GPR FOR FAST PAVEMENT ASSESSMENT

May 2007

JHR 07-310                          Project 00-2

Lanbo Liu

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This study was conducted under the Connecticut Cooperative Highway Research Program (http://www.cti.uconn.edu/crp_home.html).

This report summarizes the findings of Project JHRAC 00-2 for studying the fast assessment of road pavement with the ground penetrating radar (GPR). The report contains four parts. The first two on actual GPR data acquisition and analysis: one on laboratory measurements and one on field surveys. The last two parts examine the GPR signal forward modeling and signal data processing.

We conducted laboratory tests of engineered materials using the RAMAC radar system with the 1-GHz antenna. The experiments used geotechnical fundamental measurements as the known parameters and correlated with the electromagnetic (EM) parameters obtained by GPR measurements. The fundamental parameters include thickness, density, aggregate material ratio, and air void ratio, etc. The GPR experiments test the materials to get the dielectric constant that directly determines EM wave velocity. Asphalt tests have been conducted on 30 asphalt specimens. The asphalt specimens produced at the Connecticut Advanced Pavement Laboratory have a dimension of 15 cm in diameter with 11.5 cm in height. Serving as the strong reflector to mark the travel time, an aluminum plate is placed underneath the specimen, to allow an easier identification of the time travel to and reflected back from the plate. The calculated EM wave velocity is about 131 m/microsecond for most dry asphalt specimens. The corresponding dielectric constant is ranging from 4 to 5. We have also tested the response of the asphalt specimens in different ambient states (dry, saturated with water, and frozen).

GPR data using the 1-GHz antenna were collected several times on a then-newly paved road segment on the Depot Campus of the University of Connecticut (UConn) under different meteorological conditions. The GPR data clearly showed signature changes of the asphalt response between dry and water-saturated conditions. The radar wave velocity reduced about 5% when the asphalt was water-saturated (after heavy rain, collected in the morning of September 20, 2000). This change makes a relative clearer identification. Meanwhile, the reflectivity increased 60%, making the reflection from the bottom of the base of the asphalt layer much more visible.

To theoretically understand the effect of a thin dielectric layer (such as the hot mixed asphalt pavement) on radar signal propagation, a finite difference time domain (FDTD) forward modeling algorithm was developed. The simulation clearly demonstrated the wave guide effect of this surface thin layer. This simulation can be used as guidance for developing multi-channel GPR systems.

To improve the resolution and preserve the penetration, if high-and low-frequency surveys are conducted simultaneously over the same road segment, it is possible to extrapolate the high frequency signal to a deeper depth numerically through a digital signal processing algorithm known as extrapolation with deterministic deconvolution (EDD) and consequently gain a higher resolution to a greater depth.
Acknowledgments

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### SI* (MODERN METRIC) CONVERSION FACTORS

#### APPROXIMATE CONVERSIONS TO SI UNITS

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**NOTE:** Volumes greater than 1000 L shall be shown in \( \text{m}^3 \).

| **VOLUME** | | | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| \( \text{ft}^3 \) | cubic feet | 0.028 | cubic meters | m³ |
| \( \text{yd}^3 \) | cubic yards | 0.765 | cubic meters | m³ |

#### MASS

| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or “metric tons”) | Mg (or “T”) |

**TEMPERATURE (exact degrees)**

\( ^\circ\text{F} \) Fahrenheit \( 5 \left( ^\circ\text{F}-32 \right)/9 \) \( \text{Celsius} \)

\( ^\circ\text{C} \)

#### ILLUMINATION

| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/m² | cd/m² |

#### FORCE and PRESSURE or STRESS

| lbf/in² | poundforce per square inch | 4.45 | newtons | N |
| kilopascals | 6.89 | kilopascals | kPa |

#### APPROXIMATE CONVERSIONS FROM SI UNITS

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<td>yd³</td>
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</table>

| **MASS** | | | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg | megagrams (or “metric tons”) | 1.103 | short tons (2000 lb) | T |

**TEMPERATURE (exact degrees)**

\( ^\circ\text{C} \) \( 1.8^\circ\text{C}+32 \) \( \text{Fahrenheit} \)

**ILLUMINATION**

| lx | lux | 0.0920 | foot-candles | fc |
| cd/m² | candela/m² | 0.2919 | foot-Lamberts | fl |

**FORCE and PRESSURE or STRESS**

| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | lbf/in² |

*Si is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)
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1. Introduction

A fast, economical, and accurate means of assessment of road pavement conditions, at both the network and project levels, is of great significance to highway management and maintenance. The emerging ground penetrating radar (GPR) technology has a natural application as a supplementary device for other road survey techniques such as the road video and infrared surveys. GPR can be used to identify valuable parameters that cannot be obtained from a visual evaluation of the road surface. These parameters include pavement-layer thickness and, potentially, damaged, or deteriorated subsurface areas. Moreover, it would be possible to obtain an more accurate characterization of the pavement structure by combining the data provided by such a non-destructive testing (NDT) system with that supplied by destructive testing (coring and sampling). Over the last decade, these potential benefits have prompted transportation agencies and private industry in North America, Europe, and some developing countries, to start incorporating GPR technology into pavement-assessment engineering practice. However, the most challenging aspects for using GPR are, inevitably, the precise identification of subsurface targets and the fast reduction of a huge amount of data into a form that is readily interpretable to highway engineers.

To solve these problems, automatic acquisition and interpretation of GPR data for pavement assessment has recently attracted tremendous attention and research efforts. As a preparation phase for future research on the application of GPR techniques for pavement and bridge assessment, the Principal Investigator (PI) of this project conducted a feasibility investigation on state-of-the-art use of ground penetrating radar to rapid pavement assessment (Liu, 1998).

This report summarizes the major research results conducted by Project JHRAC 00-2 in 6 chapters. As an overall introduction, this chapter lays out the structure of the report. Chapter 2 reports the results on GPR laboratory testing results conducted in the Connecticut Advanced Pavement Laboratory (CAP Lab). Chapter 3 summarizes the major findings of GPR field tests over a low traffic volume road over a long period of time under different meteorological conditions. Chapter 4 reports a piece of theoretical work on numerical simulation of the GPR response to a surface thin layer of dielectric materials. Chapter 5 presents a digital processing algorithm to improve the resolution of GPR signals and preserve the penetration depth. Finally,
Chapter 6 provides an overall summarization and makes recommendations for using GPR as an engineering tool for pavement assessment in the future.

2. GPR laboratory tests of asphalt specimens in three states

There are two major purposes for using ground penetrating radar (GPR) field survey in pavement assessment. The first is for determining the thickness of the asphalt pavement; and the second is for detecting subsurface deterioration. Determination of thickness needs to know the velocity of radar waves, and deterioration between layers involves reflectivity of radar wave at the interfaces. Both velocity and reflectivity are determined by the dielectric constant of the asphalt pavement. This section of the report discusses the dielectric constant determination of asphalt specimens in laboratory-controlled conditions. The experiment results may provide certain degree of constraints for interpreting GPR field data for seeking thickness variation and subsurface deterioration.

A series of laboratory experiments was conducted to determine the dielectric constant of hot mix asphalt (HMA) pavement specimens in dry, water-saturated, and frozen states. We used the RAMAC GPR system with the 1-GHz ground coupled antenna to measure the travel times for the direct and reflected waves to calculate the radar wave velocity and dielectric constants of 30 specimens. Our major conclusions are: (1) In general, radar wave travels fastest in the asphalt specimens under dry condition and slowest in water-saturated condition. When the water-saturated specimens are frozen, radar wave velocity increases again to some degree, but slower than that in dry condition; (2) Radar wave velocity increases slightly with the increase of void ratio for dry samples. In contrast, it decreases significantly through water-saturated samples as their void content increased. Correspondingly, the dielectric constant decreases noticeably with an increasing void ratio in dry conditions, and increases appreciably in saturated conditions, in the range of void ratio from 0.57% to 6%; (3) The changes of EM velocity and resulting dielectric constant for dry, saturated, and frozen conditions can be reasonably predicted by the complex refractive index model (CRIM) for porous media; (4) Variations in EM velocity and resulting dielectric constant with respect to asphalt binder content implies that a lower value in asphalt binder content corresponds with a higher void ratio; and (5) For a particular HMA specimen with a given void ratio, the observed variations in EM velocity and resulting dielectric constant can be attributed to the changes...
in moisture content under different physical states.

2.1. Introduction

One of the most important factors affecting the life span and deformation of the HMA pavements is the void content expressed by the void ratio (Saarenketo, 1997). Void ratio denotes the volumetric fraction of void (or pore) space relative to aggregate and asphalt binder of a pavement. The void ratio is important because void space could be filled with air, water, ice, or any fractional combination of these three depending on the temperature environment. Each of these three void materials has different mechanical properties which may influence the HMA’s overall strength, durability, and stability. For example, the presence of water in void space can significantly change the shear modulus of an HMA pavement. In contrast, the presence of ice in the voids will effectively change an HMA’s bulk modulus. Moreover, freeze-thaw processes lower the tensile strength of an HMA pavement and facilitate tensile failure (cracks). Clearly, the amount of moisture penetrating into an HMA pavement, whether from above or below, depends on the HMA’s void ratio and connectivity, and can have detrimental effects on the durability of that pavement. In the last decade, ground-penetrating radar (GPR) has emerged as one of the most widely used non-destructive testing tools in assessing HMA pavements (Saarenketo, 1992; al-Qadi, 1992; Davis et al., 1994; Maser, 1996; Liu, 1998; Saarenketo and Scullion, 2000).

A rapid and reliable estimation of the void ratio of an HMA pavement is necessary to understand the role of moisture content in HMA durability and stability. Conventionally, HMA void ratio and moisture content have been assessed by direct excavation or drill sampling, or by radioactive methods (Saarenketo, 1997), which are costly and invasive. In this context, if a robust relationship between radar wave velocity, void ratio and moisture content can be established; non-destructive testing using GPR can be an efficient complementary tool for HMA pavement assessment.

