Guidelines for the Use of Ground Penetrating Radar (GPR) and Portable Seismic Property Analyzer (PSPA) in Full Depth Reclamation Projects

Technical Report
06-13
April 2007

MaineDOT

A Publication from the Maine Department of Transportation's Research Division

Technical Report Documentation Page

1. Report No. ME 06-13	2.	3. Recipient's Accession No.
4. Title and Subtitle Guidelines for the Use of Ground Penetrating Radar (GPR) and Portable Seismic Property Analyzer (PSPA) in Full Depth Reclamation Projects		5. Report Date April 9, 2007 6.
7. Author(s) Rajib B. Mallick Civil and Environmental Engineering Department; Kenneth Maser President Infrasense, Inc.; Soheil Nazarian Professor, University of Texas.		8. Performing Organization Report No.
9. Performing Organization Name and Address Worcester Polytechnic Institute (WPI) Civil Environmental Engineering Department 100 Institute Road Worcester, MA. 01609		10. Project/Task/Work Unit No. 11. Contract © or Grant (G) No.
12. Sponsoring Organization Name and Address Maine DOT 16 State House Station Augusta, ME 04333-0016		13. Type of Report and Period Covered 14. Sponsoring Agency Code
15. Supplementary Notes		
16. Abstract (Limit 200 words)		
17. Document Analysis/Descriptors Full depth reclamation, non destructive testing, ground penetrating radar, portable seismic property analyzer.		18. Availability Statement
19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages 57 | 22. Price

Full Depth Reclamation (FDR) of existing asphalt pavements into base courses has become an attractive option of rehabilitation for state Department of Transportation (DOT's). MaineDOT relies on two recycling techniques for base courses. Foamed asphalt (FA) adds heated asphalt and water to the in-place full depth reclamation. Plant mix recycled asphalt pavement (PMRAP) is 100% RAP and emulsion prepared at the plant.

The objectives of this study were to develop and recommend practical methods to: 1. Determine stiffness of foamed asphalt and plant mixed RAP (PMRAP), 2. Determine the pre-construction pavement layer structure, and the variations of that structure throughout the project with the help of Ground Penetration Radar (GPR) and 3. Check the post-construction thickness of the reclaimed layers with the help of GPR. The scope of work consisted of using a GPR and a PSPA in several MaineDOT recycling projects, before and after recycling, analyzing, the data, and developing conclusions and recommendations.

Final Report

On

Guidelines for the Use of Ground Penetrating Radar (GPR) and Portable Seismic Property Analyzer (PSPA) in Full Depth Reclamation Projects

Submitted by:

Rajib B. Mallick
Civil and Environmental Engineering Department
Worcester Polytechnic Institute (WPI)
100 Institute Road
Worcester, MA 01609
Phone: 508 831 5289, Fax: 508 831 5808, e-mail: rajib@wpi.edu

Kenneth Maser
President, Infrasense, Inc.,
14 Kensington Road
Arlington, MA 02476-8016
Phone: 781-648-0440, Fax: 781-648-1778, e-mail: kmaser@infrasense.com

and

Soheil Nazarian
Professor, Department of Civil Engineering,
University of Texas at El Paso, Texas, 79968, USA,
Tel: 915-747-6911, FAX: 915-747-8037, e-mail: nazarian@utep.edu

4/9/2007

(Appendices A, B and C are submitted as separate files/documents)

EXECUTIVE SUMMARY

Full Depth Reclamation (FDR) of existing asphalt pavements into base courses has become an attractive option of rehabilitation for state Departments of Transportations (DOTs). In the FDR process, the properties of the constructed FA and PMRAP layer are significantly dependent on the existing materials. At present, accurate information regarding moduli of FA and PMRAP are not available to Maine DOT.

The objectives of this study were to develop and recommend practical methods to: 1. Determine stiffness of foamed asphalt and plant mixed RAP (PMRAP) layers with the help of the Portable Seismic Pavement Analyzer (PSPA), 2. Determine the pre-construction pavement layer structure, and the variations of that structure throughout the project with the help of Ground Penetrating Radar (GPR) and 3. Check the post-construction thickness of the reclaimed layers with the help of GPR. The scope of work consisted of using a GPR and a PSPA in several MDOT recycling projects, before and after recycling, analyzing the data, and developing conclusions and recommendations.

GPR works using short electromagnetic pulses radiated by an antenna which transmits these pulses and receives reflected returns from the pavement layers. In this study the GPR had a dual role, first to determine thickness of different layers prior to recycling, to help take cores at significantly different areas, to conduct a proper mix design, and second, to check the depth of reclamation, immediately after recycling. GPR testing was carried out on projects prior to rehabilitation and on projects just after rehabilitation.

GPR testing was carried out using a vehicle-mounted 1 GHz horn antenna GPR system. The data was analyzed to develop thickness profiles. The depths, as recorded by borings show the utility of the GPR data for segmentation of a project on the basis of correct pavement layer thickness, for mix design and construction.

The data of pavement depth obtained from both the GPR and the boring data show that while the average values are generally similar, both sources of data show high variability, a fact that suggests that the GPR (analyzed at every foot) is more able to capture the details of this variability. The analysis clearly shows the need of using GPR, to get continuous and accurate depth data, at traffic speed, to make sure that the designs are appropriate for specific rehabilitation projects.

As part of this project, an automated GPR analysis technique has been investigated. This automated technique seeks to simplify the data analysis by highlighting the predominant pavement features over a length of the pavement section. This process has also been structured to eliminate the need to directly interact with the GPR data, and thus could be available to a wider range of DOT personnel. Finally, the automated processing technique provides a means for characterizing the pavement layer structure prior to the availability of core data. The layer structure determined from the automated processing can then be finalized when core data becomes available.

