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Ground Penetrating Radar Surveys to Characterize Pavement Layer Thickness Variations at GPS Sites

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Abstract

Pavement layer thickness data are required for network- and project-level pavement management. Until now, adequate amounts of these data were difficult to obtain because of the cost, time, and interference involved in taking cores. A new nondestructive, noncontact method for thickness measurement is available and can be implemented from a survey vehicle moving at highway speed. The technology incorporates horn antenna radar equipment coupled with customized processing software called PAVLAYER©.

This report describes an accuracy evaluation of this technology in which results from 10 SHRP Long Term Pavement Performance (LTPP) asphalt pavement sections in 10 states were compared to core data. The results were evaluated in two steps: (1) "blind," without benefit of prior information from any core data; and (2) calibrated, using core data at one location per site. The evaluation showed deviations from cores of ±8% for blind evaluations and ±5% when calibration cores were used.

Executive Summary

The objective of this study was to evaluate the accuracy of ground penetrating radar (GPR) for measuring pavement thickness. Previous work has shown radar to be an accurate, nondestructive pavement thickness evaluation technique that can be implemented at highway speed. Such a technique is applicable to pavement engineering and management, and is of particular relevance to the SHRP Long Term Pavement Performance (LTPP) program. Radar can detect thickness variations within LTPP test sections that would not otherwise be revealed. Undetected thickness variations can produce errors in the LTPP data analysis and in the performance models being developed under SHRP.

This study was carried out at 10 LTPP General Pavement Study (GPS) asphalt pavement sites representing a range of environmental conditions and pavement structures. The surveys were carried out from February 24 to March 24, 1992. The sites were located in 10 southern and eastern states. Asphalt thicknesses at these sites ranged from 3 to 16 in. Cement-treated and granular base materials were included in these sites. Each radar survey was 1,500 ft long, beginning 500 ft before the GPS test section and ending 500 ft after the section. Radar data were processed at 5 ft longitudinal intervals, producing 300 thickness data points for each 1,500 ft site.

The GPS sites were surveyed in the following order:

GPS Site No.	Location	Plan Data: Layer Thickness from State Records (in.) Asphalt	Base	Base Material
223056	Bunkie, LA	10.0	8.0	Cement Treated Base
124108	Ft. Walton Beach, FL	10.6	12.0	Soil/Aggregate
134112	Brunswick, GA	16.5		None
371645	Whiteville, NC	7.5	7.0	Cement Treated Base
512004	Danville, VA	7.4	6.5	Cement/Aggregate
242401	Edgewood, MD	6.7	4.0	Lean Concrete
341033	Trenton, NJ	7.0	6.0	Crushed Stone
479024	Murfreesboro, TN	9.3	5.0	Crushed Stone
053071	Rogers, AR	17.0		None
482108	Texas City, TX	3.0	14.0	Cement/Aggregate

The radar data were analyzed using INFRASENSE's PAVLAYER© software. This software tracks the amplitudes and arrival times of the significant reflectors in the radar data and computes layer properties and thicknesses from this information. The accuracy of the radar-based calculations was evaluated using core data obtained from the SHRP LTPP database at 67 locations. These core data were collected during the 1989-90 period using a standard pattern of coring and test pits.

The accuracy of the radar asphalt thickness calculations was evaluated against information provided in a stepwise fashion by SHRP. The steps were: a "blind" evaluation, an update using pavement structure information from plan data, an update using partial core data from one location, and a final calibration. An evaluation of the accuracy of the base thickness data could not be carried out because a complete set of data was unavailable from SHRP.

The results indicated that blind radar asphalt thickness data correlated with the core data with an R^2 of 0.98 and a root mean square (RMS) deviation of ±0.78 in., or ±7.1%. Plan data had little influence on revising the blind radar calculations for asphalt thickness. The availability of the approach end core data helped to identify an error in detecting the asphalt bottom at one site. Once this was corrected, the RMS deviation was reduced to ±0.68 in. Finally, the full set of radar data was calibrated with the approach end core data from each GPS site. The resulting RMS deviation was reduced to ±0.51 in., or ±5.1%. These deviations would have been lower if comparison and calibration cores were taken after, rather than before, the radar survey.

The radar data revealed deviations from the LTPP cores within the GPS sections that exceeded 10% in 5 of the 10 sites surveyed. The maximum deviation between LTPP core data and radar data within a GPS site ranged from 6% to 21%. The potential errors in LTPP data analysis and modeling associated with these deviations could be reduced if radar thickness data were available for each site.

The accuracy demonstrated in this study indicates that, using appropriate equipment and software, radar can satisfy the thickness information needs of both LTPP and the pavement engineering and management community.

1. Introduction

1.1 Background and Objectives

The objective of this study was to evaluate the accuracy of ground penetrating radar (GPR) for measuring pavement thickness. Accurate, continuous thickness data are important to many areas of project- and network-level pavement management, including establishment of load ratings, prediction of pavement life, design of overlays, and interpretation of the results of falling weight deflectometer (FWD) and other structural tests. For new construction, it is important to ensure that the thickness of material being placed by the contractor meets specifications.

Layer thicknesses are often determined from historical records. However, records are frequently inaccurate or nonexistent. At present, the only accepted method for pavement thickness measurement is through core sampling and test pits. These direct testing methods are time-consuming, detrimental to the pavement structure, and intrusive to traffic. In addition, they only provide data at the location of the test, and assumptions must be made regarding variations between cores.

Continuous pavement layer thickness data have a particular significance to the SHRP Long Term Pavement Performance (LTPP) program. Currently, pavement thickness measurements at LTPP sites are obtained from core and test pit data taken at each end of the site, and these measurements are used to estimate the layer thickness within the 500 ft test section. It was SHRP's decision not to conduct destructive tests within the test section in order to avoid damage to the pavement structure.

In actuality, however, the pavement thickness can vary substantially within the 500 ft section. Figure 1.1 indicates radar-based pavement thickness data at an LTPP site in Texas, along with confirming core data. These data indicate endpoint measurements of 7 in., when in fact the thickness within the site ranged from 7 to 9 in.

Undetected thickness variations can produce errors in the LTPP data analysis and in the performance models being developed by SHRP. Small undetected layer thickness variations result in large errors in backcalculated modulus (e.g., Eckrose, 1989; Maser and Scullion, 1992). The type of undetected thickness variations shown in Figure 1.1 would produce an error in base modulus of more than 100%. Undetected thickness variations also influence the validity of pavement performance models being developed by SHRP. This influence is due to the unknown deviations from the assumed layer thicknesses and material properties within the SHRP LTPP sections.

The efficacy of GPR for thickness evaluation has been suggested in a number of research and experimental studies over the past 10 years (e.g., ASTM, 1987; Berg et al., 1986; Eckrose, 1989; Rosetta, 1980). In these early applications, reflected radar pulses were collected at low speed with the antenna in contact with the ground, and data analysis was qualitative and manual. There was no systematic investigation comparing predicted to actual thickness for a range of conditions.

A more recent GPR study of four Texas SHRP asphalt pavement test sites resulted in radar prediction accuracies for asphalt thickness within ±0.32 in. (±5%) using the radar data alone (Maser and Scullion, 1992). When one calibration core was used per site, the accuracy was improved to ±0.11 in. The accuracy of the radar predictions for base thickness was within ±1.00 in. The nominal layer thickness at these sites ranged from 1 to 8 in. of asphalt and 6 to 10 in. of base.

The above surveys were carried out at speeds ranging from 5 to 40 mph, and data were acquired at longitudinal intervals of 1 ft. The radar data were analyzed automatically using software that operated directly on the raw radar waveforms. This software is based on an electromagnetic model of the pavement layer structure. The 1992 study indicated that the pavement thickness calculations were independent of survey speed, and that the thickness results were repeatable.

More recent follow-up studies have been carried out by Texas Transportation Institute (TTI) under Texas Department of Transportation (TxDOT) sponsorship and by Kansas University under Kansas Department of Transportation (KDOT) sponsorship (Maser, 1992; Roddis et al., 1992). These studies have confirmed the accuracy levels obtained in the original study. Typical results of the TxDOT and KDOT studies are shown in Figures 1.1 and 1.2. Figures 1.3 and 1.4 summarize the correlations between radar data and cores obtained in these two studies. The above results indicate that radar can provide continuous, accurate, nondestructive measurement of pavement layer thickness.

1.2 Scope of the Study

The study described in this report was carried out to verify the accuracy of radar-based thickness predictions over a range of conditions of interest to SHRP. Ten LTPP General Pavement Study (GPS) sites located in 10 different states were selected for evaluation. Asphalt thicknesses at these sites ranged from 3 to 16 in. Cement-treated and granular base materials were included in these sites.

The study was organized to evaluate the accuracy of the radar calculations by providing INFRASENSE with varying levels of prior information. The steps were:

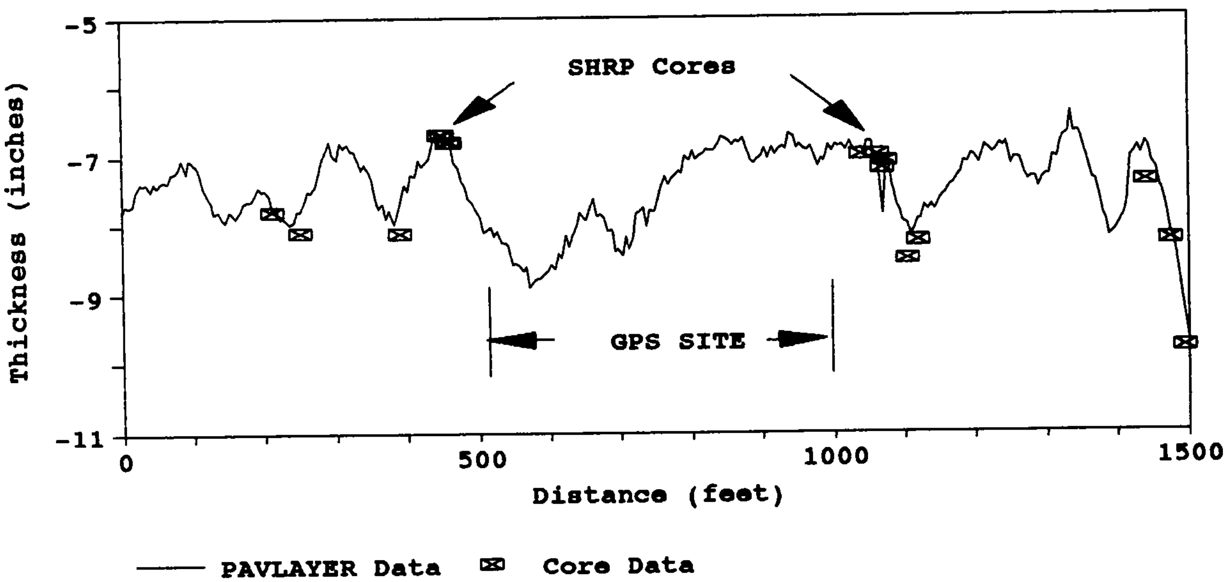


Figure 1.1 Typical Results from Texas Study

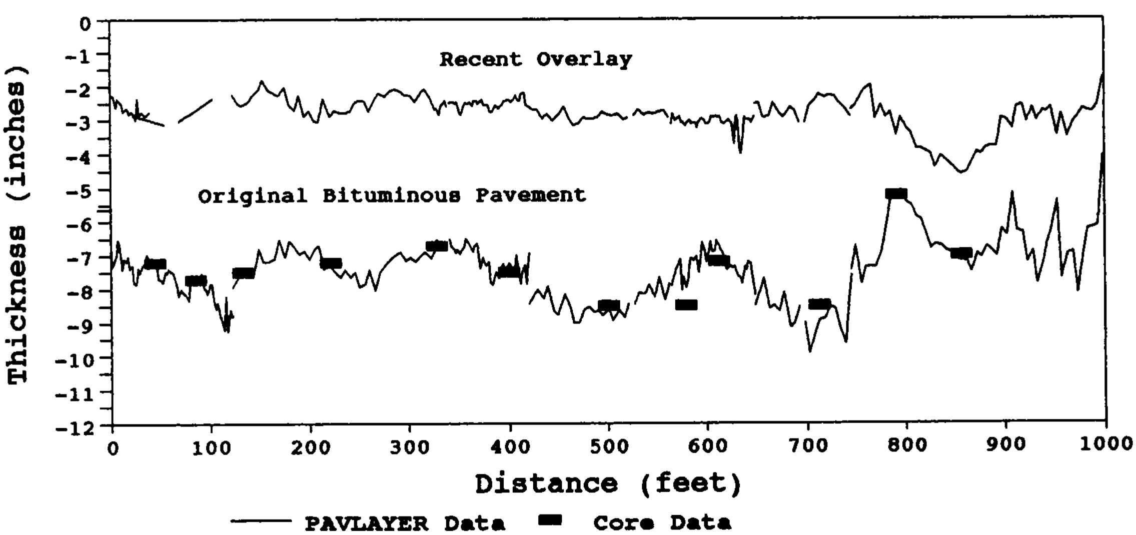


Figure 1.2 Typical Results from Kansas Study

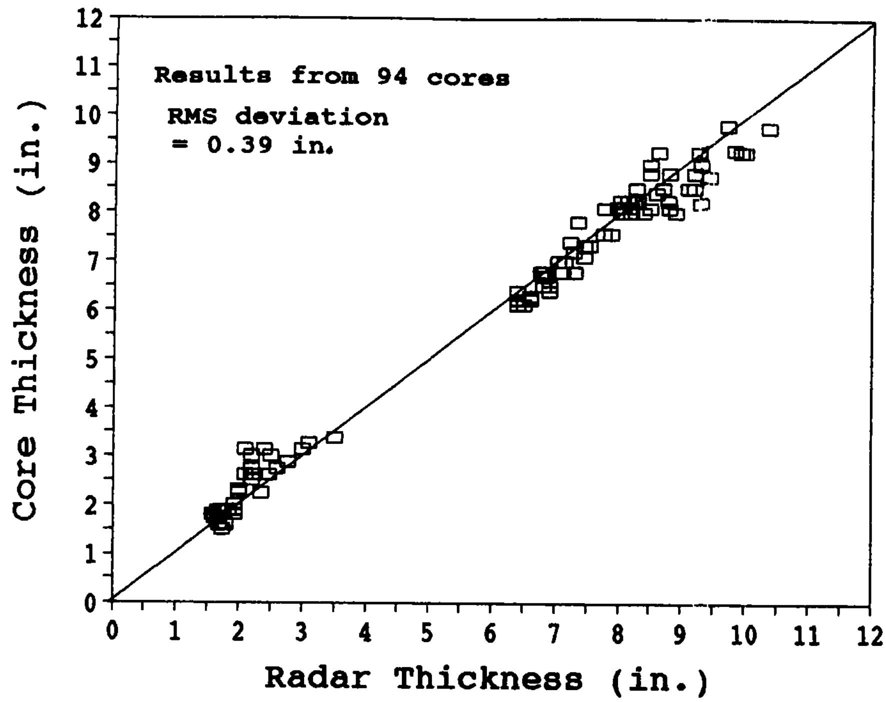


Figure 1.3 Summary of Texas Study Cores vs. Radar Data

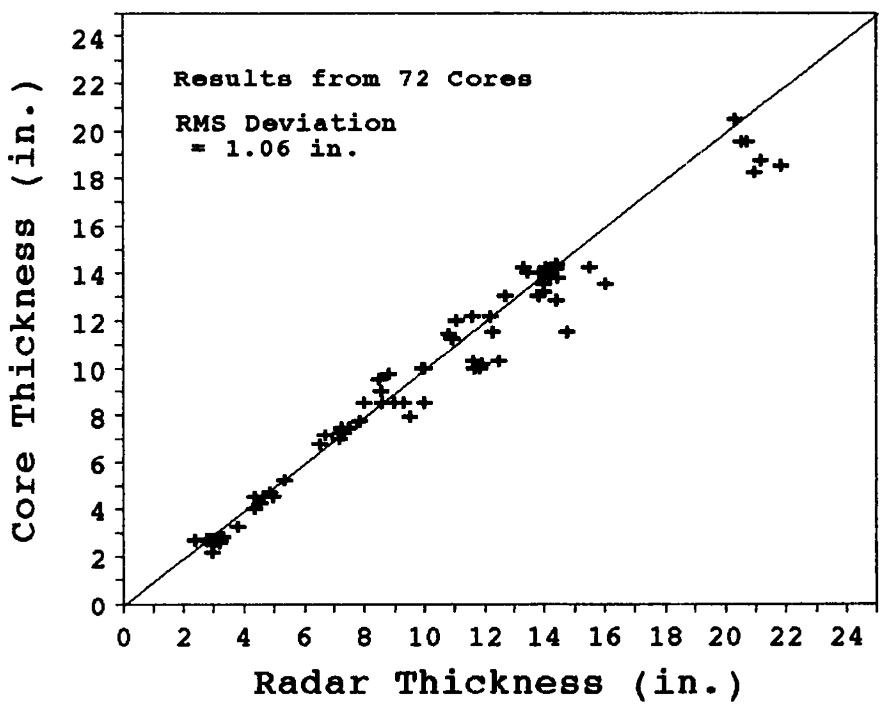


Figure 1.4 Summary of Kansas Study Cores vs. Radar Data

1. "Blind" evaluation. The initial radar evaluation was done "blind;" that is, no information regarding pavement structure was provided to INFRASENSE.

2. Update with "plan" data. INFRASENSE was provided with "plan" data (i.e., data made available to SHRP from state records) for each of the sites. State records of pavement layer thickness are not always current or accurate, but they do represent some useful information regarding the pavement structure. Consequently, the plan data were made available as a possible source of information to be used to update or modify the blind calculations.

