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Highway IDEA Program

Development of a Portable Pavement Thickness/Density Meter

Final Report for Highway IDEA Project 61

Prepared by:
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August 2002

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Development of a Portable Pavement Thickness/Density Meter

IDEA Program Final Report

July 1999 through January 2002

NCHRP "IDEA" Project NCHRP-61

Prepared for

IDEA Program
Transportation Research Board
National Research Council

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August 7, 2002

Table of Contents

PAGE

Executive Summary 1

1. Introduction 2
2. Review of Previous Work 5
3. Antenna Evaluations 10
4. Software Development 16
5. Laboratory Testing 23
6. Data Collection on Constructed Pavements 28
7. Summary and Conclusions 39
8. References 40

Attachment A 42

List of Figures:

Figure 1 – Pavement Thickness Density Meter (PTDM) Concept 2
Figure 2 – Schematic Block Diagram of PTDM 4
Figure 3 – Waveforms Produced by the PTDM vs Pavement Structure 4
Figure 4 – Typical GPR Pavement Thickness Results) 6
Figure 5 – Core Data vs. GPR Data for MnROAD Research Test Road 6
Figure 6 – Air Content vs. GPR Dielectric Constant for WESTRACK Sections 7
Figure 7 – Horn Antenna Density Measurement from Roller Compactor 8
Figure 8 – EM Dielectric data showing area of severe segregation in asphalt between 2400 and 2600 m 9
Figure 9 – Results of Laboratory Studies in Finland Air Voids from Pulsed EM (Radar) vs. Standard Lab Measurements 9
Figure 10 – Schematic of Antenna Types Evaluated in this Project 11
Figure 11 – Photos of Antennas Evaluated in this Project 12
Figure 12– Testing on Controlled Thickness Test Strip at GSSI 13
Figure 13 – Data Samples from Controlled Thickness Test Strip at GSSI 13
Figure 14 – Portsmouth Route 1 Test Site 14
Figure 15 – Antenna Configurations Tested in Portsmouth 14
Figure 16 – Analyzed Data from Portsmouth Test 15
Figure 17 – Initial Parameter Setup Screen 18
Figure 18 – File Selection Menu 19
Figure 19 – Display of Air and Plate Files 20
Figure 20 – Graphic Display of Continuous Processing with Waveform Display 21
Figure 21 – Graphical Output from PTDM Processing 21, 22
Figure 22 – Saving Results in ASCII File Format 22, 23

PAGE

Figure 23 – Laboratory Testing of Asphalt Samples using Two Antennas 24
Figure 24 – Laboratory Testing of Asphalt Samples using a Dielectric Probe 25
Figure 25 – Typical Results for Multiple Measurements Using Dielectric Probe on One Asphalt Specimen 25
Figure 26 – Measured Sample Dielectric Constant vs. Air Content 26
Figure 27 – Testing the Horn Antenna over Simulated Asphalt 27
Figure 28 – Field Data Collection with 4108 Horn Antenna on I-195 in Saco 29, 30
Figure 29 – Equipment Setup for I-93 31
Figure 30 – I-93 Test Section, Northbound, South End, High Speed Lane 31
Figure 31 – Data Collection Setup at the FAATC 32
Figure 32 – FAA Technical Center Pavement Test Sections 33
Figure 33 – PTDM Testing at the FHWA ALF Facility in McLean, VA 34
Figure 34 – Data Collection at the NCAT Facility in Auburn, AL 35
Figure 35 – Thickness Contours and Core Locations at the FAATC 36
Figure 36 – Cores Taken at the FAATC 37
Figure 37 – Core vs PTDM Data for 3 Test Sites 37
Figure 38 – Mean Density vs. Mean Dielectric For Sections Using Granite Aggregate 38

List of Tables:

Table 1 – Proposed PTDM System Specifications 10
Table 2 – Comparative Assessment of Antenna Types 11
Table 3 – Results of Horn Antenna Measurements on Simulated Asphalt Slabs 27
Table 4 – Summary of Pavement Test Site 28

EXECUTIVE SUMMARY

The Pavement Thickness/Density Meter (PTDM) concept developed in this research represents a new and innovative method for automatically determining pavement thickness and density. Pavement thickness and pavement density are two key variables that determine the future life and performance of asphalt pavement. In many cases, due to variations in placement conditions, the actual in-place thickness and density can vary considerably from specifications. Current testing methods based on coring are time consuming and do not provide adequate coverage. The PTDM system provides a means for quickly obtaining complete thickness/density coverage assessment of the pavement. The device is transportable and easily operated with limited training. It provides continuous data, in the form of profiles of the pavement thickness and density as a function of distance along the pavement. The method is safe, since it is based on low-powered pulsed electromagnetic waves.

The key technological innovations required for the development of the PTDM are (1) the implementation of smaller and more portable components, particularly the transmitting antenna; (2) the implementation of software which automatically produces the readings that will be directly displayed for the operator; and (3) the packaging of all of these components in a small portable device that can be easily used and handled as a routine piece of field test equipment. The work carried out under this program has successfully achieved objectives (1) and (2). Through collaboration with Geophysical Survey Systems, Inc. (GSSI), antenna alternatives have been evaluated. After laboratory and field evaluation of three antenna options, a compact horn antenna was selected. The selection was based on its ability to achieve the highest degree of accuracy in the lab (within 0.2" of actual thickness), and the fact that it can operate without contact with the pavement. The non-contact feature permits continuous and rapid data collection, and it allows for data collection on newly placed hot asphalt. The alternative ground-coupled configurations evaluated in the program showed good potential, but had limitations in range and versatility.

Automated software was developed for analyzing the PTDM data. The software enables the operator to automatically calculate pavement thickness and density as a function of distance. The prototype version of the software presented in this report incorporates options and features useful in the development work, but may not be necessarily required in the field version. It is estimated that a field technician could be trained to operate this equipment and software in 1 to 2 days.

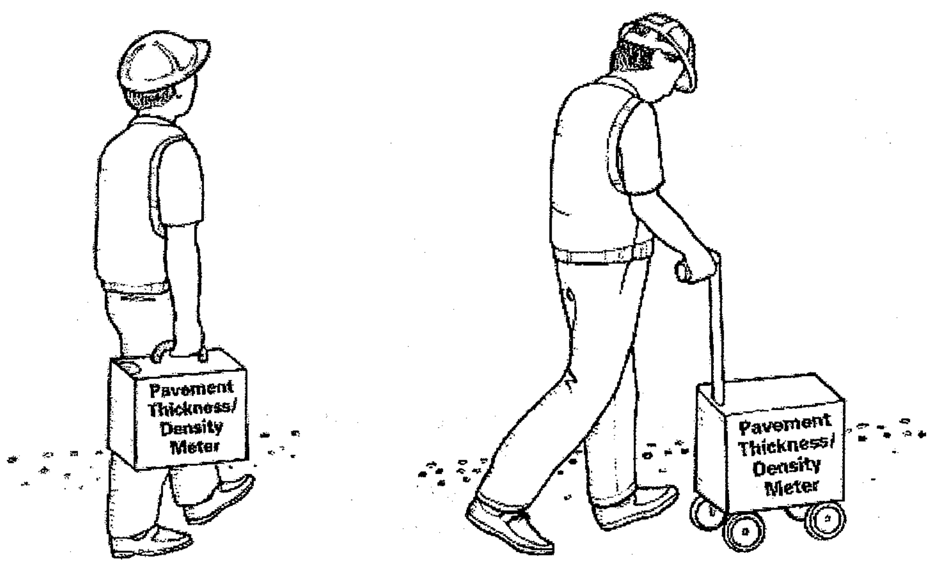
The PTDM system was tested and evaluated on several full-scale pavement sites, and the results were correlated with cores and other available site data. The PTDM thickness results showed good correlation with pavement cores ($R^2 = 0.99$). Site calibration to one core was required for one of three sites in order to achieve this correlation. The density results showed a good correlation with known density data. The specifics of the density relationship will require site calibration. Field data collection during this program was carried out using a test cart and using a portable mounting arrangement operated from the back of a vehicle. The mounting requires only a standard square receiver hitch. The components for packaging a complete self-contained system are now available through GSSI, and the packaging of the system is proposed for the next phase of this work.

1. Introduction

1.1 Background and Approach

Pavement thickness and pavement density are two key variables that determine the future life and performance of asphalt pavement. In many cases, due to variations in placement conditions, the actual in-place thickness and density can vary considerably from specifications. At the present time, quality control of pavement thickness is obtained by taking cores, which are destructive to the pavement. Cores are time consuming to take and provide a limited sampling of information regarding the thickness of the asphalt pavement. Asphalt density is determined either from the cores or by using nuclear type gages. These gages with their nuclear sources present a safety hazard and require special certifications of the operators. Like coring, nuclear tests only provide local samples of the actual in-place density.

The Pavement Thickness/Density Meter (PTDM) concept developed in this research represents a new and innovative method for automatically determining pavement thickness and density. The proposed equipment is portable and easily operated with limited training. It provides continuous data, in the form of profiles of the pavement thickness and density as a function of distance along the pavement. The method is safe, since it is based on low-powered pulsed electromagnetic waves whose power levels are 2 orders of magnitude less that that of a conventional cellular phone. The method quickly provides complete coverage of the newly constructed pavement. The data can be used to provide complete quality assurance and quality control over the construction. The potential benefits of this new system are enormous. Pavement thickness and pavement density play a crucial role in the load capacity and future life of an asphalt pavement. Substandard thickness and density result in premature pavement deterioration, costing millions of dollars in unplanned and unnecessary repairs and rehabilitation.



(a) Easily Transported (b) Provides Continuous Measurement

FIGURE 1 – Pavement Thickness Density Meter (PTDM) Concept

The proposed PTDM will enable agencies to maximize pavement life and minimize life cycle costs by accurately and completely determining, at the time of construction, whether the pavement has been built according to specifications. With the PTDM, problems can be addressed at construction time and the contractor can then take responsibility for corrective action. This is far more desirable than having problems go undetected, thus passing the responsibility to the owner at some future time, and at significantly increased costs. The proposed PTDM would be available at a price comparable to other non-destructive pavement testing devices; and thus would be accessible for routine use by contractors, state highway testing organizations and by private and contracted testing laboratories. The very existence of such a comprehensive testing device would of itself represent a very strong force towards increasing the quality of construction.

The technology required for developing and implementing the PTDM has already been developed and utilized in other quarters. For example, pulsed electromagnetic systems (commonly referred to as "Radar" systems) are now being routinely used for measurement of pavement thickness. These systems, however, are cumbersome and expensive due to the required support, training and data processing as well as associated software costs; consequently they are not routinely used by inspectors and technicians. The proposed PTDM seeks to package and implement this type of technology in a way that has never been done before.

The key technological innovations required for the development of the PTDM are:

1) The implementation of smaller and more portable components, particularly the transmitting antenna;
2) The implementation of software which automatically produces the readings that will be directly displayed for the operator; and
3) The packaging of all of these components in a small portable device that can be easily used and handled as a routine piece of field test equipment.

1.2 Detailed Concept Description

Before going into detail of the individual tasks, it is important to understand the key components of the system and how they relate to one another. This is described using the schematic block diagram shown in Figure 2.

The detection method utilizes short electromagnetic pulses created by a pulse generator according to a pulse repetition frequency (PRF) defined by a **controller**. These pulses are transmitted via cable to an **antenna**. The antenna transmits the electromagnetic pulses down towards the pavement. Part of the pulse energy is reflected back from each pavement layer, and part is transmitted through to the next layer. The reflected pulses are also received by the antenna and directed to a sampler also included in the controller. The sampler, under the control of the controller, produces waveforms as shown in Figure 3. These waveforms are digitized by the A/D converter, and interpreted by the microprocessor. The microprocessor computes the amplitude and arrival times from each main reflection.

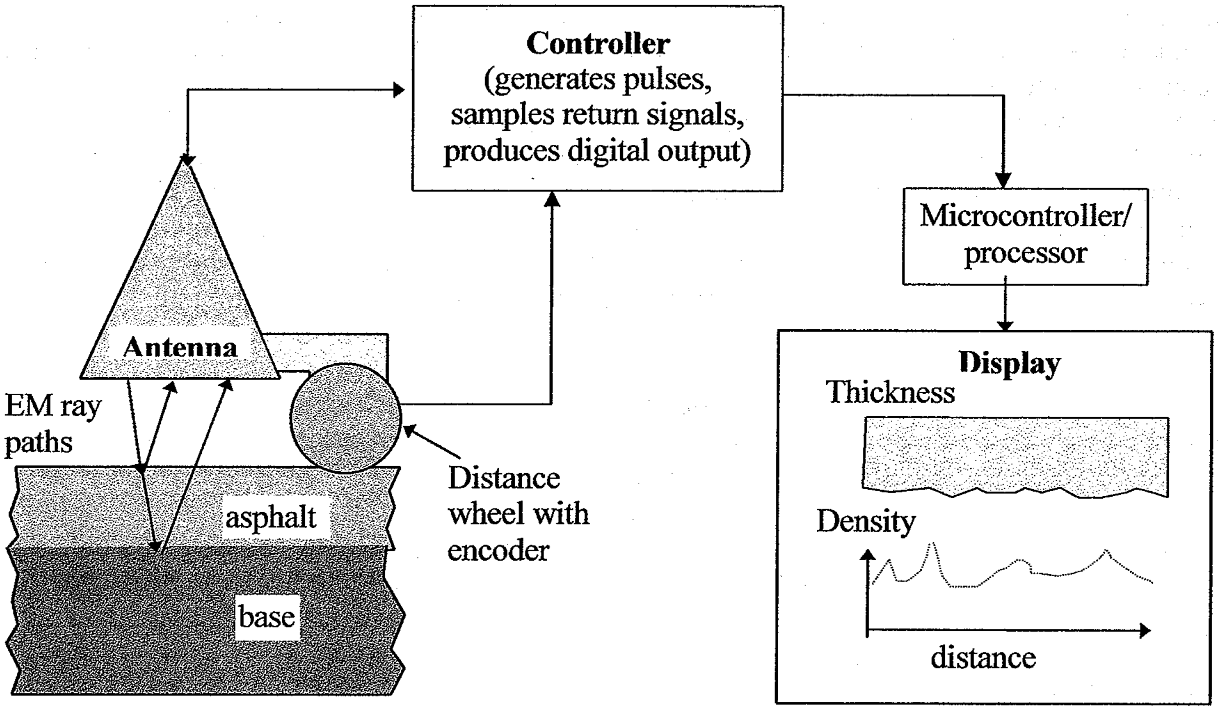


FIGURE 2 – Schematic Block Diagram of PTDM

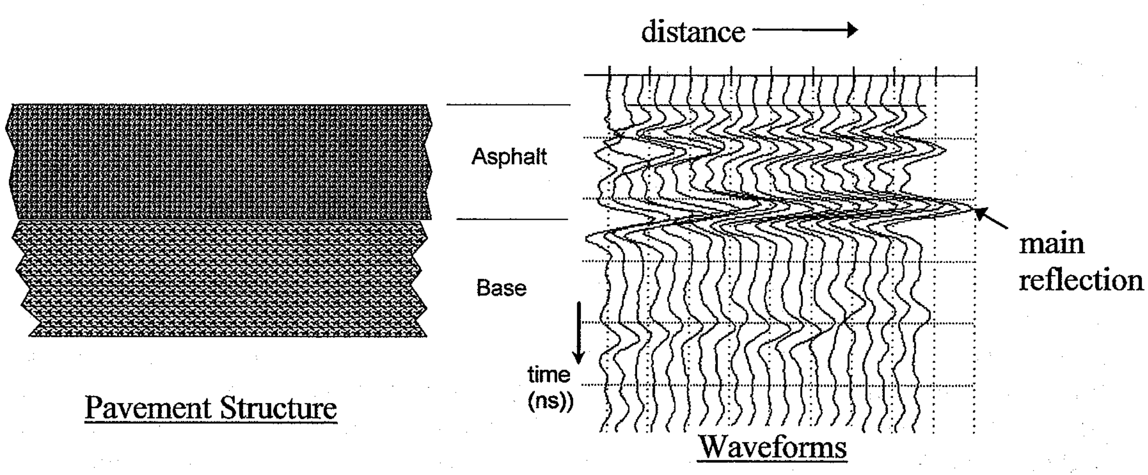


FIGURE 3 – Waveforms Produced by the PTDM vs Pavement Structure

The pavement thickness and density can be computed from these amplitudes and arrival times according to the following equations (Maser et.al., 1992) *(1)*:

$$\text{Thickness(mm)} = (150\ t)/\sqrt{\varepsilon_a} \qquad (1)$$

$$\text{Volume fraction of air} \approx (\sqrt{\varepsilon_a} - K_1)/K_2 \qquad (2)$$

$$\varepsilon_a = [(A_{pl} + A)/(A_{pl} - A)]^2 \qquad (3)$$

where ε_a is the dielectric constant of the asphalt; t is the time delay between the reflections from the top and bottom of the asphalt, computed from each waveform; A is the amplitude of the reflection from the top of the asphalt, computed from each waveform; and Apl is the amplitude of the reflection from a metal plate, obtained during calibration. The factors K_1 and K_2 depend on the dielectric constants of the aggregate and bituminous components, and on volume fraction of the asphalt paste. Since the volume fraction of the asphalt paste does not significantly affect the calculation, these two factors can be combined into a single calibration constant which can be computed as part of a field calibration procedure.

2. Review of Previous Work

The proposed pavement thickness/density meter is based on the use of pulsed electromagnetic waves for evaluation of the thickness and material properties of pavement material. A considerable amount of previous work has been carried out which lays the basis for the proposed development. The following discussions deals separately with thickness and density measurements.

2.1 Pavement Thickness

The use of pulsed electromagnetic waves for the measurement of pavement thickness has been available as a practical field procedure for over 10 years, and a specification for this measurement, ASTM 4748-98, exists (ASTM, 1998) *(2)*. Most of the practical procedures used for pavement evaluation have been based on a technology commonly referred to as "radar", "Ground Penetrating Radar", "impulse radar", or "GPR". This technology was developed in the late 1960's and early 1970's for two applications - geological exploration (Morey, 1974) *(3)*, and mine detection. Applications to civil engineering structures (e.g., pavements, bridge decks) were developed in the 1980's. For example, Steinway (1981) *(4)* conducted an NCHRP study using a horn antenna for the detection of voids in pavement, and Ulricksen (1983) *(5)* explored numerous applications, including bridge decks, geotechnical studies, and water pipe detection and evaluation. Applications to pavement thickness were developed in the late 1980's, and advanced with the implementation of improved horn antennas and more sophisticated processing software. For example, SHRP conducted an evaluation of pavement thickness measurements on test LTPP sections in 10 states (Maser, 1994) *(6)*. Other research studies confirming the accuracy and reliability of the GPR technology for pavement thickness have been carried out by several state highway departments, the FHWA, and by agencies overseas. At present, the method has been adapted for routine use by a number of agencies (Fernando, 1994) *(7)*, (FHWA, 2000) *(8)*.

