pulses evaluated from signal filtering of a broadband signal in Fig. 3 accurately represent GPR signals that propagate through a concrete specimen with dielectric properties shown in Fig. 1.

4.2. Other effects of filtering

There are two other aspects of the output pulses in Fig. 3, which can be attributed to the effects of the frequency-dependent dielectric properties of the concrete specimen. The first aspect is that the principal cycles in the output pulses are losing some of their high frequency components. This effect stretches the output pulses to become a little bit longer than the input pulse, which is consistent with the modelling of the signal as the output of a low-pass filter. This also means that the center frequency, f_c of the output pulse will be smaller than that of the input pulse. The effects of the dielectric properties of concrete on the center frequency, f_c of three input pulses, which propagate over a distance z of up to 600 mm, are shown in Fig. 4. The center frequencies of the input pulses used in this study are 650, 750 and 850 MHz and these pulses are fed through two filters which correspond to concrete specimens with MC of 6.2 and 9.3%. Fig. 4 shows that there is a significant reduction in the center frequency, f_c of the input pulses over the travelled distance, especially when the MC is high. A practical implication of this effect is a reduction in the vertical resolution of a GPR antenna when inspecting closely spaced targets at greater depths.

The second change of the output pulses, which can be related to the effect of a low-pass filter is the observation that their trailing half-cycles are attenuated at a higher rate than the leading half-cycles. This effect is seen clearly in Fig. 3, and is more significant for the output pulse to a filter corresponding to concrete specimen with a MC of 9.3%. This change in the shape of the output pulses can be attributed to the variation of wave speed with frequency through Eq. (7a). Although the speed of the electromagnetic radiation is constant for any frequency in free space, in any other material the speed varies with the frequency of the signal. Alternatively, the change in the shape of the output pulse may be attributed to the variation of the attenuation rate with frequency through Eq. (8). Indeed both of these actions may be affecting the output pulse.

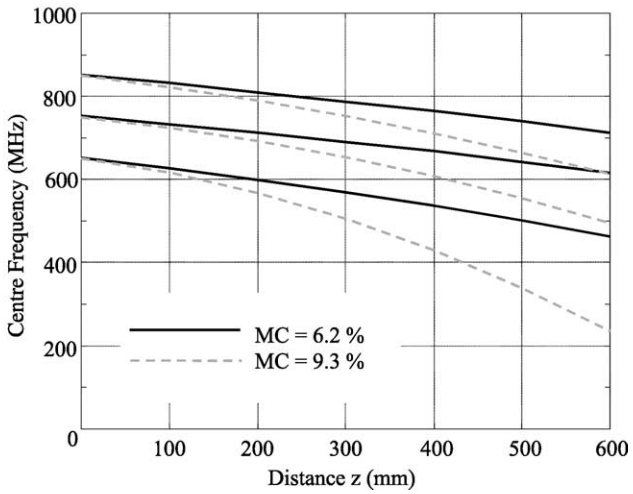

Fig. 4. Variations of the centre frequency, f_c with distance, z.

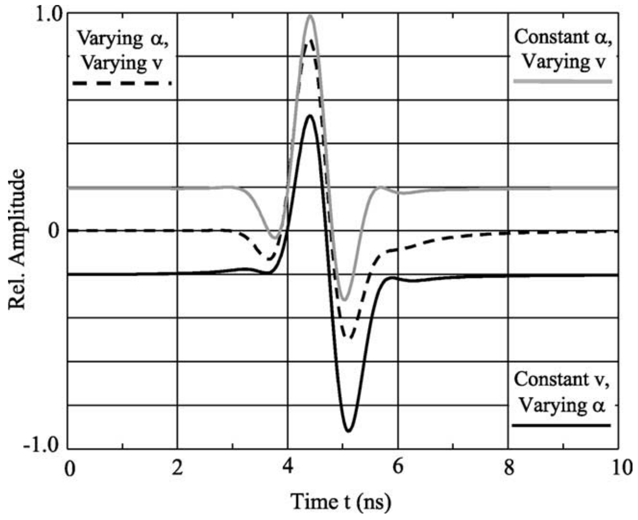

Fig. 5. Variations of the shape of the output pulses.