3. Correlation (and calibration) with cores from approach end. The radar results from step 2 were correlated with core data from the approach end of the LTPP site. The "leave" end data were omitted. This was done to assess the influence of an approach end calibration on the accuracy of the leave end data. During this step, radar data were calibrated using the approach end data.

4. Correlation with all available core data. The "leave" end data were provided; the accuracy of the radar data vs. core data was assessed using both the uncalibrated data (step 2) and the calibrated data (step 3).

The following sections describe the principles of radar relevant to this application, the conduct of the test program, the analysis procedure used, the data generated, and the correlation of the radar data with the core data.

2. Principles of Ground Penetrating Radar

Ground penetrating radar (GPR) operates by transmitting short pulses of electromagnetic energy into the pavement using an antenna attached to a survey vehicle (Figures 2.1 and 2.2). These pulses are reflected back to the antenna with an arrival time and amplitude that vary according to the location and nature of dielectric discontinuities in the material (air/asphalt, asphalt/base, etc.). The reflected energy is captured and can be displayed on an oscilloscope to form a series of pulses that are referred to as the radar waveform. The waveform contains a record of the properties and thicknesses of the layers within the pavement. Figure 2.3 shows a typical set of pavement waveforms collected during this project.

Figure 2.1 Radar Van Supplied by Pulse Radar, Inc.

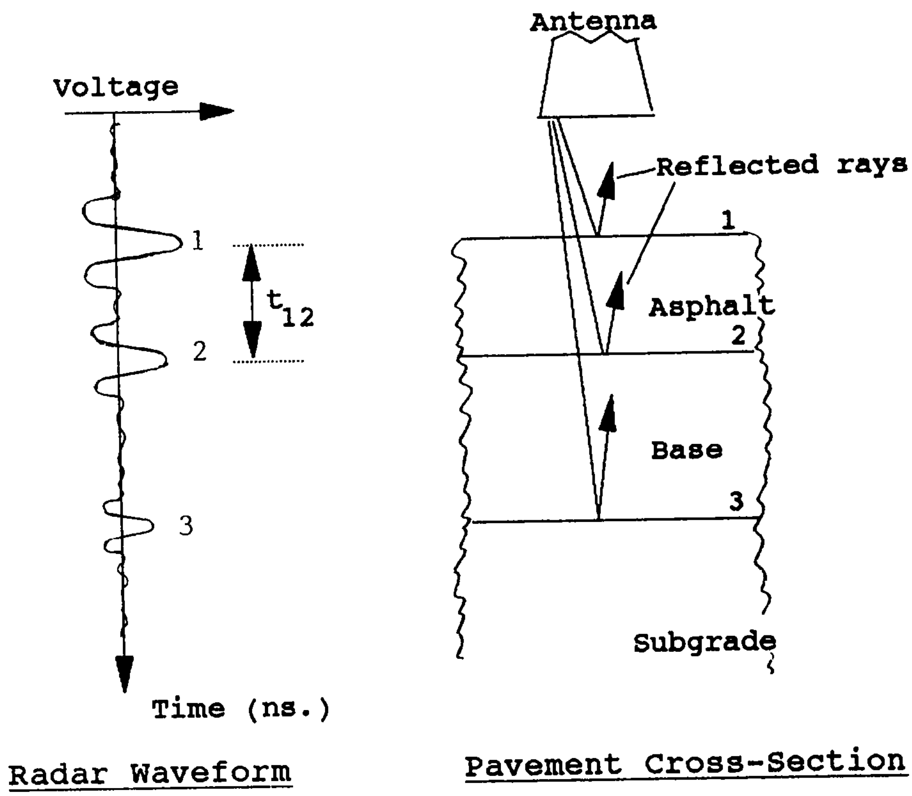


Figure 2.2 Model of Radar Pavement Data

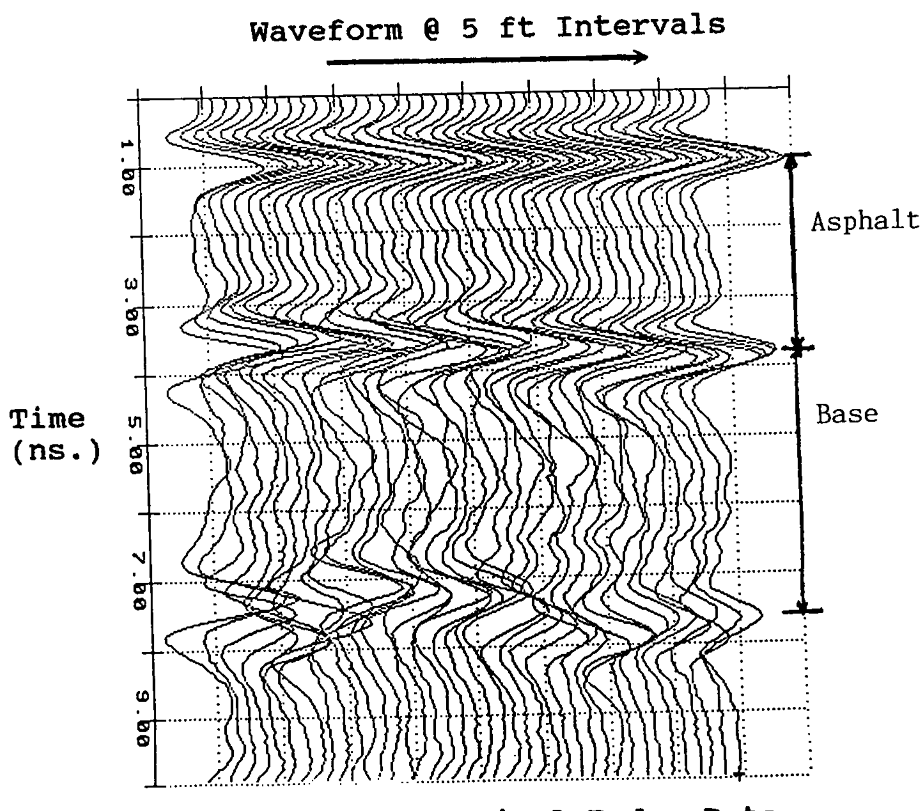


Figure 2.3 Typical Radar Data

The pavement layer thicknesses and properties can be calculated by measuring the amplitude and arrival times of the waveform peaks corresponding to reflections from the interfaces between the layers (Figure 2.3). The travel time of the transmit pulse within a layer in conjunction with its velocity determines the layer thickness:

$$\text{Thickness} = \text{velocity} \times (\text{time}/2) \qquad (1)$$

Because the measured time between peaks represents the round-trip travel of the radar pulse, the thickness computation is based on time divided by 2. The radar velocity can be computed from the dielectric constant ϵ of the medium:

$$\text{Velocity} = 11.8/\sqrt{\epsilon} \quad (\text{inches/nanoseconds}) \qquad (2)$$

where 11.8 is the radar velocity in free space in inches/nanoseconds. Combining Equations 1 and 2 yields:

$$\text{Thickness} = (5.9 \times \text{time})/\sqrt{\epsilon} \quad (\text{inches}) \qquad (3)$$

where time is measured in nanoseconds.

The dielectric constant of a pavement layer relative to the layer above can be calculated by measuring the amplitude of the waveform peaks corresponding to reflections from the interfaces between the layers. The surface layer dielectric constant can be computed by measuring the ratio of the radar reflection <u>from</u> the pavement surface to the radar amplitude incident <u>to</u> the pavement surface. This ratio, called the reflection coefficient, can be expressed as follows:

$$\text{Reflection Coef } (1\text{-}2) = (\sqrt{\epsilon_1} - \sqrt{\epsilon_2})/(\sqrt{\epsilon_1} + \sqrt{\epsilon_2}) \qquad (4)$$

where the subscripts 1 and 2 refer to the successive layers. The incident amplitude on the pavement can be determined by measuring the reflection from a plate on the pavement surface because the plate reflects 100%. Using this amplitude, rearranging Equation 4, and noting that the dielectric constant of air is 1, the asphalt dielectric constant ϵ_a can be obtained:

$$\epsilon_a = [(A_{pl} + A)/(A_{pl} - A)]^2 \qquad (5)$$

where A = amplitude of reflection from asphalt
A_{pl} = amplitude of reflection from metal plate (= negative of incident amplitude)

A similar analysis can be used to compute the dielectric constant ϵ_b of the base material. The resulting relationship (Maser, 1989) is:

$$\epsilon_b = \epsilon_a [(F - R2)/(F + R2)]^2 \qquad (6)$$

where $F = (4\sqrt{\epsilon_a})/(1 - \epsilon_a)$

R2 = ratio of reflected amplitude from the top of the base layer to the reflected amplitude from the top of the asphalt

Because the radar pulse has a width of its own, the layers must be thick enough for the reflections from each layer to be clearly resolved. This minimum thickness can be calculated from the radar pulse width (in nanoseconds) and the radar velocity in the medium. For the horn antennas commonly used for this application, this thickness is approximately 2.5 in. in asphalt. With ground-coupled dipole antennas such as those commonly used for geotechnical applications, the transmit pulses are two to three times longer (due to ringing) and the thickness resolution is limited to much thicker layers.

To determine thicknesses less than this minimum resolution, a numerical procedure called deconvolution is required. This procedure decomposes overlapping reflections into their individual components. In a previous study (Maser, 1992) deconvolution analysis indicated that thickness calculations can be accurate for layers as thin as 1 in.

Note that these analyses make two important assumptions: (1) the layers are homogeneous, and (2) the layers are nonconductive. Assumption 1 is violated when the layers within the asphalt are not uniform, which may occur due to overlays or to differences in properties of successive lifts of the initial pavement. When these layers are not uniform, intermediate reflections will occur within the asphalt, hence the use of Equation 3 for the entire asphalt layer will be incorrect. This error can be corrected by recognizing the possibility of layering within the asphalt and by incorporating this layering into the pavement model. Assumption 2 is generally valid for asphalt but may be less valid for concrete and base material due to higher moisture content.

3. Design and Conduct of the Test Program

Radar surveys were carried out at General Pavement Study (GPS) sites in 10 southern and eastern states. All sites were asphalt pavements. The surveys were carried out from February 24 to March 24, 1992. The GPS sites were surveyed in the following order:

GPS Site No.	Location	Plan Data: Layer Thickness from State Records (in.) Asphalt	Base	Base Material
223056	Bunkie, LA	10.0	8.0	Cement Treated Base
124108	Ft. Walton Beach, FL	10.6	12.0	Soil/Aggregate
134112	Brunswick, GA	16.5		None
371645	Whiteville, NC	7.5	7.0	Cement Treated Base
512004	Danville, VA	7.4	6.5	Cement/Aggregate
242401	Edgewood, MD	6.7	4.0	Lean Concrete
341033	Trenton, NJ	7.0	6.0	Crushed Stone
479024	Murfreesboro, TN	9.3	5.0	Crushed Stone
053071	Rogers, AR	17.0		None
482108	Texas City, TX	3.0	14.0	Cement/Aggregate

All 10 surveys were carried out under INFRASENSE supervision using equipment and personnel provided by Pulse Radar, Inc. The equipment was the Pulse Radar R-II radar system used in conjunction with its RDAS data acquisition software. This equipment was used in prior published studies conducted by INFRASENSE in Texas and Kansas (Section 1.1). All radar data were continuously digitized and stored to hard disk using a 386 PC computer housed in the van. The radar data were subsequently analyzed by INFRASENSE using PAVLAYER© software.

Each site survey was completed within 2 hours. A 1,500 ft survey length was laid out at each site using a survey wheel, beginning 500 ft before the start of the GPS section and ending 500 ft beyond the GPS section. This means that SHRP core and test pit data occurred from 430 to 460 ft and from 1,040 to 1,070 ft in the 1,500 ft survey. All startpoints and endpoints for these 1,500 ft sections were painted on the pavement.

One radar survey was conducted in the right wheelpath at each site. At nine sites, additional surveys were carried out in the center of the lane and/or in the left wheelpath. Metal plates placed on the pavement surface provided markers in the data for identifying the beginning and end of the test section.

Two types of traffic control were provided for these surveys. In seven states, the test lane was fully closed with traffic cones. In three states, the surveys were conducted with a trailing arrowboard truck. Surveys were carried out at speeds ranging from

10 to 20 mph. Higher speeds can be used but were not convenient or necessary for these short test sections.

Pavement surface conditions were dry, and the most recent precipitation was more than 12 hours before each survey. The one exception was in Arkansas, where there had been precipitation the previous night. The Arkansas pavement had an open graded friction course that retained visible moisture below the surface. Areas that did not have this friction course were surface dry. The presence of this surface moisture did not affect the data analysis, although it may have influenced the accuracy of the results by distorting the computed dielectric constant for the top layer.

Three calibration tests are normally conducted by INFRASENSE for each survey: (1) an internal reflection test, (2) a plate reflection test, and (3) a time calibration test. These calibrations are usually carried out each time the radar equipment is set up, either for a new site or for a new survey day. Experience has shown, however, that these calibrations do not change significantly during the course of a project. Consequently, one set of calibrations is normally used for the analysis of the entire project data set.

4. Data Analysis and Results

4.1 Data Analysis Procedures

The data were analyzed using INFRASENSE's PAVLAYER© software. This software tracks the amplitudes and arrival times of the significant reflectors in the radar data and then computes layer properties and thicknesses.

The bottom of the asphalt layer is generally identified as the first major subsurface reflector (Figure 2.3). This occurs because the dielectric properties of asphalt are usually very different from those of typical base materials. The bottom of the base is usually identified as the second major reflector. The base/subgrade interface reflection is usually much weaker because base and subgrade materials are more similar than asphalt and base materials. In many cases, the base and subgrade are so similar that an interface cannot be detected, hence the base thickness cannot be calculated. This would be the case, for example, when there is a stabilized base created from the local subgrade material.

The data analysis was carried out using Equations 1 through 6 (Chapter 2). Asphalt pavement thickness was calculated in two steps: (1) determination of the radar velocity in the asphalt, using the asphalt dielectric constant determined from the surface reflection using Equation 5, and (2) computation of the thickness from the velocity and the arrival time of the reflection from the bottom of the asphalt using Equation 4. The base layer thickness was calculated in a similar fashion, except that the radar velocity in the base material was determined from the base material dielectric constant computed from the magnitude of the reflection at the asphalt/base interface using Equation 6.

4.2 Analysis Results

Typical asphalt and base thickness results calculated from the radar data are shown in Figure 4.1, which represents 300 data points calculated at 5 ft longitudinal intervals. Plots of asphalt thickness for each of the 10 sites are presented in the Appendix (A.1-A.10). The bottom of the asphalt layer was very clear in all sites (as in Figure 2.3) except for New Jersey, which indicated multiple weak layer interfaces. The following paragraphs describe these results in further detail.

4.2.1 Blind Results vs. Plan Data

Table 4.1 presents statistics of the blind results and compares these to the plan data supplied by SHRP. The means and standard deviations (SDs) of the radar thickness data were computed from the 300 data points representing 1,500 ft survey lengths.

Asphalt thickness. The following observations can be made from Table 4.1:

(1) Radar asphalt thickness measurements for Louisiana, Florida, Georgia, and Arkansas are 7% to 10% less than plan data. This suggests the possibility of a systematic error that may be related to calibration of the radar equipment.

(2) Radar data indicates asphalt thicknesses at North Carolina, Tennessee, and New Jersey that are respectively 2.5, 1.9, and 4.0 in. greater than indicated by the plan data. As can be seen in Figure 4.2, the bottom of the asphalt layer is very clear at North Carolina, and it was therefore assumed that there was a recent overlay not accounted for in the plan data.[1] A similar conclusion was reached for Tennessee. Figure 4.3 shows more ambiguity at New Jersey. The bottom of the asphalt was originally selected at interface "C"; although "B" may correctly represent the asphalt bottom, "C" was the strongest.

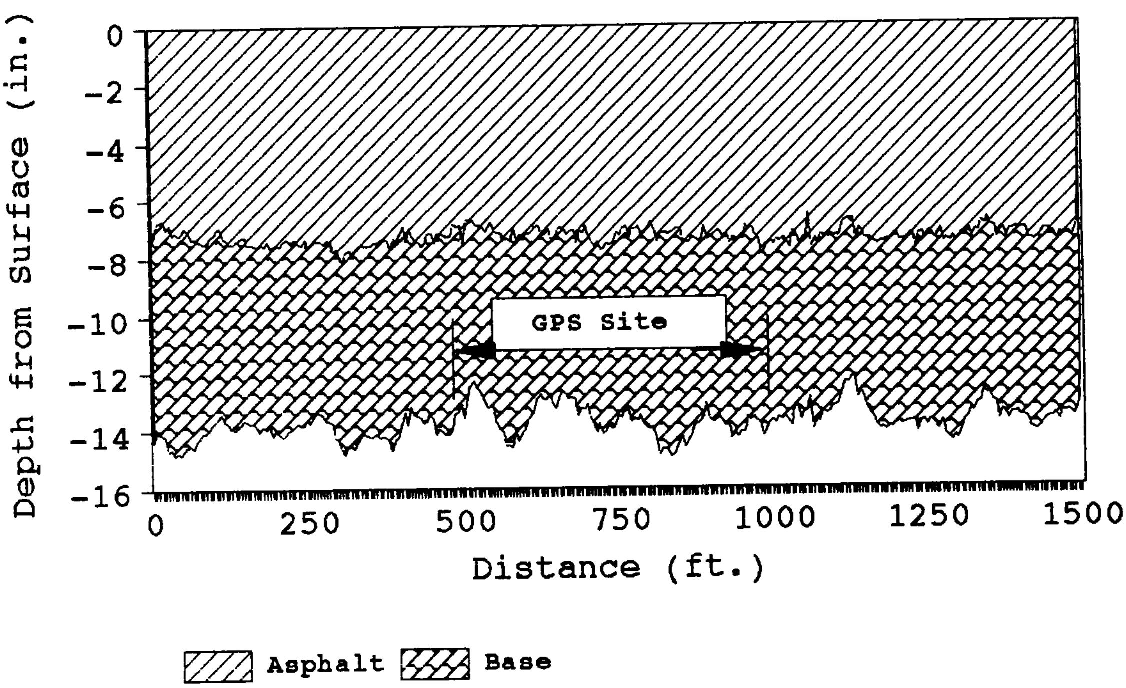


Figure 4.1 Sample Analysis Results
(SHRP GPS Site 512004, Danville, VA)

[1] It was later learned that the North Carolina data were incorrectly transcribed from the North Carolina records to the SHRP database.