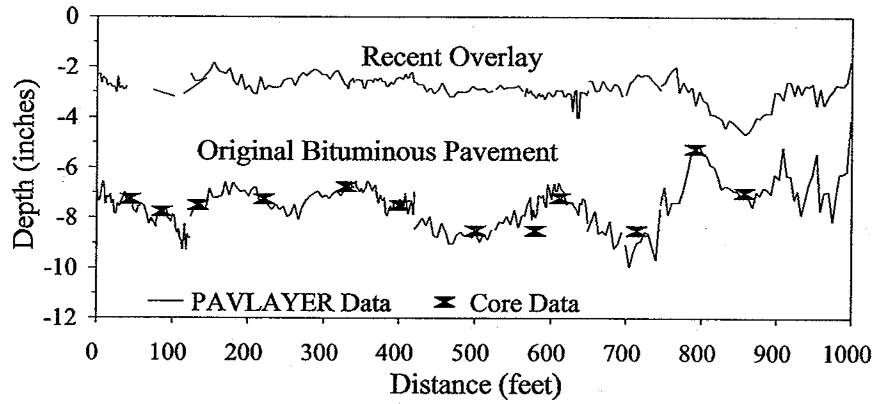


FIGURE 4 – Typical GPR Pavement Thickness Results (Roddis, et. al., 1992) *(9)*

Figure 4 shows the relationship between the GPR thickness data and core data for an older overlaid pavement. Figure 5 shows the comparison between core thickness and GPR thickness data for a newly constructed test pavement in Minnesota. The GPR data was collected shortly after the road was constructed. Both samples of data show that GPR can provide a measure of pavement thickness that is very close to values obtained from cores.

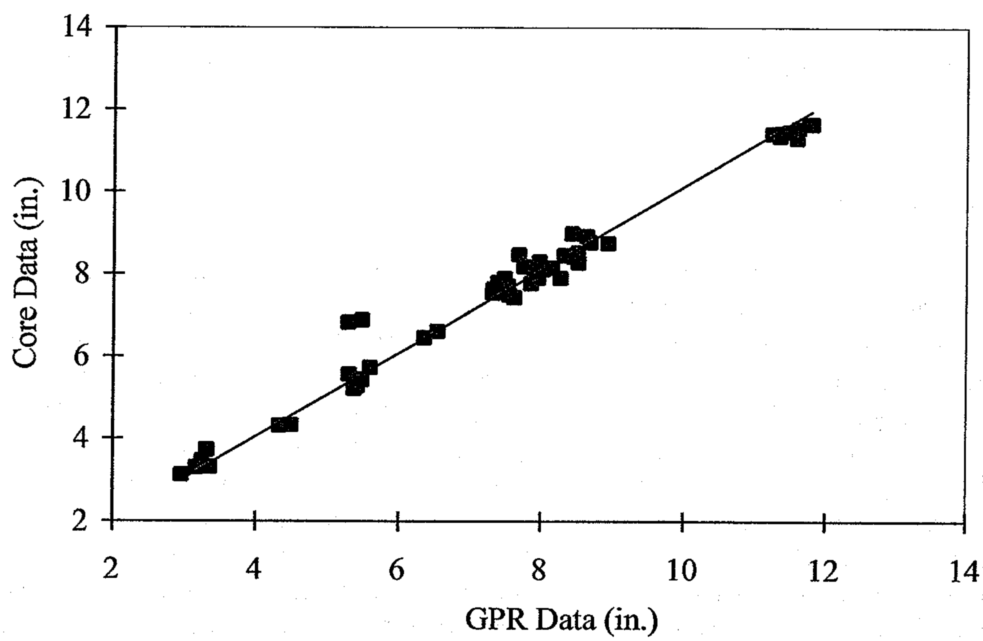


FIGURE 5 – Core Data vs. GPR Data for MnROAD Research Test Road (Maser, 1994) *(10)*

2.2 Asphalt Density

The use of pulsed electromagnetic waves for evaluating material properties is also well developed. Various physical properties, such as moisture content and density, can be obtained from the dielectric properties which are directly determined from the amplitudes and arrival times of electromagnetic pulses. The initial work of this type was carried out for soils (Hoekstra and Delaney, 1974) *(11)*, but has subsequently been extended to concrete (Halabe et. al., 1995) *(12)* and asphaltic materials (Al-Qadi, 1996) *(13)*. This theoretical and laboratory development has been confirmed in field measurements. For example, Figure 6 shows that surface dielectric constant measurements made with a 1 GHz horn antenna at WESTRACK correlated very well with the actual in-situ air content measurements (Hughes, et. al., 1996) *(14)*. Figure 6 is plotted for each of the 26 WESTRACK pavement sections representing a different asphalt mix design. The average dielectric constant computed from the GPR data is compared to the asphalt air content.

Recently a horn antenna system shown in Figure 7 has been implemented as part of a paving machine to continuously monitor the air content of the placed asphalt (Saarenketo and Roimela, 1998) *(15)*. Figure 8 shows how the direct dielectric constant output is used to identify locations of substandard density.

Asphalt air content is determined from GPR by calculation of the asphalt dielectric constant from the reflection of a pulsed EM (radar) wave. The asphalt dielectric constant is a function of the dielectric constant of the asphalt constituents (aggregate, bitumen, and air). With aggregate and bitumen properties relatively uniform, the dielectric constant varies directly with air content.

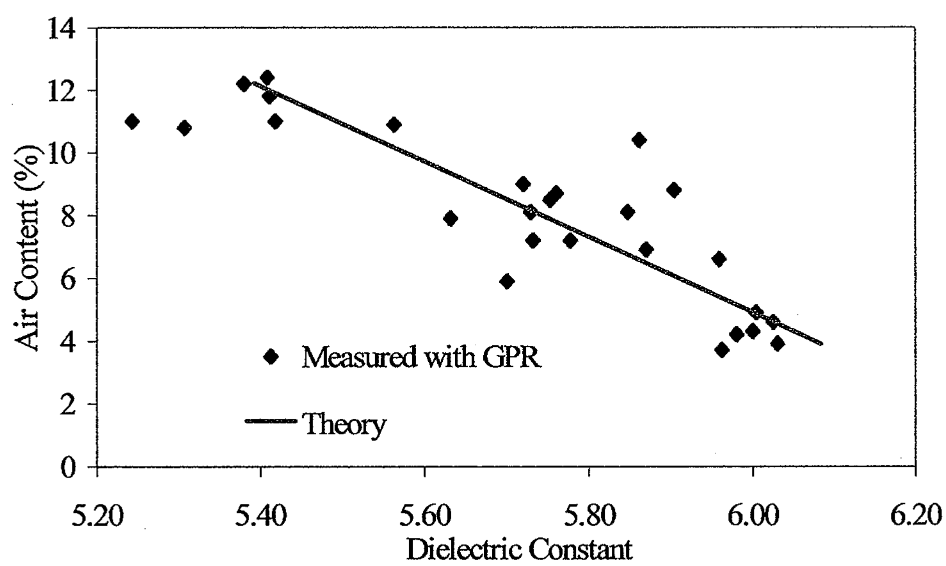


FIGURE 6 – Air Content vs. GPR Dielectric Constant for WESTRACK Sections

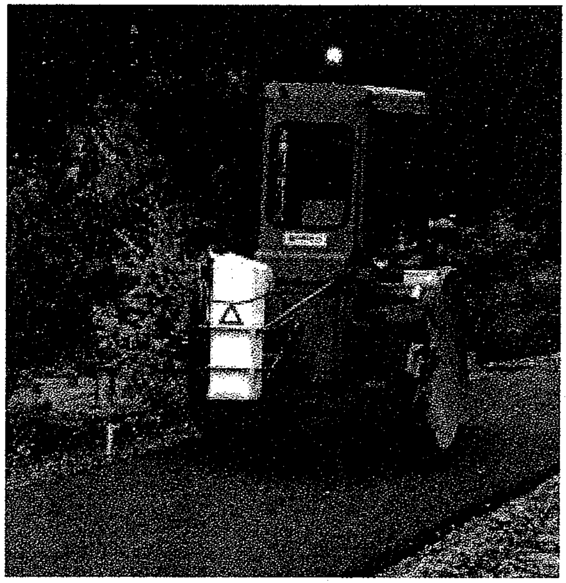


FIGURE 7 – Horn Antenna Density Measurement from Roller Compactor

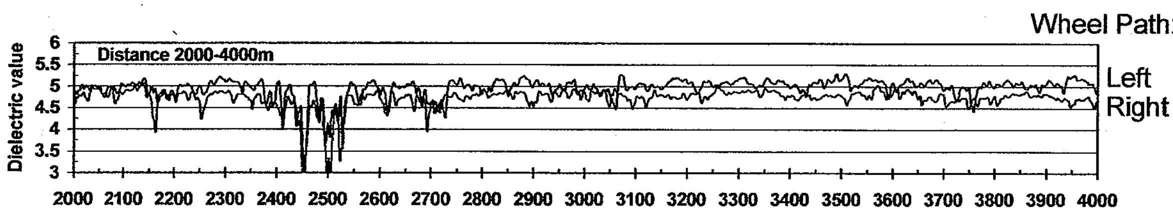


FIGURE 8 – EM Dielectric data showing area of severe segregation in asphalt between 2400 and 2600 m (red line presents right wheelpath and black line left wheelpath)

The ability to measure asphalt air content with pulsed EM (radar) waves has been extensively verified in the laboratory. Tests of this system's results in comparison to over 50 cores at 10 different sites show a correlation coefficient of 0.9223 (Figure 9). The method is now an accepted standard for asphalt quality control in Finland.

In addition to the GPR approach described above, other devices and methods are under development for the measurement of pavement density. Devices such as the Pavement Quality Indicator (PQI) and PaveTracker are small, hand-held units which make point measurements of asphalt density (NCHRP, 1999) *(16)*). Both devices operate in direct contact with the pavement, and have been developed as "non-nuclear" alternatives for density measurement. A roller-mounted device has been developed by Iowa State University for operation in conjunction with the roller compactor.

The PQI emits an electromagnetic field and relates changes in electrical impedance to changes in pavement density. PaveTracker appears to operate in a similar fashion but details on its mode of operation are not provided by the manufacturer. The Iowa State device is based on a high frequency microwave source. The PQI and PaveTracker have been under test for the past 2 years, but detailed assessments of their capabilities and limitations have not yet been published.

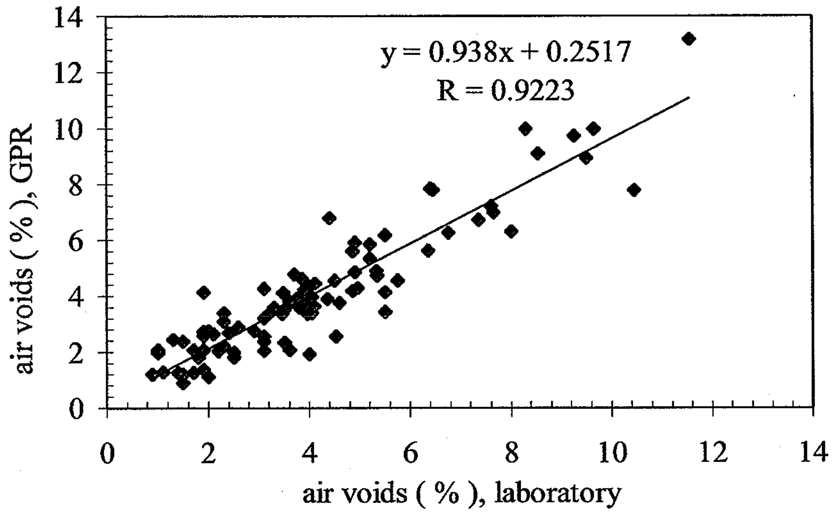


FIGURE 9 - Results of Laboratory Studies in Finland
Air Voids from Pulsed EM (Radar) vs. Standard Lab Measurements

2.3 Summary and Specification

From the above discussion it is clear that a GPR-type system, as envisioned in the PTDM, is required in order to determine both thickness and density. All of the "radar" type systems which have been implemented in practice as discussed above are expensive (> $50,000), they require a support vehicle for mounting and operating the equipment, and they require post-processing of the data. Therefore, they can only be used in limited situations by operators with adequate training and experience. The proposed PTDM, while exploiting some of the established radar technology, seeks to overcome these limitations by implementing components, system design, and processing which lead to a self contained, portable, automatic device.

The key technological innovations required for the development of the PTDM are:

1) The implementation of smaller and more portable components, particularly the transmitting antenna;
2) The implementation of software which automatically produces the readings that will be directly displayed for the operator; and
3) The packaging of all of these components in a small portable device that can be easily used and handled as a routine piece of field test equipment.

Systems specifications have been proposed to meet the requirements described above. These are listed in Table 1 below.

TABLE 1 – Proposed PTDM System Specifications

Size:	6 cu. ft. maximum
Weight:	less than 20 lbs.
Price:	$10,000 - $12,000
Data Collection speed:	2-5 feet/second
Output:	LCD display, ASCII file paper strip chart (optional)
Thickness Accuracy:	within ±5% of core
Density Accuracy:	within ± 10% of actual
Resolution:	>1.0 inch
Calibration:	required for absolute density
Units:	English or metric
Modes of Operation:	a. directly behind the paver for QC b. behind the roller compactor for QC/QA c. at the completion of paving for QA

These specifications were discussed with the project expert panel early in the program. The general view of the panel was that a relative measure of density or air voids would be valuable as a means for identification of segregation or other placement problems. Absolute density measurements were not considered essential, since agencies still rely heavily on cores for this information.

The effort carried out to achieve these objectives is described in the following chapters.

3. Antenna Evaluations

Three different antenna configurations were considered for the PTDM, as shown in Figure 10. Each configuration is based on an antenna manufactured by Geophysical Survey Systems, Inc. (GSSI). There are tradeoffs with each antenna option (see Table 2), and hence each was evaluated more thoroughly before a final selection was made.

The horn antenna is a non-contact device which operates at 12 to 20 inches above the pavement surface. The dielectric constant of the pavement material can be calculated from the horn antenna surface reflection since the dielectric constant of air is known. The ground-coupled antenna is a contact device which is commonly used for locating reinforcing steel and measuring the thickness of slabs. Due to its ground contact, the dielectric properties of the pavement material cannot be directly calculated from the data. It is possible, however, to calibrate the direct coupling of the antenna to the dielectric properties of the pavement materials. Also, the direct coupling of the ground coupled antenna overshadows pavement reflections that are less than about 2.5 inches from the surface.

To overcome some of the limitations of the ground-coupled antenna, a spacer was introduced. The effect of the spacer is to allow the reflection from the pavement to show up distinctly from the direct coupling of the antenna. In this way, the dielectric constant of the pavement can be calculated, and some of the limitations on the minimum pavement thickness can be overcome. Attachment 1 shows the formulation of an analytic procedure for use in conjunction with the dielectric spacer configuration. Figure 11 shows the antenna configurations evaluated in this project.

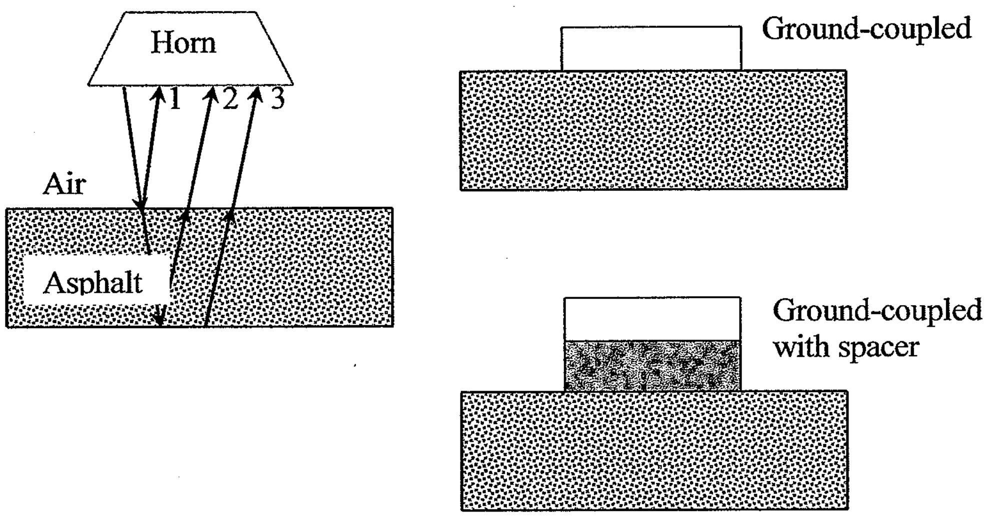
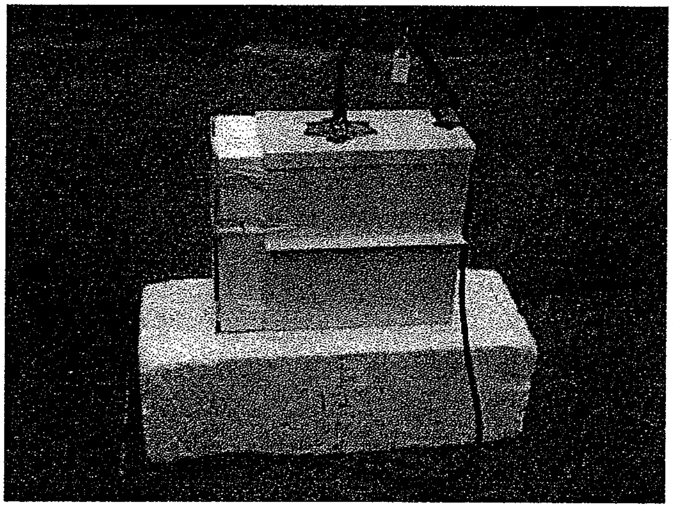


