Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. and Technol. 1(3):107-112

Thickness Measurement of Thin Pavement Layers Using Time-Frequency Analysis of Ground Penetrating Radar Data

Xiang-Tang Li[1], Duan-Yi Wang[2], and Xiao-Ning Zhang[2+]

Abstract: Accurate knowledge of pavement layer thickness can provide important information to determine the quality of newly constructed pavements, and to estimate the remaining service life of pavements. Ground penetrating radar (GPR) is one of current technologies for determining pavement layer thickness. However, the estimation of the thickness of very thin pavement layers is not satisfied by the use of commercial impulse GPR. Hence, a thickness measurement approach for very thin layer of multilayered pavement structures is introduced. The technique presented in the present work is based on the evaluation of the instantaneous bandwidth of GPR receiving signals by means of S-transform. One unique feature of the current technique is that it only requires common impulse GPR system operated at relatively low frequency. The algorithms were tested on simulation as well as experimental data. Specific challenges on dispersion effect in dissipative media and random noise effects were also discussed and addressed.

Key words: *Ground penetrating radar; Instantaneous bandwidth; Thin layer; Time-frequency analysis.*

Introduction

Pavement layer thickness is an important factor in affecting the quality of newly constructed pavements and overlays, since deficiencies in thickness reduce the life of the pavement. For asphalt pavement, the relationships between thickness deficiency and its service life have been quantitatively described by a performance model [1]. These relationships show, for example, that a 1.3cm thickness deficiency in a nominally 9.1cm thick asphalt pavement can lead to a 40% reduction in pavement life [2].

In order to obtain pavement thickness as a measure of quality assurance, it is necessary to have an accurate and reliable method for making the thickness measurement. Pavement cores can generally provide accurate thickness information; however, it is time consuming to obtain field core samples. Further, the process would damage the pavement, and the limited number of samples could only represent a very small portion of the actual pavement. To alleviate these shortcomings, ground penetrating radar (GPR) has been used in pavement engineering since the 1980s [3]. The technique is currently one of the leading technologies in investigating the measurement of pavement layer thickness.

GPR is a non-destructive method used to generate high-resolution images of subsurface conditions. In impulse GPR systems, a short pulse of electromagnetic energy is transmitted into the ground. A proportion of this energy is reflected back towards the surface at interfaces of media with differing electromagnetic properties. Information about the subsurface is then extracted from the amplitude and time delay of these reflections. The high data acquisition speed and resolution capabilities make the method well suited for road applications. The past two decades have witnessed a tremendous increase in the use of GPR technology in highway engineering [4].

The advancement of pavement designs with varying pavement structures has concurrently been on the rise; thereby more and more surface layers with thinner thicknesses have been constructed, such as thin asphalt overlay over existing or fractured concrete pavement, and ultra-thin white topping over asphalt pavement [5]. The estimation of the thickness of very thin pavement layers is often not satisfactory by using commercial impulse GPR employing traditional data processing techniques [6, 7]. This is primarily because the first two echoes from such a pavement are overlapped, since the frequencies and bandwidths of commercial pulse GPR are limited to about 2GHz. Generally, these obstacles can be overcome by using GPR with a much higher central frequency [8, 9]. However such GPR systems suffer from shallow penetration depth. Recently, O'Neill developed a waveform recognition approach based on frequency domain to detect layers that are very closely spaced [10]. Unfortunately, standard frequency domain methods require some prior knowledge about internal geometry of the system being evaluated, such as the number of interfaces and maximum depth. Pieraccini et al. used joint time–frequency analysis as a processing tool to detect and characterize layered structures of a few centimeters behind tens of centimeters of masonry [11]. Applying time–frequency representation does not give good visualization. Moreover, it is difficult to quantitatively evaluate the thickness of thin layers in practical applications. Strange et al. proposed a pattern recognition approach using features derived from the bispectrum and a nearest-neighbor classifier to estimate coal layer thickness within the near-surface range [12]. However, the technique is unreliable when the surface layer thickness is greater than 6cm, which means it must be operated in conjunction with the traditional approaches to provide a complete profile of layer thickness.