The Portable Seismic Pavement Analyzer (PSPA) is a rapid nondestructive testing device that provides the modulus of the top pavement layer in real-time. The data analysis procedure uses the surface wave energy to determine the variation in modulus with wavelength.

In this study, two tasks were accomplished:1. The use of PSPA for rapid determination of modulus of reclaimed layers during construction was demonstrated, and 2. A procedure was developed to utilize the PSPA to determine the modulus of Full Depth Reclaimed base layers underneath HMA.

Testing of projects during reclamation behind the reclaimer (for FDR)/paver (for PMRAP) showed that the procedure is fast, nondestructive and can be conducted by one person. Testing was done and the data was corrected and reduced in terms of temperature and seismic-to-design modulus. The variation in the collected data can be used as an indicator of the quality of the recycling operation, and any out of the ordinary test data would indicate a potential problem. Since in base recycling with foamed asphalt or emulsion there is sufficient workability of the material to allow for reworking, any deficiency can be corrected before the application of the HMA layer. This method should be followed for continuous monitoring of the pavement during recycling work.

The modulus versus wavelength plot (dispersion curve) provided by the PSPA is used to estimate the modulus profile versus depth. The actual modulus profile differs from this approximation, and previous researchers have used a backcalculation process to recover this true variation. To eliminate the backcalculation process, an innovative method was developed in this study. A series of simulations was carried out to relate the ratio of the composite modulus of the top two layers to modulus of the top layer to the ratio of the actual surface wave velocities of the top and second layer. In these simulations, the velocity of the top layer was maintained constant and the velocity of the base was varied from 20% to 100% of the velocity of the top layer. The resulting best fit curve was used to directly estimate the actual modulus of the base, knowing the modulus of the top layer and the composite modulus of the top two layers.

The developed procedure was evaluated with extensive testing and analysis of data. The evaluation program consisted of performing Falling Weight Deflectometer tests on a selected uniform section (ascertained through the use of GPR and MDOT data) of each route at multiple load levels, and with PSPA.

From the analysis of data obtained from FWD, GPR and PSPA the following conclusions can be made: 1. The seismic testing and a proposed analysis method can provide reliable estimates of moduli of reclaimed layers in HMA surface pavements. 2. The process is fast and hence can be used to collect a large number of data – something that is very important for layers which exhibit a large variation in properties. 3. The predicted moduli can be used effectively in mechanistic empirical design of pavement structures. 4. The seismic method presented in this study should be used on a regular basis to develop a large database of in-place layer moduli for pavements with thin HMA surface for use in mechanistic-empirical design methods.

Guidelines for the use of Ground Penetrating Radar and Portable Seismic Pavement Analyzer (PSPA) for design of full depth reclamation projects are provided.

PROBLEM STATEMENT

Full Depth Reclamation (FDR) has been defined as a recycling method where all of the asphalt pavement section and a predetermined amount of underlying materials are treated to produce a stabilized base course (*1*). FDR of existing asphalt pavements into base courses has become an attractive option of rehabilitation for state departments of transportations (DOTs). The advantages of recycling include savings in natural resources and energy, lower cost, and often rapid construction processes. More importantly, because of recent developments in in-place recycling methods and equipment, recycling operations with different types of additives are becoming routine in many parts of the country. Organizations such as Asphalt Recycling and Reclaiming Association (ARRA), Portland Cement Association (PCA), and several research organizations, including those working on Federal Highway Administration (FHWA) funded projects, have developed useful guidelines for determination of optimum amounts of specific recycling additives (such as emulsion or Portland cement) for DOTs and other users.

Maine DOT is currently using foamed asphalt and plant mixed RAP (PMRAP) for most of their base stabilization projects. The FDR process used for foamed asphalt (FA) and plant mixed RAP (PMRAP) base stabilization are expected to be an economic process of rehabilitation, with several advantages. Since 2001, Maine DOT has conducted more than thirty foamed asphalt and plant mixed RAP projects in low and medium volume roads throughout the state. The lessons learnt from FA and PMRAP and PMRAP projects constructed in Maine since 2001 can be summarized as below:

- Lack of data regarding modulus makes it very difficult to estimate the structural strength of reclaimed layers
- FA and PMRAP properties are highly variable
- Existence of unknown layers in the existing pavement (large aggregates) cause variability in FA and PMRAP properties
- Low density and modulus in reclaimed layers are caused by the presence of large particles
- Lack of proper test method make is very difficult to control quality during construction

In the FDR process, the properties of the constructed FA and PMRAP layer are significantly dependent on the existing (recycled) materials. At present, accurate information regarding moduli of FA and PMRAP is not available to Maine DOT. There is a need to know modulus of stabilized base course for structural evaluation and design of FA and PMRAP stabilized pavements. This need is made more critical by the anticipated adoption of mechanistic-empirical design methods (such as the AASHTO 2002 Mechanistic-Empirical Pavement Design Guide) by the DOTs.

Some work with resilient modulus (Mr) and Falling Weight Deflectometer (FWD) testing have been conducted in the past (*2*). However, complications related to the structural composition of these pavements make the use of Mr and FWD ineffective. For example, most of the foamed asphalt and plant mixed RAP stabilized pavements in Maine have very thin, approximately 60 mm, HMA layers above the stabilized base layers. Most of these pavements also have relatively thin (50 mm) to moderately thick (250 mm) unstabilized RAP and unknown material layers underneath the stabilized base course. Therefore, it is not possible to use FWD readings and backcalculation to obtain accurate moduli for base courses in such pavements. Furthermore, it is not possible to obtain full depth cores from the stabilized base course layers for determination of laboratory Mr; only the top half to one third portion of the cores can be retrieved intact. Also, the FA and PMRAP layers are not entirely bound layers like HMA, and hence their stiffness properties are significantly affected by the in-place confining conditions.