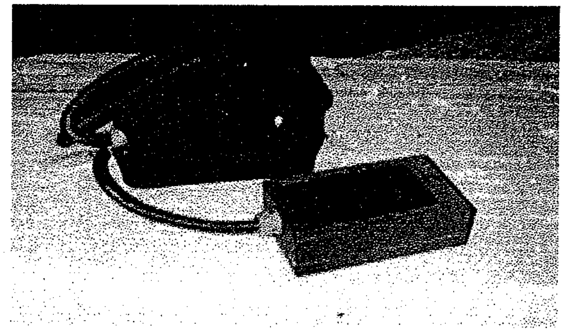
FIGURE 10 – Schematic of Antenna Types Evaluated in this Project

TABLE 2 – Comparative Assessment of Antenna Types

TYPE	ADVANTAGES	DISADVANTAGES
Horn	• Non-contact • Well developed for this application • Best quality data	• Bulky • Higher cost
Ground- coupled	• Small • Economical	• Needs development for this application • Need surface contact
Ground- coupled with spacer	• Small • Economical	• Need surface contact • Block adds weight • Some development needed



Prototype Horn Antenna



Model 5100
Ground-Coupled Antenna & Electronics

Model 5100
with spacer block

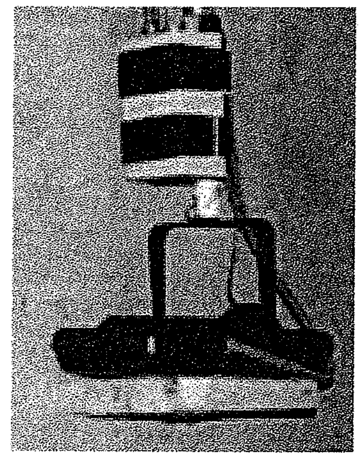
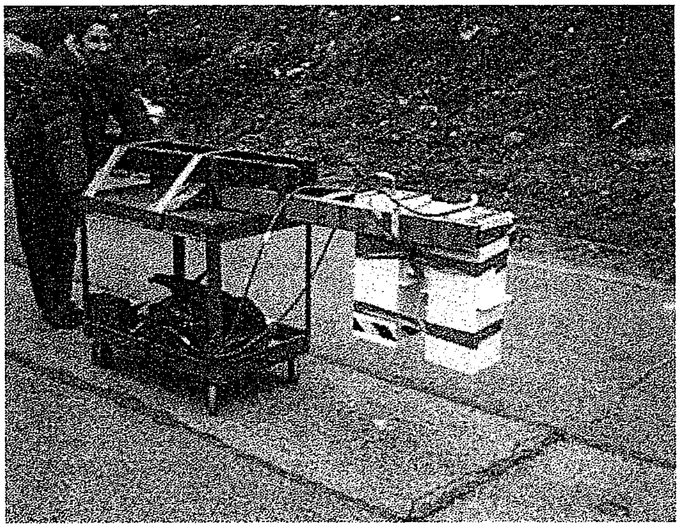


FIGURE 11 – Photos of Antennas Evaluated in this Project

3.1 Laboratory Evaluations

Preliminary tests were carried out at the GSSI laboratory and on a controlled thickness test strip to evaluate some of the characteristics of these antenna configurations. The test strip is constructed of 5 asphalt sections, of thickness 2", 4", 6", 8" and 10" respectively. Figure 12 shows this testing. Figure 13 shows graphical data generated on this test strip. Note that there is a metallic pipe at the boundary between each different thickness. The purpose of this pipe was to provide a strong boundary between the different thickness sections.

Figure 13 clearly shows the different sections with each antenna configuration. The pipe between sections produces a strong signal in the ground-coupled data, but is not as evident with the air-coupled horn. The intensity of the asphalt bottom signal appears to be strongest with the horn antenna. The ground-coupled configurations also reveal the boundary, but with less clarity, and produced the best quality data, while the other configurations produce acceptable data. Due to the size and cost of the horn antenna, the other antenna configurations remained potential options.



Horn Antenna Setup Ground Coupled Antenna Setup

FIGURE 12 – Testing on Controlled Thickness Test Strip at GSSI

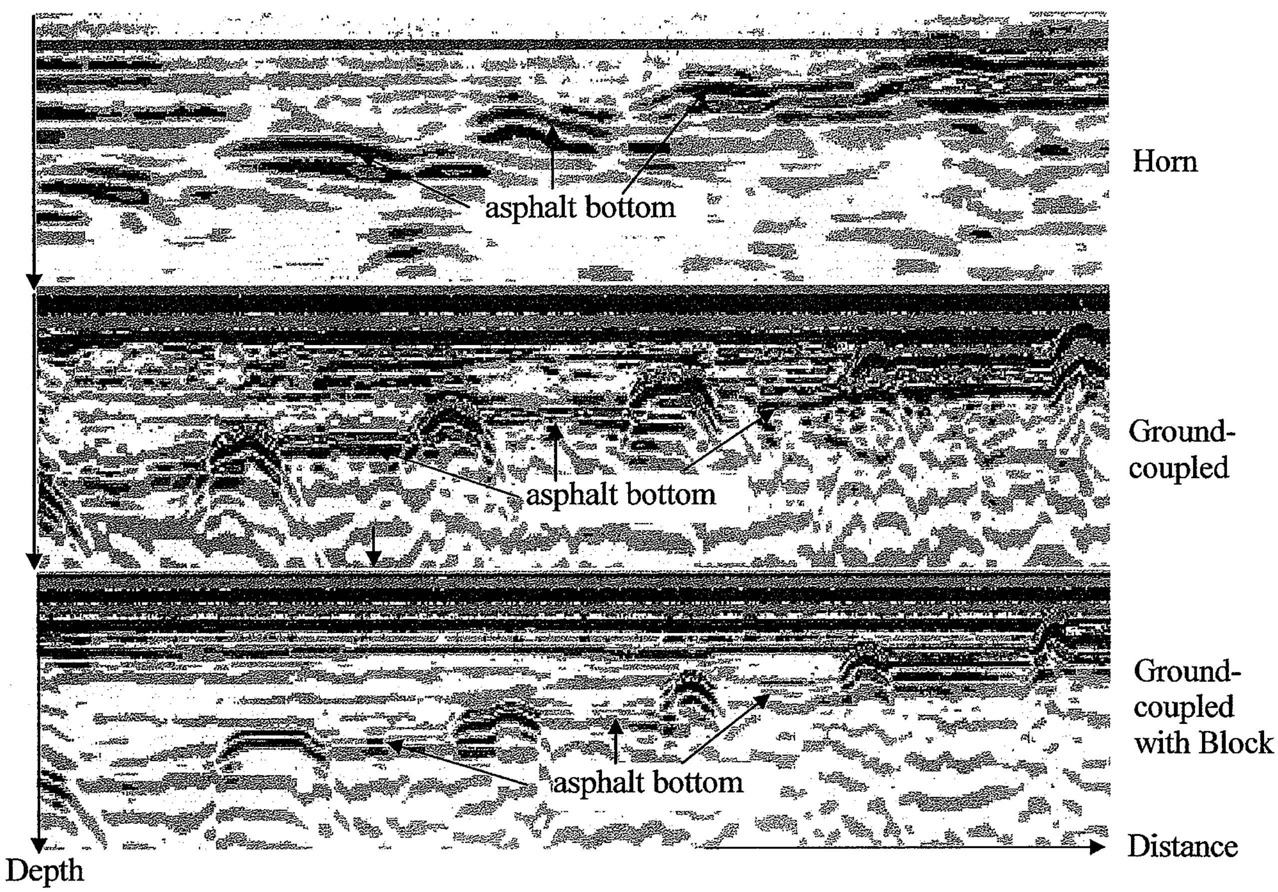


FIGURE 13 – Data Samples from Controlled Thickness Test Strip at GSSI

3.2 Field Data Collection and Evaluation

Field data was collected on February 2, 2000 on a newly paved section of road on Route 1 in Portsmouth, NH. The objective of the data collection was to further test the antenna configurations, to evaluate potential thickness accuracy, and to provide a data set for software development. Since the test section was open to traffic, the antennas were deployed from a survey vehicle so that data could be collected without the need for lane closures.

Figure 14 shows the test pavement, and Figure 15 shows the deployment of the three antenna configurations for the Portsmouth test. Note that the ground-coupled antennas were deployed with a plastic skid to insure that they could be continuously dragged by the survey vehicle without damage and obstruction. The data collected with these was analyzed using Infrasense's standard software (PAVLAYER) for asphalt thickness and density. The thickness results agreed closely with available core data. The data was also analyzed with newly developed automated PTDM software, described later in this report. Samples of both analysis results are shown in Figure 16.

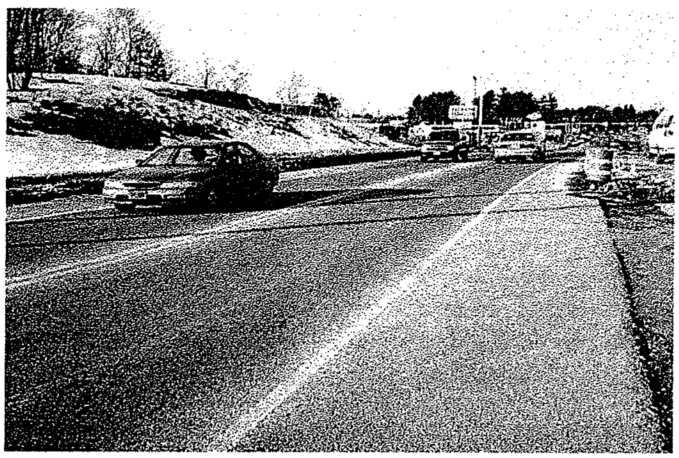


FIGURE 14 – Portsmouth Route 1 Test Site

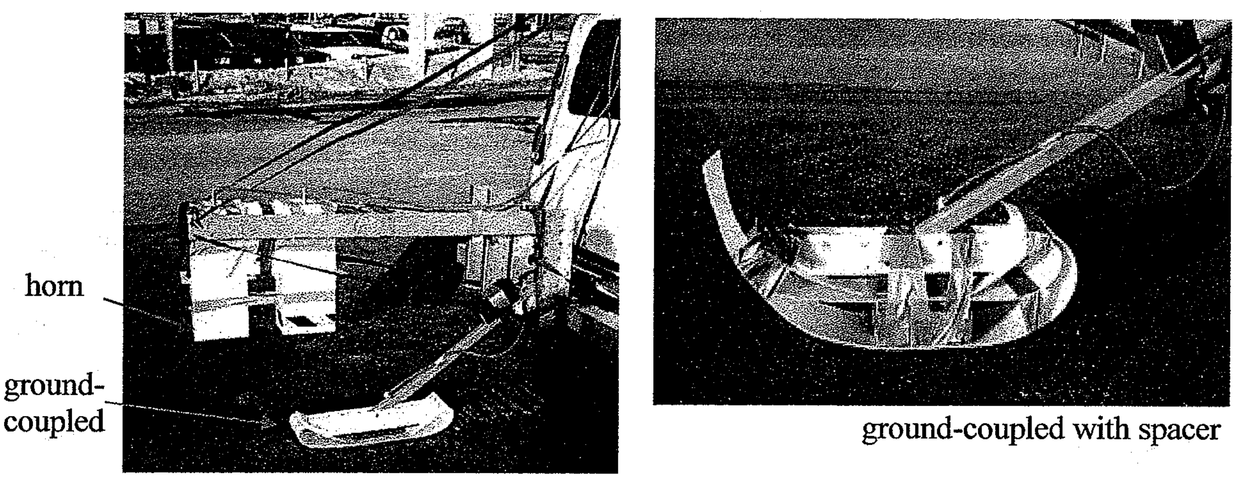
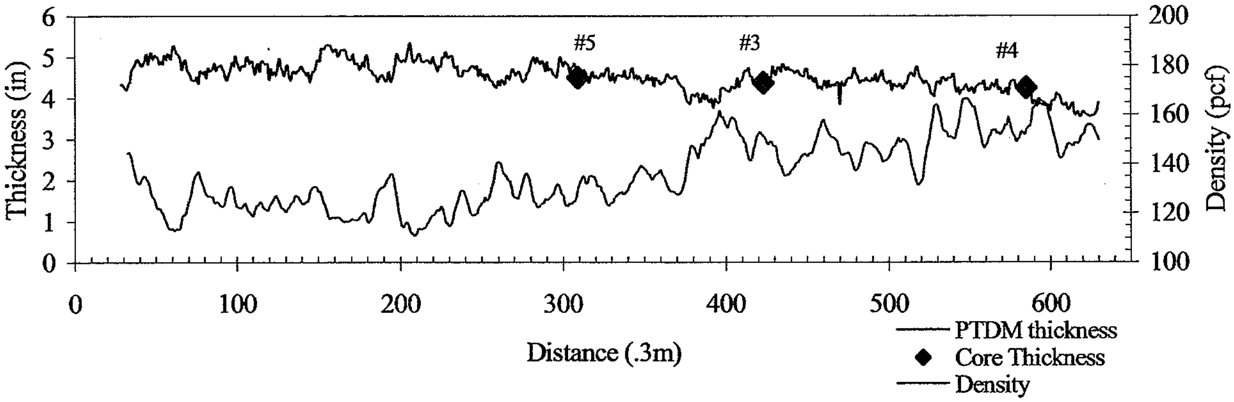
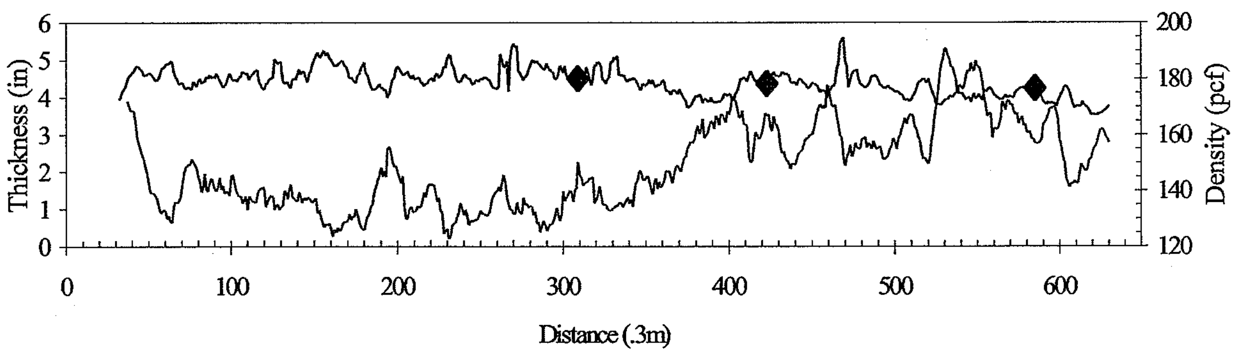


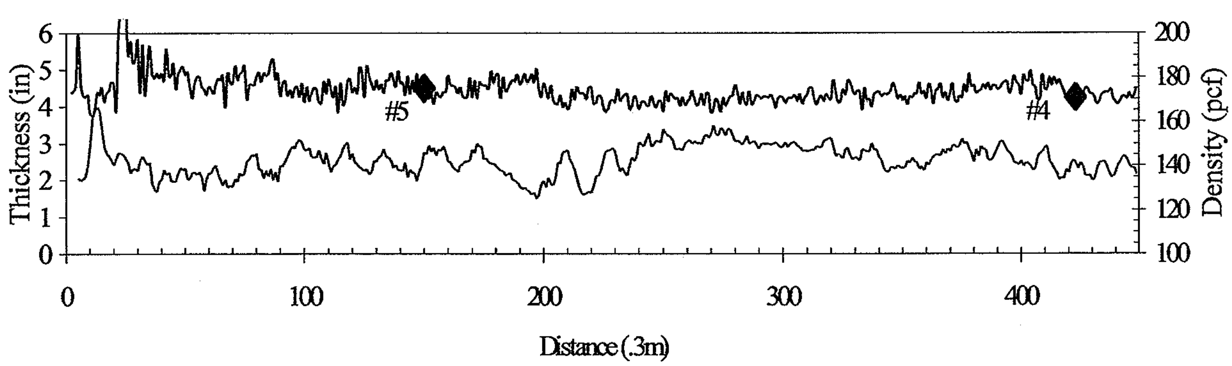
FIGURE 15 – Antenna Configurations Tested in Portsmouth



(a) Horn Antenna w/ PAVLAYER



(b) Horn Antenna w/ PTDM SW



(c) Ground Coupled Antenna with Spacer – PTDM Software

FIGURE 16 - Analyzed Data from Portsmouth Test

The close agreement between GPR and core thickness data from the Portsmouth test led to the conclusion that either the horn antenna or the ground-coupled antenna with spacer would represent a viable alternative for the PTDM. Further consideration of the potential applications, however, indicated that direct contact with the asphalt (as required with the ground-coupled arrangement) might not be desirable. There was concern that direct contact with the hot asphalt, as would occur if the measurement were made directly after paving, would not be feasible. As a result, the project team concluded that the horn antenna represented the most versatile approach for the PTDM for both QC and QA applications.

4. Software Development

Prototype software was developed and tested on the field data. The prototype software was designed to operate with input from a field technician, and to automatically output the thickness and density as the data was collected. The software was initially designed using sample data taken from the Portsmouth testing described previously. Further software development continued using different data sets as they became available to the project. The following section describes the structure and operation of the PTDM software.

4.1 Software Structure

Upon starting PTDM the user is presented with the File Formats input screen. This screen allows tailoring of the processing and file parameters. The file structure can vary depending upon how the data is collected in the field. All available formats are based on the GSSI system options, since these are the systems that serve as the platform for the PTDM.

Each radar scan can be either 256, 512, 1024 or 2048 words long. Each word can be either 8 or 16 bits (1 or 2 bytes). Larger scan sizes and bigger words create a data set with more resolution. However the tradeoff for the extra resolution is slower collection speeds and larger data files. Each scan represents the variations of a radar pulse in time. The user can set the amount of time stored in each scan in nanoseconds (ns). A smaller value for the scan size allows more resolution over a shorter time interval and is useful when analyzing shallow structures. A larger value for the scan size is appropriate for analysis of deeper structures.

It was determined through evaluations on sample data that the 1024, 16 bit word format, with a 10 nanosecond range, was the most suitable format for the PTDM. Future versions of the software, therefore, do not have to present these parameters as options.