In this paper, a data processing method is presented for determining the thickness of an ultra-thin pavement layer. Based on time–frequency analysis approach, a time delay estimation of the superimposed signal is implemented using instantaneous bandwidth analysis. The thin layer thickness is then estimated subsequently. This

[1] Guangzhou Institute of Measuring and Testing Technology, Guangzhou, 510030, China,

[2] Road Engineering Research Institute of South China University of Technology, Guangzhou, 510640, China

[+] Corresponding Author: E-mail prozxn@163.com

Note: Submitted December 15, 2007; Revised March 1, 2008; Accepted March 13, 2008.

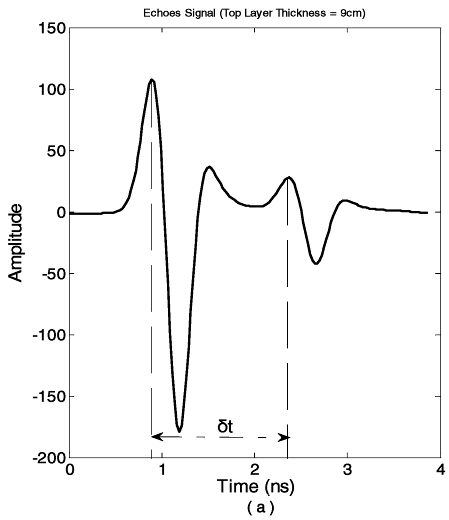

Fig. 1(a)

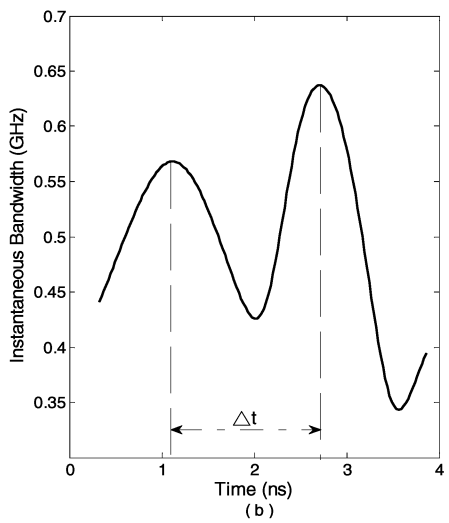

Fig. 1(b)

Fig. 1. Two-Layer Model Experience with 9cm Thick Top Layer (a) Received Echoes Signal, (b) Instantaneous Bandwidth.

method can be applied successfully to layers of any thickness in the range of GPR penetration depths.

Time-frequency Analysis

Time-frequency analysis has been used as an effective tool in analyzing the time-dependent spectral components of GPR signals. Time-frequency representations (TFRs) provide a technique for investigating how the frequency content of a given signal changes as a function of time. The output of these representations is the energy density or intensity of various components of a signal at given points in time. Typical methods used for time-frequency analysis include linear TFRs, concentrating on the Short-Time Fourier Transform (STFT), Gabor expansion, the wavelet transform (WT), and quadratic TFRs (e.g., Wigner-Ville Distribution), a commonly-used and well-studied Cohen's class [13]. In this study, time-dependent spectral analyses were performed using S-transform [14].

The S-transform

The S-transform can be considered as an extension to the ideas of the Gabor transform and the WT. The S-transform of a signal *x(t)* is defined as the following:

$$P(t,f)=\int_{-\infty}^{\infty}x(\tau)\frac{|f|}{\sqrt{2\pi}}\exp\left[-\frac{(\tau-t)^2f^2}{2}\right]\exp(-j2\pi f\tau)d\tau \tag{1}$$

where t is the time and f is the frequency.

The S-transform can be regarded as a hybrid of the WT and the Gabor transform, a version of the STFT in which a Gaussian window function is employed. Like the STFT, the S-transform analyzes a signal using windowed harmonics, and thus yields a true measure of frequency. Similar to the WT, features are analyzed with a resolution suited to their scale because the effective width of the Gaussian window changes with frequency. High frequencies are analyzed using a short time window with the S-transform while low frequencies are analyzed using longer time windows.