GPR has been used in the field to determine subsurface soil moisture content below highway pavement (Topp et al., 1980; Greaves et al., 1996; Berktold et al., 1998; al Hagrey and Muller, 2000; Charlton, 2000; Redman et al., 2002). In laboratory experiments, Saarenketo (1998) reported the effects of water in determining the dielectric permittivity of clay and silty soils. Saarenketo and Scullion (2000) reported the relationship between void content and dielectric constant for dry HMA
samples. Their studies resulted in the development of vehicles that can be used to assess pavement properties of a newly placed mat by combining some GPR with infrared sensing technology with the calibration from coring. Shang and Umana (1999) studied the dielectric constant and relaxation time of asphalt pavement materials. In this paper, we are reporting the laboratory results of GPR on prepared HMA specimens in three distinctive states (dry, water-saturated and frozen).

Using a radar system with 1-GHz antenna we tested HMA pavement materials in the CAP Lab at the University of Connecticut. The experiments correlated the dielectric constant obtained by GPR measurement with aggregate material composition, and void ratio of HMA specimens under dry, water-saturated, and frozen states. Our objectives were to (1) determine the dielectric properties of the asphalt specimens; (2) correlate the dielectric constants with void ratio and asphalt binder content ratio; and (3) elucidate the evolution of the dielectric constant with respect to simulated environmental states (dry, saturated and frozen). These results can be used as a baseline for GPR field surveys over road pavements in real world conditions, as well as for quality control of pavement compaction assessment using radioactive methods.

2.2. Laboratory measurements

We tested 30 HMA specimens in dry, water-saturated, and frozen conditions. These cylindrical asphalt specimens were produced at the CAP Lab using the applicable AASHTO standard at the time TP4 for the fabrication of Superpave gyratory specimens. They are 15 cm in diameter, about 11.3 cm in height, and are composed of the same aggregate source materials. The GPR antenna was set on top of a specimen, which, in turn, was set on a metal (aluminum) plate to gain total reflection (Figure 2.1). The use of a metal plate facilitates an easy identification of the reflected waves by providing perfect reflectivity.
Figure 2.1. This figure depicts the EM wave's general paths as it travels through the specimen. Idealized near-surface, near-field propagation paths along the interface of the air and an HMA pavement layer (or HMA specimen) with a thickness of H. T: the location of the transmitter; R: the location of the receiver. The separation of T and R is D. The air wave travels from T to R above the surface at the fastest velocity \( c_0 \) (speed of light). The ground wave travels from T to R below the surface at a velocity of \( c_0/\sqrt{\varepsilon_r} \), where \( \varepsilon_r \) is the dielectric constant of the HMA. The reflected wave has a longer ray path: it hits the HMA-base (here a metal-plate) interface, and then is reflected to the receiver.

The experimental setup for testing the specimens in saturated condition is shown in Figure 2.2.

Figure 2.2. GPR measurement setup for a test on the water-saturated HMA specimen using the 1-GHz antenna in the CAP Lab, University of Connecticut.
The asphalt binder grade (nomenclature for the binder grade is PG 64-28) used for producing these specimens is identical for all samples. The asphalt binder content (AC %) in any one specimen is given in terms of weight percentage. The samples consist of a range of proportions of aggregates to form a void ratio that varies from 0.57% to 6.0%. The parameters of these 30 specimens are listed in Table 2.1.

The EM wave velocity of these newly produced HMA specimens were first tested in dry state. Each specimen was then submerged into tap water in a sealed container and vacuum pumped, such as is done for the $G_{mm}$ (the max theoretical density of HMA test) to extract the air for 10 minutes to reach water saturation. The samples were then submerged in a water tank to hold water-saturated status until testing. These saturated specimens were measured with the 1-GHz GPR again to get the water-saturated velocity. After this, the specimens were immediately refrigerated with a constant temperature of –18 °C for 20 hours to reach a frozen state. (Specifications for classic pavement freezing-thawing experiments request the specimen to be frozen no less than 18 hours in one freezing-thawing cycle). Finally, the frozen specimen was tested by the same procedure as was done in dry conditions to get the EM velocity in frozen states. All tests were conducted at room temperature in a time period as short as possible to prevent pore water dripping or thawing. For one specimen under a given state, 10 GPR measurements were taken. The average of the 10 measurements on the reflected wave travel time was used to calculate the EM wave velocity for that state.

### Table 2.1 Basic parameters of the HMA specimens used in GPR laboratory experiments

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<th>Specimen Label</th>
<th>Height (cm)</th>
<th>Volume (cm³)</th>
<th>Dry Weight (g)</th>
<th>Surface wet Weight (g)</th>
<th>Submerged Weight (g)</th>
<th>10-min. vacuum Weight (g)</th>
<th>$G_{mm}$ (g/cm³)</th>
<th>AC (%)</th>
<th>Void Ratio (%)</th>
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*G_{mn} is the maximum theoretical specific gravity.

2.3. Calculations of EM wave velocity and dielectric constant

We make three justifiable assumptions about the electromagnetic parameters of an HMA to simplify the EM velocity calculation. The first is that velocity does not depend on the magnetic permeability because the asphalt binder and most crushed stones used for making pavement aggregates are essentially non-magnetic. Second, most of the minerals composing the aggregates, such as quartz, mica, and feldspar, are good insulators. The asphalt binder can also be regarded as insulation material. Since the void ratio of an HMA is small, even when the voids are fully saturated with fresh water, the conductivity is still very small. This fact warrants us the third assumption, that the imaginary part of the dielectric permittivity can be considered negligible. Therefore, EM wave velocity only depends on the real part of the dielectric permittivity.

The electromagnetic (EM) velocity $v$ can be measured in a number of ways. The easiest way is to measure the time difference between the direct air wave traveling in air and the ground wave
traveling in the HMA (Figure 2.1). Unfortunately, for a near-offset (the separation distance between the transmitter and the receiver is very short) survey, the arrival time difference is very small and hard to measure accurately. Another way is the reflection method, in which the travel time difference for the direct and reflected waves is the fundamental information for computing EM wave velocity. As shown in Figure 2.1, the thickness of an HMA is comparable to GPR transmitter-receiver separation. Taking this into account \( v \) was calculated by:

\[
v = \sqrt{\frac{D^2 + 4H^2}{(t_0 + \Delta t)^2}},
\]

(2.1)

where \( D \) is the separation between the transmitter and receiver; \( H \) is the thickness of the specimen; \( t_0 \) is the direct air wave travel time to the receiver, and \( t \) is the time difference between the reflected wave from the underlying metal plate and the direct air wave. All parameters on the right-hand side of Eq. (2.1) are measurable in terms of either geometry or time. For example, the transmitter-receiver separation is 0.1 m for the 1-GHz ground-coupled antenna of RAMAC/GPR manufactured by MALA Geoscience, Inc., which was used in this study. The reason for choosing the ground-coupled antenna is due to its smaller foot-print than the air-coupled horn antenna that is more suitable for measuring the asphalt specimens with a diameter of 15 cm. The air-coupled horn antenna has the advantage of rapid data acquisition that we do not need in this project for measuring asphalt specimens in lab, but its larger foot print is definitely a disadvantage for measuring small-sized asphalt specimens.

As argued before, due to the justified simplification, the velocity depends only on the real part of the relative dielectric permittivity (the dielectric constant) through

\[
v^2 = \frac{c_o^2}{\varepsilon_r} \quad \text{or} \quad \varepsilon_r = \frac{c_o^2}{v^2},
\]

(2.2)

where \( \varepsilon_r \) is the dielectric constant; and \( c_o \) is the electromagnetic wave velocity in vacuum.
Figure 2.3. An example of raw waveform of GPR surveys over a dry asphalt specimen which was placed on an aluminum plate. The arrow with letter D indicates the arrival of the direct wave, while the arrow with letter R indicates the arrival of the reflected wave from the aluminum plate. The wave trains in the later times are multiple reflections irrelevant to travel time estimation.
Figure 2.4. Variations of EM wave velocity (a) and the dielectric constant (b) as a function of the void ratio obtained from GPR measurements of 30 HMA specimens for dry (Vd and Ed, with blue symbols and lines), water-saturated (Vw and Ew, with magenta symbols and lines), and frozen (Vz and Ez, with yellow symbols and lines) conditions.

EM wave velocity and the dielectric constant were calculated by this approach for all of the 30 pavement specimens. A typical time domain radar record is shown in Figure 2.3. The results of EM velocity and the inferred dielectric constant as functions of the void ratio are shown in Figure 2.4 and discussed in detail in the next section.

2.4. Results discussion

To the first order, the results (Figure 2.4) clearly show that the zero-void velocity is about 130 m/s and the zero-void dielectric constant is about 5.3. It implies that the HMA specimens are good dielectric materials and quite transparent in an electromagnetic sense. When the void ratio becomes larger, the EM velocity spreads out among dry, water-saturated, and frozen conditions up to a value of 13% of the reference velocity (130 m/s) when the void ratio is 6%.
The corresponding changes in the dielectric constant reach as large as 25%.