The parameters (as they appear on the initial program menu) and their definitions are:

- **Scan size in words** - size of a scan in words (each word is either 1 or 2 bytes)
- **Data sample size in bits** - scan resolution in bits (word size is either 8 or 16 bits)
- **Scan size in ns** - size of scan interval in ns
- **Time calibration (in per ns)** - inches per ns scale factor – (this value depends upon the velocity of the radar wave in the asphalt, which can be estimated at 2.5"/ns)

A second set of parameters relates to the distance measuring device and the units of distance measurement. For this project this value was typically set at 1 to 2 scans per linear foot of travel. Start distance and total length of analysis is also a required input for analysis. Finally, it is not necessary to process every scan. The operator can choose to process data every foot, or every two feet, or every meter. The above parameters are set as follows:

- **Distance calibration (scans per ft)** – the number of scans that are collected and saved in the data file per foot along a trace
- **Start Foot** – the distance value in the file (in feet) at which to begin analysis
- **Total number of Feet to process (or inf)** – The number of feet of collected data to analyze
- **Processing Interval (ft)** – the interval (in feet) over which the user requires analysis of the data

Certain calibrations are required in order to accurately analyze the data. These include collection of a metal plate file and an air file at the beginning of each survey. The metal plate file is collected with a metal plate on top of the pavement directly under the antenna. The air file is collected with the antenna pointed away from the pavement. The parameters associated with these calibrations are listed below:

- **Plate file scan number to read in** – the wave number in the plate file to use for plate reflection scan
- **Air file scan number to read in** – the wave number in file to use for the air reflection scan
- **Number of scans to stack for averaging plate/air** – the number of waves to average in calculating the plate and air scans that will be used in the analysis

While the choice of these values was desirable in the prototype software, future versions can have these values fixed and eliminate them from the user menu.

The user then inputs the expected pavement thickness based on the project specifications.

- **Window location (in)** – the center of the window location for locating the thickness peak reflection in inches (this value should be the expected asphalt thickness measured from the surface)
- **Window size (+/- in)** – the width of the window location in inches where the user expects to find the thickness peak reflection

The following parameters provide a correction for varying height of the antenna above the pavement surface. Such height variations occur if the antenna is attached to a vehicle or other platform which can have vertical motion. These parameters are obtained from a laboratory calibration and are generally unchanged.

- **h.slope** – this value is obtained from the slope of the laboratory calibration curve for the specific antenna
- **h.int** – this value is obtained from the intercept of the laboratory calibration curve for the specific antenna

The user is given the option of computing a running average of the thickness data. Such a data format is often easier to look at and interpret. The associated parameter is the following:

- **Final processed data waves to stack** – the number of data analyses to average for the final plots

Once the parameters are entered, the user may save them to a PTDM initialization file (*.ptd) by choosing the **File Save** option from the window's pull down menu. Similarly, previously saved PTDM initialization files may be loaded by choosing the **File Load** option from the window's pull down menu.

Selecting the **OK** button loads the Main PTDM processing screen. The File Formats screen may be selected and the parameters modified at any time by choosing **File FileOptions** from the PTDM window's pull down menu. Selecting the **Cancel** button on the File Formats screen causes the parameter values to be reset to the values that were present when the form was loaded.

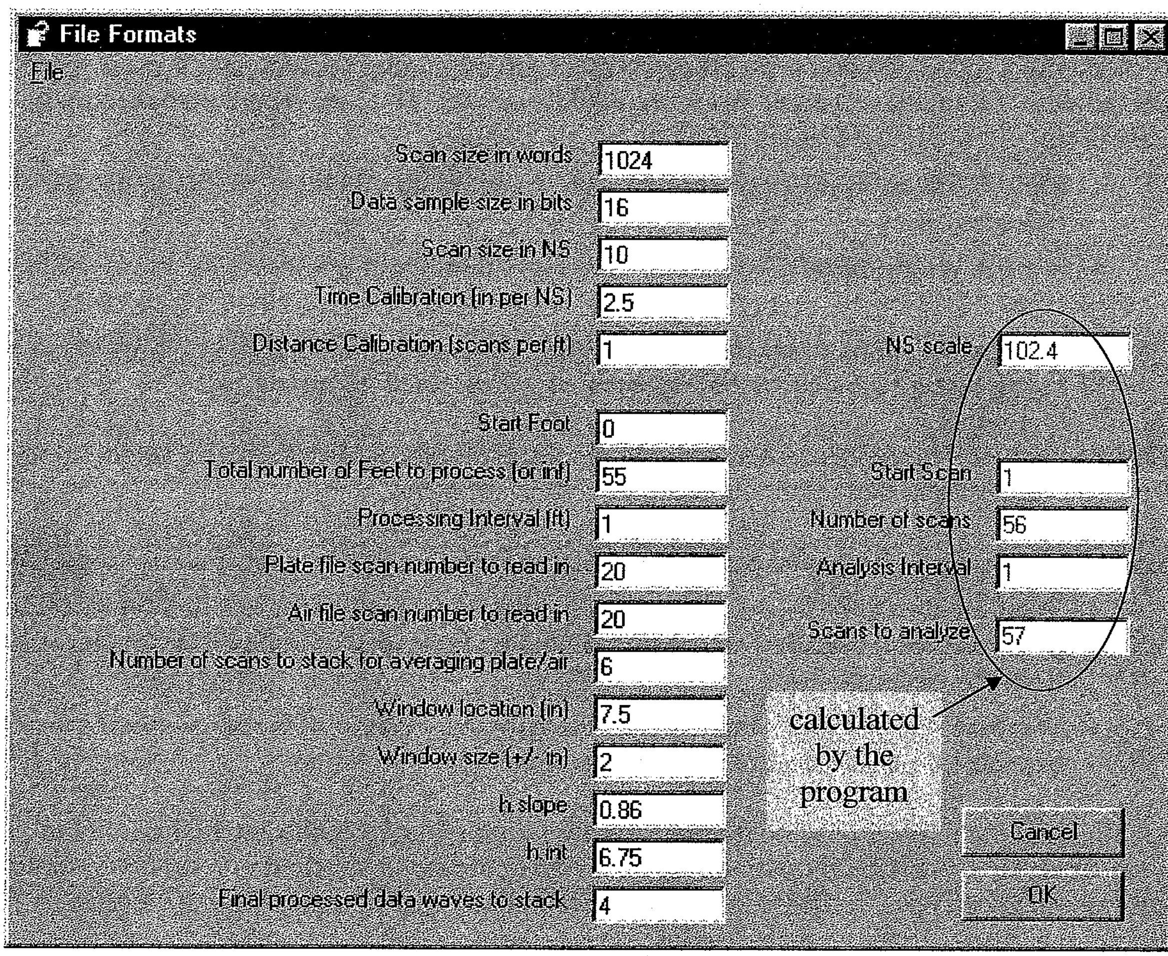


FIGURE 17 – Initial Parameter Setup Screen (these parameters can be saved and reloaded for different projects)

In order to begin processing the user must select an Air file, a Plate file and a Data file. The Air file contains scans which represent the radar pulse reflections received when the antenna is directed into the air. The Plate file contains scans which represent the radar pulse reflections received when the antenna is directed at a metal plate positioned on the ground beneath the antenna. The Data file contains the scans collected according to the user's specifications in the File Formats screen. All three files must be collected using the same file specifications. The user can select these files by clicking on the white box which stores the file name or by choosing **Select Air file, Select Plate file,** and **Select Data file** from the PTDM window's **File** pull down menu.

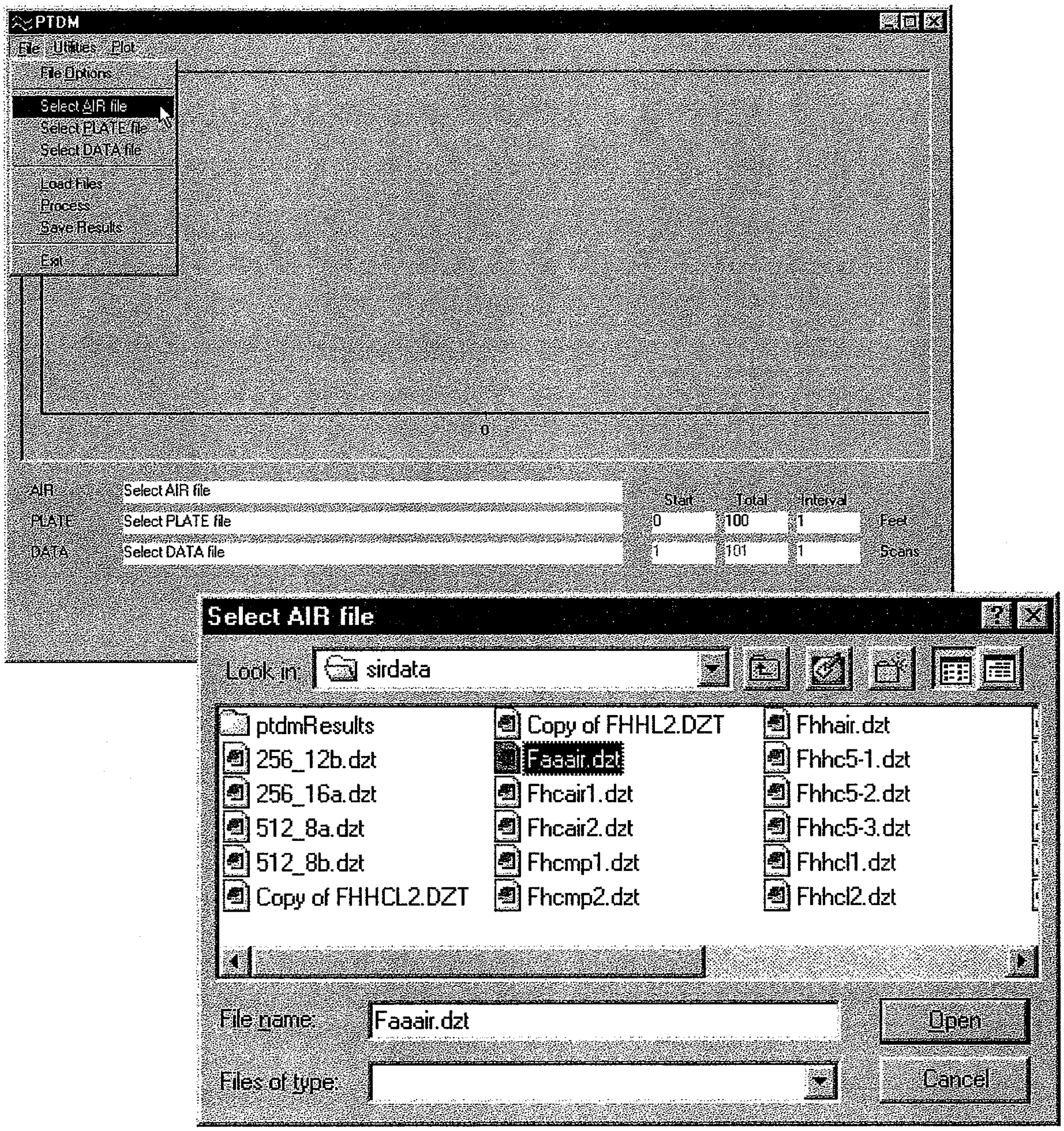


FIGURE 18 – File Selection Menu

The selection menu shows that all data files are named by the operator when the data is collected. The air and plate files are named, and are selected during data playback and analysis. The air and plate files are displayed upon selection, as shown in Figure 19.

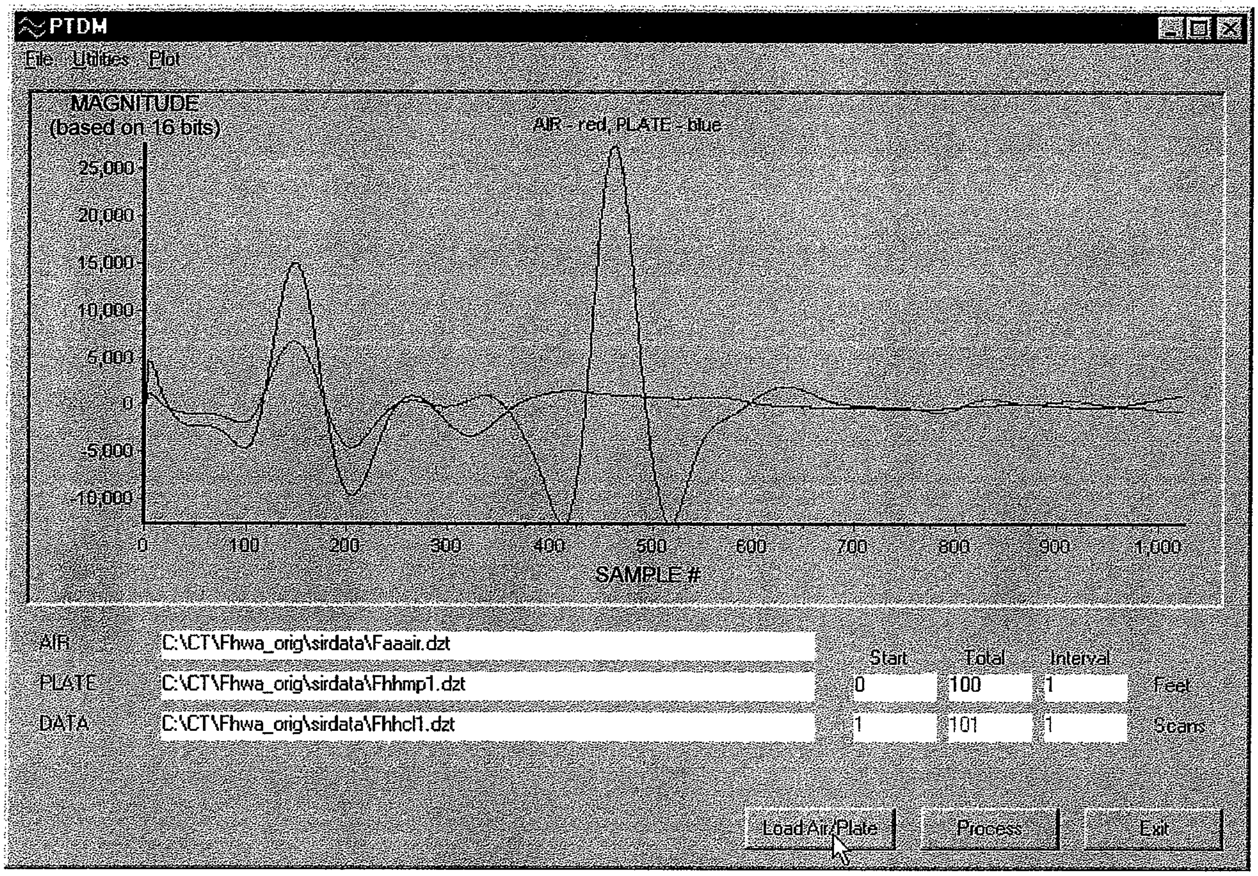


FIGURE 19 – Display of Air and Plate Files

To begin processing the pavement thickness data, the operator clicks on the **Load Air/Plate** button or chooses **Load Files** from the PTDM window's **File** pull down menu. The selected Plate and Air scans will be displayed in the graphics window and the files can be assessed at this point to make sure that the wave subtractions are performed correctly. The Plate wave selection utility can be used to graphically select a different plate wave from the Plate file if there is a problem. To access this utility choose **ScanPlateWaves** from the **Utilities** pull down menu.

To begin processing the data, click on the Process command button or choose **Process** from the **File** pull down menu. To view the selection of peaks as the processing progresses, turn **On Graphics** from the **Plot** pull down menu at any time before or during processing. Turning this option **On** allows the user to graphically view the selection of the thickness peak. Turning the **Graphics Off** will allow the program to process the data more rapidly.

A data image screen will be displayed which shows a color coded scheme of the unprocessed radar data file. The color-coding indicates the magnitude of the peaks in the radar scans. The user can select a color, gray, bone or cool color scheme for this plot.

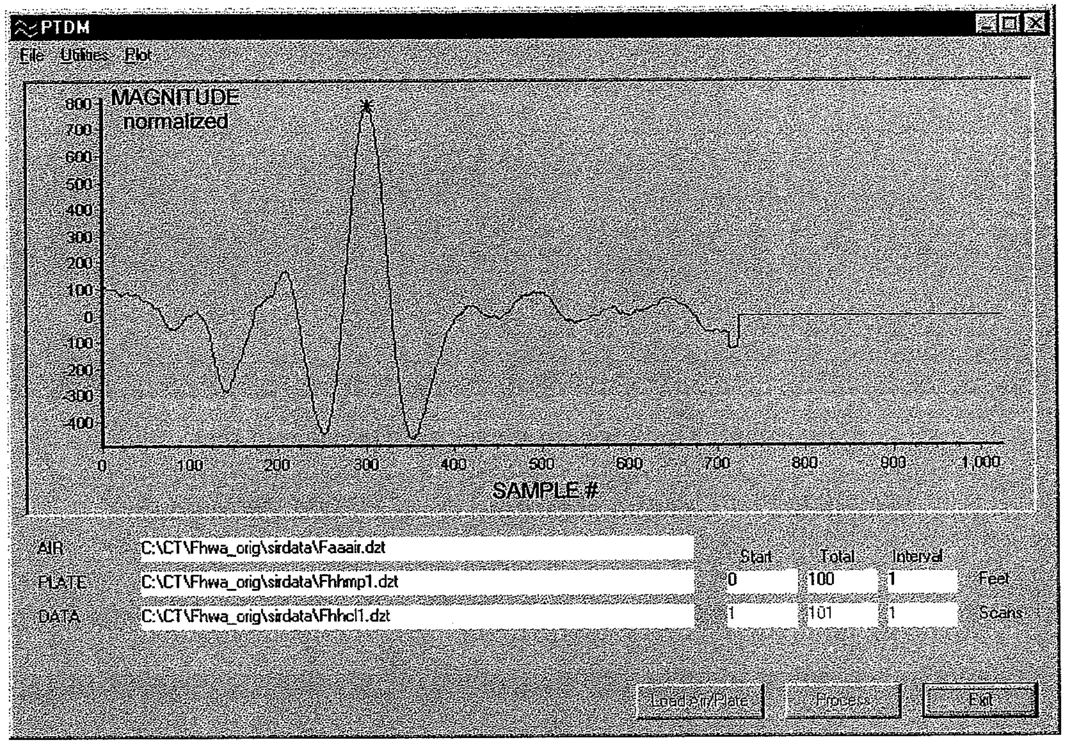


FIGURE 20 – Graphic Display of Continuous Processing With Waveform Display (red star is at peak associated with asphalt bottom)

When processing is complete, the user may view the results by plotting graphs of calculated thickness and calculated dielectric constant by choosing these options from the **Plot** pull down menu. Figure 21a and 21b shows the displayed results for asphalt thickness and dielectric constant. The pavement density can be directly calculated from the dielectric data.