Instantaneous Frequency and Instantaneous Bandwidth

From Eq. (1), the time-frequency distribution or the joint energy density, *P(t, f)*, can be obtained. One can calculate instantaneous frequency (*IF*) and instantaneous bandwidth (*IB*) subsequently. *IF* is the first conditional spectral moment which is given by [13]:

$$IF(t)=\frac{1}{P(t)}\int_{-\infty}^{\infty}fP(t,f)df \tag{2}$$

where $P(t)=\int_{-\infty}^{\infty}P(t,f)df$ is the time marginal of the joint density.

IB can be obtained from the second conditional spectral moment or the squared deviation:

$$IB(t)^2=\frac{1}{P(t)}\int_{-\infty}^{\infty}[f-IF(t)]^2P(t,f)df\cdot \tag{3}$$

As the standard deviation of frequency, *IB* is useful as an indicator of interference due to other signal components. Therefore, in this study, it is employed for detection of abrupt changes of GPR signals even if the changes are indiscernible in time domain.

Numerical Experiments

A 2-D finite-difference time-domain (FDTD) simulator was employed in generating the data used for the experiments. To simulate actual monostatic impulse GPR detection scenarios, the transmitter and receiver antenna were located in the air, and the excitation source was the Ricker wavelet (the first derivative of the Gaussian function) of the centre frequency of 1GHz. Top half of a pavement profile, 600 (in width) × 180mm (in height), was truncated as the main computational domain including two layers where the top and bottom layers were asphalt concrete and Portland cement concrete respectively. The FDTD cell size was 1.5 × 1.5mm and time step was about 0.0035ns. Perfectly matched layers were

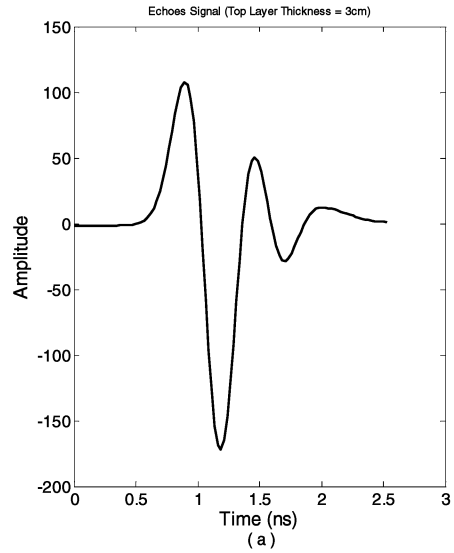

Fig. 2(a)

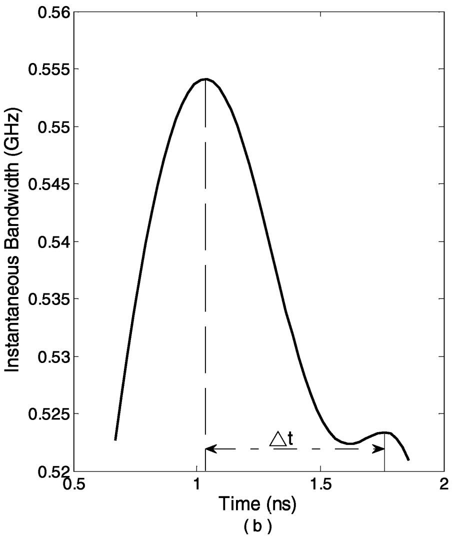

Fig. 2(b)

Fig. 2. Two-Layer Model Experience with 3cm Thick Top Layer (a) Received Echoes Signal, (b) Instantaneous Bandwidth.

assumed to minimize artificial reflections from the boundary. The permeability for the top and bottom layers was equal to that of a free space. There were some controllable parameters in the FDTD simulation, where ε_1, ε_2, σ_1, and σ_2 were relative permittivity and conductivity of the top and bottom layers, respectively and h was the top layer thickness. After the FDTD simulation, the electric field signal was sampled with time interval about 0.025ns, which is adopted in the actual GPR system.