**The CRIM model**

For analyzing the EM velocity in a porous medium like an HMA, a good approximation for a hybrid material model is a solid skeleton containing void space, with the void filled with two kinds of fluid. A dielectric model formulation commonly used is the complex refraction index model (CRIM) (e.g., Robert, 1998; al Hagrey and Muller, 2000):

\[
n_b = \phi S n_w + (1 - \phi) n_g + \phi (1 - S) n_a,
\]

(2.3)

where \( n \) is the refractive index, and sub-indices \( b, w, g, \) and \( a \) represent bulk, water, aggregate, and air, respectively. Also, \( \phi \) is the porosity, and \( S \) is the water saturation. The porosity \( \phi \) is related to the void ratio \( e \) through

\[
\phi = \frac{e}{1 + e}.
\]

(2.4)

In the low porosity regime (less than 7\%), the porosity and void ratio are not significantly distinguished from each other. We applied the CRIM model to analyze the observed velocity and dielectric constant by using the following parameters. Because the dielectric constant is about 5.5-6.5 for aggregates and 2.6-2.8 for asphalt binder (Saarenketo, 1997), and the asphalt content (AC\%) is only about 5\% of the total weight of a specimen, the effective dielectric constant of 5.3 was used for the solid matrix (aggregates bonded by asphalt binder). The dielectric constant is 81 for fresh water, 3.17 for fresh water ice (Arcone, 1984), and 1 for air. Replacing \( n_a \) by \( n_i \) the refractive index of ice, Eq. (2.3) was used again to compute the bulk dielectric constant for voids filled with ice-water mix. Using these values, the modeling results for the case of air-water mix filling the void space are shown in Figure 2.5. The modeling results for the case of ice-water mix filling the voids are shown in Figure 2.6.
Figure 2.5. Prediction of EM wave velocity (a) and dielectric constant (b) variations as a function of porosity for water saturation changes from 0 to 1 by the CRIM model. The value of 0.80 best fits the observed results (Figure 2.4); it implies that the water-saturation reached about 80% after 10-min air-stripping pumping.

Figure 2.6. The CRIM predicted EM wave velocity (a) and dielectric constant (b) as a function of porosity for the ice-water mix case. In this case, the void space is filled with only ice and water, no air. Water saturation changes from 0 to 1 correspond to 100% frozen to unfrozen. The curve of water saturation of 0.2 best fits the observed results in frozen conditions (Figure 2.4); it implies that 20% of the pore water is still unfrozen after 20-hours freezing in a refrigerator.

The CRIM model appears to sufficiently interpret the observed results for the dry and water-saturated conditions. When the void ratio increases, the velocity increases slightly for dry conditions and decreases significantly for water-saturated conditions. This is simply due to the fact that a larger fraction of air filling the voids leads to higher velocity, and a larger fraction of pore water leads to lower velocity. The curve of $S=0.8$ may best fit the observed results for water-saturated conditions. This implies that the pores of the HMA specimens were 80% saturated by water, and 20% filled with air (Figure 2.5). This indicates that the 10 minutes of air-
stripping pumping in the vacuum process we used to prepare saturated samples were not long enough to reach ideal 100% saturation. In frozen conditions, the CRIM model also predicts that velocity should increase with increase of the void ratio, if there is less than about 15% void space filled with water (Figure 2.5a). Actually, the observed trend for the frozen condition (Figure 2.4) slightly decreases with increase of the void ratio, and implies that there is about 20% of the pore water remaining unfrozen or being thawed when we took the GPR measurements.

**Void ratio-asphalt content correlation**

The relationships between the observed EM velocity and resulting dielectric constant with respect to the asphalt content were also studied (Figure 2.7). The variation trends are opposite to variations of the velocity and dielectric constant with respect to the void ratio (Figure 2.4). The EM velocity and resulting dielectric constant for the dry and frozen conditions do not change at all with variation in asphalt content: the asphalt bitumen is only less than 6.5% in an HMA specimen, and so has little effect upon the bulk dielectric constant. An inverse correlation was also found between the void ratio and the asphalt content (Figure 2.8). This observed inverse correlation implies that lower asphalt content may lead to a larger void ratio. Therefore, the amount of asphalt binder applied to an HMA plays a significant role in optimizing void ratio to construct a durable and stable road surface.

**Moisture content predicted by the Topp model**

Based on our fitting for the saturated condition, the moisture content varies from zero to 5.6% when the void ratio changes from zero to 7%, with 80% saturation. The EM velocity drops from 130 m/s to 113 m/s (Figure 2.4a). According to the model (Figure 2.9) given by Topp et al (1980) the moisture content is related with the dielectric constant through

\[
\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \varepsilon_r - 5.5 \times 10^{-4} \varepsilon_r^2 + 4.3 \times 10^{-6} \varepsilon_r^3.
\]  

(2.5)

Using the velocity-dielectric constant relationship given by Eq. (2.2), for the same range in velocity changes, the predicted moisture content increase by the Topp model is about 4.2%. Apparently, the observed trend agrees with the Topp model reasonably well; the Topp model slightly under-estimated the moisture changes.
Figure 2.7. EM wave velocity (a) and dielectric constant (b) variations for 30 HMA specimens as a function of asphalt binder content (AC%) in dry (Vd and Ed, with blue symbols and lines), water-saturated (Vw and Ew, with magenta symbols and lines), and frozen (Vz and Ez, with yellow symbols and lines) conditions.
2.5. Conclusions

The major conclusions from these experiments are (1) The EM wave velocity increases slightly with the increase of void ratio for dry HMA specimens. In contrast, it decreases significantly by increasing void ratio in water-saturated conditions. Correspondingly, with the increase of the void ratio, the dielectric constant decreased slightly when the samples were dry, and increased
appreciably when the samples were water-saturated. (2) The changes of EM velocity and resulting
dielectric constant for dry, water-saturated, and frozen conditions can be sufficiently predicted by
the CRIM model for porous media. (3) A comparison of the observed and predicted EM velocity
and resulting dielectric constant variations in water-saturated conditions implies that some HMA
specimens did not reach full saturation when the GPR measurements were taken. (4) The observed
change of EM velocity and resulting dielectric constant in frozen conditions implies that water in
the HMA specimens were not completely frozen when the GPR measurements were taken. (5) The
variations in EM velocity and resulting dielectric constant with respect to asphalt binder content
ratio imply that low asphalt content corresponds with a high void ratio, so that in the lower end of
asphalt content EM velocity has the maximum fluctuation among different conditions. (6) The
observed variation in EM velocity and resulting dielectric constant was essentially affected by the
changes in moisture content, as predicted by the Topp model. With more GPR and other direct
measurements, GPR may prove to be an efficient way to non-destructively detect void ratio,
moisture content, and degree of pore water freezing for road pavements. This is of special interest
to engineers who are responsible for road inspection and maintenance in cold regions.
3. GPR surveys on paved road for moisture content assessment

A series measurement using the 1-GHz direct contact antenna was conducted on a segment of low-volume traffic road on the Depot Campus of the University of Connecticut. The objective of this measurement is to observe the difference of GPR signature on the meteorological effect over different seasons, and to correlate the testing results obtained from the laboratory experiment over the HMA specimens in three conditions described in the last chapter.

3.1. Introduction

As discussed in the introduction of the last chapter, sufficient durability and stability are the two most wanted features for pavement using hot mix asphalt (HMA). The void ratio is one of the key factors affecting the durability and stability of an HMA pavement. The reason of the void ratio’s importance is obvious: void space could be filled with air, water, or ice (frozen water), or any fractional combination of all of them in a low-temperature environment. This is of particular importance in the New England area where freezing and thawing is the major player in pavement degradation and deterioration. Each of these three constituents has different mechanical properties. Thus, the presence of different amount of void constituents significantly affects the overall physical behavior of an HMA pavement, in turn, influences the HMA’s durability and stability. For example, the presence of water in void space, quantified by the moisture content, can significantly change the shear modulus of an HMA pavement. In contrast, the presence of frozen water (ice) in the voids will effectively change an HMA’s bulk modulus. Moreover, the freezing-thawing process lowers the tensile strength of an HMA pavement and facilitates tensile failure (cracks). Clearly, moisture penetrating into an HMA pavement, whether from above or below, can have detrimental effects on the durability of that pavement. Reliable estimation of the moisture content in an HMA pavement is the first step for thorough understanding of the void-filling materials’ role in HMA’s durability and stability. Conventionally, the information of an HMA’ void ratio and moisture content were assessed by direct excavation method, like drilling samples, and radioactive methods in recent years (Saarenketo, 1997). In this chapter a series of field experiments on correlating the moisture content, and EM wave velocity for a given road segment whose void ratio is assumed to be constant is discussed in details. The field data acquired over an entire annual cycle in spring, summer, fall and winter are presented and compared to link the GPR velocity and the void-
filling materials.

3.2. Practical limitations on radar wave velocity measurements

For GPR measurements, the sampling rate is usually set to be about 10 times of the signal’s central frequency. For example, the sampling frequency is 10.142 GHz for using the 1-GHz antenna to collect data presented in this chapter. It is equivalent to a time domain sampling interval of \( dt = 0.0986 \) ns. For a trace or scan contains 480 samples, the total time window is about 47.3 ns. For the 1-GHz monostatic antenna, the separation of the transmitter and the receiver is fixed at 0.1 m. Thus, the difference in travel time of the air wave and the ground wave is only

\[
\Delta t = t_g - t_a = \frac{D\sqrt{\varepsilon_r}}{c_o} - \frac{D}{c_o} (\sqrt{\varepsilon_r} - 1) \approx \frac{0.1}{0.3} (\sqrt{5.3} - 1) = 0.434 \text{ ns}
\]

where \( t_g \) and \( t_a \) are the travel time of the ground wave, and the air wave, respectively. \( D \) is the transmitter-receiver separation distance; \( c_o \) is the light speed in the air, and \( \varepsilon_r \) is the dielectric constant of the HMA pavement. Given the typical nominal values for all the quantities involved, the time difference value of 0.434 ns is about 4.4 sample intervals using the aforementioned sampling rate. Moreover, the amplitude of the ground wave is \( \sqrt{\varepsilon_r} \) times large than the air wave (Arcone, 1984). This is why the quantity of \( \sqrt{\varepsilon_r} \) is also known as the refraction index. Meanwhile, the difference in travel times of the direct ground wave and the reflected wave (see Figure 2.1) is

\[
\Delta t = t_r - t_g = \frac{\sqrt{\varepsilon_r (D^2 + 4H^2)}}{c} - \frac{D\sqrt{\varepsilon_r}}{c} (\sqrt{D^2 + 4H^2} - D) \approx \frac{\sqrt{5.3}}{0.3} (\sqrt{0.1^2 + 4 \times 0.1^2} - 0.1) = 0.9485 \text{ ns}
\]

where \( t_r \) is the travel time of the reflected wave from the pavement-base interface, and \( H \) is the thickness of the pavement layer. This value of travel time difference is about 9.6 sample intervals when using the same sampling rate mentioned above. The finite length of a source
impulse is another factor to mask accurate identification of wave phase arrivals. In the ideal nominal case, the period of a GPR source wavelet with a central frequency of 1GHz is 1 ns. This is equivalent to 10 samples in time domain. Antenna-ground coupling effect always shifts the signal significantly to a lower frequency; the exact value depends on the electromagnetic properties of the ground. This effect makes the period of the source wavelet even longer. Clearly, identification of the arriving times of different wave types is the first step and fundamental request to use GPR technique in pavement assessment correctly and fruitfully. It is not a trivial task.