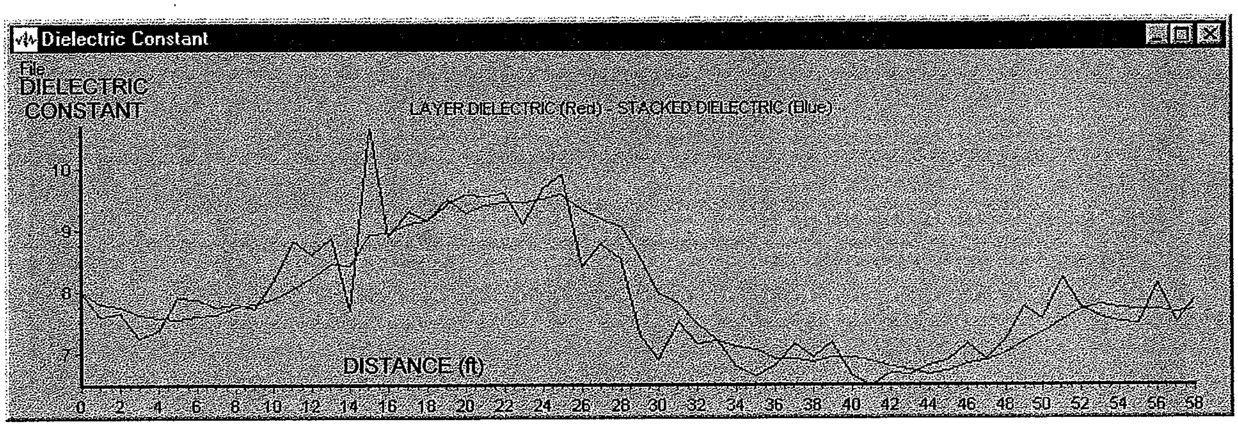
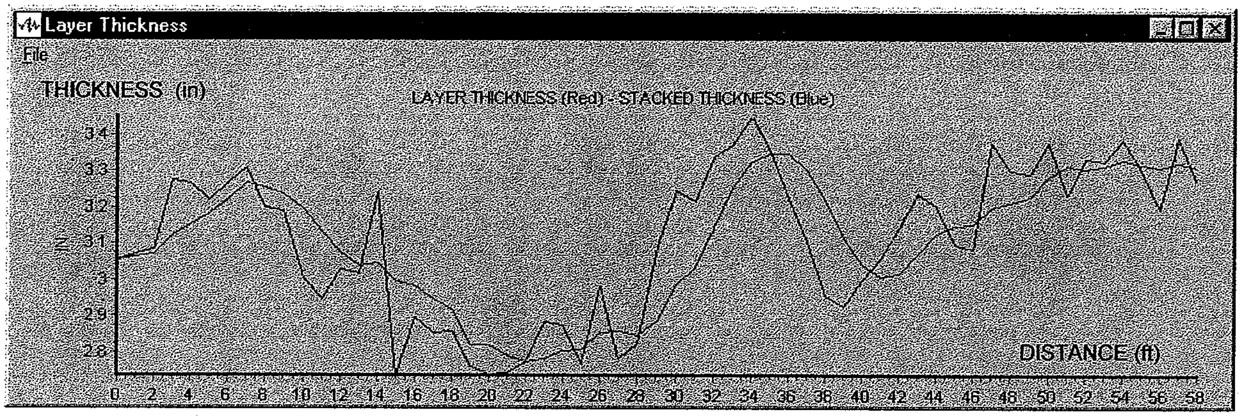


FIGURE 21 – (a) Asphalt Dielectric vs. Distance in feet



(b) Asphalt Thickness in inches vs. Distance in feet

FIGURE 21 – Graphical Output from PTDM Processing

The user has the option to save these results to an ASCII data file (Figures 22a and 22b).

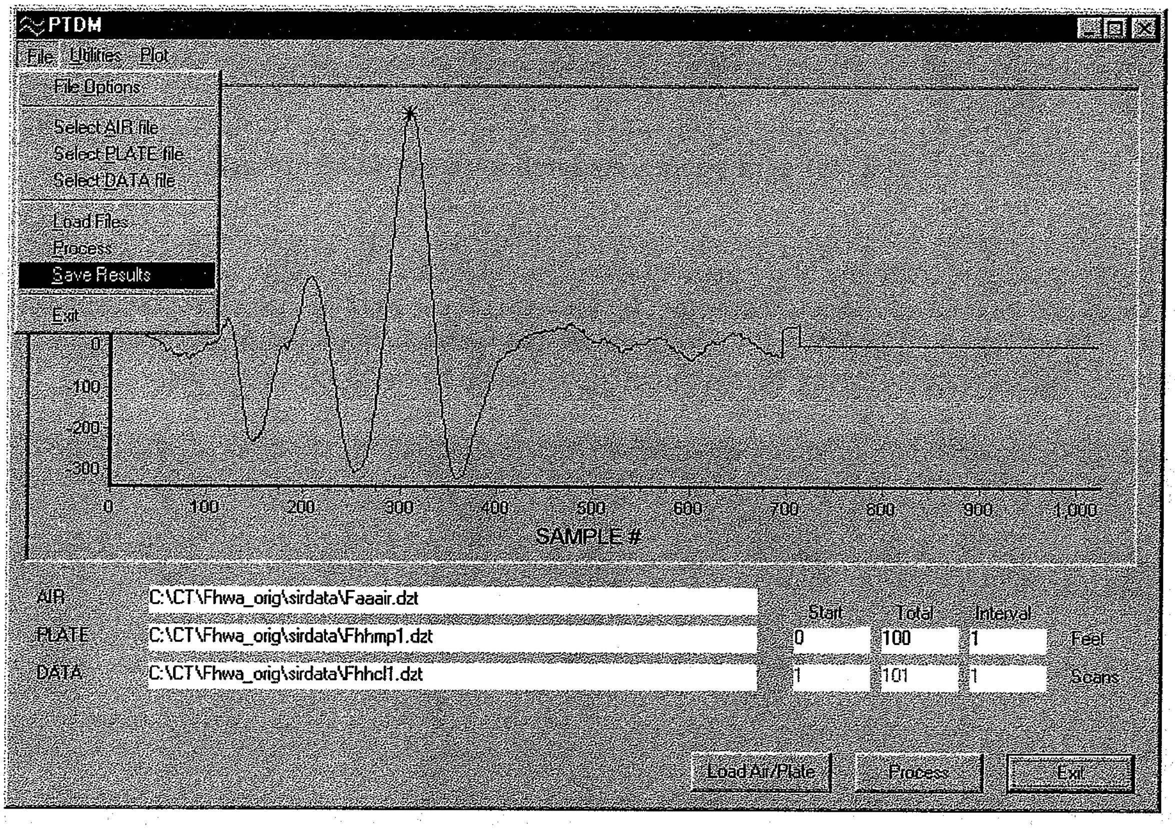


FIGURE 22 – (a) Saving Results in ASCII File Format

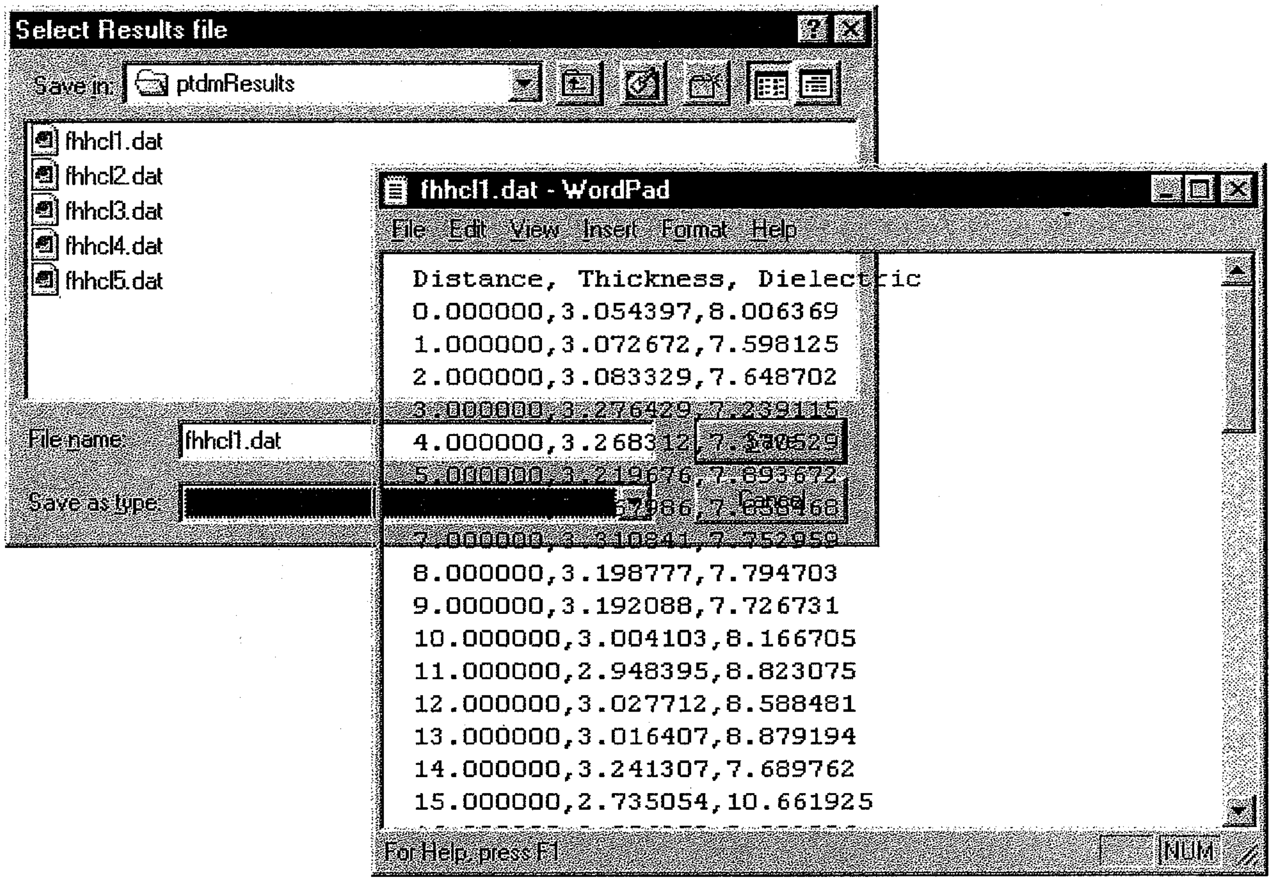


FIGURE 22 – (b) Saving Results in ASCII File Format

5. Laboratory Testing

Laboratory tests were conducted to confirm the accuracy of the pavement thickness calculations, and to correlate measured dielectric properties with asphalt air content and density. As discussed earlier, the correlation of the dielectric properties of asphalt with air content is the basis for the use of the PTDM to evaluate pavement density. The GPR equipment normally calculates dielectric properties to obtain the EM wave velocity in asphalt and thickness. The correlation of dielectric constant with density confirms the ability to determine density along with thickness. The ability to accurately calculate asphalt dielectric constant and thickness is normally confined to the field. However, a special facility was set up in conjunction with another project. This facility permitted the evaluation of dielectric constant and thickness under controlled laboratory conditions. These tests, and the results, are described in further detail below.

5.1 Dielectric Constant vs. Density

Asphalt samples of varying density were provided by Professor Rajib Mallick of Worcester Polytechnic Institute. These samples were made in the WPI asphalt lab using a gyratory compactor. The first set of tests was on samples which had been previously made by WPI and were tested with simple GPR equipment. The dielectric constant of the sample was calculated from the change in GPR travel time with and without the sample between the two antennas. Subsequent to this testing, a more sophisticated network analyzer technique was used to evaluate the asphalt sample properties. Figure 23 shows the testing of asphalt samples with two 5100 ground coupled antennas.

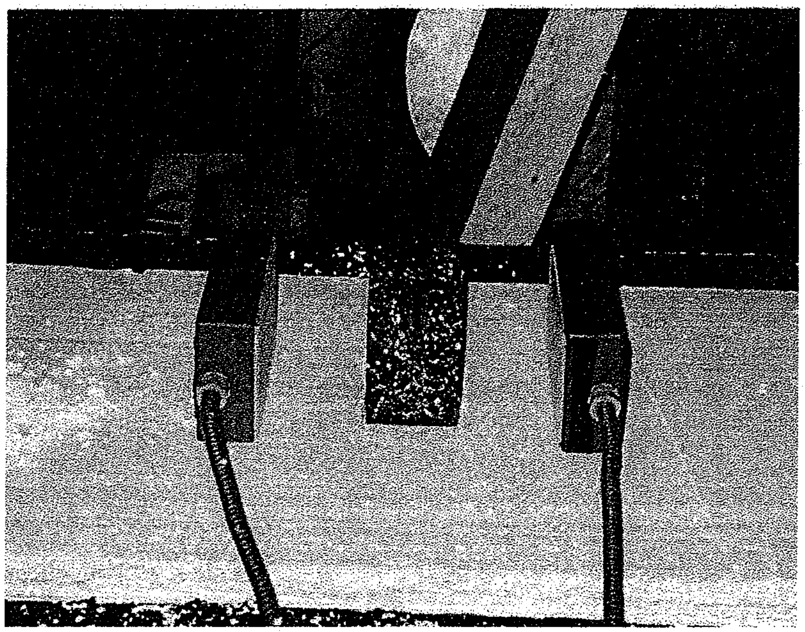


FIGURE 23 – Laboratory Testing of Asphalt Samples using Two Antennas

The initial samples tested with the two antennas gave inconclusive results for two reasons: (a) the samples available in the WPI lab had variables other than air content, and (b) the ray path between the two antennas was not as predictable as originally thought. To correct for the first problem, a set of samples was specially prepared. The samples represented two different mix designs. Within these two designs, three separate air contents were created. Thus, for a samples of a given mix, air content would be the only variable. Two to three samples of the same air content for a given mix were available for testing. To correct the second problem (b), a dielectric probe attached to a network analyzer was used. The dielectric probe measures the complex impedance of the sample, from which the dielectric constant can be calculated.

Figure 24 shows the test arrangement used for the samples tested with the network analyzer. Multiple measurements were made on each face of each sample. Sample results from these individual tests are shown in Figure 25. Note that the test data collected at the top of each sample is quite different from the test data collected at the bottom of each sample. It was visually evident that the samples were not uniformly compacted from top to bottom. According to Professor Mallick, this is a inherent problem of the gyratory compaction method.

The results of these individual tests were averaged for each mix and each air content, and this summary result is shown in Figure 26. The dielectric constant shown in Figure 26 was averaged over a range of 800 to 1200 MHz, since this represents the dominant frequency range for the horn antenna. The results in Figure 26 show a reasonable correlation between laboratory sample air content and asphalt dielectric constant.

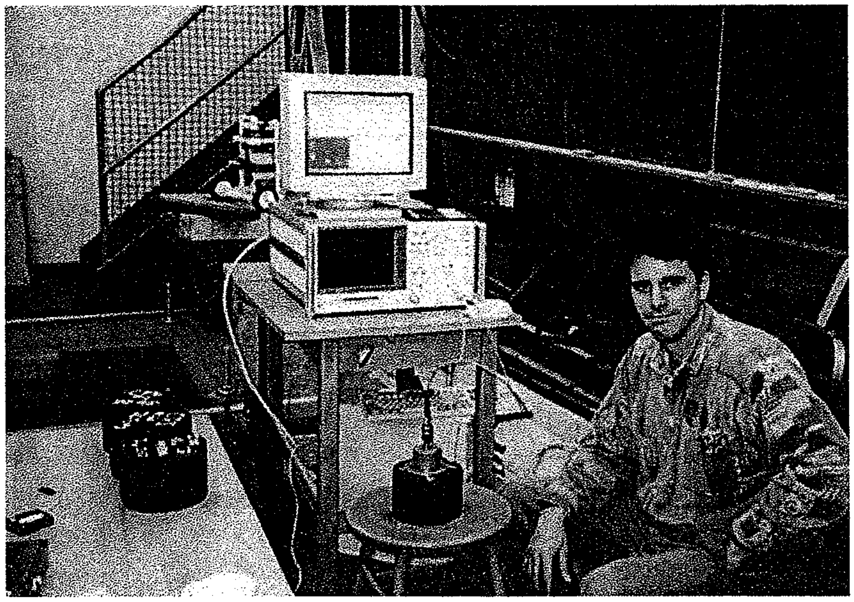


FIGURE 24 – Laboratory Testing of Asphalt Samples using a Dielectric Probe

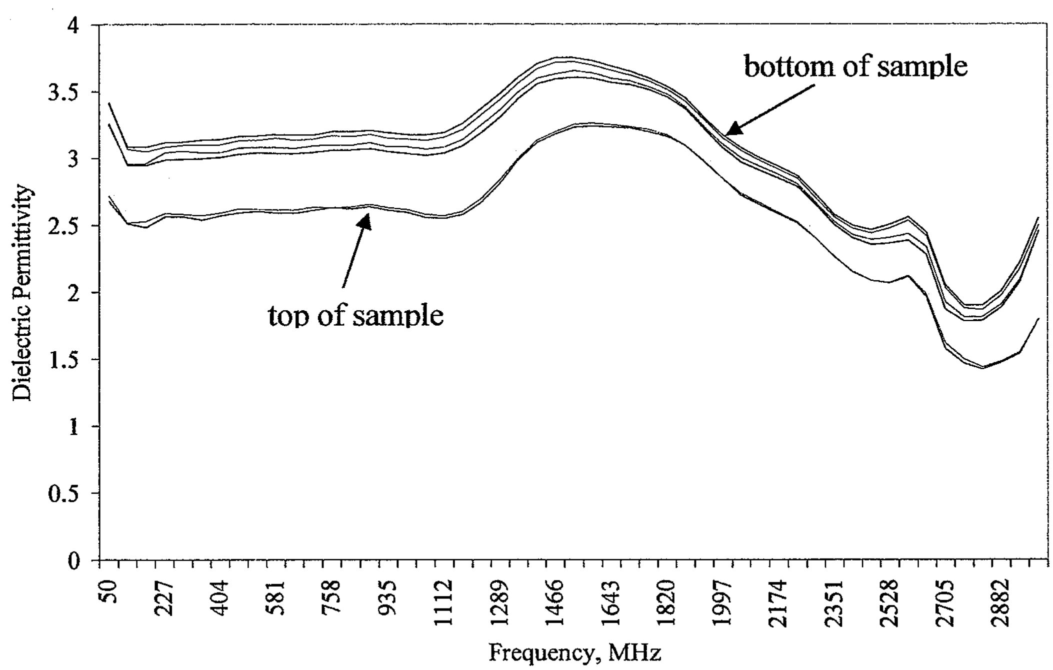


FIGURE 25 – Typical Results for Multiple Measurements Using Dielectric Probe on One Asphalt Specimen