Thick Layer

With h = 9cm, ε_1 = 6, ε_2 = 10, $\sigma_1 = \sigma_2 = 0$, the echoes signal is shown in Fig. 1(a). There are two pulses in the receiving signal with the first one coming from the top of the asphalt concrete and the second from the interface between the two pavement layers. As the two pulses are clearly separated in time domain, layer thickness

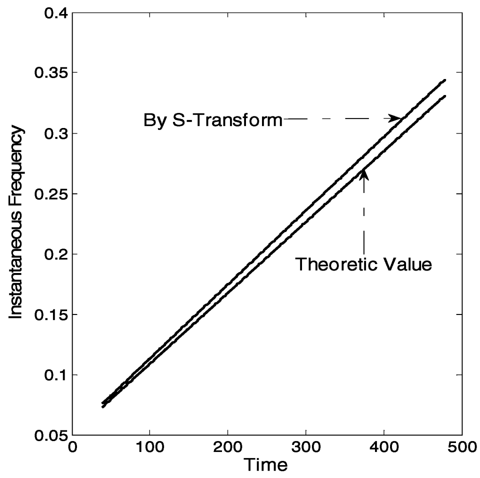

Fig. 3. Estimated Instantaneous Frequency of a Linear Frequency Modulation Signal by Using S-Transform.

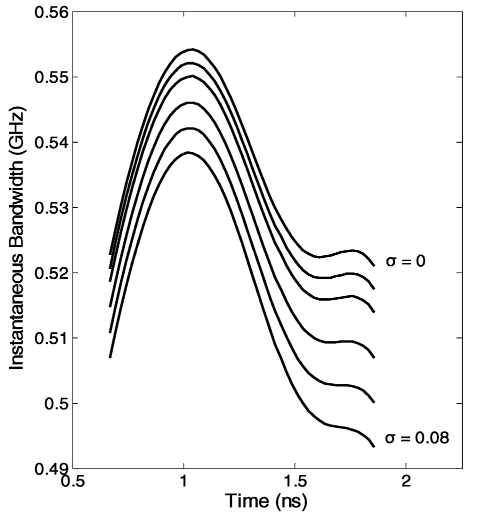

Fig. 4. Instantaneous Bandwidth Analysis with Lossy Bottom Layer of a Series of Conductivity from 0, 0.01, 0.02, 0.04, 0.06 to 0.08S/m (from Top to Bottom).

estimation is determined by the following equation:

$$h = \frac{cT}{2\sqrt{\varepsilon_1}} \tag{4}$$

Where c is the speed of light in free space; T is the time delay of the two pulses, which can be estimated as δt in Fig. 1(a); ε_1 is a constant that can be estimated using GPR with a flat metal plate as described in [15, 16], or by taking measurements with dielectric measuring equipment [17]. Fig. 1(b) shows the instantaneous bandwidth corresponding to Fig. 1(a). The two pulses can also be clearly identified, and T can be estimated as $\triangle t$.

Thin Layer

Taking h = 3cm, ε_1 = 6, ε_2 = 10, $\sigma_1 = \sigma_2 = 0$, we obtain echoes signal shown in Fig. 2(a), where the two pulses are overlapped and traditional processing techniques are unreliable to estimate the time