Table 4.1 Comparison of Blind Radar Data with LTPP Plan Thickness

Site	Bituminous Layer Thickness (in.) Radar Mean	Radar SD	Plan	Base Layer Thickness (in.) Radar Mean	Radar SD	Plan	Type
LA (223056)	8.77	0.32	10.00	not computed		8.00	Soil Cement
FL (124108)	9.81	0.28	10.60	not computed		12.00	Soil/Aggregate Subbase
GA (134112)	15.50	0.86	16.50	6.42	1.71	none	
NC (371645)	7.05	0.39	4.50	not computed		7.00	Soil Cement
VA (512004)	7.30	0.25	7.40	6.43	0.71	6.50	Cement/ Aggregate Mix
MD (242401)	7.23	0.30	6.70	4.08	0.63	4.00	Lean Concrete
NJ (341003)	11.02	0.75	7.00	4.52	0.83	6.00	Crushed Stone Subbase
TN (479024)	11.20	1.66	8.00	not computed		5.00	Crushed Stone, Gravel or Slag Subbase
AR (053071)	15.85	0.74	17.00	not computed		none	
TX (482108)	3.26	0.30	3.00	7.41	0.65	14.00	Cement/ Aggregate Mix

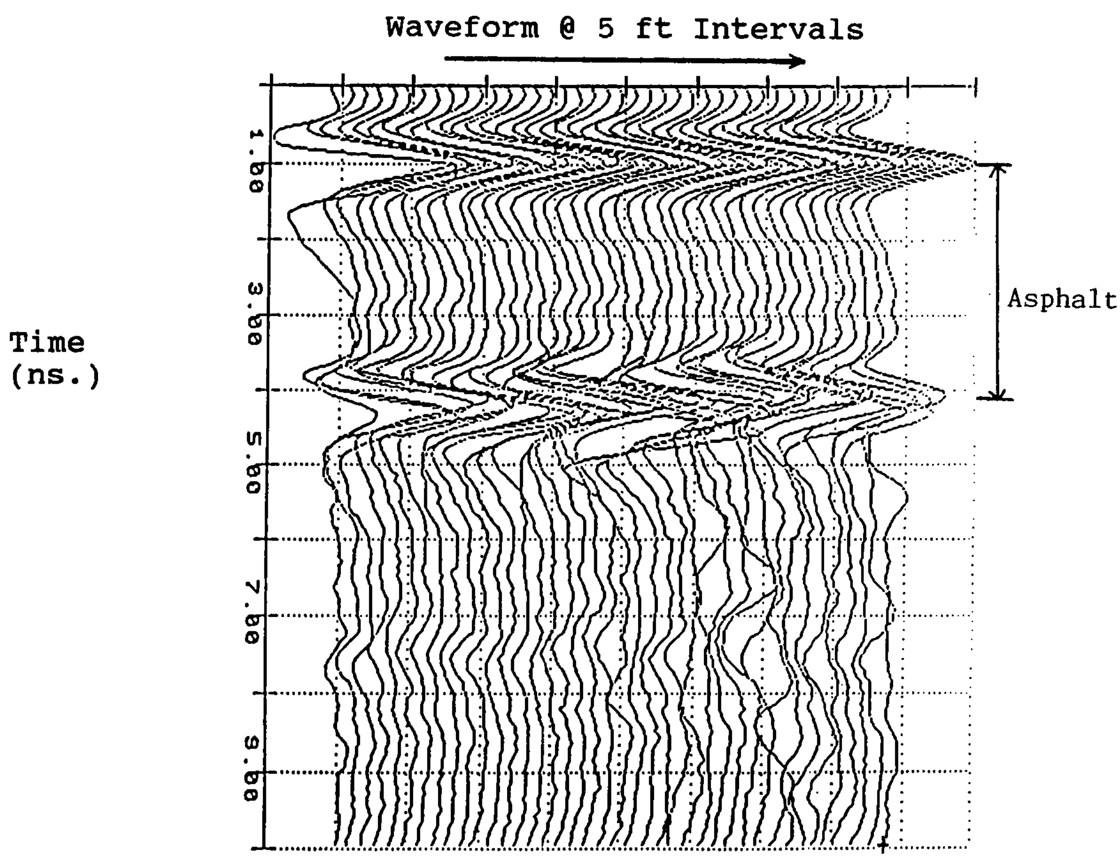


Figure 4.2 Raw Data from North Carolina

Waveform @ 5 ft Intervals

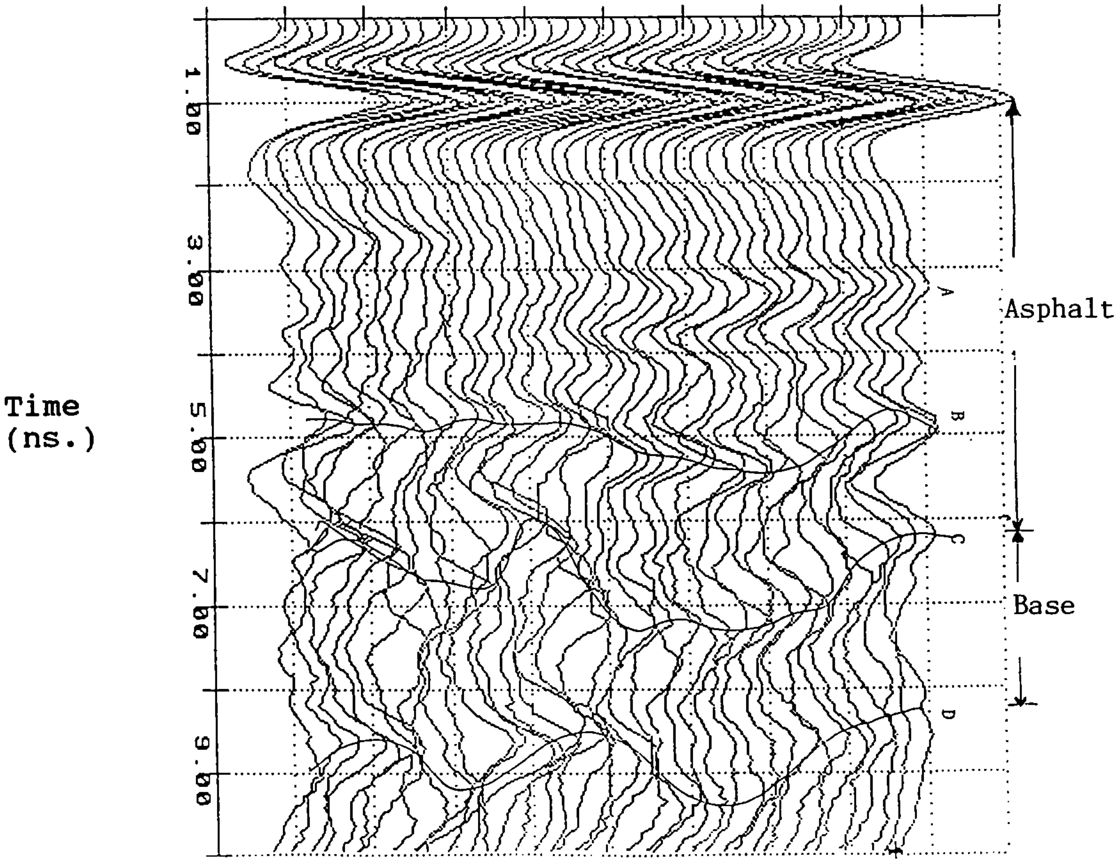


Figure 4.3 Raw Data from New Jersey

For the interim, the blind analysis results for these three sites were left unchanged until the initial core evaluation.

<u>Base layer</u>. The following observations can be made from Table 4.1:

(1) Base layers in Louisiana, Florida, North Carolina, and Tennessee, as described in the plan data, were not presented in the preliminary radar results. The treatment of each of these sites is discussed in Section 4.2.3.

(2) A base layer presented in the radar data for Georgia was not shown in the plan data. It is reasonable to assume that there is a material layer boundary not accounted for in the plan data.

(3) The base layer thickness presented in the radar data for Texas is about half of what is presented in the plan data. A second layer below the base was detected but was not reported because it was assumed to be a subbase.

Other results appeared to be consistent with the plan data.

Based on the above observations, the blind radar calculations were reviewed and selected sites were reanalyzed. The results of the reanalysis of the data are presented in Table 4.2. The differences from Table 4.1 are underlined: Four base layer calculations have been added, and one has been modified; two asphalt layer thickness calculations have also been modified.

4.2.2 Updates Using Plan Data - Asphalt

A reanalysis of asphalt thickness at two sites (Louisiana and Georgia) was prompted by observed changes in equipment calibration data. Normally these calibrations do not change during a project, and the blind results assumed that the equipment calibrations did not change from site to site. The review prompted by the plan data revealed calibration changes Zin the radar equipment at the Louisiana and Georgia sites that had previously been unnoticed. Consequently, the data at these two sites were reanalyzed with the calibration data collected specifically at these two sites. This reanalysis produced a 1 in. change in the Georgia asphalt layer thickness, and a 0.11 in. change for Louisiana. A review of the equipment calibration data at the other sites did not reveal any changes from the calibrations used in the blind analyses.

Table 4.2 Adjusted Radar Data Using Information from LTPP Plan Thickness

Site	Bituminous Layer Thickness (in.) Radar Mean	Radar SD	Plan	Base Layer Thickness (in.) Radar Mean	Radar SD	Plan	Type
LA (223056)	8.87	0.33	10.00	8.16	0.70	8.00	Soil Cement
FL (124108)	9.81	0.28	10.60	8.00	0.50	12.00	Soil/Aggregate Subbase
GA (134112)	16.43	0.89	16.50	6.83	1.82	none	
NC (371645)	7.05	0.39	7.50	4.97	0.48	7.00	Soil Cement
VA (512004)	7.30	0.25	7.40	6.43	0.71	6.50	Cement/ Aggregate Mix
MD (242401)	7.23	0.30	6.70	4.08	0.63	4.00	Lean Concrete
NJ (341003)	11.02	0.75	7.00	4.52	0.83	6.00	Crushed Stone Subbase
TN (479024)	11.20	1.66	9.30	4.17	1.11	5.00	Crushed Stone, Gravel or Slag Subbase
AR (053071)	15.85	0.74	17.00	not detected		none	
TX (482108)	3.26	0.30	3.00	7.41	0.65	(layer 1)	
				14.04	0.54	14.00	Cement/ Aggregate Mix

Note: Underlined values represent changes from Table 4.1.

4.2.3 Updates Using Plan Data - Base Thickness

The availability of the plan data had an influence on the base layer thickness calculations at sites where weak signals were observed at the base/subgrade interface. These weak signals created uncertainties in data interpretation that could be clarified with plan data.

A site-by-site review of modifications made in base thickness data is presented below.

Louisiana and North Carolina. A very weak interface was observed below the asphalt layer in certain sections of each of these sites (Figures A.1 and A.4). A weak base/subgrade interface will occur when the materials are similar, as is the case with the soil cement bases listed at these two sites. Without other supporting information, the magnitude of the interface observed in the radar data is below what is normally considered reliable. Prompted by the plan data, however, this interface was successfully tracked in selected areas. The resulting base thickness calculations have been included in the modified data of Table 4.2.

Florida. A reflection from the bottom of a base layer appeared in certain locations (Figure A.2), but not consistently throughout. The local base thickness data could have been presented with the blind data in Table 4.1, but were omitted. The base thickness results were subsequently calculated and are included in Table 4.2 and Figure A.2.

Tennessee. A clear base layer was initially observed in the data but not computed, since the radar pavement model in PAVLAYER© was designed for only three layers. Prompted by the plan data, however, a fourth layer was added to the pavement model, and the base layer thickness for the Tennessee site was computed (Table 4.2 and Figure A.8).

Texas. A layer interface below the reported base layer in Table 4.1 was initially observed in the data but was assumed to be the bottom of a subbase. Prompted by the plan data, however, this lower interface was tracked and added to the initial base computation, as shown in Table 4.2. It is possible that the base at this site was placed in two layers with slightly different material properties in each layer. Alternatively, the base may have been placed in two lifts, and the radar interface may represent the differential compaction between the lifts.

4.2.4 Description of Core Data

Core data for correlation with the radar calculations were obtained from the SHRP Long Term Pavement Performance (LTPP) database. These data were collected during the 1989-90 period using a standard pattern of cores and test pits. The cores were collected at General Pavement Study (GPS) sites in the area from

40 to 60 ft before each test section (the approach end) and in the area from 40 to 60 ft after the end of each test section (the leave end). Figure 4.4 shows the standard core pattern for the approach and leave ends.

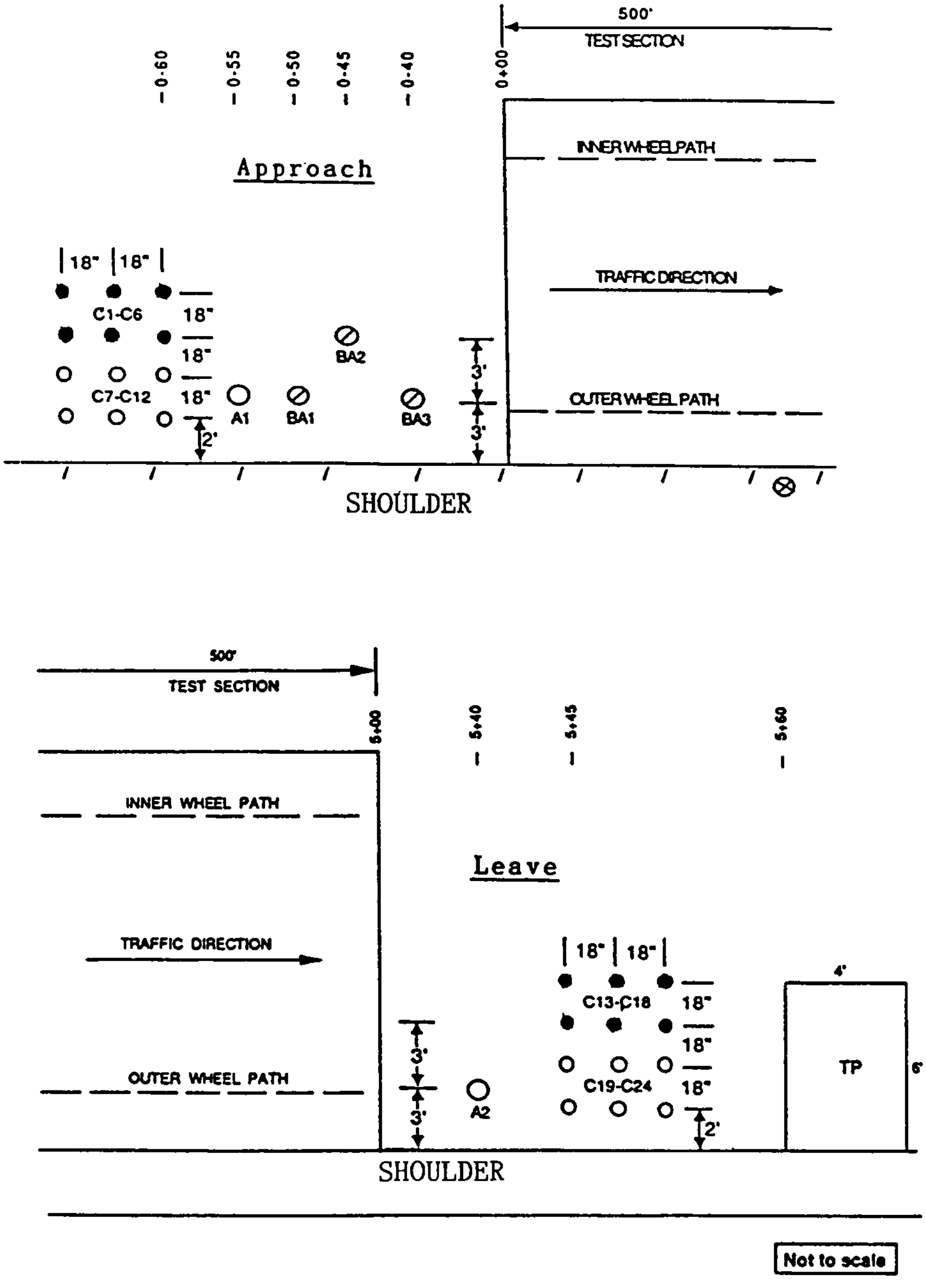
The radar surveys were carried out in the right wheelpath. Therefore, the following cores were considered to be in the line of the survey: C7 to C12, C19 to C24, A1 and A2, BA1 to BA3, and the test pit. Occasionally, where there were deviations from the standard pattern, the nearest available cores were selected.