During initial construction and subsequent maintenance and rehabilitation of the FA and PMRAP pavements, different construction practices were used, resulting in highly variable in-place composition of in-place material. The existence of unknown layers within the depth of reclamation has proven to be the most decisive factor in success or failure of the FDR process. The observations can be summarized as follows:

- Presence of large, plus 50 mm diameter particles is very detrimental to the FDR process
- Presence of high air void pockets – from large particles and stripped layers cause problems
- Need to determine the exact depth to such layer, if any, such that the proper FDR depth can then be determined, and proper decision regarding adding new materials on the surface prior to FDR can be made
- Determination of accurate depths of existing pavement layer is crucial for mix design
- Determination of areas which are different from other areas – excessive moisture, excessive air voids/large particles or areas needing extra asphalt/cement/lime is crucial
- Getting representative samples from all significantly different areas, and making sure that proper mix (additional aggregate/asphalt/lime/cement) is used in specific areas are very important
- At present, no pre-FDR survey is conducted that can take care of the above concerns.
- FDR to depths from which no sample has been tested can result in problems
- No consideration of changing subsurface conditions is made to adjust cutting heights, before any problem is encountered.

Hence the observations can be summarized in terms of three major questions:

- How do we get a reliable estimate of FA and PMRAP moduli?
- How do we make sure that the plans for conducting reclamation with FA and PMRAP are appropriate for the existing subsurface conditions?
- How do we control quality during FA and PMRAP construction, specifically by checking the thickness of the reclaimed layer?

PROJECT OBJECTIVE

The objectives of the proposed project are to develop and recommend practical methods to:
1. Determine stiffness of foamed asphalt and plant mixed RAP (PMRAP) layers with the help of the Portable Seismic Pavement Analyzer (PSPA), 2. Determine the pre-construction pavement layer structure, and the variations of that structure throughout the project with the help of Ground Penetrating Radar (GPR) and 3. Check the post-construction thickness of the reclaimed layers with the help of GPR.

SCOPE OF WORK

The scope of work consisted of using a GPR and a PSPA in several MDOT recycling projects, before and after recycling, analyzing the data, and developing conclusions and recommendations for specifications. This report is divided into two sections. The first section reports the use of GPR and the second part discusses the use of the PSPA.

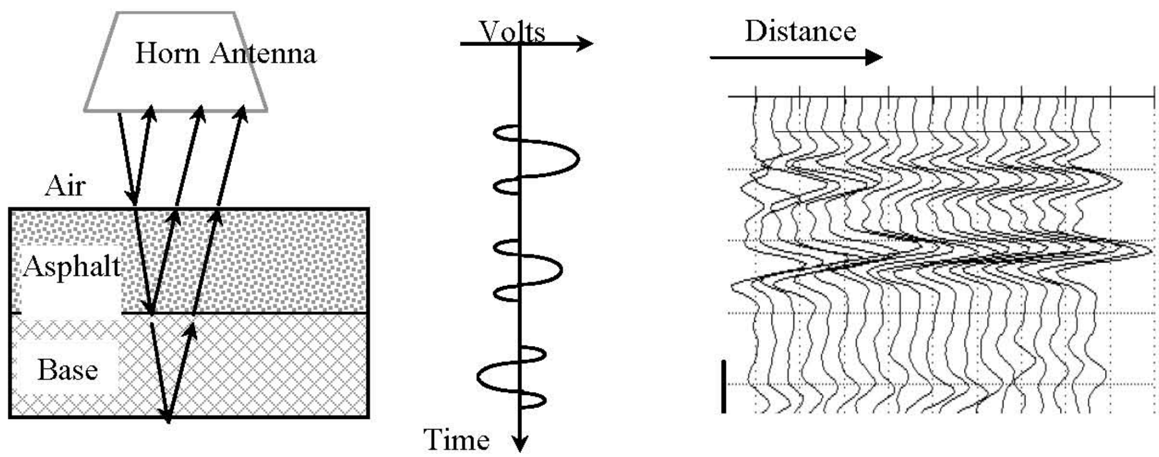
GROUND PENETRATING RADAR (GPR)

GPR works using short electromagnetic pulses radiated by an antenna which transmits these pulses and receives reflected returns from the pavement layers, as shown in Figure 1a below. The reflected pulses are received by the antenna and recorded as a waveform, as shown in 1b. As the equipment travels along the pavement, it generates a sequence of waveforms as shown in Figure 1c. The layer boundary between the asphalt and base is clearly visible in this sequence of waveforms. These waveforms are digitized and interpreted by computing the amplitude and arrival times from each main reflection. The pavement thickness and density can be computed from these amplitudes and arrival times according to the following equations (*3*):

$$\text{Thickness(mm)} = \text{velocity} * \text{time}/2 = (150\ t)/\sqrt{\varepsilon_a} \qquad (1)$$

$$\varepsilon_a = [(Apl + A)/(Apl - A)]^2 \qquad (2)$$

where velocity is calculated from ε_a ,the dielectric constant of the asphalt; t is the time delay between the reflections from the top and bottom of the asphalt, computed automatically 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. Numerous research evaluations have been conducted to establish and confirm the accuracy of this GPR method for determining the thickness of existing (older) pavements.