Fig. 5 shows the output pulses of three filters corresponding to concrete with MC of 9.3% and propagation distance, z of 300 mm. In one filter both, the speed, v and the attenuation coefficient, α vary with frequency, f. A second filter has a constant speed, v but the attenuation coefficient, α varies with frequency, f. The third filter on the other hand has a constant attenuation coefficient, α but the speed, v varies with frequency, f. The three pulses have been shifted vertically so that their differences can be observed more clearly.

It can be noted from Fig. 5 that the second filter (constant v, varying α) attenuates equally both leading and the trailing cycles of the pulse while the third filter (constant α, varying v) attenuates the trailing cycles more than it does on the leading ones. The effect of first filter (varying α, varying v) is simply the superposition of the effects of the two previous filters.

The previous discussion and modelling shows that the center frequency, f_c of a traveling pulse decreases as the propagation distance, z increases. The question then arises on how to relate the frequency-dependent dielectric properties of a medium such as concrete to observations from GPR signals. In the following studies, the dielectric permittivity, ε'_r of concrete is estimated using two different approaches.

1. In the frequency-domain (narrow-band) model, the value of ε'_r is taken to be equal to that corresponding to the center frequency, f_c of the pulse at a particular distance traveled, z. Since the center frequency, f_c decreases as the traveled distance, z increases this means that the value of ε'_r must increase with the distance.
2. In the time-domain (broad-band) model the value of the ε'_r is estimated using Eqs. (7a) and (7b). In both cases the filter used corresponds to a concrete

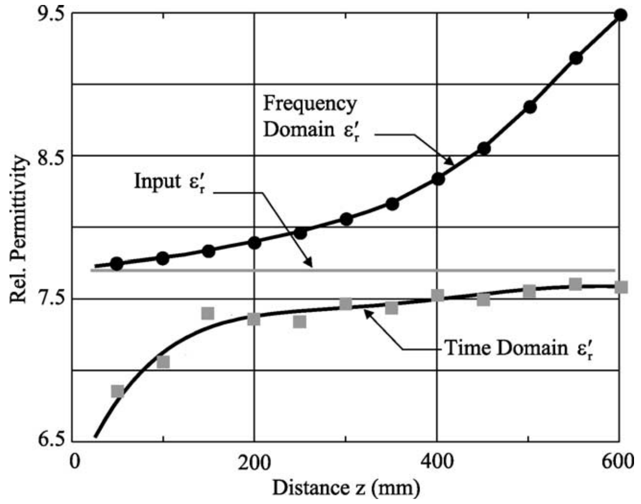

Fig. 6. Estimates of the dielectric permittivity, ε_r' of concrete; frequency-domain and time-domain approaches.

specimen with MC of 9.3% and an input pulse with a center frequency, f_c of 650 MHz. The results are shown in Fig. 6.

As expected, the values of the dielectric permittivity, ε_r' obtained from frequency-domain approach increase with the propagation distance and are diverging from the actual value. Similarly, the results from the time-domain approach also increase with distance but are approaching the actual value. These results indicate that the latter approach is a more reliable method of estimating the dielectric permittivity, ε_r' of the concrete.

It should also be noted that the results in this study are based on one-way, traveled distance, which, in the case of a typical, monostatic GPR antenna, is equivalent to twice the target depth.

5. Validation against real radar measurements

In practice, for real radar measurements the initial pulse from GPR antenna is either not fully known or is very

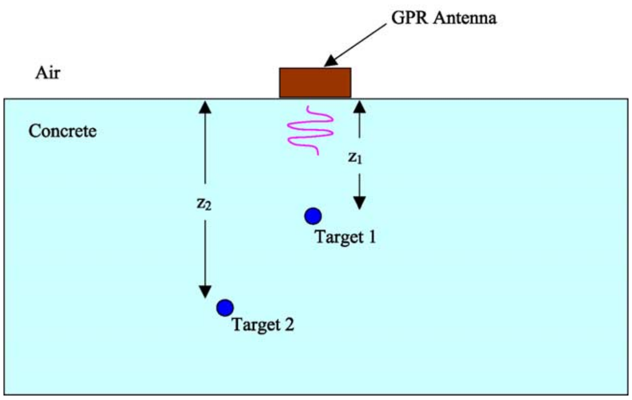

Fig. 7. GPR survey of two known targets at different depths.