The core data were provided in two installments. The first installment consisted primarily of the approach end data, and the second installment consisted of the remaining data. The first installment offered the possibility of a final calibration of the radar data based on one general location (Maser and Scullion, 1992). The accuracy improvement resulting from this calibration could then be tested against the leave end data. The resulting correlations are described below.

4.2.5 Correlation of Radar Data with Core Data

Initial evaluation with approach cores. The match between radar and core data is very good, with one exception at the New Jersey site. Excluding this exception, the radar and core data correlated with a slope of 1.02 and an R^2 of 0.98. The complete statistics for these data are presented in Table 4.3. Figure 4.5 shows a plot of radar vs. core values for the initial installment of data obtained primarily from the approach end of each site.

The New Jersey radar results were recalculated based on tracking interface "B" (Figure 4.3), the one that most closely agreed with the approach end cores. The revised calculation matches closely with the core values at both ends of the GPS site (Figure 4.6). As noted earlier, the presence of four interfaces in the data led to an initial misidentification of the bottom of the asphalt layer. Once the core data were provided, the analysis was redone to focus on interface "B" (Figure 4.3) rather than on interface "C", which was used in the blind analysis.



4" OD Core of AC pavement surface (overlay and original AC surface): C13-C18

4" OD Core of AC pavement surface and treated layers: C19-C24

6" OD Core of AC pavement surface and treated layers; augering of unstabilized base and subbase; splitspoon sampling and/or Shelby tube sampling as directed by authorized SHRP representative to 5' below top of subgrade: A2

Test pit (4' x 6' x 12" below top of subgrade) Removal of pavement layers; collection of pavement slabs; nuclear density measurements on AC pavement and AC treated layers; nuclear density and moisture measurements on unstabilized layers and subgrade; bulk sampling of unstabilized layers and subgrade: TP

(Taken from SHRP-LTPP Field Material Sampling Guide/Version 1.0/20 January 1989)

Figure 4.4 Sampling Point Locations for GPS Sites

Table 4.3 Statistics for Blind Radar Data vs. Cores

Asphalt Thickness Statistics:

RMS Deviation Between Radar and Cores

(a)	All Data	= ±0.76226 in.
		= ±7.1%
(b)	Excluding New Jersey	= ±0.60259 in.
		= ±5.6%

Regression Data (Excluding New Jersey and inconsistent data points)

Constant	-0.063(intercept)
Standard Error of Y Estimate	0.5568 in.
R^2	0.9843
Number of Observations	43
X Coefficient(s)	1.028(slope)
Standard Error of Coefficient	0.0203

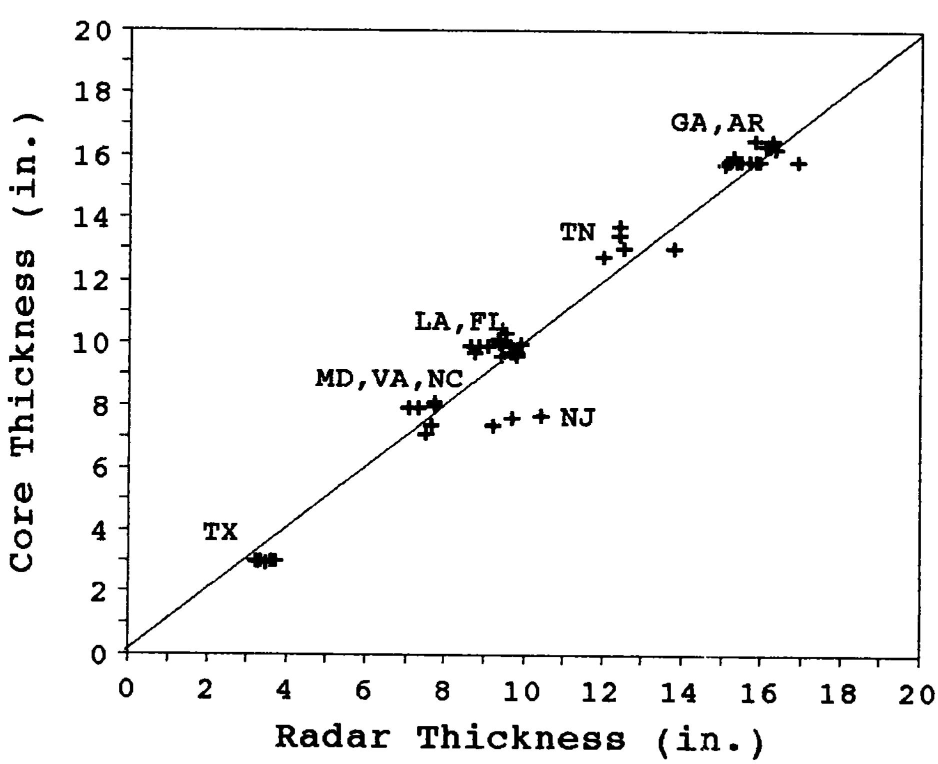


Figure 4.5 Initial Correlation of Approach Cores with Radar

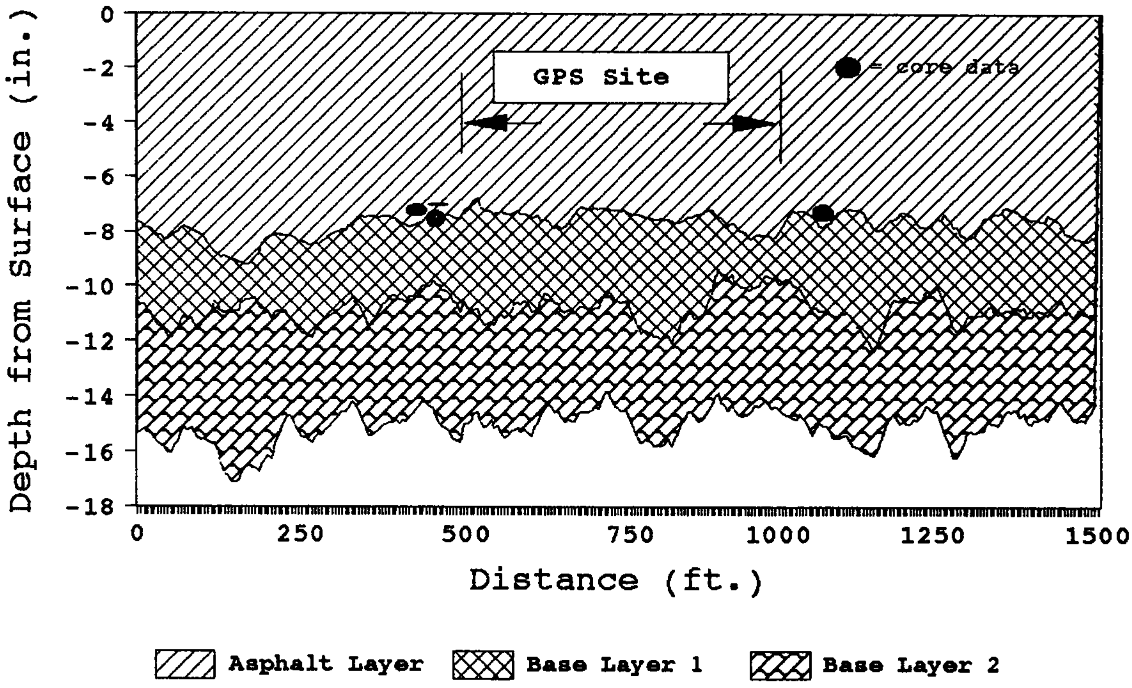


Figure 4.6 Revised New Jersey Radar Data
(GPS Site 341033, near Trenton)

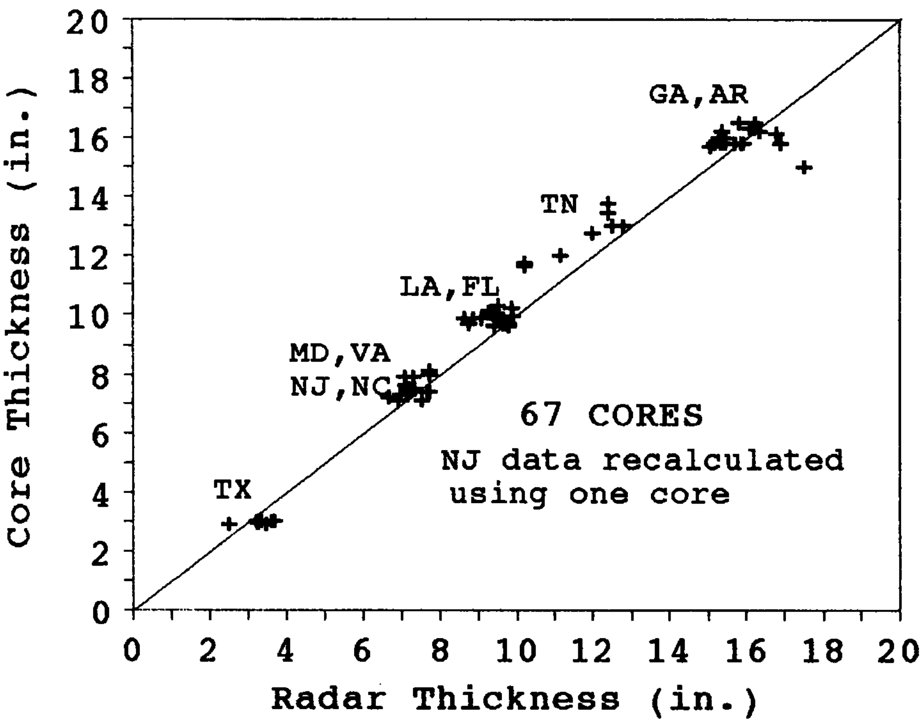


Figure 4.7 Radar vs. Core Values for Asphalt

Evaluation of all core data. Figure 4.7 is a plot of radar values against core values for asphalt thickness. A cluster of data appears around the 45-degree line, indicating a strong correlation. This is statistically confirmed in Table 4.4 with an R^2 of .98.

Table 4.4 presents the uncalibrated radar and core thickness values for asphalt and base at all of the LTPP core locations for which data were available. Radar asphalt thickness values were computed at all of the standard LTPP test locations. Core data provided by SHRP is shown next to each corresponding radar value.

The radar data were analyzed at 5 ft longitudinal intervals. Cores at the approach end and leave end were also spaced 5 ft apart and are in (or close to) the right wheelpath, except for the "C" cores, which form an 18 in. rectangular pattern (Figure 4.4). Cores C7 to C12 and C19 to C24 straddle the right wheelpath. Because of their close spacing, the value presented for the "C" cores is the average of the six individual values, except as noted.

Locations marked with ** in Table 4.4 produced radar thickness values that were initially inconsistent with data from neighboring points. "Inconsistent" is defined as a value that differs by more than 1 in. from the neighboring points. These inconsistencies were suspected to be due to the disturbances in the asphalt caused by the coring and fill material. A further investigation of the asphalt dielectric constant at these locations revealed the data shown in Figures 4.8 to 4.11.

An anomaly in the asphalt dielectric constant at each location in question reveals the presence of a patching material that differs from the original pavement material. At these locations, the filled coreholes produce a local difference in pavement thickness. In order to provide a calculation representative of the <u>original</u> pavement thickness, the final radar values at these locations were obtained from the average of the two adjacent thickness values. This is not to say that the patches themselves prevent the computation of layer thickness with radar. Rather, radar detects the thickness of the as-patched pavement, not the original pavement.

A complete set of radar and core data for the base thickness was not available. This is because (1) base thickness core data from Virginia, Maryland, New Jersey and North Carolina were not yet available from SHRP (these are the sites where the base layer was most clearly revealed in the radar data); (2) two sites have no reported base layers; and (3) at sites where the base/subgrade interface was weak, radar base thickness values could not always be computed at the location of the SHRP cores.

Table 4.4 Comparison of Radar Prediction to SHRP Core Data (without corrections using cores)

Site #	Sample	Location	Bituminous Layer Thickness (in.) Core	Bituminous Layer Thickness (in.) Radar	Base Layer Thickness (in.) Core	Base Layer Thickness (in.) Radar	Type
LA (223056)	C7-C12	438	9.97	9.91	7.52	n.c.	Soil
	A1	445	9.90	8.86	7.60	n.c.	Cement
	BA1	450	9.70	8.75	7.50	n.c.	
	BA2	455	9.90	8.64	7.60	n.c.	
	BA3	460	9.90	9.08	7.50	n.c.	
	A2	1040	10.10	9.26	8.30	n.c.	
	C19-C24	1046	10.22	9.88	8.27	n.c.	
	BA4	1062	10.10	9.34	8.50	n.c.	
	BA5	1067	10.30	9.53	8.10	n.c.	
	BA6	1072	10.00	9.36	8.50	n.c.	
FL (124108)	C7-C12	438	9.70	9.67	n.a.	8.75	Soil/
	A1	445	9.70	9.80	13.30	8.90	Aggregate
	BA1	450	9.70	9.71	13.30	8.18	Subbase
	BA2	455	9.90	9.65	13.10	8.26	
	BA3	460	9.60	9.42	12.40	8.97	
	A2	1040	9.90	9.47	12.60	n.c.	
	C19-C24	1046	9.96	9.55	n.a.	7.70	
	Test Pit	1060	9.60	9.80	6.00	6.60	
GA (134112)	C7-C12	438	15.70	15.06		6.14	No Base
	A1	445	15.80	15.45		n.c.	
	BA1	450	15.80	15.69		7.63	
	BA2	455	15.80	15.93		n.c.	
	BA3	460	15.80	15.86**		8.40	
	A2	1040	15.00	17.50		n.c.	
	C19-C24	1046	16.12	16.80		7.67	
	Test Pit	1063	15.80	16.90		n.c.	
NC (371645)	C11&C12	438	8.00	7.73	n.a.	n.c.	Soil
	A1	445	7.90	7.30	n.a.	n.c.	Cement
	BA1	450	n.a.	7.32	n.a.	n.c.	
	BA2	455	n.a.	7.04	n.a.	n.c.	
	BA3	460	n.a.	7.18	n.a.	n.c.	
	A2	1040	7.20	6.65	n.a.	n.c.	
	C19-C21	1046	7.50	7.18	n.a.	n.c.	
	Test Pit	1063	n.a.	7.65	n.a.	n.c.	
VA (512004)	C7-C12	438	7.40	7.65	n.a.	6.68	Cement/
	A1	443	7.10	7.50	n.a.	7.45	Aggregate
	BA1	450	n.a.	7.19	n.a.	6.85	Mix
	BA2	455	n.a.	7.17	n.a.	7.26	
	BA3	460	n.a.	7.45	n.a.	7.63	
	A2	1040	7.30	7.15	n.a.	5.58	
	C19-C24	1046	7.40	7.66	n.a.	5.84	
	Test Pit	1063	n.a.	7.50**	n.a.	5.60**	

Table 4.4 (continued)

Site #	Sample	Location	Bituminous Layer Thickness (in.) Core	Radar	Base Layer Thickness (in.) Core	Radar	Type
MD (242401)	C7-C12	438	7.90	7.07	n.a.	n.c.	Lean
	A1	443	8.10	7.74	n.a.	4.55	Concrete
	BA1	450	n.a.	7.54	n.a.	n.c.	
	BA2	455	n.a.	7.72	n.a.	n.c.	
	BA3	460	n.a.	7.67	n.a.	n.c.	
	A2	1040	7.10	6.92	n.a.	5.71	
	C19-C24	1046	7.27	6.96	n.a.	n.c.	
	Test Pit	1063	n.a.	7.20**	n.a.	n.c.	
NJ (341033)	C7-C12	438	7.40	7.70	n.a.	n.c.	Crushed
	A1	445	7.60	7.10	n.a.	n.c.	Stone
	BA1	450	n.a.	7.7494	n.a.	n.c.	Subbase
	BA2	455	n.a.	7.3597	n.a.	n.c.	
	BA3	460	n.a.	7.2821	n.a.	n.c.	
	A2	1040	7.50	7.31	n.a.	n.c.	
	C19-C22	1046	7.43	7.20	n.a.	n.c.	
	Test Pit	1062	n.a.	8.10	n.a.	n.c.	
TN (479024)	C7-C12	438	13.42	12.40	n.a.	4.32	Crushed
	A1	445	13.00	12.80**	n.a.	3.66	Stone,
	BA1	450	13.00	12.50	n.a.	3.40	Gravel
	BA2	455	13.75	12.40**	n.a.	2.83	
	BA3	460	12.75	12.00	n.a.	2.89	
	A2	1040	11.75	10.20**	7.75	4.40**	
	C19-C24	1046	11.62	10.20	n.a.	4.40	Slag
	Test Pit	1063	12.00	11.16	6.00	3.97	Subbase
AR (053071)	C7-C12	438	16.50	16.26			No Base
	A1	445	16.20	16.35			
	BA1	450	16.30	16.10**			
	BA2	455	16.50	15.82			
	BA3	460	16.30	16.22			
	A2	1040	16.00	15.45			
	C19-C24	1046	16.20	15.36			
	BA4	1062	15.80	15.17			
	BA5	1067	16.00	15.28			
	BA6	1072	15.80	15.36			
TX (482108)	C7-C12	438	2.95	3.25	14.13	14.22	
	A1	445	3.00	3.61	14.40	13.51	Cement/
	BA1	450	2.90	3.47	14.40	14.36	Aggregate
	BA2	455	3.00	3.34	14.40	13.25	Mix
	BA3	460	3.00	3.24	14.40	13.71	
	A2	1040	n.a.	2.40	n.a.	14.60	
	C19-C24	1046	2.90	2.50	14.42	15.20	
	Test Pit	1062	3.00	3.70	17.40	13.50	

** Radar values corrected for distortion caused by SHRP coring.
n.a. = not available.
n.c. = not computed.

Table 4.4 (continued)