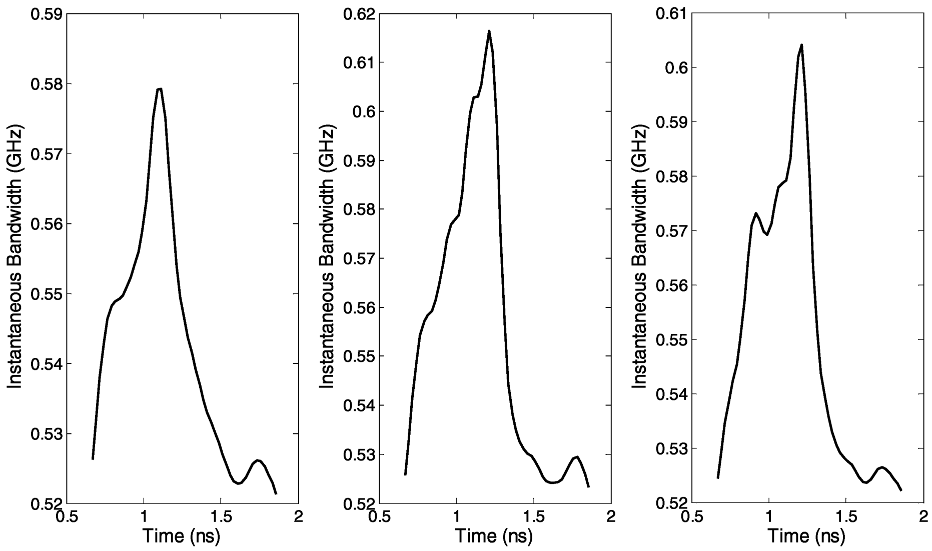

Fig. 5. Same as Fig. 2(b), Except That Uniformly Distributed Random Noise of 2% Added to the Echoes Signal.

delay *T*. By computation of the instantaneous bandwidth, the second pulse obviously reveals, as seen in Fig. 2(b). As presented in Fig. 2(b), *T* is estimated to be $\triangle t$ = 0.7182ns. Compared with the theoretic value of *T* = 0.4899ns, the estimation has an obvious error, which is caused primarily by S-transform and also from sampling error. The similar phenomenon is also found in Fig. 1(b). After testing its performance of analyzing the instantaneous frequency of a linear frequency modulation signal, we observed that S-transform would overestimate instantaneous frequency, as shown in Fig. 3. This observation indicates that the estimation error of the proposed technique is an inherent systemic error that can be effectively eliminated as described in [16].

Lossy Case

In the previous analysis, the pavement materials were treated as lossless. However, in the actual pavement structures, they are dissipative media, especially when the pavement suffers from moisture damage. Due to the presence of a dispersion effect, the returned echoes signal will be distorted in the lossy case. In this instantaneous bandwidth analysis, the values of σ_2 were varied from 0, 0.02, 0.04, 0.06 to 0.08S/m while the others remained constant (h = 3cm, ε_1 = 6, ε_2 = 10, and σ_1 = 0). The results are shown in Fig. 4. From this figure, it is clear that the time delay can be reliably estimated when σ_2 is smaller than 0.02S/m. When σ_2 is larger than 0.02S/m, the second pulse becomes undistinguishable, which makes this method unreliable. Hence, the proposed technique works successfully in the weak lossy case only.

Noise Effects

The stability of the proposed technique was investigated by adding artificial random noise to the echoes amplitudes. In our experiments, 2% uniformly distributed random noises were added to the data of Fig. 2(b) to simulate practical applications. The results of such numerical experiments are illustrated in Fig. 5, which indicates that the two pulses are highly distinguishable regardless whether the amplitudes of the instantaneous bandwidth are affected. These findings suggest that the proposed technique is not susceptible to the influence of noise.

Applications

The performance of the technique discussed in the paper was tested with a monostatic impulse GPR system with the pulse width of 1ns antenna. Two asphalt concrete pavement layer samples, with different thicknesses, were prepared in a laboratory using the same hot mix asphalt mixtures. The thicker one, about 8cm thickness, was used to determine the value of ε_1. The value of ε_1 was determined to be 5.1. The thin one, with a 3.1cm thickness, was placed on the surface of a concrete pavement in the campus, and then the GPR field tests were conducted in the static position. The tests were repeated 30 times without any shift of the GPR antennas. The 30 waveforms were ensemble averaged to suppress noise. Fig. 6(a) shows the actual echoes signal truncated from the averaged pavement. The signal shows the reflections of the layered structure, but there is no way to interpret the data directly from the waveform. Corresponding instantaneous bandwidths are illustrated in Fig. 6(b) indicating two distinct pulses, and the time delay can be directly calculated to be $\triangle t$ = 0.5ns. Using Eq. (4), the thickness h is estimated to be 3.32cm. The estimation error of the evaluation is7.1% without any calibration procedure. The result indicates that it is possible to use a relative low-frequency GPR system to obtain higher resolution.