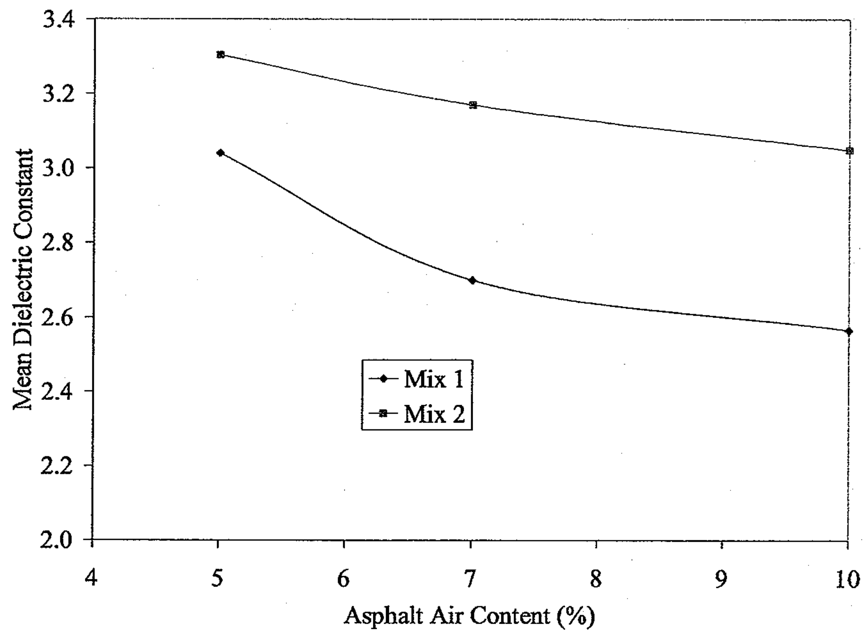


FIGURE 26 – Measured Sample Dielectric Constant vs. Air Content (each data point is the average of 3 test specimens)

5.2 Horn Antenna Measurement of Dielectric Constant and Thickness

To overcome the difficulty of creating a wide variety of asphalt slabs for laboratory testing, a special simulated asphalt tank was used. The tank utilizes an oil emulsion that simulates the dielectric properties of asphalt. By adjusting the water content for a given amount of oil, the dielectric properties of the oil can be adjusted to cover the range of dielectric properties representative of asphalt in the field. The emulsion, which is a thick liquid, is pumped into a rectangular tank to a depth representative of the asphalt thickness to be tested. Testing involves positioning the horn antenna over the tank and collecting data.

The emulsion test setup at GSSI consists of a large 150 gallon polypropylene storage vat connected via hoses and a gear pump to a 47x47x12" polypropylene box used for data collection. The emulsion consists of a mixture of canola oil, distilled water and sodium lauryl sulfate. The sodium lauryl sulfate acts as the emulsifier. The radar propagation velocity in the emulsion is determined by the canola oil/water weight ratio of the emulsion.

The emulsion test was designed to approximate three different radar wave propagation velocities simulating the range of propagation velocities typically observed in asphalt. Consequently, three different emulsions were mixed to obtain propagation velocities of approximately 5.9"/ns (diel. permittivity = 4), 5.4"/ns (diel .permittivity = 5.5), and 4.5 "/ns (diel. permittivity = 7).

Four different asphalt thicknesses (1", 3", 5", and 8") were simulated by pumping the appropriate amount of emulsion out of the storage vat to cover a metal sheet placed at the bottom of the data collection box. Figure 27 shows the testing arrangement. The antenna is positioned at a fixed height above the emulsion as shown. After data was collected, the depth of the emulsion was changed to represent a different thickness. After all of the thicknesses were tested, the emulsion was remixed to a different dielectric constant, and the process is repeated. Table 3 shows the results of these tests.

TABLE 3 – Results of Horn Antenna Measurements on Simulated Asphalt Slabs

EMULSION MIX	ACTUAL DEPTH (IN)	CALC. DEPTH (IN)	ERROR (IN)	CALC. VEL.(IN/NS)	CALC. REL. PERM
low diel	2.91	2.83	-0.08	5.59	4.47
low diel.	5.04	4.89	-0.15	5.51	4.59
low diel	7.87	7.05	-0.83	4.91	5.79
med. diel.	2.91	2.78	-0.13	5.14	5.27
med. diel.	4.80	4.67	-0.13	5.08	5.41
med. diel.	7.76	7.67	-0.08	4.96	5.68
high diel.	2.91	2.67	-0.25	4.60	6.59
high diel.	4.88	4.88	0.00	4.58	6.65
high diel.	7.80	7.98	0.18	4.60	6.59

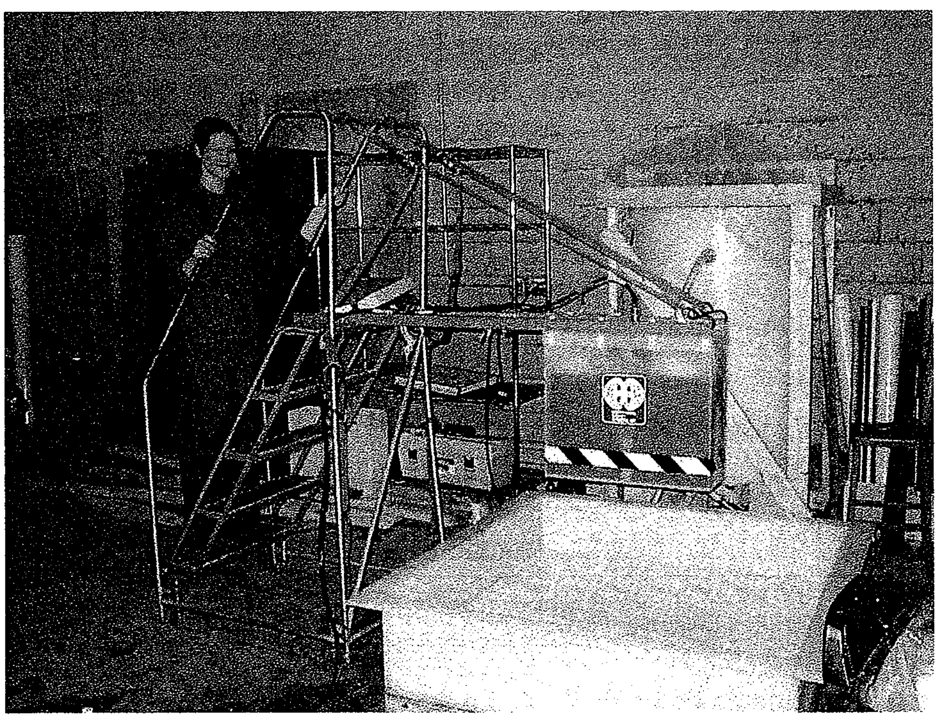


FIGURE 27 – Testing the Horn Antenna over Simulated Asphalt

Examination of Table 3 reveals calculated depth errors less than 0.2" with two notable exceptions. The largest depth error, 0.83", is associated with the thickest high-velocity emulsion mix. Despite the mixing efforts, the emulsion that was pumped into the tank contained numerous inhomogeneous low-velocity globules that appeared to be floating on the emulsion surface. In retrospect, the emulsion should have been pumped back into the holding tank and remixed to ensure complete homogeneity. It is highly likely that these inhomogeneities contributed to a higher reflection coefficient from the emulsion surface that resulted in a lower calculated propagation velocity and subsequent lower calculated emulsion thickness. All other emulsion measurements were made with visually homogeneous emulsion.

The second largest depth error, 0.25", corresponds to a measurement obtained over the low-velocity emulsion. The calculated velocity obtained from the surface reflection is consistent with the calculated velocities obtained from the other two thickness measurements. Consequently, the thickness error can reasonably be attributed to an error in the bottom reflection arrival time. A visual examination of the reflection from the emulsion bottom revealed no apparent reason for the arrival time discrepancy.

6. Data Collection on Constructed Pavements

The final phase of the PTDM effort involved the collection of data from sites representing realistic conditions of newly constructed pavements. Some of the sites were newly constructed pavements, for which core data was available. Other sites were research sites which were well documented with cores. The purpose of the tests was to verify the accuracy and viability of the PTDM equipment and automated software. A summary of test sites is shown in Table 4.

TABLE 4 – Summary of Pavement Test Sites

SITE	LOCATION	DESCRIPTION	NEW ASPHALT THICKNESS	DATE
I-195	Saco, ME	In-service pavement rehab - mill/overlay	1.5" overlay, 4.0" total	10/02/00
I-93	Thornton, NH	In-service pavement rehab - total asphalt replacement	4.5" mainline 2.0" shoulder	9/05/01
FAA Tech Center	Atlantic City, NJ	Pavement load testing research facility	5" (section 3-3) 9" (section 3-2)	10/18/01
FHWA ALF	McLean, VA	Pavement load testing research facility	4" (sections 1, 2) 8" (sections 3,4)	10/19/01
NCAT	Auburn, AL	Pavement load testing research facility	4" all 52 sections	10/22/01

6.1 Preliminary Tests on I-195 Tests in Saco, Maine

Field data was collected on a mill and overlay paving project on I-195 in Saco, Maine, in coordination with Richard Bradbury, the project expert panel member from the Maine DOT. The project was not yet open to traffic, and access was relatively simple. One objective of the testing was to obtain data with a newly developed single unit version of the antenna evaluated earlier in the program. GSSI, the equipment partner in this program, had made substantial improvements in the electronic performance and packaging of this antenna, and it was desirable to obtain some field data with the improved antenna before the end of the construction season. A second objective was to provide an example of field data on a mill and overlay project for further evaluation. Core data was supplied by the Maine DOT, and core locations were noted in the field data.

Figure 28 shows the arrangement used for field-testing. A test cart was configured which held the data acquisition unit, an electronic distance measurement wheel, a battery, and a pair of rails for suspending the antenna. Note in the figure that the antenna is a single unit (vs. the two separate unit antenna tested in Portsmouth, NH. The overall dimensions of the unit are relatively small. The antenna, referred to as the Model 4108, weighs about 7 lbs. and is easily transported.

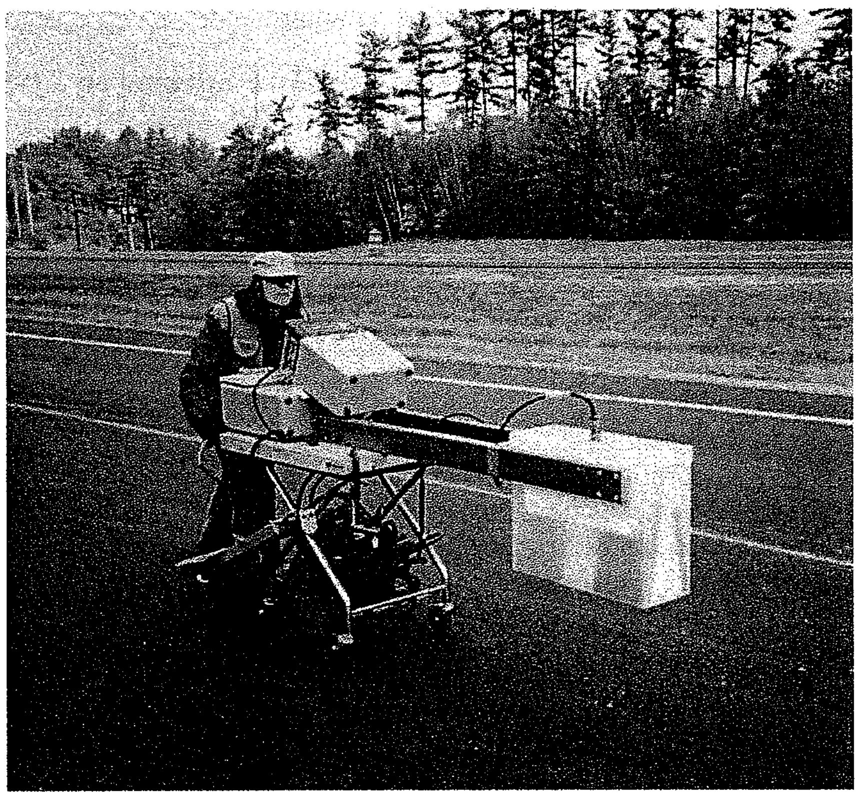
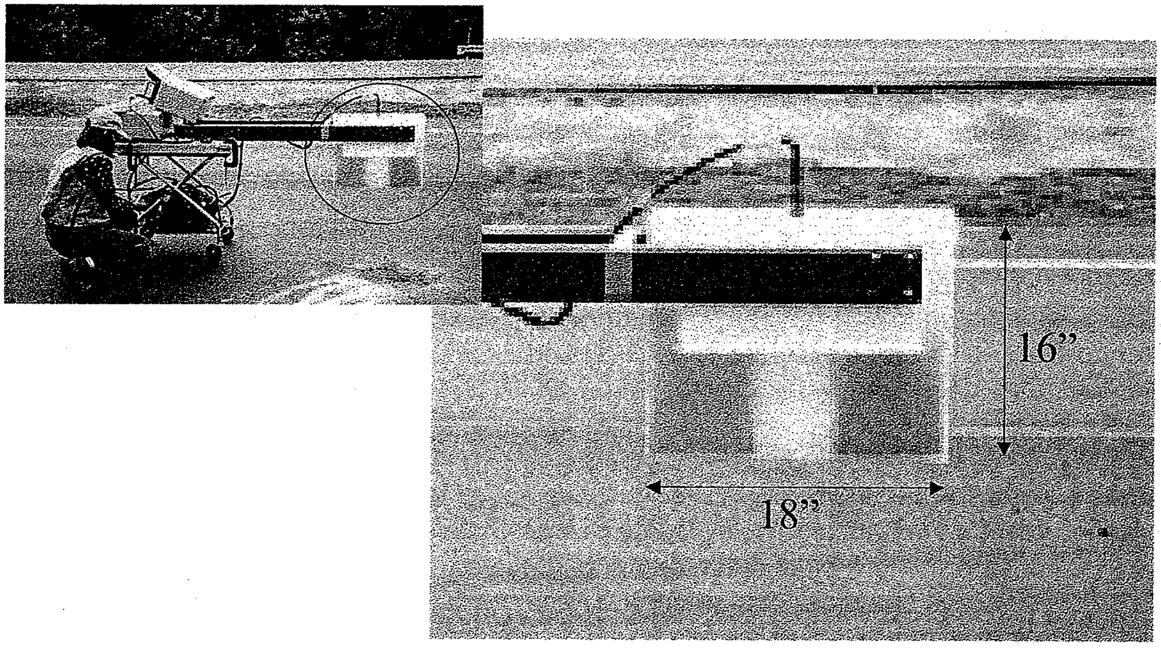


FIGURE 28 – (a) Overall Test Arrangement



(b) Details of Antenna

FIGURE 28 – Field Data Collection with 4108 Horn Antenna on I-195 in Saco

The data collection and control equipment used on the cart was a GSSI SIR-10B, powered by a car battery. Since the time of this test, newer, more powerful, and more compact data collection and control equipment has become available. This new system, the SIR-20, is controlled through a laptop computer, and thus provides a platform for operation of the PTDM software directly on the data at the time of collection.

6.2 Data Collection on I-93, FAA, FHWA, and NCAT Pavements

After the testing in Saco, additional modifications and improvements were made to the 4108 antenna. The improved antenna was then subjected to the laboratory tests described earlier in this report. Once the performance had been validated, and accuracy established in the lab, a final set of tests were conduced on fully constructed pavement sections. In all of these tests data collection was carried out using a portable "bike rack" arrangement mounted to a standard square receiver hitch at the back of a vehicle. The electronic distance wheel was mounted to the vehicle bumper (see Figure 29).

<u>I-93 in Thornton, NH</u>

The asphalt pavement was completely removed and replaced on I-93 during the summer of 2001. The section tested had been repaved, and was about to be open to traffic. Two lanes were available for testing – the high speed lane, and the shoulder. The nominal asphalt thickness was 4.5 inches on the main line, and 2 inches on the shoulder. Both were supported by a granular base. The setup at the I-93 maintenance shed is shown in Figure 29. The pavement section is shown in Figure 30. The data was collected in short continuous strips as the vehicle drove down the lane. Data collection was initiated as the core location was approached, and a mark was placed in the data when the antenna passed alongside the core location. In this way, the data at the core location could be easily identified in the analysis.