1a) Measurement Setup 1b) GPR Waveform 1c) Sample Field

In this study the GPR had a dual role, first to determine thickness of different layers prior to recycling, to help take cores at significantly different areas, to conduct a proper mix design, and second, to check the depth of reclamation, immediately after recycling. Any deviation from the idealized pavement (such as the existence of large size particles, such as those in penetration Macadam layers, and thicker hot mix asphalt pavements) needs to be determined prior to reclamation. GPR has been used successfully in identifying in-place structural and material variability by other researchers. Similarly, any variations in the depth of reclamation need to be considered for quality control as well as during structural design.

TEST RESULTS

GPR testing was carried out on projects prior to rehabilitation, and on projects just after rehabilitation. The purpose of the pre-rehabilitation surveys was to characterize the bituminous layer structure for the design of the appropriate milling depth. The purpose of the post-rehabilitation surveys was to determine the in-place thickness and variability of the recycled base material. Table 1 summarizes the projects that have been surveyed and the timing of each survey.

Table 1. Projects Surveyed with GPR

Route	Location	Length (mi.)	Rehab	Date Surveyed	Timing
7	Jackson-Dixmont	4.01	PMRAP	08/02/05	pre-rehab
116	Chester-Lincoln	4.79	FA	08/02/05	pre-rehab
				06/06/06	post-rehab
Conant Rd	Presque Isle	3.64	?	08/03/05	pre-rehab
Station Rd	Easton	1.51	FA	08/03/05	post-rehab
69, 139	Winterport	4.53	PMRAP	04/06/06	pre-rehab
				06/28/06	post-rehab
226	Chelsea-Randolph	4.72	PMRAP	04/06/06	pre-rehab
Jefferson St.	Waldoboro	0.52	FA	04/06/06	pre-rehab

Table 1 shows that six sites were evaluated prior to rehabilitation, and three sites were evaluated after rehabilitation. Two of the three were surveyed both before and after rehabilitation.

GPR testing was carried out using a vehicle-mounted 1 GHz horn antenna GPR system (Figure 2). Data was collected at normal driving speeds, and passes were carried out in the wheelpaths and centerline of each lane in each direction. The data was analyzed to develop thickness profiles, as shown in Figure 3. The depths, as recorded by borings (locations are shown on Figure 3) are also shown. Table 2 shows the utility of the GPR data – segmentation of a project on the basis of correct pavement layer thickness, for mix design and construction.

Figure 2. GPR survey with vehicle mounted antenna

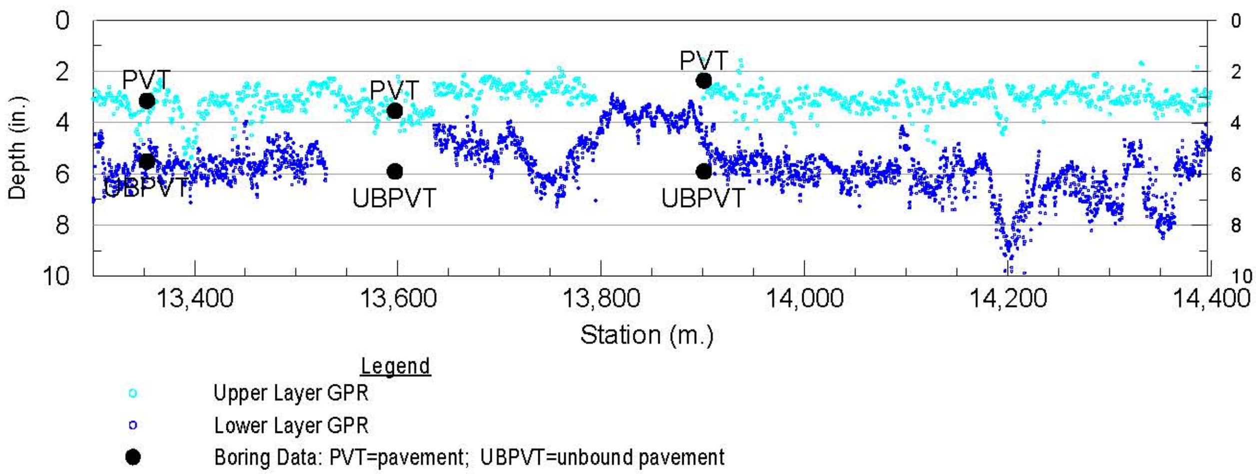


Figure 3. Sample of Processed GPR Data with Data from Borings

Table 2. Segmentation of Representative AC Depths (Rt. 7)

Station (ft.)		Milepoint		representative AC depth
from	to	from	to	
0	4200	0.000	0.795	5.0
4200	8800	0.795	1.667	7.5
8800	11300	1.667	2.140	5.5
11300	16800	2.140	3.182	8.0
16800	19300	3.182	3.655	6.0
19300	20550	3.655	3.892	7.0
20550	21159	3.892	4.007	5.0

Additional plots are presented in Appendix A.

Table 3 below compares the average and standard deviations of pavement depth obtained from both the GPR and the boring data. Note that while the average values are generally similar, both sources of data show high variability, a fact that suggests that the GPR (analyzed at every foot) is more able to capture the details of this variability. An example of this capability is illustrated at the Jefferson Street site, where a difference of 1.95 inches between GPR and boring averages occurs. The details of this difference are shown in Figure 4, where there is a distinctly thicker segment of pavement not captured by the boring data.