Asphalt Thickness Statistics (New Jersey reanalyzed, no other calibrations):

RMS Deviation Between Radar and Cores	= ±0.68in.
	= ±7.8%

Regression Data

Constant	0.2677(intercept)
Standard Error of Y Estimate	0.6389in.
R^2	0.9765
Number of Observations	67
X Coefficient(s)	1.00(slope)
Standard Error of Coefficient	0.019

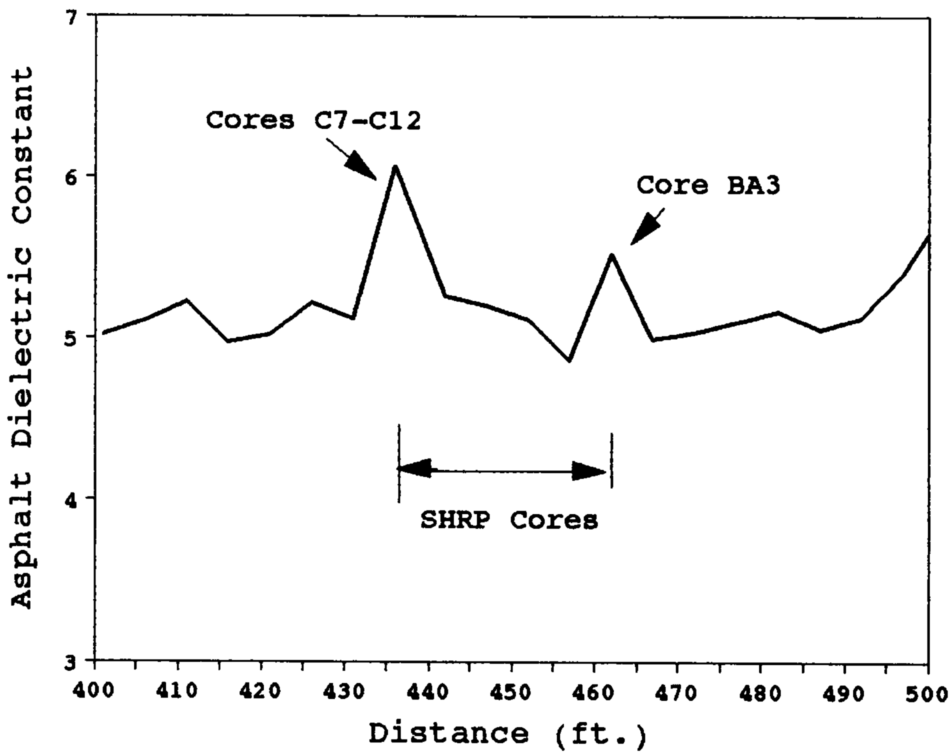


Figure 4.8 Dielectric Anomalies at Brunswick, GA
(GPS Site 134112)

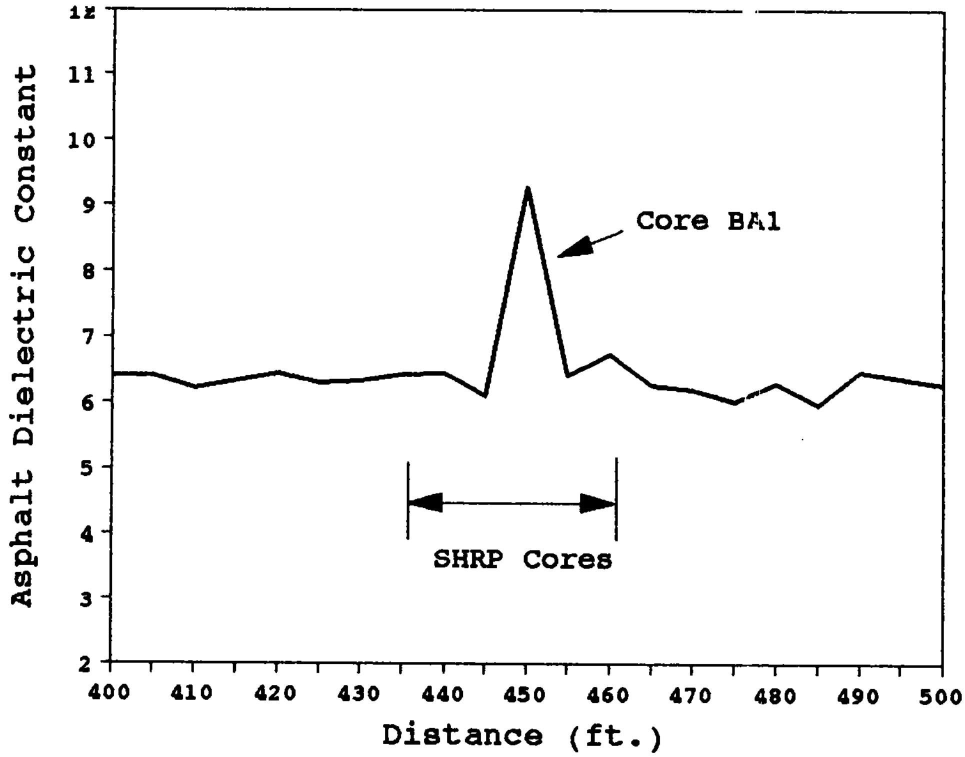


Figure 4.9 Dielectric Anomalies at Rogers, AR
(GPS Site 053071)

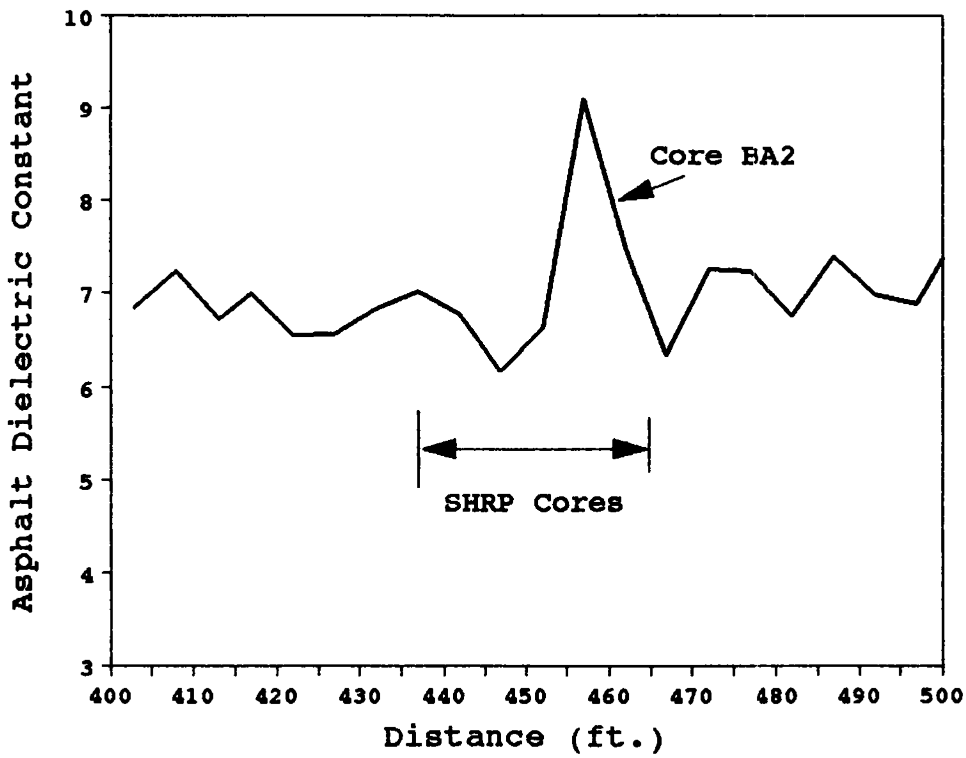


Figure 4.10 Dielectric Anomalies at Murfreesboro, TN
(Core BA2) (GPS Site 479024)

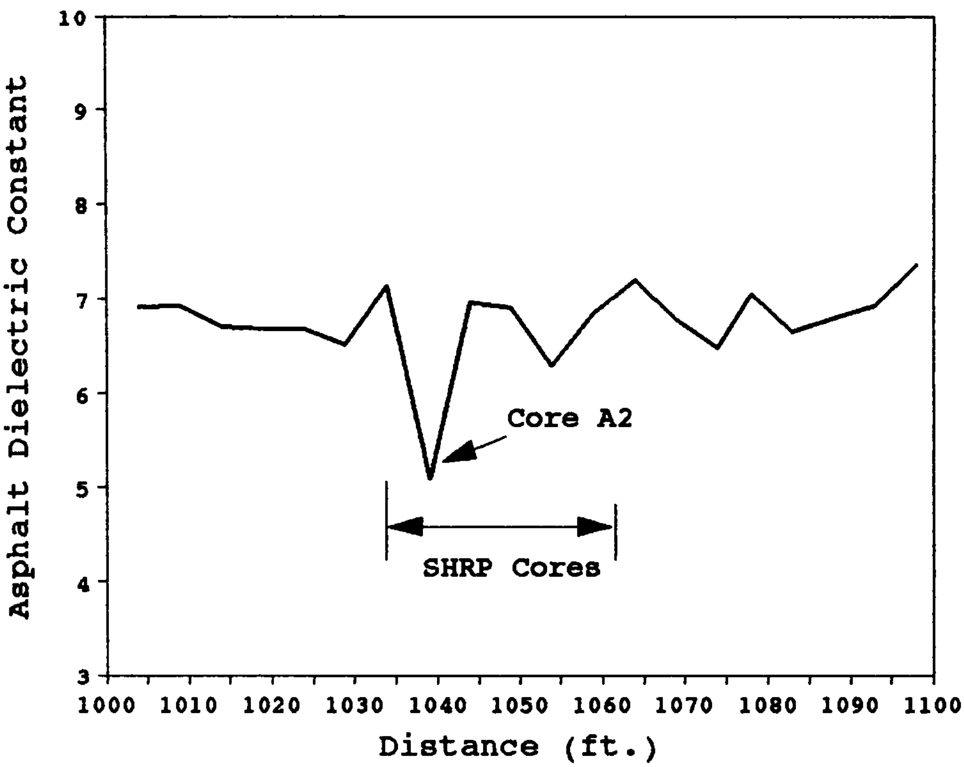


Figure 4.11 Dielectric Anomalies at Murfreesboro, TN
(Core A2) (GPS Site 479024)

Because of the sparseness of the base thickness data, no significant analysis of the data can be presented.

Calibration of radar data. It was previously shown (Maser and Scullion, 1992) that the maximum possible accuracy can be obtained by using one calibration core per site. This calibration can correct for systematic errors peculiar to the particular pavement section. For this project, calibration was based on the data initially provided from the approach end. This calibration was then tested against the complete data set, including the leave end data.

The calibration scheme is based on the ratio of the average of the approach cores to the average of the radar data at the approach core locations. All computed asphalt thicknesses are then calibrated by multiplying them by this ratio. Averages were selected instead of single core values. This was because the intensive SHRP core pattern created local radar anomalies at the core location, as was discussed earlier.

Table 4.5 presents the uncalibrated data, the calibration factor computed as described above, and the resulting calibrated data. The 10 calibration factors ranged from 0.88 to 1.09. This indicates that there appears to be no bias toward under- or overprediction of asphalt thickness. Five of the calibration factors were between 0.98 and 1.01. The statistics for these calibrated data are presented at the end of Table 4.5. These statistics indicate a root mean square (RMS) deviation between radar and core data of 0.51 in., or 5.1%. This represents a 25% improvement over the uncalibrated data.

Table 4.5

Comparison of Radar Predictions to SHRP Core Data (with calibration using approach cores)

Site #	SHRP Sample	Location	Core	Calibrated Radar Data	Calibration Factor	Un-calibrated Radar Data
		Bituminous Layer Thickness (in.)				
LA (223056)	C7-C12	438	9.97	10.81		9.91
	A1	445	9.90	9.67	1.09	8.86
	BA1	450	9.70	9.55		8.75
	BA2	455	9.90	9.43		8.64
	BA3	460	9.90	9.91		9.08
	A2	1040	10.10	10.10		9.26
	C19-C24	1046	10.22	10.78		9.88
	BA4	1062	10.10	10.19		9.34
	BA5	1067	10.30	10.40		9.53
	BA6	1072	10.00	10.22		9.36
FL (124108)	C7-C12	438	9.70	9.74		9.67
	A1	445	9.70	9.87	1.01	9.80
	BA1	450	9.70	9.79		9.71
	BA2	455	9.90	9.72		9.65
	BA3	460	9.60	9.48		9.42
	A2	1040	9.90	9.54		9.47
	C19-C24	1046	9.96	9.62		9.55
	Test Pit	1060	9.60	9.87		9.80
GA (134112)	C7-C12	438	15.70	15.24		15.06
	A1	445	15.80	15.63	1.01	15.45
	BA1	450	15.80	15.87		15.69
	BA2	455	15.80	16.12		15.93
	BA3	460	15.80	16.05		15.86
	A2	1040	15.00	17.70		17.50
	C19-C24	1046	16.12	17.00		16.80
	Test Pit	1063	15.80	17.10		16.90
NC (371645)	C7-C12	438	8.00	8.40		7.73
	A1	445	7.90	7.93	1.09	7.30
	BA1	450	n.a.	7.96		7.32
	BA2	455	n.a.	7.66		7.04
	BA3	460	n.a.	7.80		7.18
	A2	1040	7.20	7.23		6.65
	C19-C24	1046	7.50	7.80		7.18
	Test Pit	1063	n.a.	8.31		7.65
VA (512004)	C7-C12	438	7.40	7.50		7.65
	A1	443	7.10	7.36	0.98	7.50
	BA1	450	n.a.	7.05		7.19
	BA2	455	n.a.	7.03		7.17
	BA3	460	n.a.	7.31		7.45
	A2	1040	7.30	7.01		7.15
	C19-C24	1046	7.40	7.51		7.66
	Test Pit	1063	n.a.	7.36		7.50

Table 4.5 (continued)

Site #	SHRP Sample	Location	Core	Calibrated Radar Data	Calibration Factor	Un-calibrated Radar Data
			Bituminous Layer Thickness (in.)			
MD (242401)	C7-C12	438	7.90	7.50		7.07
	A1	443	8.10	8.21	1.06	7.74
	BA1	450	n.a.	7.99		7.54
	BA2	455	n.a.	8.18		7.72
	BA3	460	n.a.	8.13		7.67
	A2	1040	7.10	7.34		6.92
	C19-C24	1046	7.27	7.38		6.96
	Test Pit	1063	n.a.	7.63		7.20
NJ (341033)	C7-C12	438	7.40	7.76		7.70
	A1	445	7.60	7.16	1.01	7.10
	BA1	450	n.a.	7.81		7.75
	BA2	455	n.a.	7.42		7.36
	BA3	460	n.a.	7.34		7.28
	A2	1040	7.50	7.37		7.31
	C19-C24	1046	7.43	7.26		7.20
	Test Pit	1062	n.a.	8.17		8.10
TN (479024)	C7-C12	438	13.42	13.16		12.40
	A1	445	13.00	13.59	1.06	12.80
	BA1	450	13.00	13.27		12.50
	BA2	455	13.75	13.16		12.40
	BA3	460	12.75	12.74		12.00
	A2	1040	11.75	10.83		10.20
	C19-C24	1046	11.62	10.83		10.20
	Test Pit	1063	12.00	11.85		11.16
AR (053071)	C7-C12	438	16.50	16.47		16.26
	A1	445	16.20	16.56	1.01	16.35
	BA1	450	16.30	16.31		16.10
	BA2	455	16.50	16.03		15.82
	BA3	460	16.30	16.43		16.22
	A2	1040	16.00	15.65		15.45
	C19-C24	1046	16.20	15.56		15.36
	BA4	1062	15.80	15.37		15.17
	BA5	1067	16.00	15.48		15.28
	BA6	1072	15.80	15.56		15.36
TX (482108)	C7-C12	438	2.95	2.85		3.25
	A1	445	3.00	3.17	0.88	3.61
	BA1	450	2.90	3.05		3.47
	BA2	455	3.00	2.93		3.34
	BA3	460	3.00	2.84		3.24
	A2	1040	n.a.	2.11		2.40
	C19-C24	1046	2.90	2.19		2.50
	Test Pit	1062	3.00	3.25		3.70

Table 4.5 (continued)

Asphalt Thickness Statistics (calibrated using approach cores):

RMS Deviation Between Radar and Cores	= ±0.58in.
	= ±5.1%

Regression Output	
Constant	0.228(intercept)
Standard Error of Y Estimate	0.507in.
R^2	0.985
Number of Observations	67
X Coefficient(s)	0.976(slope)
Standard Error of Coefficient	0.015

5. Discussion and Evaluation of Results

5.1 Accuracy of Radar Data

The level of accuracy as demonstrated by the root mean square (RMS) deviations supports the use of radar for asphalt pavement thickness evaluation. The same equipment and analysis procedures have now been used in three studies. Taken together, the results of these studies indicate that the use of appropriate horn antenna radar equipment, coupled with the PAVLAYER© data analysis procedures, provides accuracy levels within ±8% for asphalt thickness. Plan data appear useful only for adjustments to the base layer thickness data. The use of calibration core data in this study produced a moderate improvement in accuracy.

The validity of using plan data to identify base thickness where the radar data were weak could not be verified because a complete set of base thickness ground truth data was not available. Plan data appear to be most reliable for this application because the base layer is not normally modified during pavement maintenance and rehabilitation.