Conclusions

In this paper, a technique based on the instantaneous bandwidth analysis has been proposed to detect the echoes in GPR measurements, to evaluate the time delay, and to calculate the thickness

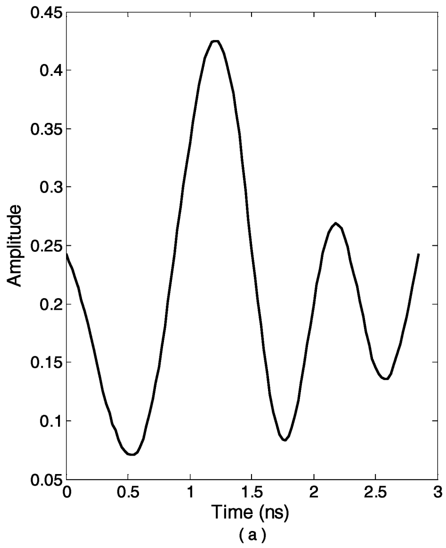

Fig. 6(a)

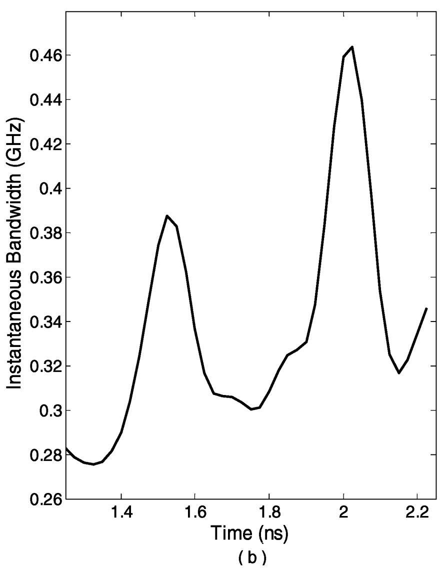

Fig. 6(b)

Fig. 6. Field Test of a Thin Asphalt Concrete Slab over Concrete.

of pavement layers subsequently. The instantaneous bandwidth of GPR signal is obtained using time-frequency analysis. With a pavement with very thin layers, the overlap of reflected pulses has made traditional processing techniques unreliable. However, the proposed approach can still yield satisfactory results. Numerical and field examples have demonstrated that the technique is not susceptible to the influence of noise and suitable for the case that the pavement is composed of lossless or low-loss materials. Although the authors focus attention on the surface layer, the proposed methodology can be applied to the analysis of any thin layer in the range of GPR penetration depths, e.g., a typical application for pavement void detection. Furthermore, it should be noted that the evaluation errors in the examples and practical applications could be eliminated effectively by employing an appropriate calibration method.

Thickness measurement of thin pavement layers using GPR is a great challenge to pavement engineers. Theoretically, GPR with a much higher central frequency is very helpful to the measurement, but there will be interference with existing radio transmissions. In many countries, the fundamental bandwidth of the emissions spectrum from a GPR must be authorized. Under such a limitation, much importance has been attached to some data processing techniques. In this paper, we have reported the primary attempt for the measurement of thin pavement layers' thickness using GPR. More field tests on the pavement with different damage will be carried out for a further study. Other data processing techniques will also be evaluated, and the results will be reported later.