Table 3. Comparison of GPR and Boring Data for Pavement Depth

			GPR		Borings		
Route	Location	Length (mi.)	Avg	Stdev	Number	Avg	Stdev
7	Jackson-Dixmont	4.01	6.30	1.22	21	5.27	1.02
116	Chester-Lincoln	4.79	3.65	1.23	23	4.10	1.67
Conant Rd	Presque Isle	3.64	3.39	0.73	24	3.08	1.05
69, 139	Winterport	4.53	5.84	1.46	23	4.90	1.04
226	Chelsea-Randolph	4.72	6.26	1.40	26	6.67	1.33
Jefferson St.	Waldoboro	0.52	5.49	1.74	8	3.54	1.47

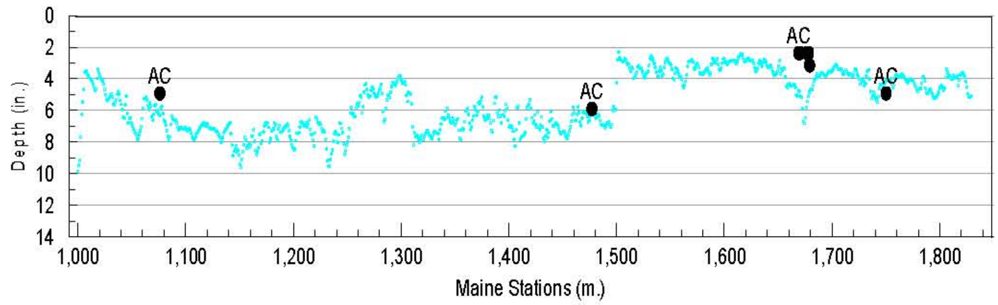


Figure 4. Example of Pavement Segments not revealed by Borings (Jefferson St.)

The analysis clearly shows the need of using GPR, to get continuous and accurate depth data, at traffic speed, to make sure that the designs are appropriate for specific rehabilitation projects.

The results of GPR testing from 3 completed projects are shown in Table 5. The data was analyzed to determine variations in depth. Table 5 shows the average and standard deviations, as well as the target reclamation depth.

Table 5. Results of GPR tests conducted on post-reclaimed projects

				GPR Pavement Thickness (in.)				Plan Thickness (in.)	
			Length	HMA Overlay		RAP Base		HMA	RAP Base
Route	Location	Dir.	(mi.)	Avg	Stdev	Avg	Stdev	Overlay	
Station Rd.	Easton	NB	1.51	2.94	0.23	7.48	1.10	3.0	6.0
		SB	1.51	3.20	0.26	7.76	0.90		
116	Chester-Lincoln	NB	4.79	2.00	0.16	4.49	0.85	n.a.	n.a.
		SB	4.79	1.85	0.18	4.24	0.71		
69, 139	Winterport	NB	0.47	1.69	0.20	4.28*	0.71	1.2 + shim	3.0 RAP + 2.8 HMA
		SB	0.38	2.06	0.54	7.19	1.89		

notes:
n.a. = not available
* = appears to be RAP only

Additional plots are shown in Appendix B.

AUTOMATED STATISTICAL GPR ANALYSIS

The analysis of the GPR data presented in the previous sections involves locating and tracking the layer interfaces in the GPR data, and using core data to distinguish bound from unbound layers. This process involves experience with processing of GPR data, and deals with all of the detailed layer structure features within each pavement section. With older pavement sections, the detailed layer structure features can be fairly complex and locally detailed, and the analysis process can be time-consuming.

As part of this project, an automated GPR analysis technique has been investigated. This automated technique seeks to simplify the data analysis by highlighting the predominant pavement features over a length of the pavement section. This process has also been structured to eliminate the need to directly interact with the GPR data, and thus could be available to a wider range of DOT personnel. Finally, the automated processing technique provides a means for characterizing the pavement layer structure prior to the availability of core data. The layer structure determined from the automated processing can then be finalized when core data becomes available.

The automated processing technique consists of the following steps:

1. Auto-picking of the GPR data
2. Statistical analysis to highlight the predominant layers
3. Summary of predominant layers by distance interval
4. Layer type identification (using cores)

Auto-picking of the GPR data

The automated technique begins with a process called "auto-picking" of the GPR data. The auto-picking algorithm divides the pavement into depth intervals, and determines the most significant reflection peak within each depth interval. The process is carried out automatically, and does not require any user interaction with the GPR data. An example of the auto-picking process is shown in Figures 5 and 6. Figure 5 shows the results obtained for Conant Road using the manual processing technique discussed earlier in this report. Figure 6 shows the same section with the auto-picked results. The manual results are certainly easier to look at, but considerable time was taken to generate these results. The results in Figure 6 were generated automatically. The output shown is a series of automatically generated reflection points. Comparison of Figure 6 to Figure 5 reveals the same basic features, but in a less polished presentation.

Statistical Analysis

The data in Figure 6 is analyzed statistically using a histogram function to reveal the depths of the predominant layers. The statistical analysis process is shown in Figure 7.