For the SHRP sites, the use of core data for calibration contained a built-in error. This was because the core data were taken before the radar survey, and there were significant disturbances to the pavement due to the intensive core pattern. Thus, the radar data at these core locations were collected on pavements that were significantly different from their state when the cores were first taken. Evidence of these differences was implicit in the radar data. In the Texas and Kansas studies cited in Section 1.1, cores were taken <u>after</u> the radar data collection.

5.2 Variability of the GPS Sites

Of interest to the LTPP program is the variability of the pavement thickness within the General Pavement Study (GPS) sections. This was evaluated using the radar data for each 500 ft section.

Table 5.1 shows the results of the variability analysis. It presents the maximum deviation between the core data and the radar thickness data for the GPS site asphalt thickness. This is computed as the maximum absolute difference between the radar maximum and minimum and the site average core data. The reported maximum deviations ranged from 6% to 21%. Because the RMS deviation of the radar data from the core data is 5%, any deviation in excess of 10% can be considered significant with 95% confidence. Such deviations occurred at 5 of the 10 sites.

Table 5.1
Deviation of GPS Section Thickness:
Radar Data vs. Core Data

Site #	Calibrated Radar Data Mean (in.)	SD	Max. (in.)	Min. (in.)	Core Data Average (in.) Approach	Leave	Site Average (in.)	Maximum Deviation in.	%
LA (223056)	9.52	0.11	9.75	9.31	9.87	10.14	10.01	0.70	7
FL (124108)	10.04	0.21	10.46	9.55	9.72	9.82	9.77	0.69	7
GA (134112)	16.15	0.40	16.94	15.30	15.78	15.64	15.71	1.23	8
NC (371645)	8.11	0.30	8.68	7.66	7.95	7.35	7.65	1.03	13
VA (512004)	6.95	0.24	7.36	6.55	7.25	7.35	7.30	0.75	11
MD (242401)	7.64	0.31	8.24	7.14	8.00	7.19	7.59	0.65	9
NJ (341003)	7.31	0.38	7.79	6.04	7.50	7.47	7.48	1.44	20
TN (479024)	11.48	0.49	12.28	10.40	13.18	11.79	12.49	2.08	18
AR (053071)	16.09	0.43	17.13	15.47	16.36	15.96	16.16	0.97	6
TX (482108)	3.01	0.22	3.60	2.76	2.97	2.95	2.96	0.64	21

6. Conclusions

This study has shown that radar can be used as an accurate, nondestructive technique for evaluation of asphalt pavement thickness. Accuracy of ±8% can be expected for blind surveys, and improvements to ±5% can be achieved with preexisting calibration cores. Calibration cores taken <u>after</u> the radar survey would yield greater accuracy.

The study has also shown that radar can be used to accurately characterize asphalt thickness variation within SHRP LTPP GPS sites. This characterization can be used to provide more accurate thickness information than is currently available from cores outside the test section. For the sites investigated in this study, the maximum deviation between LTPP core data and radar data within a GPS site ranged from 6% to 21%. The potential errors in LTPP data analysis and modeling associated with these deviations could be reduced if radar thickness data were available for each site.

7. References

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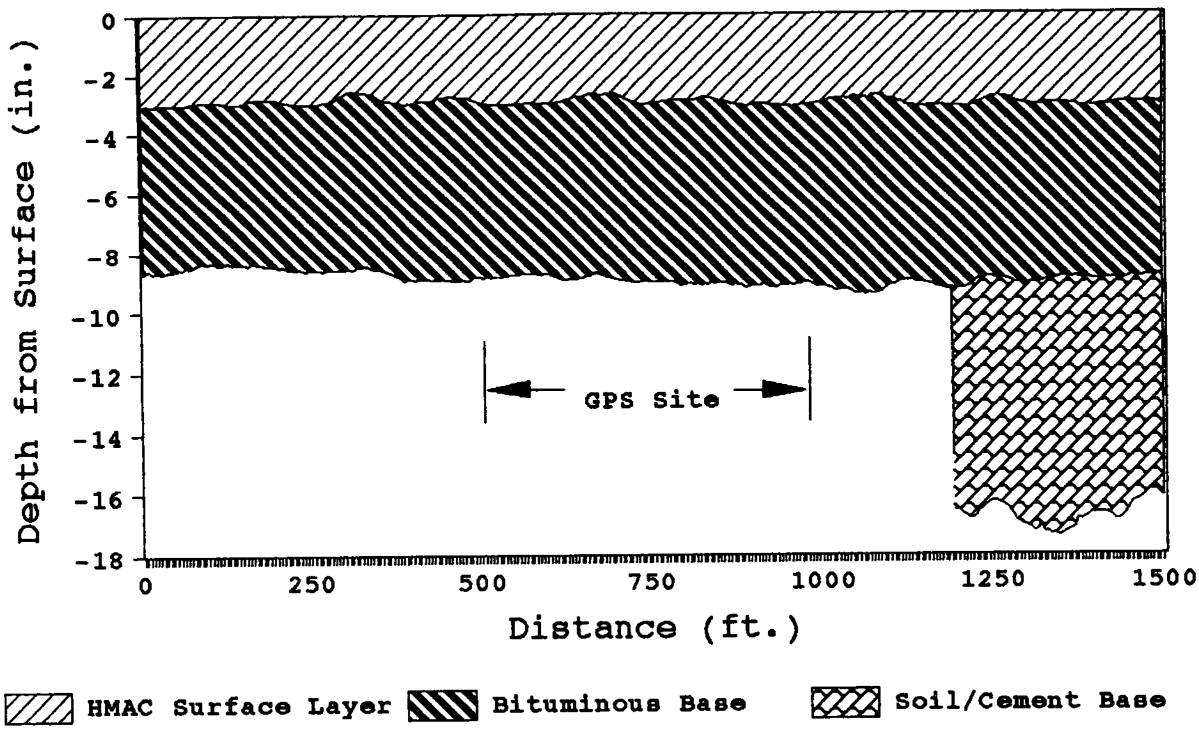
Appendix

Pavement Layer Thickness Calculations
and Representative Raw Data Samples
for 10 SHRP GPS Sites

List of Figures



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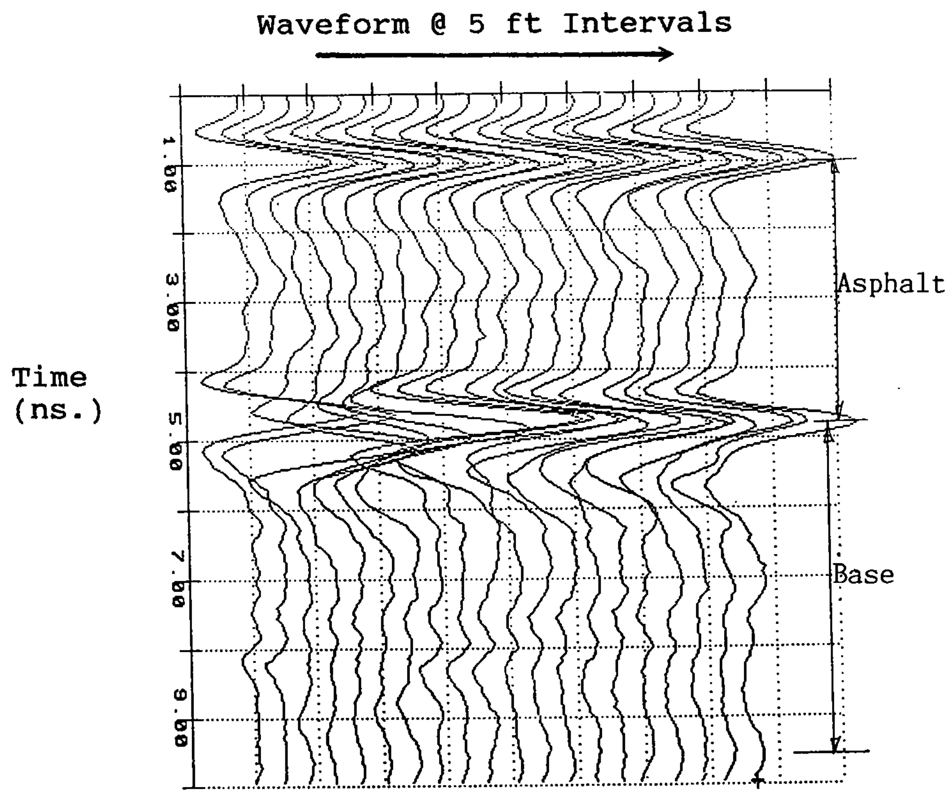
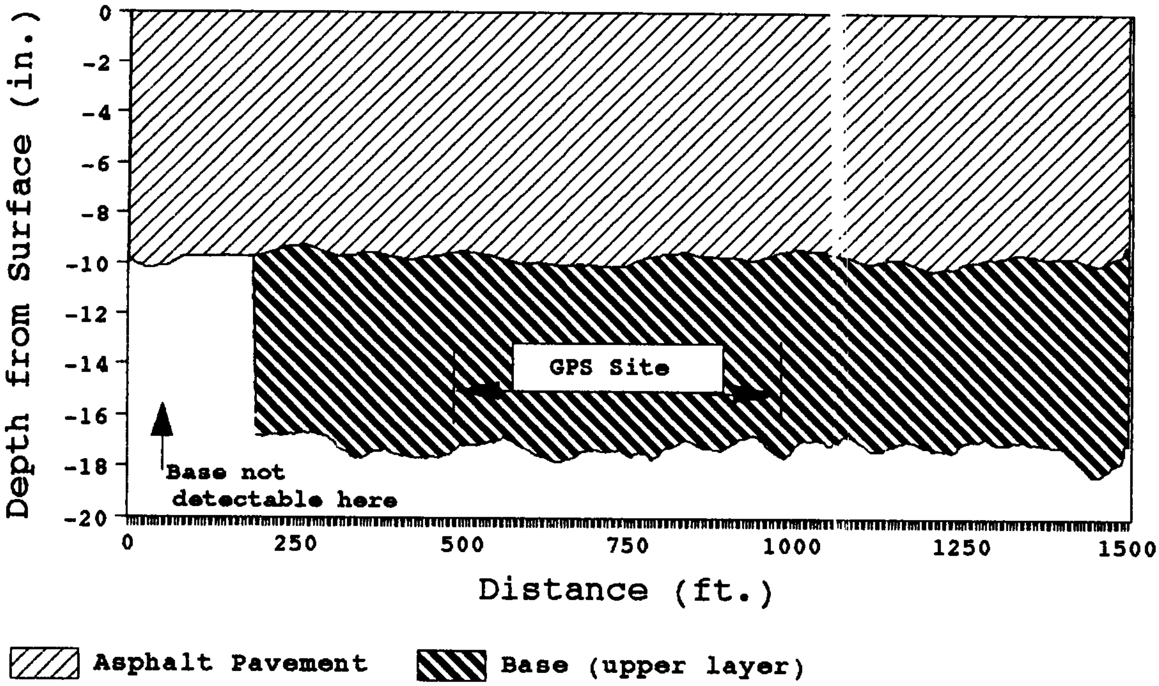


(b) Sample Raw Data

Figure A.1 SHRP GPS Site 223056
Near Bunkie, LA



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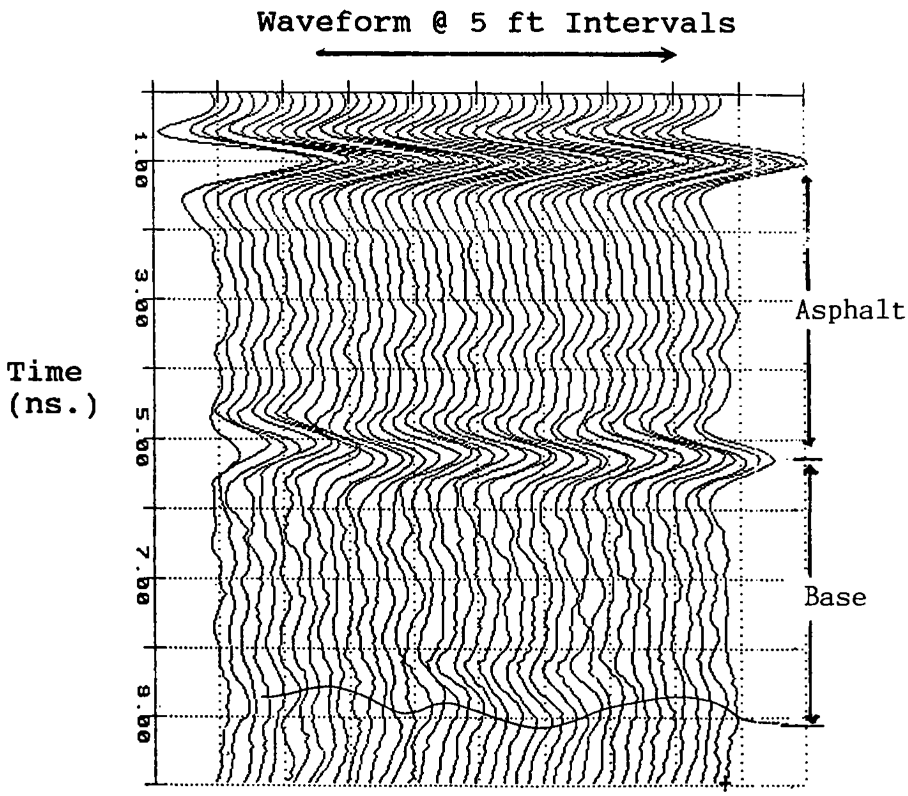

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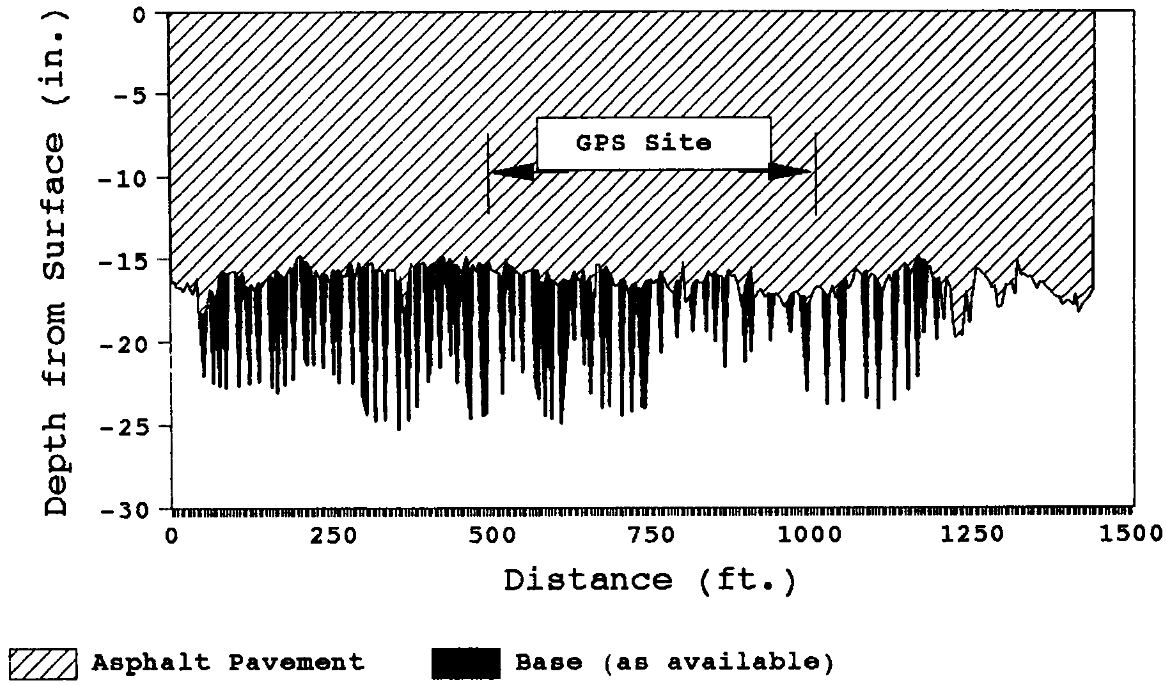
Figure A.2 SHRP GPS Site 124108
Ft. Walton Beach, FL