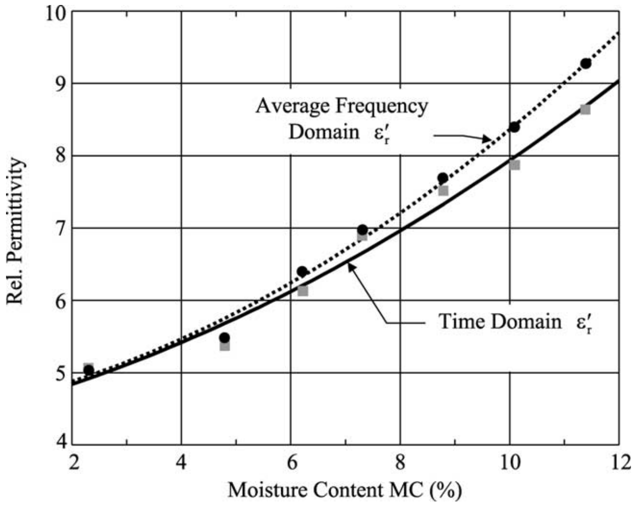

Fig. 8. Variation of the relative dielectric permittivity, ε_r' of concrete with moisture content; frequency-domain and time-domain approaches.

susceptible to the medium–antenna coupling conditions. A more practical way of estimating the dielectric permittivity, ε_r' of a medium is by measuring the delay time between two pulses reflected from two targets of known (different) depths and substituting the relevant values in Eq. (7b). In this study the reliabilities of the frequency-domain and the time-domain approaches are investigated by applying almost the same procedures as in the previous case. The exception is that the information is obtained from two output pulses, which travel over two known (different) distances such as those shown in Fig. 7.

In the frequency-domain approach the average value of the two permittivities corresponding to the center frequency, f_c of the respective pulses is calculated. In the time-domain approach the delay time between the two pulses is measured and the dielectric permittivity, ε_r' is calculated using Eq. (7b). The results from the two approaches are plotted against the MC of the specimen and they are shown in Fig. 8. It can be seen from the figure that both results agree well with each other in particular when the MC of the concrete specimen is low. These results again indicate that the time-domain approach, which is the most common approach used with GPR method, is a reliable means of estimating the dielectric permittivity, ε_r' of concrete. In addition if the need is to relate the frequency-dependent permittivity, $\varepsilon_r'(\omega)$, such as seen in Fig. 1, to the estimated value obtained from two pulses in a GPR survey then it is necessary to use the average value of the permittivities, which correspond to the center frequencies, f_c of the respective pulses.

6. Conclusions

The effects of the frequency-dependent dielectric properties of concrete on the shape, delay time and amplitude of propagating pulses can be studied by assuming the concrete to behave like a low-pass filter. The effects of stretching the pulse and losing the trailing half-cycle at higher rate compared to the leading one are believed to be responsible for the significant decrease in the center frequency, f_c of the pulse that is observed in real GPR measurements. Thus when the MC of a concrete specimen is high, the effects of the frequency-dependence upon the dielectric properties cannot be ignored. The time-domain (broadband) approach, which is the common method use in GPR survey, is a more reliable method of estimating the dielectric permittivity, ε_r' when compared to the frequency-domain (narrow-band) approach.

References

[1] Shaari A. Antenna charactersitics and signal propagation of GPR applied to concrete. PhD Thesis. University of Liverpool; 2000.

[2] Cooke JA, Gladwin MT. GPR Performance in Typical Australian Soils. http://www.cat.csiro.au/dem/msg/scirev/revradar.pdf. 2002.

[3] Shaari A, Millard SG, Bungey JH. Coupling effects on GPR surveys. British Journal of NDT, International Conference on Non-Destructive Testing in Civil Engineering: NDT-CE '97; 1997. pp. 247–60.

[4] Roden MS. Analog and digital communication systems. Englewood Cliffs, NJ: Prentice-Hall; 1985.

[5] Padaratz I. A numerical and experimental investigation of radar coupling and propagation through concrete. PhD Thesis. University of Edinburgh; 1996.