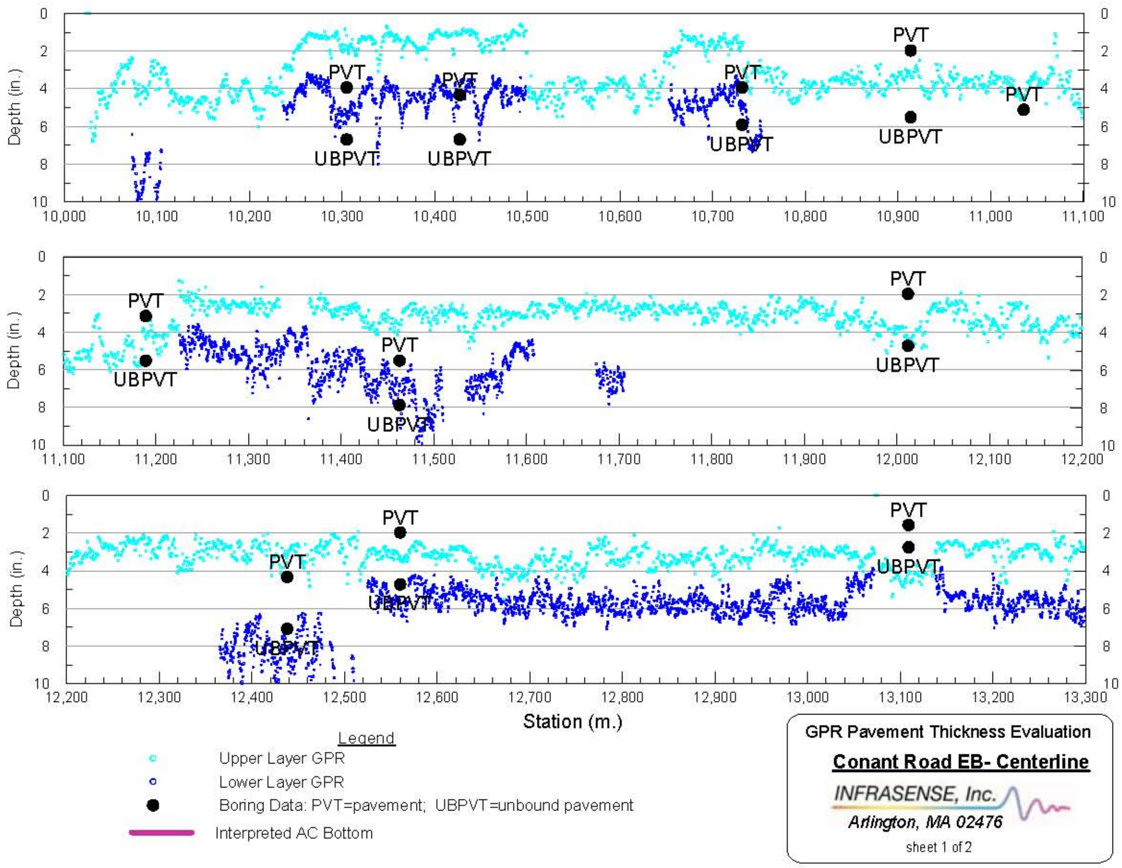


Figure 5. Layer Thickness Analysis using Manual Method

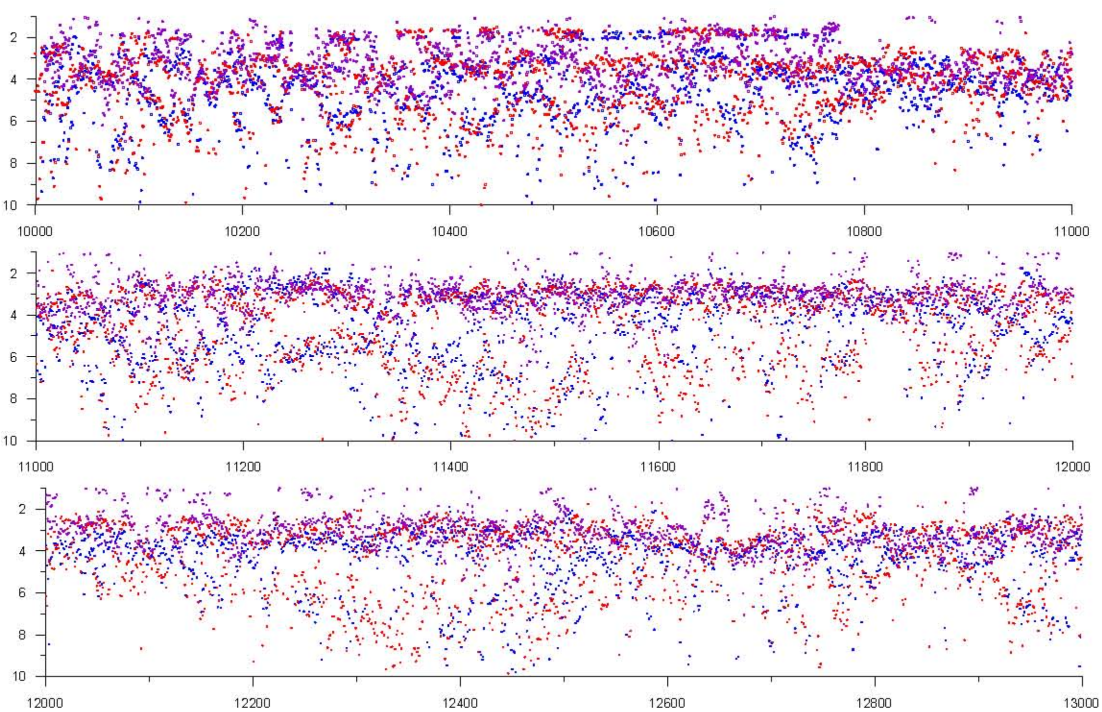


Figure 6. Layer Depth Results from Auto-Picking

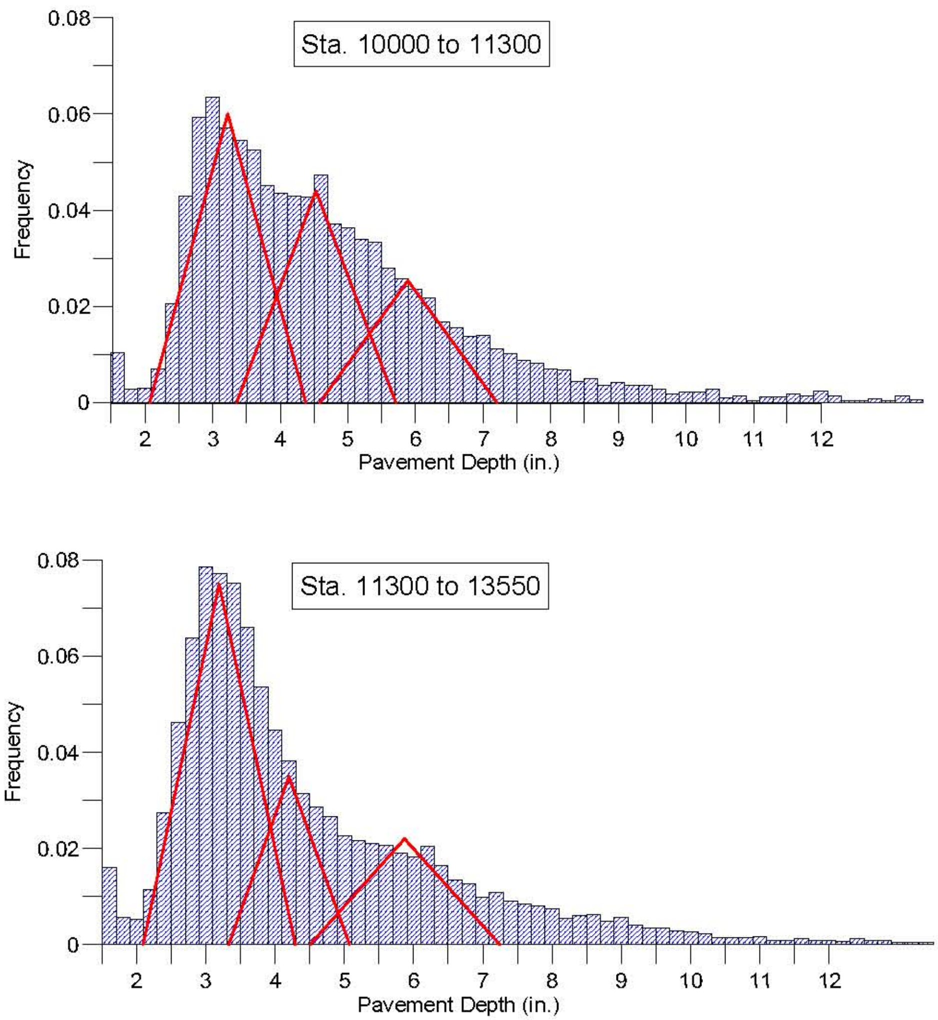


Figure 7. Statistical Analysis for Different Areas of the Pavement

Figure 7 shows the reflection point histograms for two different sections of Conant Road – between stations 10000 and 11300, and between stations 11300 and 13550. The peaks or humps in the histogram represent depths where a pavement layer was frequently identified in the auto-picking analysis. A series of triangular distribution functions was used to divide the histogram into a set of prominent reflection peaks. The mean value, or peak, of each triangle represents the pavement depth for a particular layer; the height represents the frequency of occurrence of the layer; the width represents its variability, or standard deviation.

Summary of Predominant Layers

The summary data from Conant Road generated from these distributions is shown in Table 6. For each segment of the pavement, the table shows the layers that were detected (L1, L2, etc.) and the mean value, standard deviation, and frequency of each detected layer. Note that up to this point there has been no interpretation of material type for these layers. Also, note that up to this point, no use has been made of core data.

Table 6 – Summary Statistical Data for Conant Road

Conant	GPR	EB			WB			Cores		