In the field data, the relative velocity changes associated with rainwater wetting in the HMA can be up to 3-5%. This corresponds to 2-3 sample intervals’ change in GPR travel times. By applying the Topp model (Topp, et al., 1980), this range in velocity variation suggests a moisture change of 0.8-1.4%, and corresponds to the saturation change of 10-20% in an HMA with 7% void ratio.

3.3. Field measurements

GPR surveys with the 1-GHz antenna were repeatedly carried out on an HMA paved, low traffic volume road segment on the University of Connecticut’s Depot Campus on August 26, 2000, September 20, 2000, and May 21, 2002. The surveys were conducted along the edge of the travel way, relatively close to the old highly distress pavement. The total length of this segment under test is 23 meters. The spatial sampling interval of GPR scans (the distance between 2 adjacent time traces) is 0.05m; there are 450-460 scans in a GPR profile. Figure 3.1 shows the typical survey setup. The field data clearly show the interface of the HMA pavement and the base (Figure 3.2). The thickness of the HMA pavement layer varies from 0.05m in one end of the survey profile, to 0.18 m in the other. The GPR profile shown as Figure 3.2a was acquired on August 26, 2000, and the one shown as Figure 3.2b was acquired in the morning of September 20, 2000, after an overnight heavy rain. Though the surface of the asphalt layer might be completely saturated with water, due to rapid run-off, the water table might not have significant changes and was well beyond the detection depth of 1-GHz GPR, thus irrelevant to the GPR surveys conducted at this site. Finally, Figure 3.2c shows the GPR profile surveyed on the same segment on May 21, 2002. There was no rainfall directly before that date. Obviously, the
pavement-base interface was enhanced and became more continuous in the GPR profile when the condition changes from dry to water-saturated. The reflectivity at this interface increased by 60%, as indicated by the amplitude changes in the single traces extracted at the horizontal position x=18 m shown at the right side of the GPR profiles (indicated by the arrow points red ellipse about 3 nanoseconds in travel time).

Figure 3.1. GPR field survey with the 1-GHz antenna on a newly HMA paved road segment on the University of Connecticut’s Depot Campus on August 26, 2000.
Figure 3.2. GPR profile acquired with the 1-GHz antenna on the HMA paved road segment shown in Figure 3.1. (a) data acquired on August 26, 2000; (b) data acquired on September 20, 2000 after overnight rain; (c) data acquired on May 21, 2002. The single traces for each survey date on the right are located at the distance of 18 meters in the profile. The reflectivity at the bottom of the pavement for September 20, 2000 was significantly increased (the red ellipse) implying strong presence of water in the base.

3.4. Results discussion

Careful examination of the reflector position of the pavement-base interface reveals a delay of 2-3 sample intervals in the GPR profile in water-saturated conditions (Figure 3.2b), when compared with GPR survey in dry conditions as shown in Figure 3.2a. This is equivalent to a velocity change of 0.003-0.006 m/ns, about 2-5% relative change of a nominal dry velocity of 0.13 m/ns for the dry HMA pavement. By applying the Topp model, this variation range in
velocity implies a moisture content change of 0.8-1.4 %, and corresponds to a saturation change of 10-20%, by using the CRIM model, in an HMA with 7% void ratio, a nominal value for HMA pavement in natural conditions. Nevertheless, there is no direct measurement (e.g., coring) to verify or validate these estimations. More coordinated work should be done in the future to make this indirect method improve its applicability for road pavement assessment.

From the GPR profile we can see that it is still hard to accurately delineate the bottom of the pavement layer. This is mainly due to that the period of the GPR signal generated by the 1-GHz antenna is still too long. The wavelet of the direct wave masked the reflection from the pavement bottom. In the future, an antenna with higher frequency (1.5 to 2 GHz) would be a better choice for it will generate a shorter period wavelet and therefore with a higher resolution.

3.5. Conclusions

Field experiments using the 1-GHz GPR were conducted to study the effects of water content on EM velocity and resulting dielectric constant under natural meteorological conditions. The main conclusions are: (1) The changes of EM velocity and resulting dielectric constant for dry and water-saturated conditions can be interpreted by the Topp model for accounting for the water content variations. (2) The detected velocity change caused by rain water wetting results in GPR signals velocity change of 0.003-0.006 m/ns, suggests the moisture content changes on the order of 0.8-1.4% using the Topp model. Using GPR to determine subsurface moisture content has been a sustainable interest in geology and geophysics (Berktold, et al., 1998; Charlton, 2000; Greaves, et al., 1996; Haslund and Nost, 1998) at a larger scale than highway pavement. With finer sampling intervals in time domain and an established baseline (obtained from direct depth control, or repeated GPR surveys), GPR should also be capable to provide an efficient way to detect moisture content variation, and pore water freezing for the purpose of HMA pavement assessment.
4. Numerical modeling of GPR surveys over dielectric thin layers

The asphalt pavement is a typical dielectric thin layer for GPR surveys. Though monostatic reflection mode survey is the most economical way to carry out GPR data acquisition, GPR moveout survey, i.e., GPR data were acquired while the transmitter-receiver separation is changing from short to wider distance, may reveal more information regarding subsurface conditions. This chapter assesses GPR moveout survey performance in different near-surface geological stratigraphy and different antenna orientations using 2-dimensional (2D) finite difference time domain (FDTD) numerical simulations of field data. We first treat the simple cases of radar pulses propagating along (a) the interface between two half-spaces (air/ice); and (b) an ice thin layer wave-guide (air/ice/water) between two half-spaces. We then simulate four more complex cases combining two radiation polarizations (TM and TE), and two geological settings: a sandy/gravelly half-space overlain by a silty/clayey layer, and a silty/clayey half-space overlain by a sandy/gravelly layer. Both cases are represented through different dielectric constants. The results show that (1) more EM energy is radiated as an air wave for the TM mode, and more EM energy will be sent into the ground when the TE mode is used, regardless of stratigraphic sequence. (2) Where a gravelly sandy half-space overlain by a silty/clayey layer, more EM energy will be trapped in the silty/clayey layer as the guided ground wave. (3) When the TE mode is used there is much less air radiation for the case of silt overlying gravel than that of silty/clayey half-space overlain by a gravel/sand layer. (4) For the stratigraphic sequence of a sandy/gravelly half-space overlain by a silty/clayey layer, the TE mode fundamentally contains only a ground wave, and the TM mode essentially contains only air wave energy. This implies that for this case a far more complete separation of the air wave and the ground wave can be reached. (5) Dispersion of phase and group velocities of the guided ground wave will be well developed for the TE mode. These simulations imply that antenna polarization mode is an important factor when using moveout surveys to study subsurface electromagnetic properties.

4.1. Introduction

The electromagnetic properties of the uppermost 5-10 meters of the solid earth play the most important role when probing the earth with the electromagnetic devices like ground penetrating radar (GPR). For many cases, the near-surface environment can be idealized as a dielectric thin layer overlaying a half-space with different electromagnetic properties. The system of asphalt
pavement and the underlying sub-base makes a perfect example in the geotechnical world (Saarenketo, 1997; Saarenketo and Scullion 2000). An ice sheet or soil layer forms other examples (Arcone, 1984; Arcone et al., 2003). Though the thickness scale of these examples appears to be quite different, for electromagnetic sounding purposes, they all can be viewed as a wave-guide for electromagnetic probing at suitable, corresponding frequency ranges. When performing varying-offset moveout GPR surveys of such strata, highly dispersive guided-wave propagation can result, making analysis of the electromagnetic structure of the earth difficult. Here we examine the nature of this propagation with theoretical simulations, which are powerful and economical alternatives to field experiments, especially for environments in which real data acquisition is prohibited or too expensive. Moreover, numerical simulation assists designing of data acquisition geometry and procedures to make observations more effective and productive, and allows many stratigraphic combinations to be tested.

Annan (1973) systematically summarized the mathematical development in electromagnetic interferometry in a near-surface environment. He used complex integrals (e.g., Brekhovskikh, 1960) and normal mode analysis (e.g., Budden, 1961). Existing laboratory and field observations (e.g., Rossiter et al., 1973; Annan et al., 1975; Arcone, 1984; Arcone et al., 1998) indicate that the ground wave can be manifested by modal propagation over several tens of meters at lower frequencies (100 MHz or less) when wide angle offset soundings are performed to measure ground wave speeds. Nevertheless, small scale, natural near-surface layering can severely limit this path, as we will see here.

This chapter investigates the wave-guide effects of a surface layer on electromagnetic wave propagation using the finite difference time domain (FDTD) simulation technique. We first present FDTD simulation results for half-space cases to demonstrate the physical fidelity of FDTD numerical simulation. Then we treat the modal propagation case of a thin layer of ice between two half-spaces (air, and water). Finally, the results of electromagnetic wave propagation in TE and TM modes at pulse central frequencies of 400 and 65 MHz are discussed. We simulated field data acquired from Fort Richardson, Alaska (AK) (a lower dielectric constant sandy gravel half-space overlain by a higher dielectric constant sandy silt layer), and Hanover, New Hampshire (NH) (a sandy silt half-space overlain by sandy gravel layer). The field data and synthetic results were analyzed with time-frequency analysis with instantaneous parameters to
extract guided-wave group velocity dispersion characteristics. We conclude that the simulation results reasonably resemble fundamental wave propagation features in the field data and are helpful to interpret field observations.