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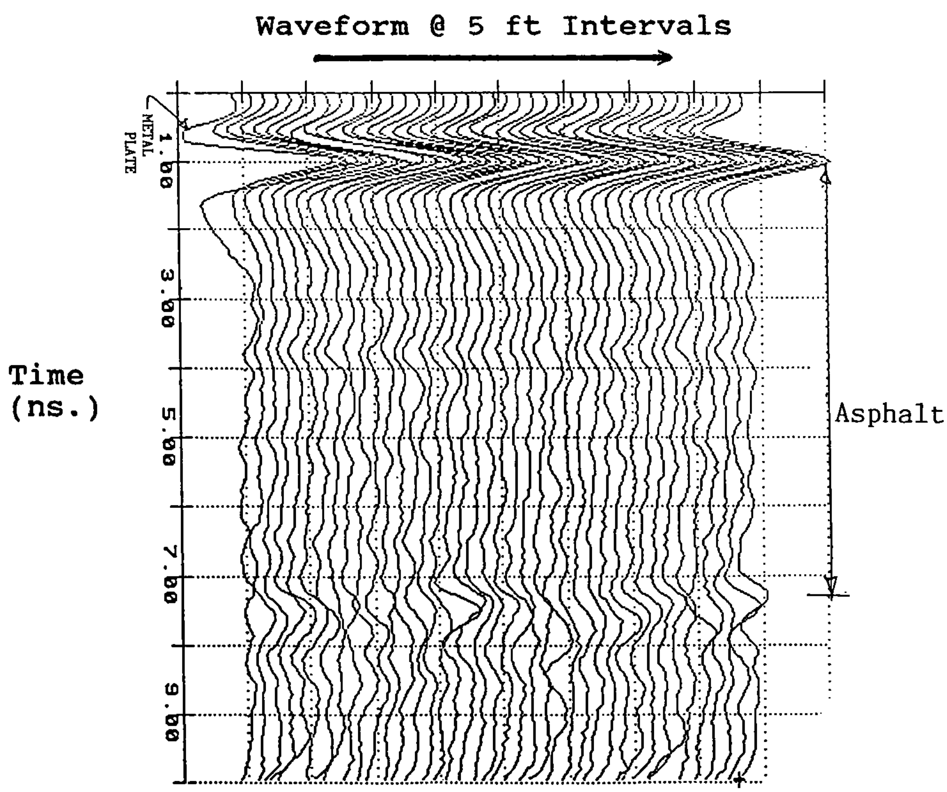
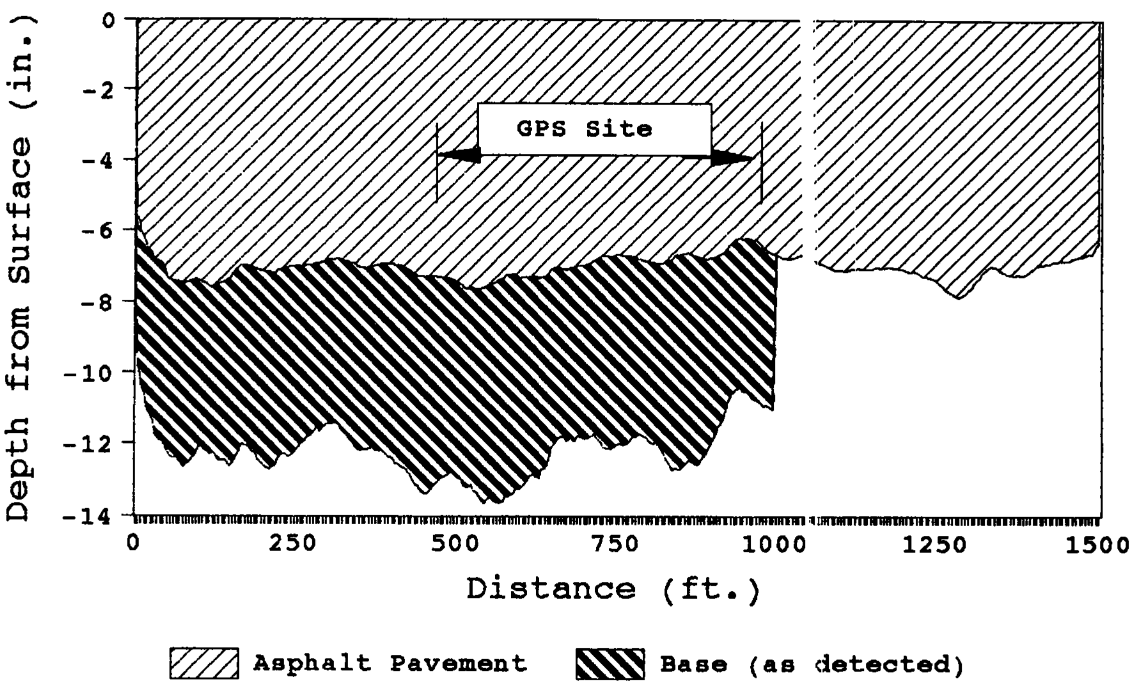


(b) Sample Raw Data

Figure A.3 SHRP GPS Site 134112
Brunswick, GA



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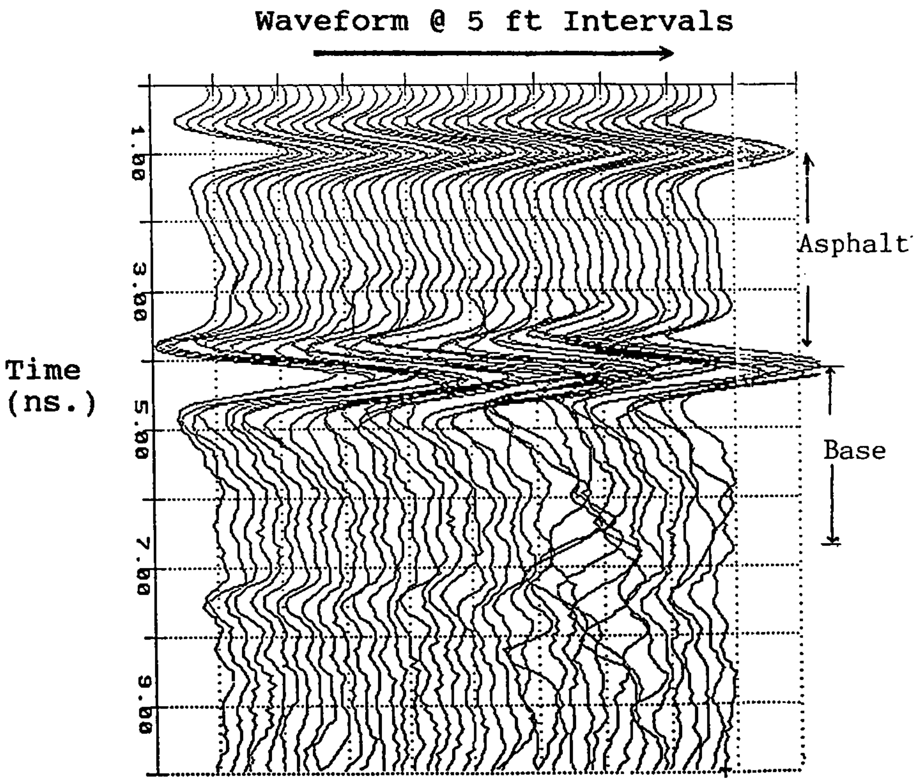
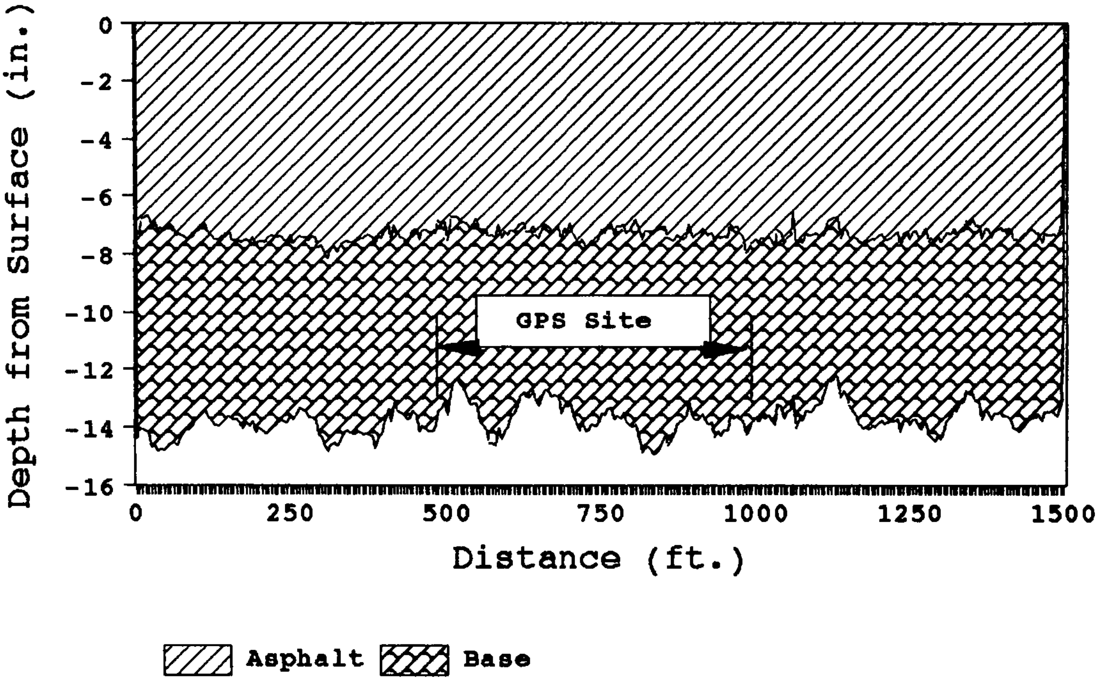


(b) Sample Raw Data

Figure A.4 SHRP GPS Site 371645
Whiteville, NC



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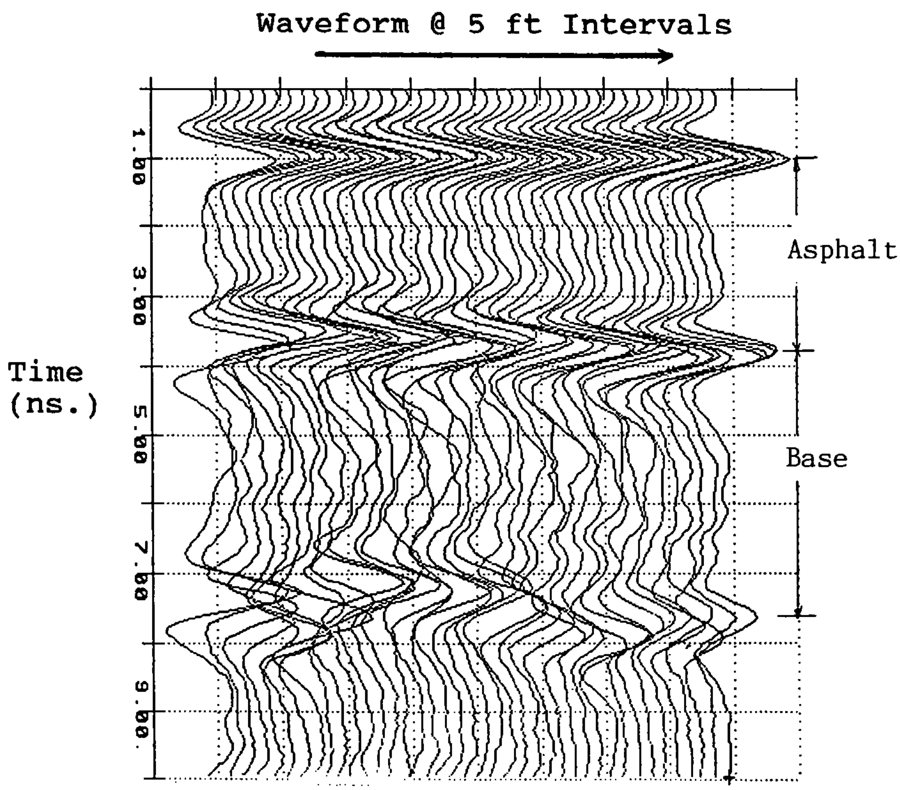

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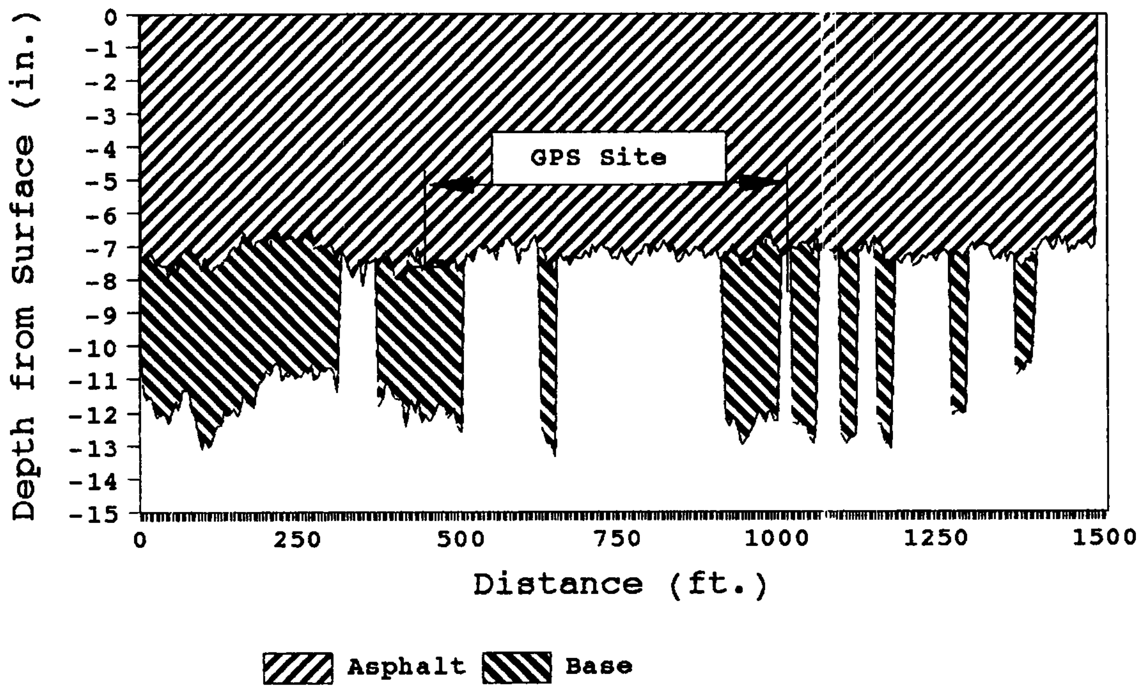
Figure A.5 SHRP GPS Site 512004
Danville, VA



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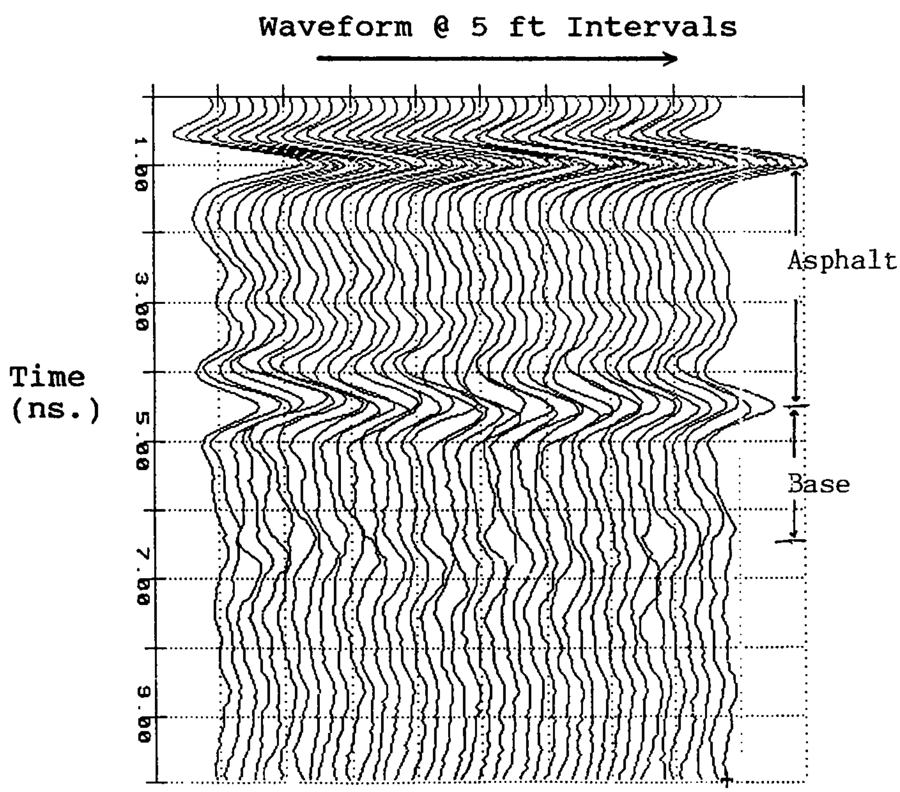

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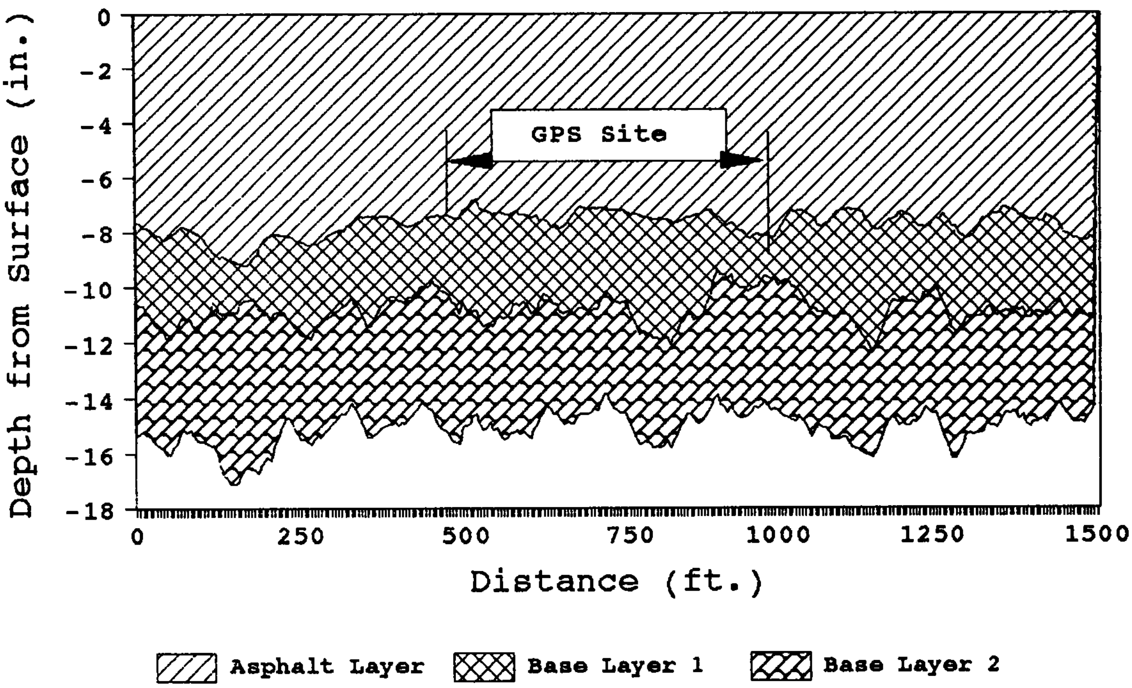
Figure A.6 SHRP GPS Site 242401
Edgewood, MD