Interval	Layer	Mean	SD	Freq	Mean	SD	Freq	Type	Mean	SD
10040 to 11300	L1	3.30	0.68	0.92	3.22	0.65	0.92	PVT	3.74	1.08
	L2	4.60	0.67	0.65	4.53	0.67	0.68			
	L3	5.89	0.74	0.39	5.89	0.74	0.39	UBPVT	6.06	0.60
11300 to 13550	L1	3.19	0.62	0.96	3.19	0.62	0.85	PVT	3.08	1.56
	L2	4.20	0.49	0.45	4.20	0.49	0.40			
	L3	5.87	0.77	0.28	5.87	0.77	0.25	UBPVT	5.45	1.84
13550 to 14200	L1	3.28	0.68	0.94	3.00	0.79	1.00	PVT	2.95	0.84
	L2	5.03	0.68	0.41	5.30	0.67	0.43		(2 cores)	
	L3	6.17	0.77	0.32	6.29	0.77	0.45	UBPVT	5.91	0.00
14200 to 15915	L1	3.38	0.72	1.00	3.51	0.84	1.00	PVT	2.72	0.54
	L3	6.17	0.77	0.29	6.17	0.77	0.34	UBPVT	5.24	0.72

For each segment there is a high frequency top layer of approximately 3.2 inches thickness. We know that this layer is asphalt mix, because the road surface layer is made up of asphalt mix. However, at this point we do not know if the deeper layers are asphalt mix or granular/unbound/stabilized base material, or of some other type. At this point, data from cores is required to make this final determination.

The three right columns show data from cores taken in each of the pavement segments. The cores characterize this first layer of pavement as PVT (asphalt pavement), and the second and third layers as UBPVT (unbound pavement). The average of the core depths for each layer are reasonably close to the GPR depths. We would not expect an exact match, since a small number of cores are being compared to thousands of GPR data points.