4.2. Summary of major features of guided wave propagation

We first define TE and TM modes used in this chapter (Figure 4.1). The TE mode is the ‘transverse-electric mode with respect to the x-direction, which is the direction of the GPR profile, and can be expressed by the 2-dimensional Maxwell’s equation with in-plane magnetic field components $H_x$ and $H_y$ and out-of-plane electric field component $E_z$ such that

$$\frac{\mu}{\partial t} \frac{\partial H_x}{\partial t} = -\frac{\partial E_z}{\partial y},$$

$$\frac{\mu}{\partial t} \frac{\partial H_y}{\partial t} = \frac{\partial E_z}{\partial x},$$

where $\mu$ and $\sigma$ are magnetic permeability, and electrical conductivity, respectively; and $J_{sz}$ is an electrical current source function in the z-direction. This case is equivalent to the TM$_z$ mode (the transverse-magnetic mode with respect to the z-direction) as defined in another convention, for example, by Taflove and Hagness (2000). Similarly, the TM mode is the ‘transverse magnetic mode with respect to the x-axis’ that has in-plane electric field and transverse magnetic field expressed by the 2D Maxwell’s equation in TM mode such that

$$\varepsilon \frac{\partial E_z}{\partial t} = \frac{\partial H_x}{\partial y} - \frac{\partial H_y}{\partial x} - J_{sz} - \sigma E_z,$$

$$\varepsilon \frac{\partial E_y}{\partial t} = \frac{\partial H_z}{\partial x} - \frac{\partial H_x}{\partial y} - M_{sz},$$

where $M_{sz}$ is a magnetic dipole source function in the z-direction. GPR data can be acquired in either a TE or TM mode, as depicted in Figure 4.1. We adopted a right-hand coordinate system with the x-direction as the strike of the GPR profile, the y-direction is vertical and downward, and the z-direction is perpendicular to the plane coinciding with the GPR profile. By using 2D
modeling we assume there are no variation in both material properties and electromagnetic fields in
the z-direction. Horizontally polarized antennas with the parallel configuration facing each other
communicate TE waves (upper panel of Figure 4.1); whereas horizontally polarized antennas with a
serial configuration communicate TM waves (lower panel of Figure 4.1).

![Horizontally polarized antennas induce TE modes](image)

![Colinearly polarized antennas induce TM modes](image)

Figure 4.1. Sketch of TE and TM modes with corresponding antenna orientations. The positive
x-direction is that of wave propagation from the transmitter to the receiver; along the GPR
profile. The y-axis is vertical downward; and the z-direction is perpendicular to the x-y plane, in
accordance with the right-hand-rule.

As indicated by Annan (1973), the propagation of radar waves along the interface between two
dielectric half-spaces (e.g., air and the ground) can be idealized by four types of propagation
(Figure 4.2). Wave A is the fundamental spherical air wave propagates through the air at the free-
space velocity $c$; wave B is the counterpart of A in the ground known as the ground wave. If the
ground is homogeneous with refractive index, $n$ ($n = \sqrt{\varepsilon}$), then ground wave B propagates at the
velocity of $c/n$ and is $n$ times stronger than the air wave. These two waves are matched at the air-
ground interface by two other waves in order to maintain field continuity across the boundary. In
air, wave C is an evanescent wave (also known as the inhomogeneous wave) that decays
exponentially with height (see Figure 4.3) and propagates horizontally at the speed $c/n$ to match the
ground wave B. In the ground, wave D, known as the head wave (also named as surface wave, or
lateral wave), propagates downward at the critical angle \( \theta_c = \sin^{-1}(1/n) \) with a planar phase front, but with a horizontal velocity of \( c \) to match the air wave A. In the near field, waves B and D are indistinguishable. The two waves are well separated with increasing propagation distance into the far field.

Figure 4.2. Idealized near-surface, near field propagation paths along the interface of the free space and a dielectric half-space (ground) for a TE mode antenna orientation ((a), modified from Annan, 1973). S: the location of the TE mode source; A: the wavefront of the air wave; B: the wavefront of the ground wave; C: representation of the inhomogeneous evanescent air wave matching the ground wave B; and D: the wavefront of the head wave (or the so-called lateral wave) in the ground matching the spherical air wave; \( \theta_c \): the critical angle. The snapshot at the time of 25 ns after the firing of the TE source from FDTD simulation (b) clearly shows the different paths illustrated in (a). The modeling was carried out at the interface of the free space and a dielectric half-space with dielectric constant of 3.17 (for freshwater ice). The source is a Ricker wavelet with central frequency of 200 MHz. The fast decay of the evanescent wave C with respect to height above the ground is illustrated in Fig. 3. Note the reversal of phases between the air wave (leading half-cycle is blue) and the ground wave (leading half-cycle is red).

The situation can change radically when the ground is layered. Depending on the relative values of refractive index \( n \) of each layer, guided modes can propagate in the layers and either vastly extend or vastly limit the range of the ground wave. To illustrate this a thin layer of ice between the
Figure 4.3. (a) Time domain synthetic records of the $E_z$ electric field along x-axis at the surface; (b) The amplitudes of the $E_z$ electric field at different elevation at elapsed time of 25 ns. The evanescent wave decays exponentially with increasing elevation above the surface, and is in phase with the ground wave below the surface; whereas the air wave and the ground wave have opposite phases. The total length of the profile is 19.25 m (350 x 0.055m).

Figure 4.4. The FDTD time domain wide-angle offset simulation of the $E_z$ electric field for the TE mode generated by a 200-MHz Ricker wavelet and received on the surface of a 40-cm thick ice layer of an air-ice-water system. Note the continual excitation of refracted air waves.
free half-space and the half-space of water was simulated with FDTD. Figure 4.4 presents the FDTD synthetic wide-angle reflection and refraction (WARR) GPR profile of the Ez field for a TE mode generated by a 200-MHz Ricker wavelet recorded along the surface of a 40-cm thick ice layer of an air-ice-water system. The ice layer has a dielectric constant of 3.17 and the cold, fresh water has a dielectric constant of 87. The profile shows shingling associated with wave mode dispersion and simulates field data presented by Arcone (1984, Figure 10) for a lake ice cover in mid-winter.

4.3. GPR wide-offset field observations

Wide offset GPR surveys were conducted at two sites with path lengths up to tens of meters, and with a quasi-infinite medium to eliminate the reflections that occur from lateral boundaries (e.g., walls) in scale models. The first site is on Fort Richardson, near Anchorage, Alaska, where a surface layer of wet, sandy silt with an average thickness of about 34 cm has a slower speed than the underlying drier strata of sands and gravel (Arcone et al., 2003). The second site is in Hanover, New Hampshire, where a thin layer of drier, gravelly sand that varies from 16 to 20 cm in thickness overlies sandy silt of glacial Lake Hitchcock. At each site we established a profile test line along which we dug several holes to aid profile interpretation. At the Hanover site we used 400-MHz antennas to acquire wide-angle, variable offset profiles (upper panel of Figure 4.5) and an 800-MHz antenna set to record reflection profiles (antennas at constant separation, lower panel of Figure 4.5). The wide-angle profiles allow us to look at the modes propagating in the layer; while the reflection profile allows us to interpret stratigraphic structure of the ground. At Fort Richardson, we acquired a 100-MHz wide-angle reflection and refraction (WARR) profile in TE mode (shown later in Figure 4.8a). At each site our structural studies include documentation of layer depth, general sediment type, water content, and mineralogy in order to determine what attenuation mechanisms may be present. In addition, GPR reflection profiles compensated for the difficulty of complete excavation in order to document near surface layering.
Figure 4.5. Varying offset, 400-MHz Wide-angle (top) and constant-offset, 800-MHz reflection (bottom) profiles recorded along a single test line in Hanover, NH. Left panel of the wide-angle offset profiles is acquired in TE mode and the right panel is in TM mode with transmitter placed at the 0-m distance of the reflection profile. Arrow indicates the reflection from the bottom of the wave-guide layer. Dielectric constant of lower layer was interpreted from hyperbolic diffraction, that of upper layer from direct observation of depth, and the time delays.

4.4. Numerical simulations of TE and TM modes for field GPR data

Our numerical simulation algorithm adapts the finite difference time domain (FDTD) method (e.g., Taflove and Hagness, 2000), based on Yee’s original staggered grid (Yee, 1966), with a perfectly matched layer as the absorption boundary condition to truncate outbound waves (Berenger, 1994). Based upon the field observations the electromagnetic parameters for soil materials and stratigraphic geometry at the two sites are listed in Table 4.1. Since the main concern is the generation and propagation of the guided ground wave caused by the surface layer, sub-strata were simplified as a uniform half-space with constant electromagnetic properties. The conductivity values were measured directly at Fort Richardson (Arcone and Delaney, 2002) and are estimated at Hanover. The quantity $h$ in Table 4.1 is layer thickness.
Table 4.1. Electromagnetic material properties and stratigraphy at the two sites under study

<table>
<thead>
<tr>
<th>Site</th>
<th>Fort Richardson site, AK</th>
<th>Hanover site, NH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>=1.0, =0.0 S/m</td>
<td>=1.0, =0.0 S/m</td>
</tr>
<tr>
<td>Surface layer</td>
<td>= 22.7, = 0.0005 S/m</td>
<td>= 8.0, = 0.0004 S/m</td>
</tr>
<tr>
<td>h =0.34 m</td>
<td></td>
<td>h =0.20 m</td>
</tr>
<tr>
<td>Sub-strata</td>
<td>= 10.6, = 0.0002 S/m</td>
<td>= 12.0, = 0.002 S/m</td>
</tr>
</tbody>
</table>

For all materials the relative magnetic permeability is equal to unity. We used a central frequency of 400 MHz for the source wavelet for both Hanover and Fort Richardson sites to carry out FDTD simulations in TE and TM modes; and also a 65 MHz source wavelet propagating in TE mode for Fort Richardson for comparison with existing WARR GPR data.