FIGURE 29 – Equipment Setup for I-93

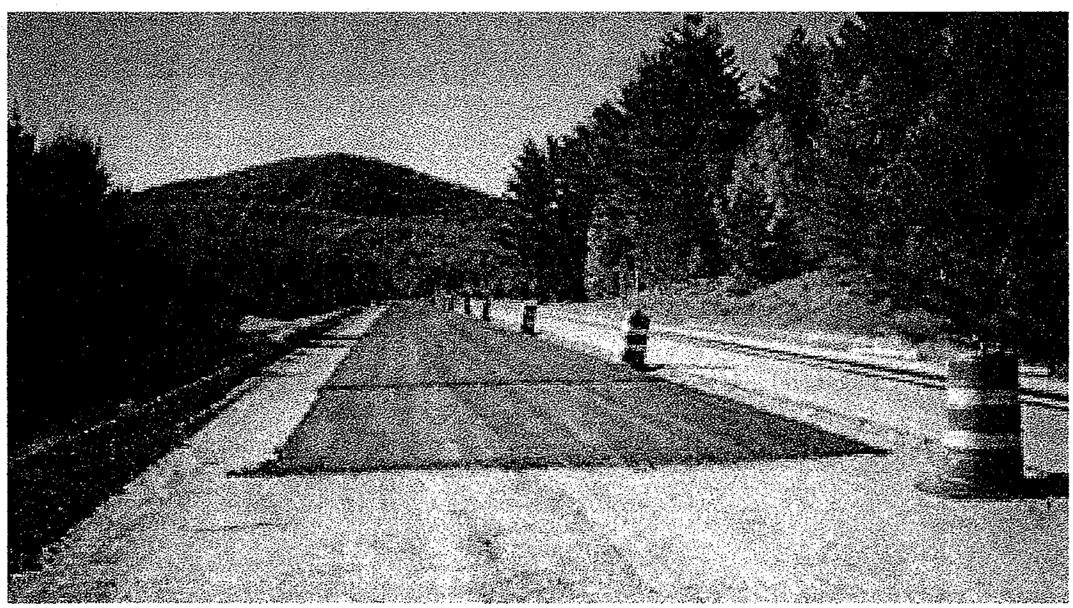


FIGURE 30 – I-93 Test Section, Northbound, South End, High Speed Lane

The FAA Technical Center (FAATC)

The FAA maintains a pavement test facility at its Technical Center in Atlantic City, NJ. The facility houses a 900-foot long by 60-foot wide test pavement. The pavement is laid out on a stationed grid. The pavement is composed of different types of pavement construction — some asphalt, and some concrete. Figure 31 shows the data collection setup at the FAATC. Two sections were tested under this program - a 5" thick section (item 3-3) and a 10" thick section (Item 3-2). Figure 32 shows the layout of these sections, with increasing station going from left to right. In both sections, the asphalt was underlain by a lean concrete ("econocrete") base.

The tests at the FAATC were carried out in a series of longitudinal survey lines, starting at station 900 and going down station, each at a different offset from the centerline of the pavement. Each survey line was 150 feet long. The first 62.5 feet were in the 5" section, then there was a 25 foot transition section, and finally 62.5 feet in the 10" section. A sample of the raw data is shown in Figure 32.

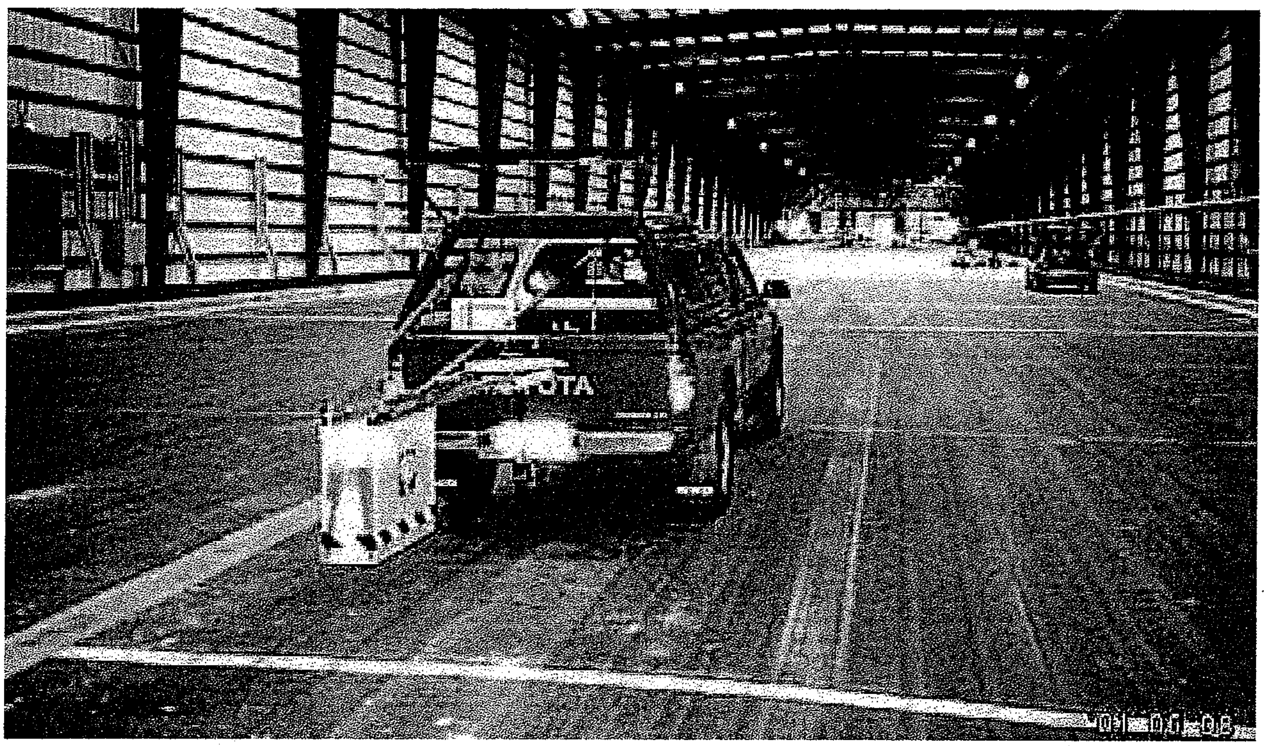


FIGURE 31 – Data Collection Setup at the FAATC

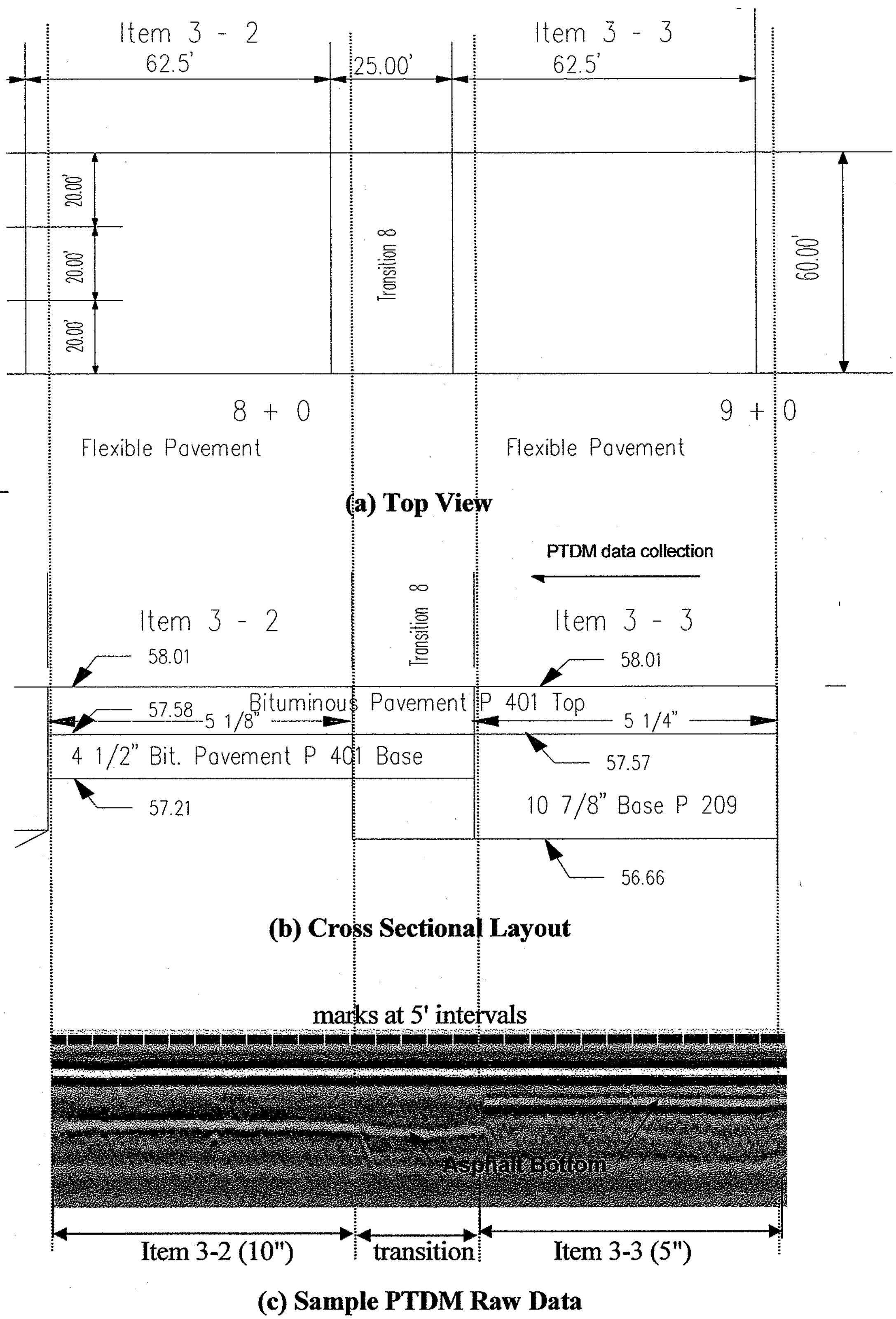
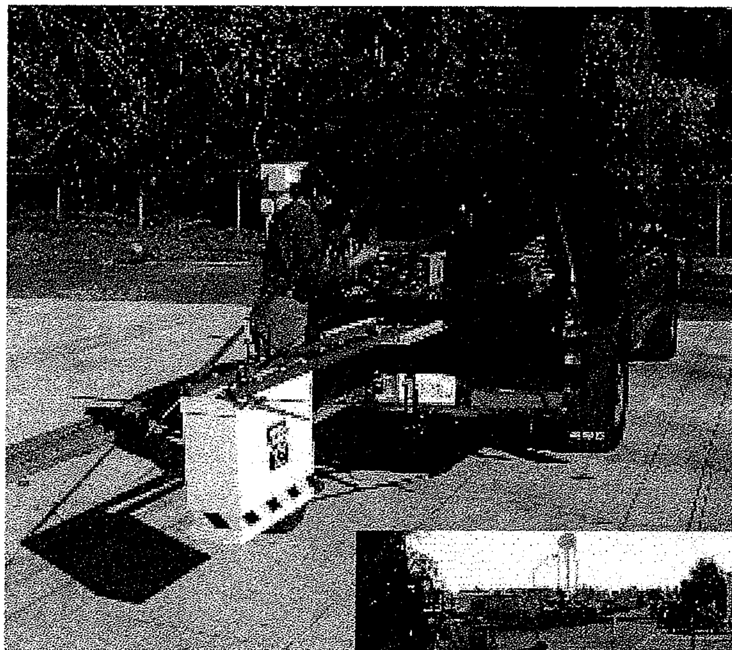


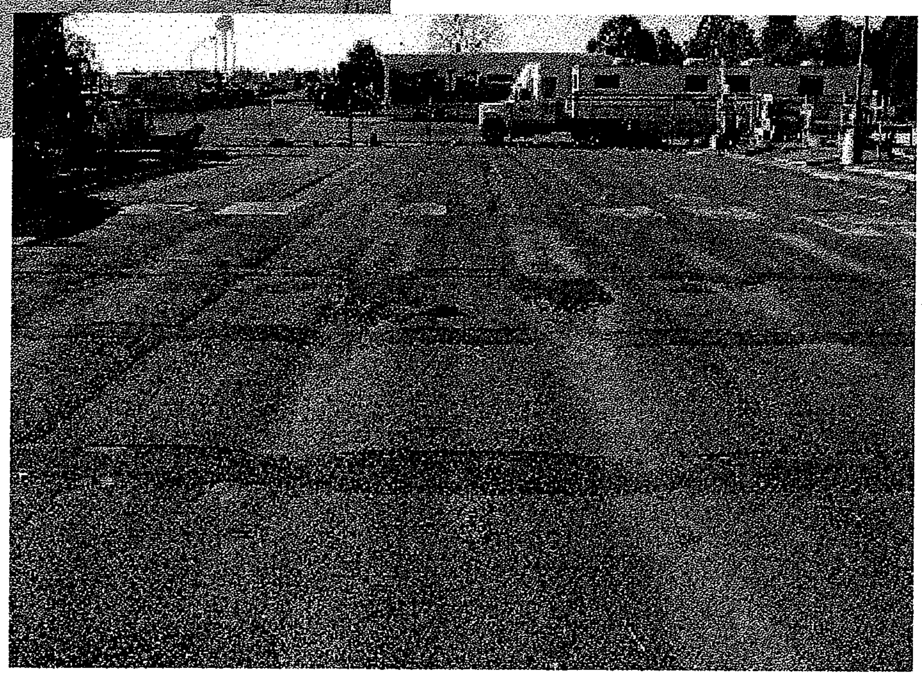
FIGURE 32 – FAA Technical Center Pavement Test Sections

FHWA Accelerated Load Facility (ALF)

The FHWA maintains an accelerated pavement facility at the Turner Fairbanks Research Center in McLean, VA. The facility is used to rapidly collect data on pavement performance under conditions in which axle loading and climatic conditions are controlled. The facility consists of 12 lanes, each 12' wide and 140' long, and each representing different types of pavement construction. Core thickness data was collected by the FHWA on the initial construction prior to application of the loading. The loading was applied in the wheelpaths of each test lane. Figure 33 shows the PTDM equipment setup and the test area. Note the heavy rutting in the loaded areas of the test lane.



(a) PTDM Equipment Setup



(b) Typical Lanes at the FHWA ALF Facility

FIGURE 33 – PTDM Testing at the FHWA ALF Facility in McLean, VA

PTDM data was collected in lanes 1, 2, 3, and 4 of the facility. These lanes were of asphalt construction, and were available for testing. The tests were carried out along the centerline of each lane in the unloaded area. The core locations were marked in the data so that the PTDM data at the core location could subsequently be identified.

National Center for Asphalt Technology (NCAT)

The NCAT facility in Auburn, Alabama, is a continuous oval-shaped test track consisting of 52 pavement sections, each with approximately 4" of asphalt surface. The principal variable amongst the 52 sections is the asphalt mix design. The design and the asphalt density of each section is well documented. Tests were carried out at NCAT for the purpose of correlating PTDM data with asphalt density.

Figure 34 shows data collection in progress at the test track. The equipment setup was identical to that used in the FHWA and FAA tests. Pavement section transition locations, marked on the side of the track, were marked in the PTDM data for reference during data analysis. Data was collected on both inside and outside wheelpaths of the primary test lane.

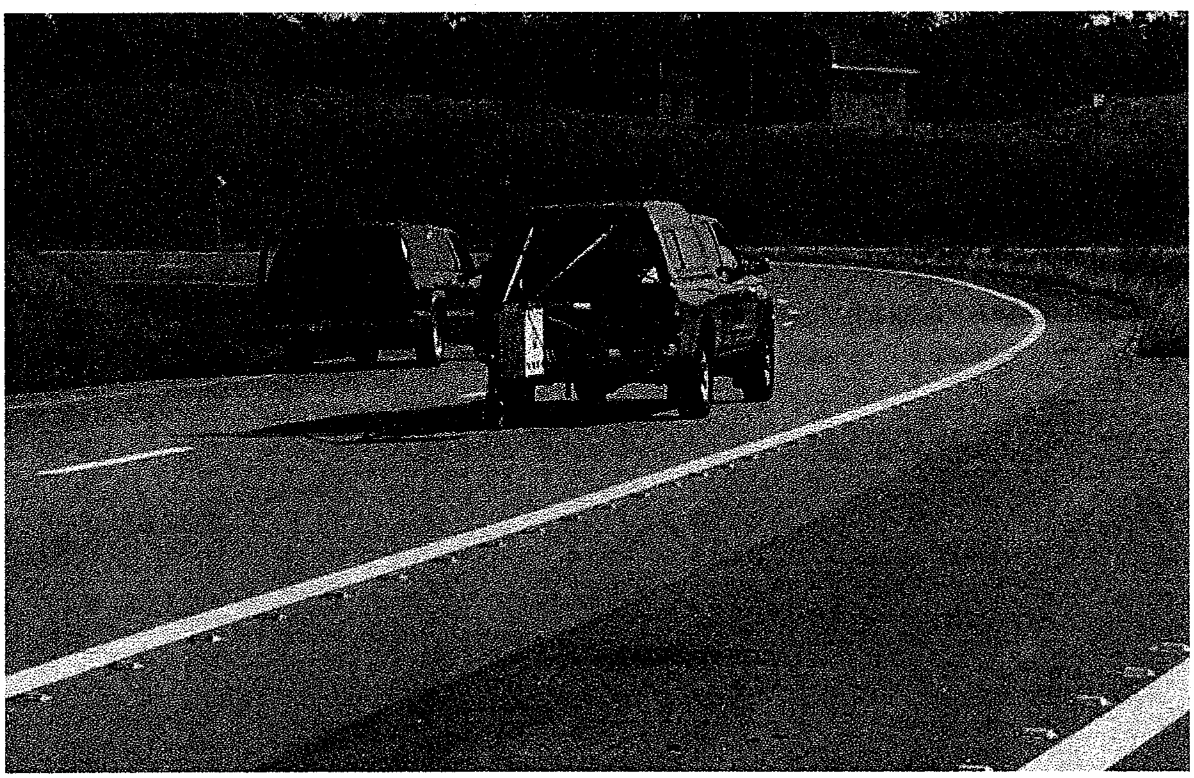


FIGURE 34 – Data Collection at the NCAT Facility in Auburn, AL

6.3 Data Analysis

The data from I-93, FAA, and FHWA facilities was analyzed for pavement thickness and correlated with available core information. For I-93 and FHWA, core data was already available for comparison. For FAA, cores were take at selected locations. The choice of location was based on the pavement thickness distribution as observed in the data. The FAA thickness data was presented as a contour plot, and locations of low, high, and typical thickness were selected for coring. The thickness maps for Items 3-2 and 3-3 are shown in Figure 35. Locations are marked with a "+" on the contour plot according to the criteria described above. Cores were taken at these locations, measured on site, and stored for future investigation (Figure 36).