References

1. Deacon, J.A., Monismith, C.L., Harvey, J.T., and Popescu, L., (2001). Pay Factors for Asphalt-Concrete Construction: Effect of Construction Quality on Agency Costs, *Technical Memorandum*, TM-UCB-PRC-2001-1, Institute of Transportation Studies, University of California, Berkeley, CA, USA.
2. Maser, K.R., (2003). Non-Destructive Measurement of Pavement Layer Thickness, *Report No. FHWA/CA/OR-2003/O3*, California Department of Transportation, California, USA.
3. Loulizi, A., Al-Qadi, I.L., and Lahouar, S., (2003). Optimization of Ground-Penetrating Radar Data to Predict Layer Thicknesses in Flexible Pavements, *Journal of Transportation Engineering*, 129(1), pp. 93-99.
4. Li, X.-T., Wang, D.-Y., and Zhang, X.-N., (2006). Review and Prospects of Ground Penetrating Radar Technology, *Nondestructive Testing*, 28(9), pp. 479-484.
5. Rea, R.C. and Jensen, W.G., (2005). A Concrete Overlay on an Asphalt Road, *International Journal of Pavement Engineering*, 6(2), pp. 111-114.
6. Spagnolini, U., (1997). Permittivity Measurements of Multilayered Media with Monostatic Pulse Radar, *IEEE Transactions on Geoscience and Remote Sensing*, 35(2), pp. 454-463.
7. Meloy, J.H., Overman IV, C.H., Kurtz, J.L., Porter, J.R., and Greene, J.H., (2002). Ground Penetrating Radar Signal Processing Techniques for Airfield Evaluations, *Radar Sensor Technology and Data Visualization*, *Proceedings of SPIE*, Vol. 4744, pp. 37-47, Orlando, FL, USA.
8. Dérobert, X., Fauchard, C., Côte, E., Le Brusq, E., Guillanton, E., Dauvignac, J.Y., and Pichot, C., (2001). Step-Frequency Radar Applied on Thin Road Layers, *Journal of Applied Geophysics*, 47(3-4), pp. 317-325.
9. Jeong Soo, L., Cam, N., and Scullion, T., (2004). A Novel, Compact, Low-Cost, Impulse Ground-Penetrating Radar for Nondestructive Evaluation of Pavements, *IEEE Transactions on Instrumentation and Measurement*, 53(6), pp. 1502-1509.
10. O'Neill, K., (2000). Radar Sensing of Thin Surface Layers and Near-Surface Buried Objects, *IEEE Transactions on Geoscience and Remote Sensing*, 38(1), pp. 480-495.
11. Pieraccini, M., Luzi, G., Noferini, L., Mecatti, D., and Atzeni, C., (2004). Joint Time-Frequency Analysis for Investigation of Layered Masonry Structures Using Penetrating Radar, *IEEE*

Transactions on Geoscience and Remote Sensing, 42(2), pp. 309-317.

12. Strange, A.D., Chandran, V., and Ralston, J.C., (2005). Coal Seam Thickness Estimation Using GPR and Higher Order Statistics - the Near-Surface Case, *Proceedings of the Eighth International Symposium on Signal Processing and Its Applications*, Sydney, Australia, pp. 855-858.
13. Cohen, L., (1995). *Time-Frequency Analysis*. Prentice Hall, Englewood Cliffs, NJ, USA.
14. Stockwell, R.G., Mansinha, L., and Lowe, R.P., (1996). Localization of the Complex Spectrum: the S Transform, *IEEE Transactions on Signal Processing*, 44(4), pp. 998-1001.
15. Saarenketo, T. and Scullion, T., (2000). Road Evaluation with Ground Penetrating Radar, *Journal of Applied Geophysics*, 43(2-4), pp. 119-138.
16. Li, X.-T., Wang, D.-Y., and Zhang, X.-N., (2006). A High-Accuracy Calibration Method for Thickness Measurements of Asphalt Pavement Using Ground-Penetrating Radar, *Proceedings of the 25th Southern African Transport Conference*, Pretoria, South Africa, pp. 305-312.
17. Shang, J.Q., Umana, J.A., Bartlett, F.M., and Rossiter, J.R., (1999). Measurement of Complex Permittivity of Asphalt Pavement Materials, *Journal of Transportation Engineering*, 125(4), pp. 347-356.