The 400-MHz, variable offset GPR simulated synthoses for the two sites at Hanover, NH and Fort Richardson, AK are shown in Figure 4.6. The time step in the simulation is 0.0667 ns, a value that sufficiently satisfies the Courant stability condition (Taflove and Hagness, 2000). The total time window is 100 ns. Figs. 6a and 6c present the transverse horizontal electric component $E_z$ for the TE mode; while Figure 4.6b and 6d present the in-plane, horizontal electric field $E_x$ for the TM mode. With similar arrangement, the wave field snapshots for different modes and different geological stratigraphies are shown as Figure 4.7. Each panel contains the snapshot at 13.33 ns elapsed time for the corresponding electric field and magnetic field.

4.5. Results discussion

When there is total reflection at the interfaces there is no loss of energy other than that due to geometric spreading of the waves, and the propagation is thus modal. This occurs when the upper and lower layers have higher wave speeds than the waveguide layer (e.g., Fort Richardson site). The total reflection occurs at a critical angle $\theta_c = \sin^{-1}(n_l/n_m)$, where $m$ is either 0 (for air) or 2 (for sub-strata). For the opposite case where $n_0$ or $n_2$ is greater than $n_1$, transmission occurs through the interface and energy is continually lost during propagation. For example, FDTD simulations predict that a much stronger TE guided ground wave occurs at Fort Richardson site (Figure 4.6c)
than at the Hanover site (Figure 4.6a) where total reflection does not occur on the bottom interface of the thin layer. For the TM mode, FDTD simulations also predict that a much stronger guided wave travels at a group velocity between that of the air wave and the ground wave, with a relatively low attenuation rate, in the low-velocity thin layer (the Fort Richardson case, Figure 4.6d) than in the Hanover site wave guide (Figure 4.6b). It is clear from Figure 4.7 that the TE mode generates more ground waves; whereas the TM model generates more air waves, with a stronger head wave matched in the thin layer, regardless of near-surface stratigraphic sequence. For the TE mode, at the same elapsed time, the case of sandy layer overlaying silty sub-strata (Hanover, NH) has a larger propagating range, while the case of a silty layer overlaying gravelly sub-strata has more electric energy being trapped in the surface thin layer.

Fig. 4.6. Simulated 400-MHz wide-angle GPR profiles of (a) the Ez component in the TE mode; (b) the Ex component in the TM mode, for the Hanover site; and (c) the Ez component in the TE mode and (d) the Ex component in the TM mode, for the case of Fort Richardson site.
Figure 4.7. The simulated 400-MHz GPR wave propagation snapshot in (a) TE mode and (b) TM mode at time step 200 (elapsed time of 13.33 ns) for the Hanover site, and in (c) TE mode and (d) TM mode for the Fort Richardson site.

Where the upper layer is electrically thin (comparable to an in-situ wavelength or shorter) and
has a faster speed than the lower sub-strata, such as a drier soil over a wetter soil (e.g., the case in Hanover, NH), or an ice layer over water (Figure 4.4), or a frozen soil over thawed soil, wave energy continually transmits into the lower layer at a rate that can only be predicted by full wave modal theory.

Theory and observations (Annan et al., 1975; Hoeskstra and Delaney, 1974, Arcone and Delaney, 2002) have proved that when the upper thin layer has a slower speed than the sub-strata, modes will propagate at angles beyond the critical angle for both interfaces and the upper thin layer becomes a refractive waveguide, just like an optical fiber. This occurs when a wetter soil overlies a drier soil, or when an unfrozen soil sits on top of permafrost, or bedrock. This is clearly shown by the field observations and FDTD numerical simulation as shown in Figure 4.8. The shingling of the waveforms is clearly associated with dispersive propagation velocity. The numerical simulation (Figure 4.8b) qualitatively resembles the observation shown in the field WARR profile. More quantitative analysis to exploit the data for more propagation characteristics using the instantaneous amplitude and the instantaneous frequency (Taner et al., 1979; Barnes, 1991; Liu and Oristaglio, 1998) is shown in Figure 4.9. In Figure 4.9a the distribution of the instantaneous amplitude is shown as a function of the corresponding instantaneous frequency at the same travel time and location. The distribution should, and does resemble the Fourier transform (FT) results with a central frequency of about 65 MHz. Much more data points are close to the central frequency, which is not so apparent by using the FT method. Direct examination of the waveforms of Figure 4.8a shows lower frequency ground wave trains arrive before the higher frequency ones (Arcone et al., 2003) to mark apparent velocity dispersion. Figure 4.9b gives a different view of the velocity dispersion phenomenon by plotting the instantaneous amplitude as a function of the instantaneous frequency and the group velocity. This is similar to the technique used by Parra (1996). The group velocity was inferred from the phase velocity (determined by the phase travel time and receiver location). Though the velocity is obviously dispersive, no clear Airy phase (Arcone, 1984) can be identified based on this analysis. This may possibly be caused by the silty surface layer being too thin, or, the bandwidth of the GPR signal being not wide enough.
Figure 4.8. The observed 100-MHz WARR GPR profile in TE mode at Fort Richardson, Alaska (a); and the corresponding FDTD simulated synthesis with a source impulse of Ricker wavelet at 65-MHz central frequency (b). The field data were generated by nominally rated “100-MHz” antenna, whose ground-loaded value determined from near-field coupling was 65 MHz (after Arcone et al., 2003).

Figure 4.9. (a) Amplitude spectrum extracted from the instantaneous parameter analysis of the 65-MHz Fort Richardson WARR data. It resembles the spectral analysis given by conventional Fourier transform with the central frequency at about 65 MHz; (b) Dispersion relationship derived by the instantaneous parameter analysis from 65-MHz field data. The wave propagation is dispersive with obvious frequency dependency, but no obvious Airy phase can be found. The frequency-velocity-amplitude technique used here follows Parra (1996).
4.6. Conclusions

Using finite difference time domain technique we have modeled four cases: a combination of 2 situations of geology (a gravelly sandy half-space overlain by a sandy silt layer, and a sandy silt half-space overlain by gravelly sand half-space) and 2 transverse modes of antenna radiation (TM and TE). The main conclusions are summarized as follows.

More EM energy is radiated as an air wave for the TM mode; and more EM energy will be sent into the ground for the TE mode, regardless of geological setting (Figure 4.6). Meanwhile, in a geological setting where a lower gravelly sand half-space is overlain by a higher sandy silt layer (the case of Fort Richardson), more EM energy will be trapped in the sandy silt layer as a TE mode in the ground wave guide and very little energy will occur as air radiation, when compared with the same radiation mode in the case of a higher sandy silt half-space overlain by a layer of lower gravelly sand. For the geological setting of a lower gravelly sand half-space overlain by a higher sandy silt layer, the TE mode mainly contains a ground wave and the TM mode mainly contains air wave energy, which is traveling at a phase velocity of c and a lower group velocity, as evidenced by the apparent shingling of the energy arrivals (Figure 4.6d). This implies that for this case a far more complete and long lasting separation of the air wave and the ground wave can be reached.

It appears that for this common case of an electrically thin drier layer over wetter sediments that both TE and TM waves are highly suppressed when compared with the case of a thin wetter layer over drier and coarser sediments (e.g., Fort Richardson), especially for TM waves. For higher frequency antennas, the guided ground wave modes may propagate better, but then strong attenuation properties (water relaxation and scattering) intrinsic to the layer itself will also become a factor in suppressing the ground modes. These properties will also be a factor for thicker layers, which will offer more path length.
5. **Mathematical treatment to improve the resolution and penetration**

At a given location if both high- and low-frequency GPR data were available, a synthetic GPR image with deep-penetration and high-resolution can be reconstructed by a signal processing procedure known as extrapolation with deterministic deconvolution (EDD). There are two fundamental assumptions to make EDD work. First, the correlation (a transfer function or filtering function) between the high- and low-frequency data at one location can be deterministically extracted. Second, this transfer function is spatially stationary so that it can be applied to another location. Based on the principle of applying EDD to seismic data, which is for generating the synthetic well logs from surface seismic data, we have extended EDD treatment to GPR data for the purpose of recovering the high-resolution contents at greater depths. The compensation of the frequency-dependent absorption loss is based on the constant Q model. This chapter presents the preliminary test results with numerical synthetic time records. EDD with the synthetic data appears to be promising. More tests need to be done before EDD can be routinely applied to GPR field data. For a successful application of EDD to real world data, a careful pre-processing of the field data is far more critical than the EDD algorithm itself.

5.1. **Introduction**

The tradeoff between penetration and resolution of a given radar pulse is a well-known phenomenon to the GPR user community. It is trivial to honor the fact that objects far away cannot be seen as clearly as those closer to an observer. Likewise, GPR images become blurry or lose resolution at greater depths, this is caused by the fact that the high-frequency content of the signal suffers more severe loss than low-frequency content. However, it has always been desirable that GPR have the ability to detect targets at greater depths and with higher resolution. In general, it is hard to obtain a subsurface image with deep-penetration and high-resolution simultaneously. However, if both high- and low-frequency data were acquired at the same location, we may be able to take the advantages of the relative deeper penetration of the low-frequency signal and the relatively higher resolution of the high-frequency signal. By taking advantage of the deep penetration of the low-frequency data and the higher resolution of the high-frequency data simultaneously, it was a common practice in the last two decades to patch the high-frequency GPR profile with shorter time window at shallow depth onto the low-
frequency GPR profile with longer time window. Clearly, the desire to get deep-penetration and high-resolution simultaneously can hardly be fulfilled with any rigidly configured physical approach. The only possible solution is seeing if digital signal processing techniques can lend us some help.