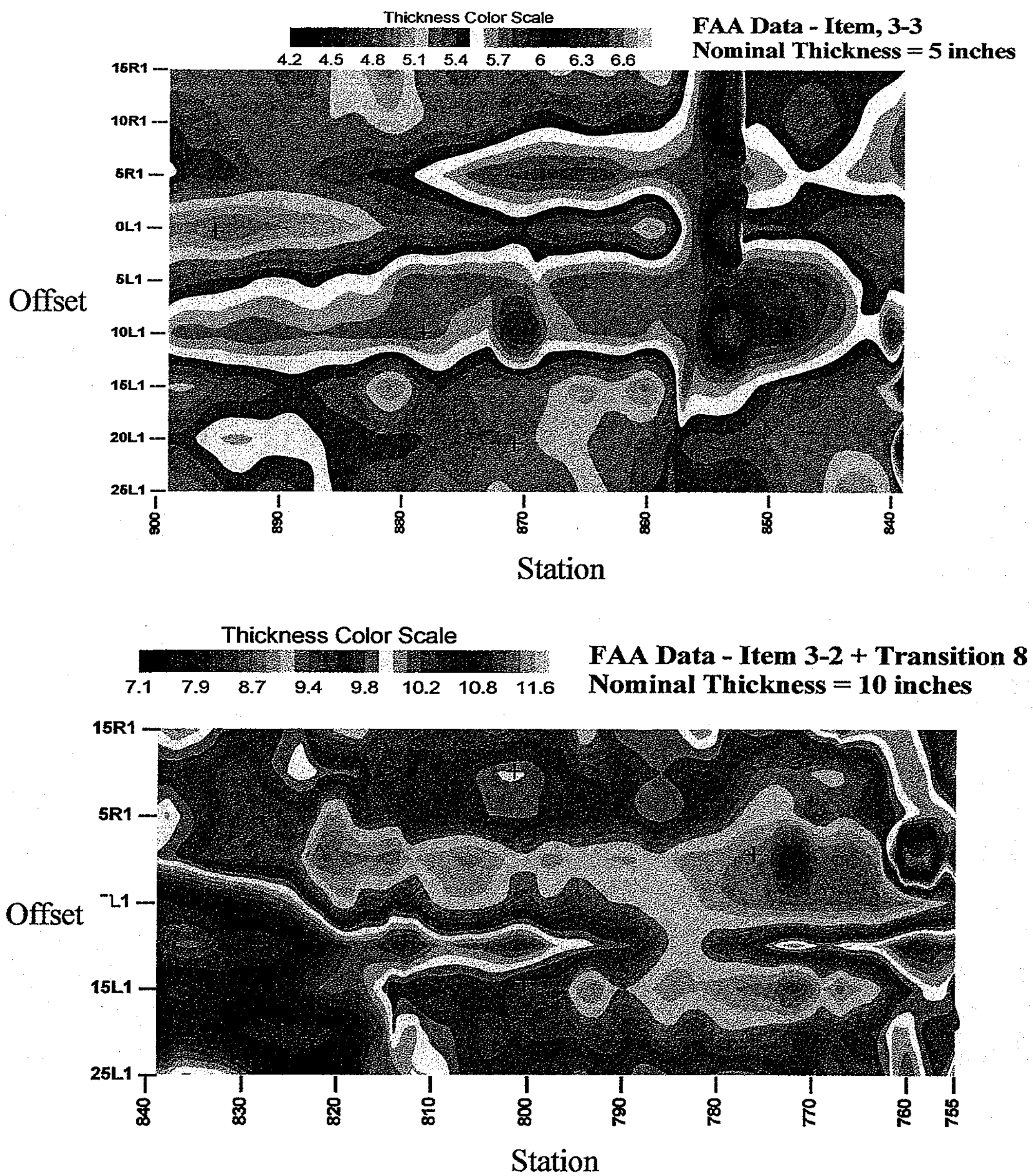


FIGURE 35 – Thickness Contours and Core Locations at the FAATC

The PTDM thickness data was correlated with all available core data, and the results of this correlation are shown in Figure 37. The results have been calculated using the PTDM software described earlier in this report. For the FAA data, one core was used for calibration purposes. Cores from the other sites were not used for calibration. The effects of the FAA calibration are shown in Figure 37.

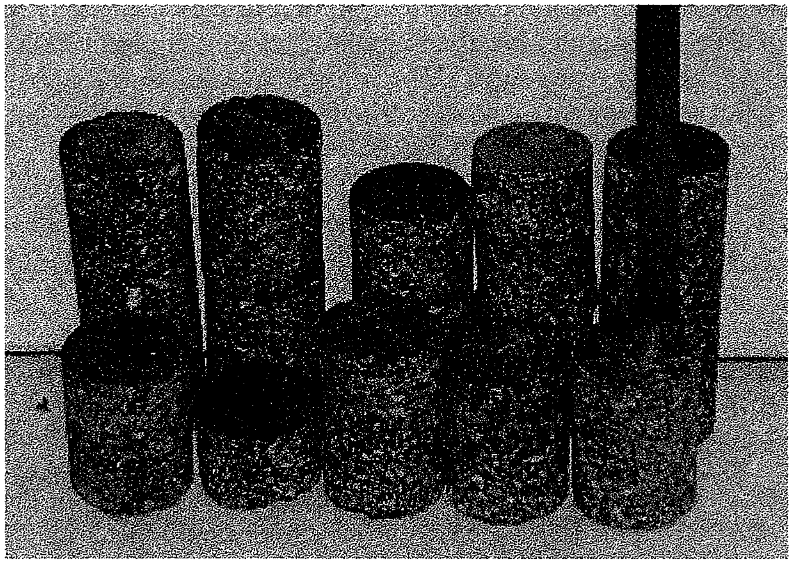


FIGURE 36 – Cores Taken at the FAATC

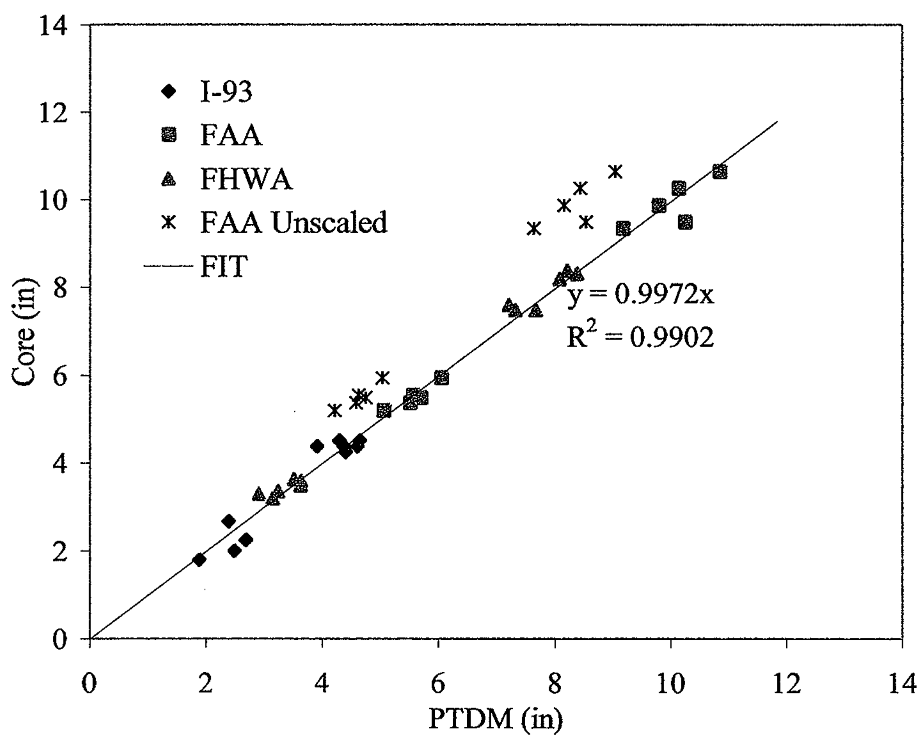


FIGURE 37 – Core vs PTDM Data for 3 Test Sites

The results with calibrated FAA data show a very good fit, with an R-squared of 0.99 and a slope of 0.997. The statistics of this data show a mean deviation between core and PTDM data of 0.01" and a standard deviation of 0.26". Assuming a Gaussian distribution, the statistics show a 95% probability than the mean error will fall between ± 0.1".

The data collected at the NCAT facility was used to evaluate density. The NCAT data log provides an average in-place density for each section. It also indicates the type of aggregate material used to make up the asphalt. For the purpose of evaluating the PTDM, the objective was to compare the average density using the PTDM with the average density provided by NCAT for asphalt mixes using the same aggregate source. The results of this comparison for asphalt sections using granite aggregates are shown in Figure 38.

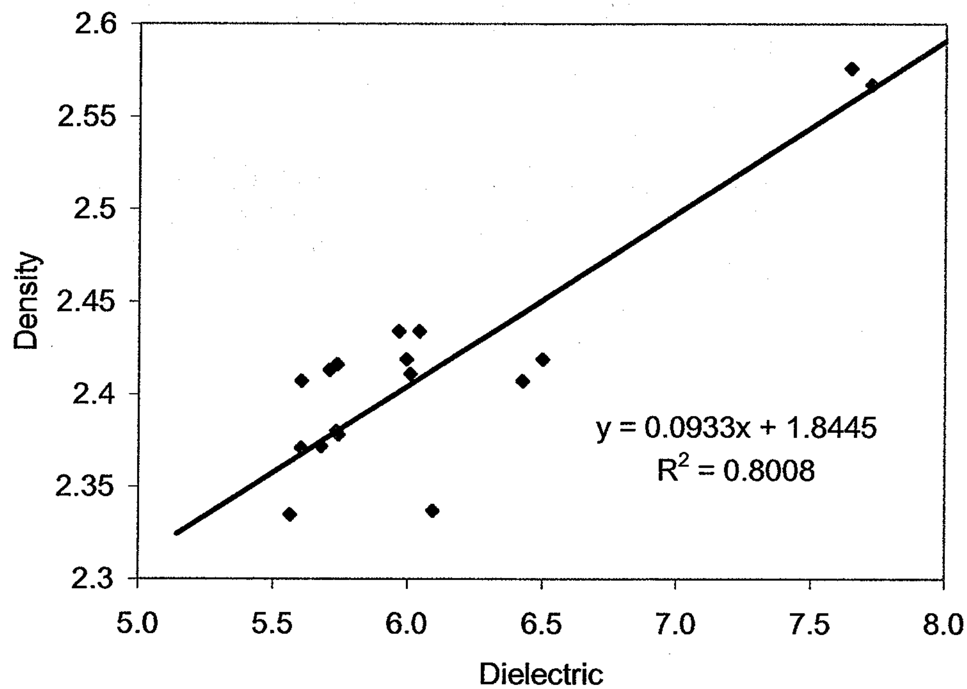


FIGURE 38 – Mean Density vs Mean Dielectric For Sections Using Granite Aggregate

Each point in Figure 38 is a mean value for a 200-foot pavement section. The mean density value is based on random cores taken from the section by NCAT. The mean dielectric value is based on the average of 200 dielectric data points analyzed from the PTDM data. The results show a reasonably good correlation, although the density range is limited.

Of more relevance to the PTDM application is the point-by-point density data, since the objective of the PTDM is to identify local density deficiencies. This data was not available at the time of this report, and thus cannot be presented at this time.

7. Summary and Conclusions

The work carried out under this project has demonstrated the feasibility of developing the PTDM. A compact horn antenna has been selected, and evaluated in the laboratory and field. Automated software has been developed and tested for calculating pavement thickness and density. The software has been designed for operation by a field technician at the time of data collection. Results obtained at several full-scale pavement sites show that this hardware/software combination provides accurate pavement thickness data. Good correlation between PTDM and core data has been demonstrated. Improvements on the thickness accuracy can be achieved by calibrating to one core per site. The asphalt dielectric constant calculated with the software has been shown to correlate with the pavement density. The dielectric readings provide a relative measure of density, and can be used to identify density deficiencies on a paving project.

It is recommended that the system be packaged using the control and acquisition capabilities of the GSSI SIR-20. The SIR-20 based systems are much smaller and more portable. The acquisition through a laptop provides a means for processing the data on site immediately after collection. The final objective will be to engineer this package into a relatively small portable unit which would be priced in the neighborhood of $10,000 to $20,000. In this price range the PTDM would be comparable to other pavement nondestructive testing devices, and thus would be available for routine use by contractors, state highway testing organizations, and by private and contracted testing laboratories. This testing device would represent a strong force towards increasing the quality of construction.

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ATTACHMENT 1

Pavement Layer Thickness Evaluation Using Ground Coupled Antenna and a Dielectric Block

As with a horn antenna, the dielectric constant of a pavement layer relative to the previous layer may be calculated by measuring the amplitude of the waveform peaks corresponding to reflections from the interfaces between the layers. The travel time (t) of the transmit pulse within a layer in conjunction with its relative dielectric permittivity determines the layer thickness:

$$\text{Thickness (in)} = (5.9\, t)/\sqrt{\varepsilon_a} \qquad (1)$$

where (t) is measured in nanoseconds from the pavement surface to the bottom of the layer being calculated, and ε_a is the relative dielectric permittivity of the pavement layer.

Using a dielectric block, the following relationships apply:

$$\varepsilon_b = \varepsilon_a \left[(1 - R_{ba})/(1 + R_{ba})\right]^2 \qquad (2)$$

or

$$\varepsilon_a = \varepsilon_b \left[(1 + R_{ba})/(1 - R_{ba})\right]^2 \qquad (3)$$

where

ε_b = dielectric constant of the dielectric block

$R_{ba} = A_{ba}/A_i$, the reflection coefficient between the block and the asphalt

A_{ba} = amplitude at the block/asphalt interface (your peak B)

A_i = the incident amplitude. Determine the incident amplitude from peak B in file 41 (metal plate under block). This can be assumed to be a constant for the survey unless there has been a change of gain. To handle gain changes, look at the ratio of the plate amplitude to the surface (peak A) amplitude (before subtraction), and use the data peak A and this ratio to calculate the incident amplitude at the pavement for each data file.

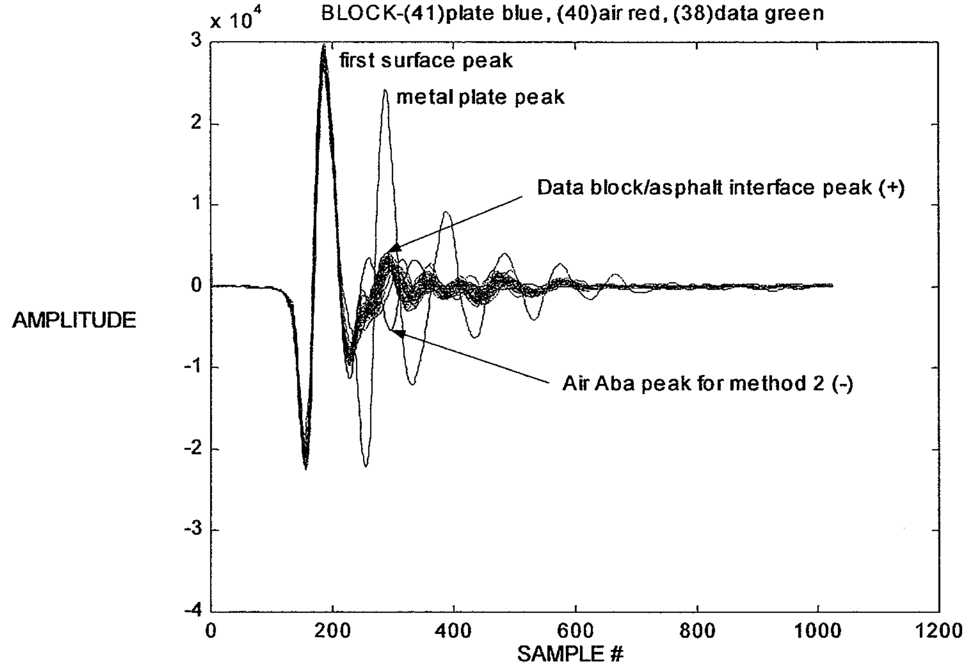
We can estimate ε_b as follows:

a) 1st Method
Using a data file collected on asphalt, assume that the average value of ε_a is 5.0. Calculate the average value of R_{ba} from the data, and, using eq. 2, calculate the average value of ε_b.

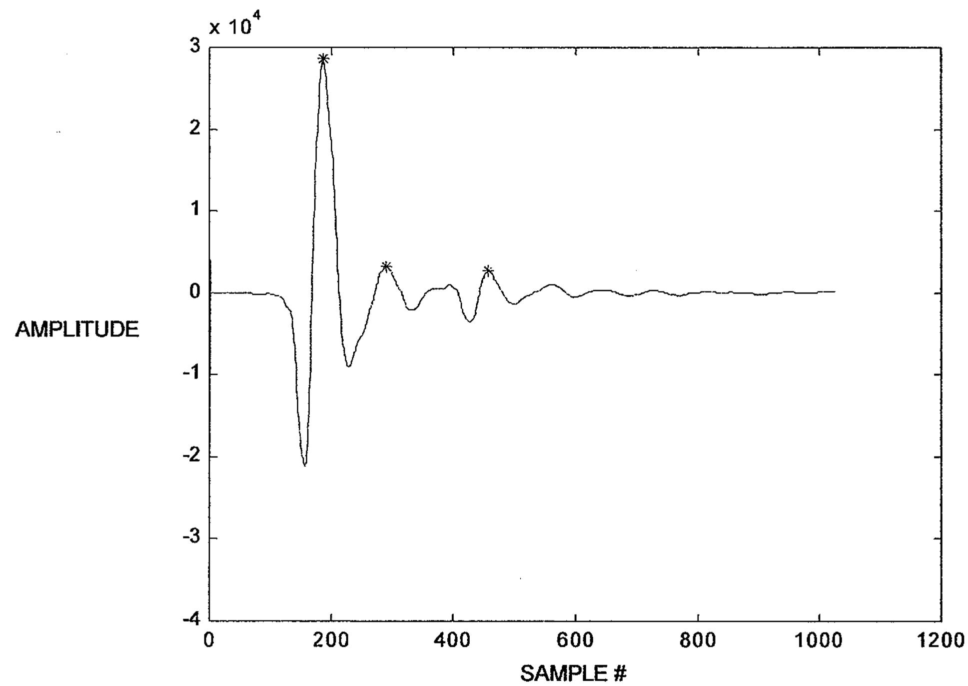
b) 2nd Method
Using an air file (antenna + block pointed away from pavement), repeat as in (a), noting, however, that here ε_a is for air, and hence = 1. Also note that since the reflection is from block to air, the peak is negative.

Once you have ε_b you can use eq. 3 to calculate ε_a directly from the data, and then eq. 1 to calculate thickness. The following figures show the calculation using Method 2.

Ground Coupled – Method 2: $\varepsilon_b = 2.3770$, Plate Ratio = 0.8575
(aligned peaks)



Peaks detected in thickness/dielectric analysis



Resulting Calculations