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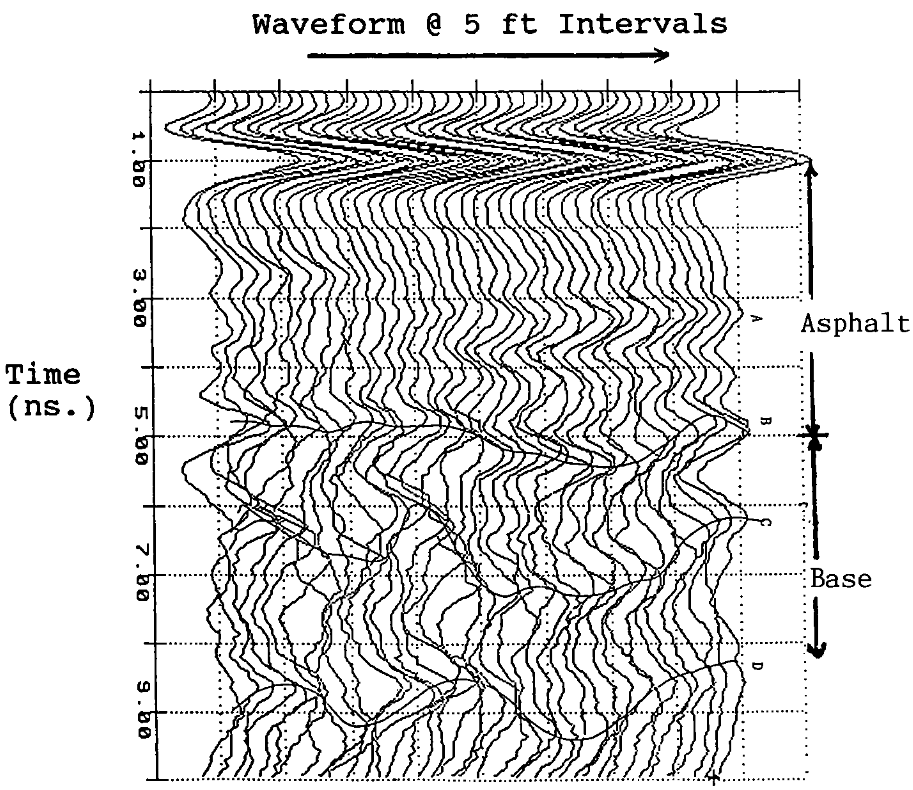
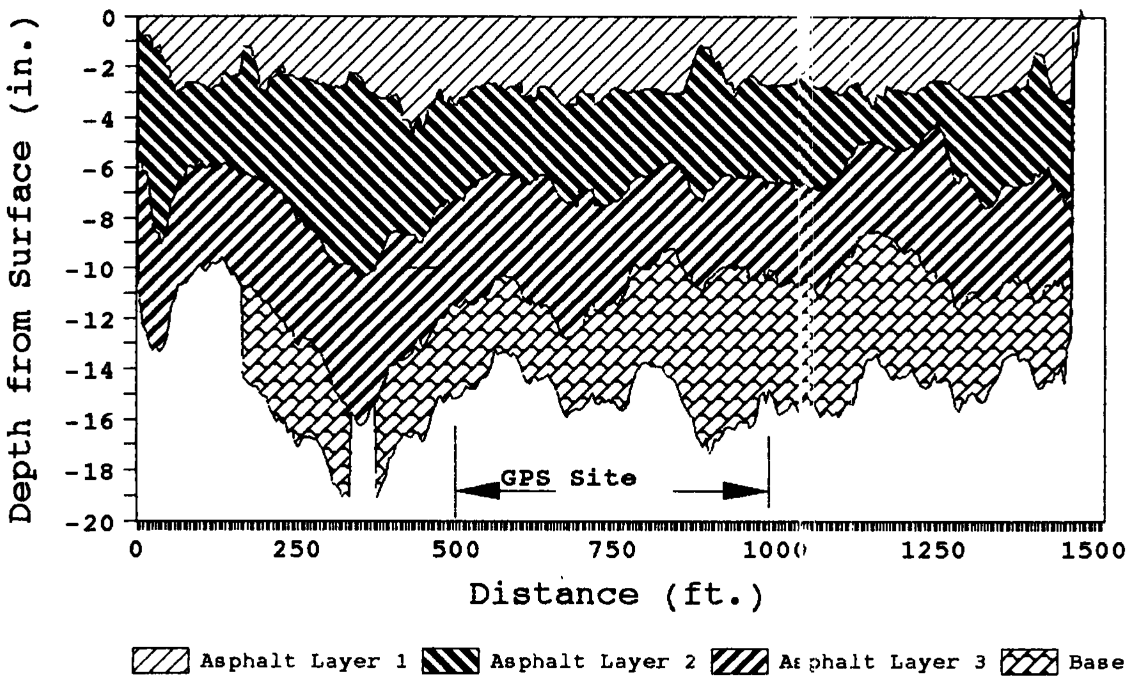


(b) Sample Raw Data

Figure A.7 SHRP GPS Site 341033 near Trenton, NJ (centerline)



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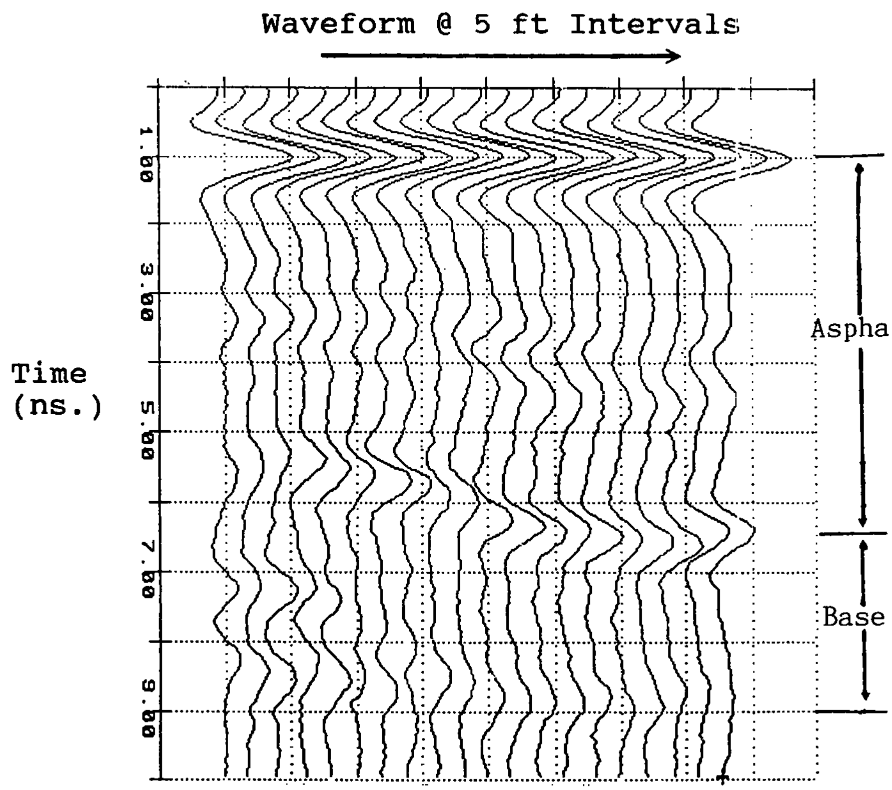

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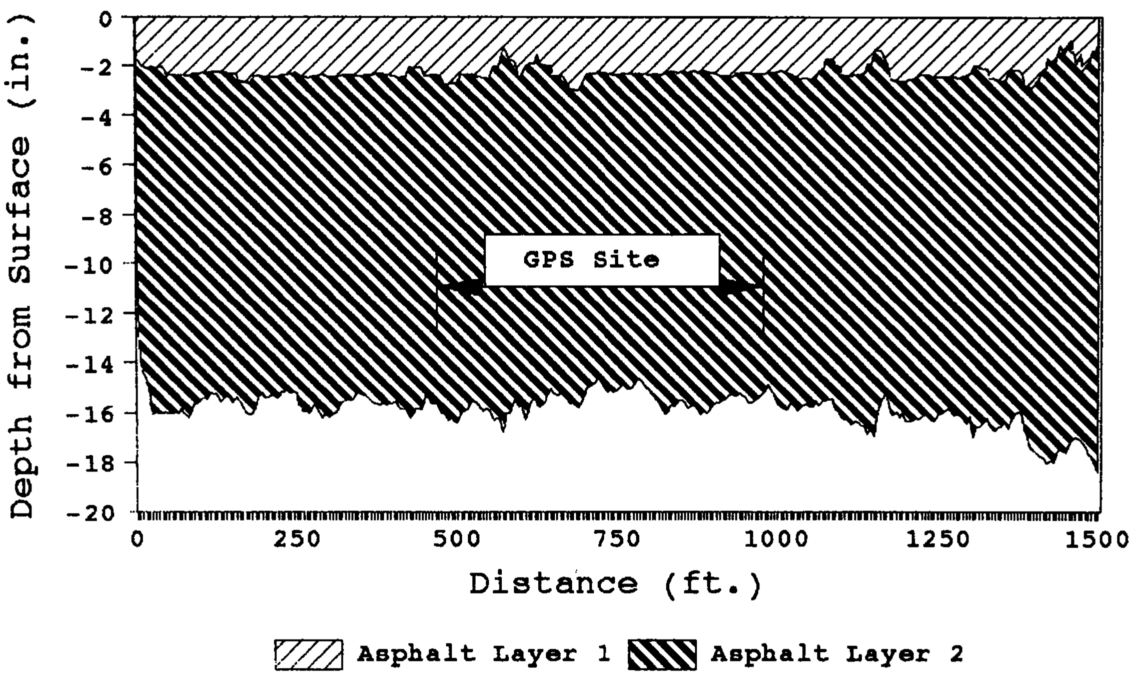
Figure A.8 SHRP GPS Site 479024
Murfreesboro, TN



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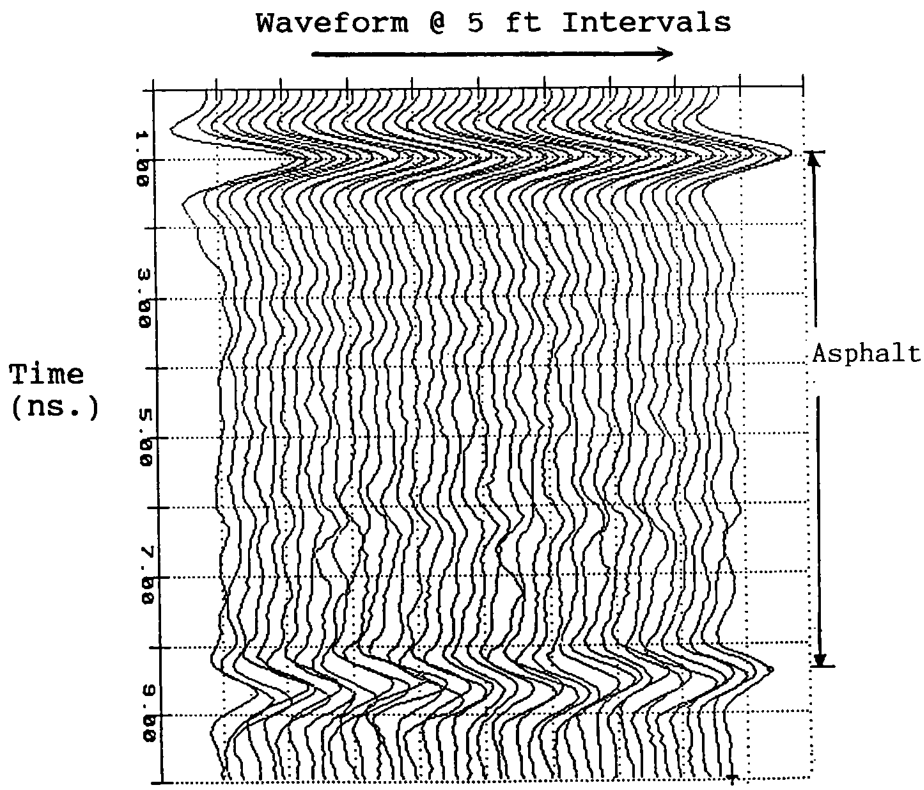
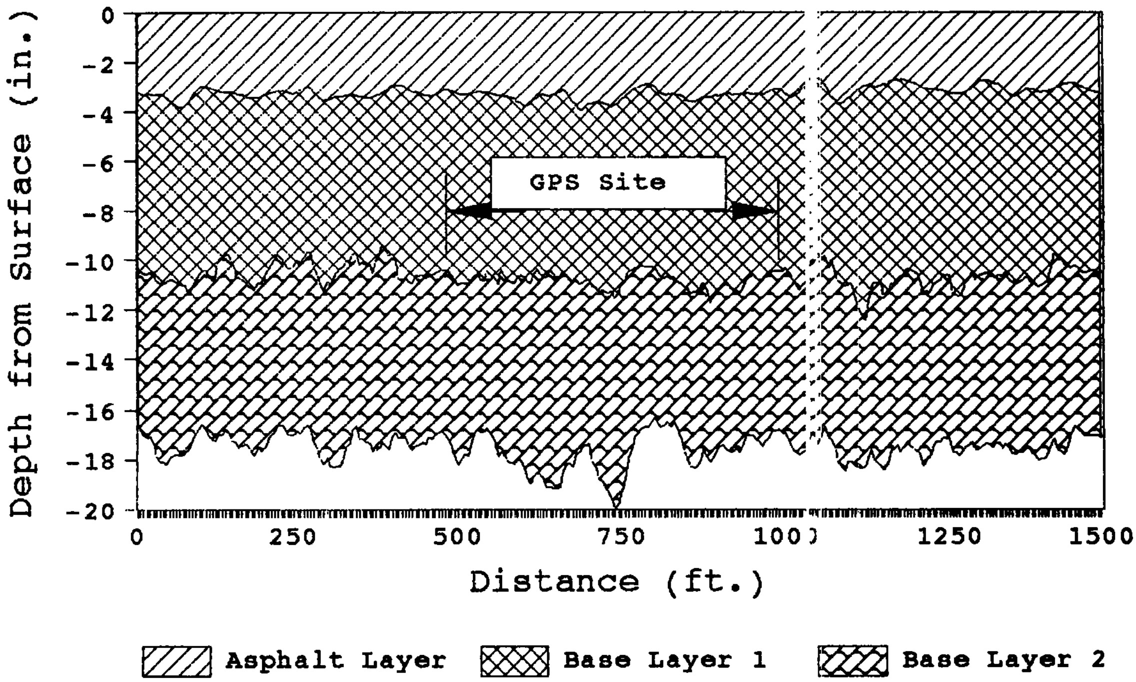


(b) Sample Raw Data

Figure A.9 SHRP GPS Site 053071
Rogers, AR (near Fayetteville)



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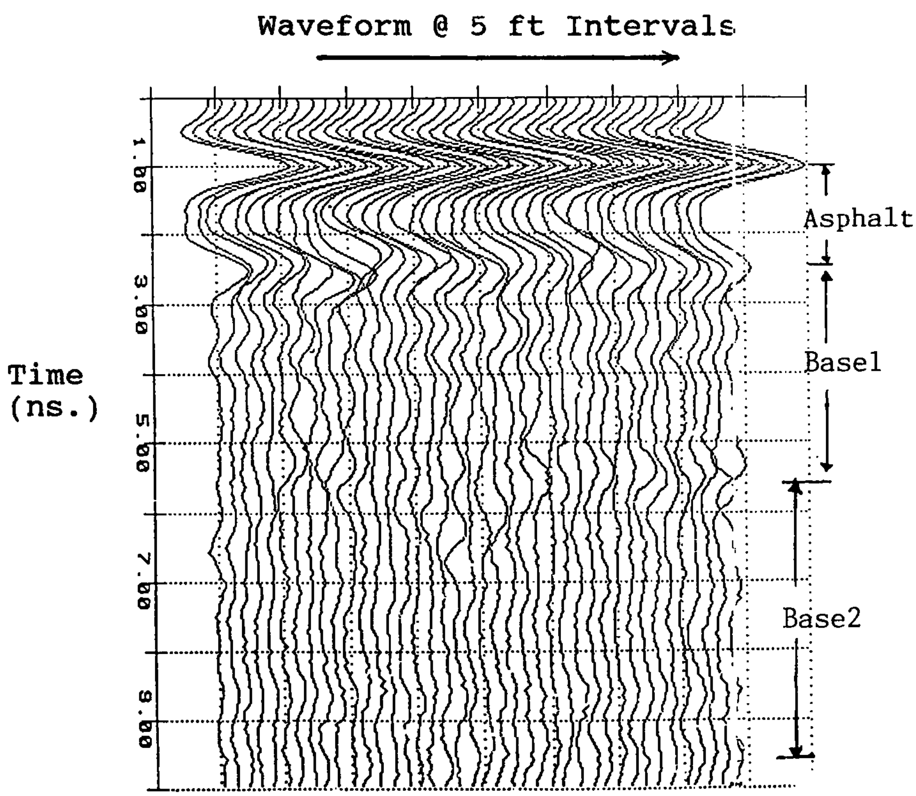

(b) Sample Raw Data

Figure A.10 SHRP GPS Site 482108
Texas City, TX (left wheelpath)

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