Deterministic deconvolution was originally used to increase signal resolution in seismic exploration (Oldenburg, et al., 1981; Treitel and Lines, 1982) then adopted to enhance GPR reflection profiles (Xia, et al., 2004). Digital signal analysis recognizes the low- and high-frequency GPR responses at a particular location as the convolutions of the low- and high-frequency source wavelets with the material properties (medium imperfection shown as attenuation and impedance contrast shown as reflectivity), respectively (Liu and Oristaglio, 1998; Treitel and Robinson, 1966; Liu, et al., 1998). If both low- and high-frequency responses at a shallower (for surface GPR) or closer (for borehole radar) location and low-frequency response for deeper or farther locations are available, one can infer the high-frequency response at the deeper or farther locations. The information about the high-frequency response for the deeper/farther locations is extrapolated by extending the relationship of high- and low-frequency correspondence at shallower parts into greater depths. In certain circumstances, this extension can be achieved through the extrapolation by deterministic deconvolution (EDD), as has been down in the treatment of seismic data (Zhou, et al., 2001).

The procedure is explained in detail in the following sections with mathematical derivations at the first, followed by applying EDD to both synthetic and field data to verify the effectiveness of this method. The examples showed that EDD has restored some high frequency contents in later times (greater depth). However, EDD is more effective at improving the resolution of synthetic data than the real field GPR data, simply because synthetic data is noise-free and real-world field data contains random noise caused by variety of sources and system errors due to differences in system response for antennae working at different central frequencies. This chapter concludes with a discussion on future research for this topic.
5.2. Extrapolation by deterministic deconvolution

Subsurface structure responses to the impinging radar source are recorded by the receiving antenna as time-domain traces. And these recorded responses \( R(t) \) can be regarded as the convolution among the GPR source signal wavelet \( W(t) \), the subsurface structures \( S(t) \), in terms of the reflectivity, and the material’s intrinsic attenuation \( A(t) \). Given this simple analytic model, the recorded responses \( R_l(t) \) for the low-frequency, and \( R_h(t) \) for the high-frequency, can be expressed as the convolutions of the source wavelet \( W_l(t) \) and \( W_h(t) \) and the material structure \( S(t) \), respectively, and \( A_l(t) \) and \( A_h(t) \), the material’s attenuation properties for low- and high-frequency GPR signal, respectively, in the following two equations:

\[
R_l(t) = W_l(t) * S(t) * A_l(t) \\
R_h(t) = W_h(t) * S(t) * A_h(t)
\] (5.1)

where the asterisk symbol ‘*’ denotes convolution. The structure function, \( S(t) \), is the same for both high- and low-frequency signals anywhere in the subsurface. Combining the two equations in eq. (5.1), \( S(t) \) cancels out and we end up with a direct relationship between \( R_l(t) \) and \( R_h(t) \)

\[
R_h(t) = G(t) * R_l(t)
\] (5.2)

where \( G(t) \) is the lump-sum transfer function that defined as the ratio of the convolutions between the source wavelet and attenuation for the high- and low-frequency signals;

\[
G(t) = \frac{W_h(t) * A_h(t)}{W_l(t) * A_l(t)}
\] (5.3)

the attenuation operator can be simplified with a reasonable theoretical model which characterizes the medium’s intrinsic attenuation property. One such model is the well-known constant Q model (Liu, et al., 1998), which defines a linear dependence of the attenuation to signal frequency, i.e., \( =_0 \), so the attenuation operator becomes:

\[
A(t) = e^{-\alpha t} = e^{-\alpha_h t} e^{-\alpha_l t}
\]

and the ratio of the attenuation operators for high- and low-frequency GPR signals is simply:
\[
\frac{A_h(t)}{A_l(t)} = e^{-\alpha_h(f_h - f_l) t} = e^{-\alpha_h \Delta t}
\]

Thus, the lump-sum transfer function can be expressed as

\[
G(t) = \frac{W_h(t) * A_h(t)}{W_l(t) * A_l(t)} = \frac{W_h(t) * e^{-\alpha_h \Delta t}}{W_l(t)} = g(t) * e^{-\alpha_h \Delta t}
\] (5.4)

where \(g(t)\) is the transfer function between the high- and the low-frequency source wavelets. Apparently, \(g(t)\) was originally defined as the spectral ratio in frequency domain. It can also be elucidated as the cross-correlation of the high- and low-frequency time sequences in time domain by the following derivations. From eq. (5.2)

\[
R_h(t) = G(t) * R_l(t) = g(t) * R_l(t) * e^{-\alpha_h \Delta t}
\] (5.5)

It is straightforward to invert eq. (5.5) and get the transfer function \(g(t)\) by

\[
G(t) = g(t) * e^{-\alpha_h \Delta t} = deconv[R_h(t), R_l(t)]
\] (5.6)

where function \(deconv[R_h(t), R_l(t)]\) means de-convolving \(R_l(t)\) out of \(R_h(t)\) and

\[
g(t) = deconv[R_h(t), R_l(t)] * e^{\alpha_h \Delta t}
\] (5.7)

Due to the assumed spatial invariability of \(g(t)\), the predicted high frequency signal response at a different location, \(R_{h2}(t)\), can be obtained by convolving \(g(t)\) with the low frequency signal response \(R_{l2}(t)\) measured at location 2. The mathematical expression can be described by

\[
R_{h2}(t) = g(t) * R_{l2}(t)
\] (5.8)

With this process, the ‘extrapolated’ \(R_{h2}(t)\) has inherited both advantageous properties of the different frequencies, high resolution and deep penetration. The inversion of \(g(t)\) is a deconvolution that is a deterministic process (eq.(5.7)), such that the high frequency signal response, \(R_{h2}(t)\), is extrapolated from the measured low frequency response, \(R_{l2}(t)\) (eq.(5.8)). Therefore, this method is regarded as the extrapolation by deterministic deconvolution (EDD).
A simple and effective way to find g(t) is to use a linear optimum discrete-time filtering method. This chapter uses the widely adapted Wiener filtering technique. The low-frequency signal, R_l(t), can be regarded as the input, g(t) is the filter system and the filter response or output is R_h(t), so that

\[ R_h(t) = R_l(t) * g(t) = \sum_{k=0}^{N} R_l(k) \cdot g(t - k) \]  \hspace{1cm} (5.9)

where N is the length of the discrete input signal. The principle of orthogonality (Haykin, 2002) specifies the necessary and sufficient conditions for the optimum operation of the filter as

\[ E[R_l(t-k)(R_h(t) - \sum_{i=0}^{N} g(i) \cdot R_l(t-i))] = 0, \quad k = 0,1,2,\ldots,N \]  \hspace{1cm} (5.10)

where g(i) is the i-th coefficient in the impulse response of the optimum filter. Expanding this equation and rearranging terms produces,

\[ \sum_{i=0}^{N} g(i) \cdot r(i-k) = p(-k), \quad k = 0,1,2,\ldots,N \]  \hspace{1cm} (5.11)

where \( r(i-k) = E[R_l(t-k) \cdot R_l(t-i)] \) is the auto-correlation of the input; while \( p(-k) = E[R_l(t-k) \cdot R_h(t)] \) is the cross-correlation between the filter input, R_l(t-k), and the desired response, R_h(t), for a time step lag (k). Let R denote the N-by-N autocorrelation matrix of R_l(t), and P denotes the cross-correlation vector between the input of the filter and the desired output, simplifying eq. (5.11),

\[ R \cdot g = P \]  \hspace{1cm} (5.12)

This is the so-called Wiener-Hopf equation (Haykin, 2002). The filter vector, g(t), can now be readily calculated by the inverse of the matrix R times P,

\[ g = R^{-1} \cdot P \]  \hspace{1cm} (5.13)

Using g(t) in eq. (5.8), we are able to calculate the high-frequency extrapolation at any location given the low-frequency response at those locations.

The resolution enhancement using EDD is illustrated with a single trace of real GPR data collected at one location using both high- and low-frequency records (Figure 5.1). The top panel
of Figure 5.1 is a snippet of 100-MHz GPR data, the low-frequency sequence, and the second panel is the 400-MHz data, the high-frequency sequence. The recording time window for high-frequency data is usually shorter than the low-frequency counterpart. The transfer function derived from the records shown in the top two panels is presented as the third panel. Apparently, the effective length of g(t) is limited by the length of the high-frequency data. The bottom panel shows the EDD synthesis of the high-frequency record. Comparison of the EDD synthesis and the original high-frequency data in the earlier time shows a reasonable agreement between these two sequences. This agreement is the base to entrust the EDD extrapolation for later times (corresponding to greater depth). The approach and effectiveness of EDD are further examined in the following sections when it is applied to synthetic and real GPR data.

5.3. Applications to synthetic data

To test the effectiveness of EDD for improving GPR data resolution, synthetic time traces are computed from a 2-dimensional (2D) finite-difference time-domain numerical modeling technique (Liu and Arcone, 2003). A five layer model was created and a metal cylinder was positioned in the center of the third layer (Figure 5.2). The model consists of 600 grid cells, 300 of which are in the horizontal or x-direction and 200 grid cells in the vertical or y-direction. All the four sides of the model domain are bounded by an 8-grid cell thick perfectly match layer (PML) absorption boundary (Berenger, 1994). All grid cells have a uniform size of 0.02 m on a side. Thus, the modeled physical domain is 6m x 4m. The material properties of different layers, from top to bottom, are:

1) A strip of air at the top of the model with the dielectric constant of vacuum and zero conductivity (ε = 1, and σ = 0.0 S/m);

2) A 0.4 m thick surface layer with ε = 9, and σ = 0.0 S/m;

3) A 1.6-m thick dielectric layer with ε = 16, and σ = 0.0 S/m;

4) An electrically conductive cylinder (ε = 25, and σ = 10^7 S/m) with a radius of 0.5 m centered in the third layer;
Figure 5.1. EDD illustration using a single trace from a piece of real data. From top to bottom: 1) the low-frequency record; 2) the high-frequency record; 3) the transfer function; and 4) the extrapolated high-frequency syntheses by EDD.
5) Another thin layer with the same thickness and property of Layer 2;

6) A dielectric half-space with the same material property of Layer 3.

The model used to generate the synthetic GPR time records for evaluating the EDD method. The dielectric constant of each layer is labeled as $\varepsilon$. The unit of the conductivity is Siemens per meter (S/m).

The synthetic time sequences are generated with a source impulse whose shape is a Ricker wavelet with the central frequency of 100- and 400-MHz, respectively. A time step of 0.026667 nanoseconds (ns) is used for both high- and low-frequency time sequences, a value fulfills the stability condition for FDTD modeling (Schroder and Scott, 2002) when the grid size is 0.02 m. The time step adapted in the forward model is about 10 times shorter than the sampling rate used in acquiring 400-MHz GPR field data. For example, the sampling frequency of 4141 MHz corresponds to a sampling interval of 0.2415 ns. Thus, it is necessary to re-sample the synthetic time traces to a longer time interval to reduce the redundancy and increase the efficiency of EDD calculation. For the numerical modeling, the total simulated time is 66 ns (2500 time steps), which allows enough time for the reflected waves from the bottom interface to travel back to the receiving points at the air-ground surface. The sources and receivers were placed one grid above the air-ground interface to mimic the monostatic reflection profiling. A total of 51 time traces were generated with this model with a 0.4-m source-receiver separation. The profile extended 5 meters in the x-direction with 0.1-m spacing between two adjacent traces.
The evaluation of EDD was conducted following procedures described in Section II with results shown in Figures 5.3, 5.4 and 5.5. The top panels of Figures 5.3, 5.4 and 5.5 are the original low-frequency (100 MHz) records. The second panels are the original high-frequency (400 MHz) records. The third panels are the calculated transfer function, g(t). Finally, the bottom panels are the extrapolated high-frequency traces with EDD.

Figure 5.3. The EDD extrapolation for the synthetic records generated with the model shown in Figure 5.2. From top to bottom: 1) the low-frequency record; 2) the high-frequency record; 3) the transfer function; and 4) the extrapolated high-frequency syntheses by EDD. The recording time windows are 66 ns for both high- and low-frequency synthetic data.
Figure 5.4. Same as Figure 5.3 with the exception of only trace No. 11 of the high-frequency record 400 MHz record is used for calculating the transfer function g(t) in EDD extrapolation.
Figure 5.5. Same as Figure 5.3 with the exception of a shorter time window (45 ns) is used for the high-frequency 400 MHz record for calculating the transfer function g(t) in EDD extrapolation.
Data in Figure 5.3 shows both the low- and high-frequency traces which are recorded with a time window of 66 ns. Each pair of the low- and high-frequency traces at one location generates one unique transfer function. A comparison of the EDD extrapolated high-frequency signal and the original 400 MHz traces shows that the extrapolation works properly: the extrapolated and the original simulated traces are literally identical, as they should be, since no extrapolation has been conducted here at all. The high-frequency information is available in all space where low-frequency information available. This step was designed to verify that the EDD algorithm can work properly for a monostatic GPR profile.

To test algorithm’s capability of extrapolation in the lateral direction, we assumed that the high-frequency 400 MHz data with the full length of the time window is available at only one location, Trace No. 11. EDD was carried out by using \( g(t) \) calculated from Trace No. 11 alone and applied to all locations on the low-frequency profile to get the extrapolated high-frequency syntheses. The extrapolation result is shown in Figure 5.4. Obviously, by losing the correlation constraints at all other locations, the image formed by the extrapolated traces is much more smeared. Nevertheless, the dominant frequency of the traces is still high and close enough to the original high-frequency record, and the reflection from the lower thin layer is clearly seen.

For surface GPR, extrapolation into greater depths is the main purpose to run EDD. We tested the capability of EDD by shortening the window of the 400-MHz record to 40 ns then carried out the EDD extrapolation again. The results are shown in Figure 5.5. Even with truncated 400-MHz data, the EDD algorithm was still able to show the reflection from the thin layer which is beyond the cut-off window for the 400-MHz data.

To examine how much high-frequency contents has been recovered, we turn to an examination of the spectra from the original and EDD extrapolated high-frequency traces. The comparison of the spectra from the EDD extrapolated syntheses and the original records corresponding to the time domain records (Figure 5.5) are shown as Figure 5.6. It is clear that EDD has recovered the high-frequency lose in deeper part effectively with the comparison of the original high-frequency records (the second panel from the top) and the EDD extrapolated syntheses (the bottom panel). From Figure 5.6 we can see that the peak value of the amplitude is about 100 MHz in the spectra of the low-frequency records, while it is corresponding to about
400 MHz for the high-frequency records. As expected, the high-frequency records have a wider frequency bandwidth than the low frequency records. The spectra of g(t) and EDD have maximum amplitude at about 400 MHz. The spectra of the high-frequency syntheses by EDD resembled the original simulated high-frequency records. This good agreement between the original and EDD data can be explained by the fact the simulated synthetic data is noise-free and has close cross-correlation at all the locations. The comparison of the four spectra plots show that the extrapolated high-frequency records retained the same resolution as the original high-frequency records.

5.4. Applications to field GPR data

For serving the ultimate objective of boosting up the resolution of the field GPR data, EDD was further examined by being applied to a set of the 100-MHz and 400-MHz field data collected in the town of New Milford, Connecticut, for highway engineering purposes (Liu, 2004). Both the 100- and 400-MHz data sets were collected along a single survey line with 10-cm trace spacing. The soil at the site is very sandy/gravelly with a great depth of penetration. Both data sets show a strong reflector at the two-way travel time 100 ns. The time window length of the 100-MHz data is 400 ns (only 250 ns is used for EDD analysis), while the length for the 400-MHz data is 105 ns. Figure 5.7 shows the original data and the EDD processing results. Though the EDD extrapolation has not reached the level of effectiveness shown in the synthetic data, it does catch the major features of the 100-MHz data beyond 105 ns and boost up them to a shorter period (higher frequency).
Figure 5.6. From top to bottom: the spectra of the 100-MHz records, 400-MHz records, the transfer function $g(t)$, and the EDD extrapolated syntheses.
Figure 5.7. EDD extrapolation of field data acquired at the New Milford, CT site (Liu, 2004).
Figure 5.8. From top to bottom: the spectra of original 100-MHz and 400-MHz field data, the transfer function $g(t)$, and the EDD extrapolated high-frequency Syntheses for the New Milford data set.
The comparison of the spectra for the field data are shown in Figure 5.8. The extrapolated high-frequency syntheses by EDD have the same resolution as the original 400-MHz data. The centroid of the spectra of the field data has a downshift to lower frequencies for both the 100- and the 400-MHz data, and it is more obvious for the 400-MHz data. The coupling effect of the antenna to the ground (Liu, et al., 1998; Zhou, et al., 2001) is the main cause for this shift. The spectra in Figure 5.8 are relatively rough in comparison with the spectra shown in Figure 5.6, due mainly to the existence of signal noise caused by real-world conditions. When comparing with the application to the synthetic data (Figures 5.3 – 5.6), without surprise, the application to the real field data shows a moderate success, caused mainly by the uncertainties and errors existing in both the high- and low-frequency data from various sources. The degree of correlation has been degraded.

5.5. Conclusions

In this chapter we described the extrapolation with deterministic deconvolution (EDD) method to enhance signal resolution in later times for a GPR profile. The EDD approach has been explained with the assistance of a number of examples using both synthetic and field GPR data. Application of EDD to synthetic data demonstrates that it can work effectively as the method designed for. The application of EDD to real GPR data achieved certain effectiveness with moderate success. Apparently, we need carry out further theoretical development before applying EDD to real field data. A sequence of carefully designed procedures of field data acquisition and data pre-processing underlies the effectiveness of the EDD method.
6. Conclusions and Future Work

6.1 A general summary

This report presents a scope of research on GPR pavement assessment covering (1) the laboratory experiments on HMA specimens in dry, water-saturated and frozen conditions; (2) a series of GPR field measurements in different meteorological conditions for assessing the water content in paved road; (3) a numerical simulation of GPR response to a surface dielectric thin layer with the finite difference time domain method; and finally, (4) a digital signal processing algorithm to improve the resolution of GPR signals. As a non-destructive testing tool for pavement assessment, GPR proves an approach supplementary to the traditional direct and impact engineering tests for HMA pavement properties.

With the combination of laboratory test results and field observations, GPR is capable of providing indirect estimate on void ratio of the pavement as well as the state of pore fluid in the voids. This information is critical for extending the durability and stability of HMA paved road, especially when the information is in-situ, and real-time (or close to real-time). Calibration of field data with laboratory test results of the HMA specimens with the same composition may substantially improve the accuracy of pavement parameter estimations.

6.2 Future work

GPR technique for pavement assessment is becoming more and more mature in the last several years. A number of commercially available systems have been emerging to the market. Advancement in electronic and computer engineering technologies will continue the reduction of GPR hardware cost. Numerous theoretical and analytical studies, including results presented in this report, could be acting as the technical support for GPR pavement assessment in production mode at both the project and network levels. Advances in hardware and software will make GPR technique affordable to most state DOTs for paved road status monitoring at the network level and quality assessment and control at project level. Close interactions among DOT laboratories, project managers, and academic researchers will push the GPR technique to a new level of engineering application and make it more attractive to pavement engineers. These interactions
can be hosted by state DOT laboratories or DOT sponsored pavement research centers in academic institutions.

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References


Liu, L. J. W. Lane, and Y. Quan, 1998, Radar attenuation tomography using the centroid

Liu, L. and Oristaglio, M., 1998, Instantaneous parameter analysis using wavelet transform, in Proc. 7th Int. Conf. on GPR, 219-224.


Appendix: A list of publications on GPR authored by the PI and his research group


Steinen, R. P., L. Liu, and T. Guo, Anatomy of an ice-contact ridge (ice channel/esker?), revealed by GPR and confirmed by excavation: Jordan Ridge, North Windham, CT, Geological Society of America, Northeastern Section, the 36th Annual Meeting (March 12-14, 2001), Burlington, Vermont.