The data of Table 6 provides a fairly complete characterization of this pavement. It has used the GPR data to divide the pavement into segments and to determine the dominant pavement layers within each segment. It then uses core data to finalize the details of the pavement structure. The analysis has been fairly automated, and does not require any specific expertise with GPR.

Statistical Results for the other pavement sections are shown in the tables of Appendix C. In general, the GPR layers are confirmed, and the type of material in each layer is clarified by the presence of the core data.

Implementation of Ground Penetrating Radar for Design of Full Depth Reclamation (FDR) Projects

Overall Methodology
The design of a FDR project requires knowledge of the thickness and composition of pavement layers, and how these properties vary throughout the length of the project. Ground Penetrating Radar (GPR), in conjunction with confirming core data, can be used to identify the pavement layer structure, and the variations in that structure, on pavement sections planned for FDR. The GPR data can provide the layer structure data and can identify locations where core data can be used confirm layer material composition. The following specifies the methods and equipment to be used for implementing this capability

Data Collection
Equipment Specifications
GPR control and data acquisition system (example, GSSI SIR-20)
GPR horn antenna with a frequency range from 0.5 – 2.5 GHz
(example – GSSI Model 4208 or 4205)
Distance Measuring Instrument (DMI) with a resolution of at least 25 ticks per foot, to be used to trigger the GPR data collection
Vehicle for mounting the GPR equipment and conducting the survey

Data Collection Protocol
One line of data should be collected in each wheel-path and in the centerline of each lane.
Data should be collected in both directions of a bi-directional road
Data collection rate should be one scan per linear foot
The start and end station of each section should be marked in each data file, and the GPR distance should be coordinated with the project stationing.

Data Analysis
GPR Data Anlaysis
Data should be analyzed statistically to identify
(a) the start and end stations of homogeneous sections
(b) the depth of significant layers within each homogenous section

Software for accomplishing this task has been demonstrated as part of this project, as described in the earlier section of this report. Some further software development will be required in order to implement this capability on a routine basis.

Locating Cores
Core locations should be specified for material composition data within each homogeneous section. The specific core locations should be selected in areas of clear layer structure as depicted in the GPR data.

Determining Layer Composition
Core data, once obtained, should be used to interpret layer material composition (see examples in Figures 5-6, presented earlier in this report)

PORTABLE SEISMIC PAVEMENT ANALYZER (PSPA)

The Portable Seismic Pavement Analyzer (PSPA) (Figure 8) is a rapid nondestructive testing device that provides the modulus of the top pavement layer in real-time. The analysis procedure uses the surface wave energy to determine the variation in modulus with wavelength (strictly speaking surface wave velocity with wavelength). The analysis method implemented in the PSPA is called the ultrasonic surface waves (USW) method which is a simplified version of the spectral-analysis-of-surface-waves (SASW) method (*4, 5*). Briefly, this method utilizes the surface wave energy to determine the variation in modulus with wavelength. A schematic of the variation in modulus with wavelength, called a dispersion curve is shown in Figure 9. For simplicity, the surface wave velocity, V_R, is converted to modulus, E, using:

$$E = 2\rho\,[(1.13 - 0.16\upsilon)\,V_R]^2\,(1 + \upsilon) \qquad (1)$$

where ρ = mass density, and υ = Poisson's ratio. Up to a wavelength equal to the thickness of the top pavement layer, the moduli from the dispersion curve are equal to the actual moduli of the layer. As such, the modulus of the topmost layer can be directly estimated without a need for backcalculation.

Figure 8. Portable Seismic Pavement Analyzer

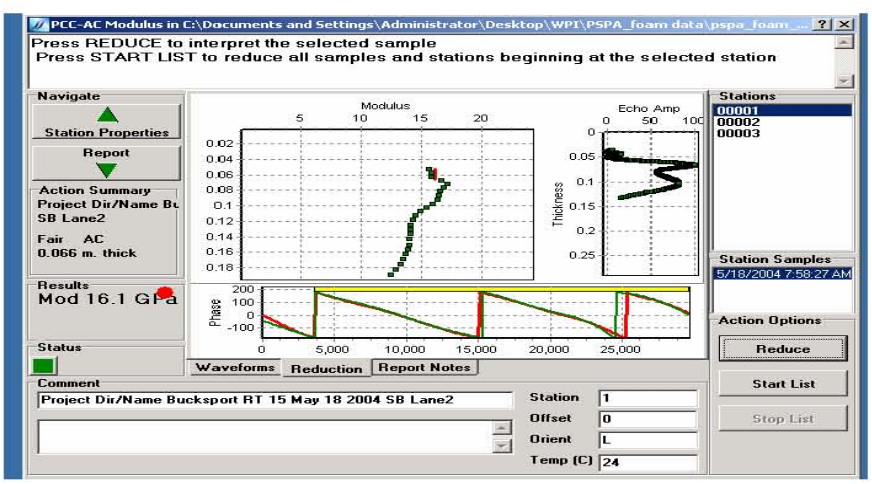


Figure 9. Dispersion curve

In this study, two tasks were accomplished:
1. The use of PSPA for rapid determination of modulus of reclaimed layers during construction (for determination of variability of materials) was demonstrated, and
2. A procedure was developed to utilize the PSPA to determine the modulus of Full Depth Reclaimed base layers underneath HMA (for estimation of structural strength). The procedure is fast, nondestructive and can be conducted by one person.

The use of PSPA provides an alternative to using FWD, which, in most cases, would require waiting for a certain period of time to let the recycled layer achieve sufficient stiffness before testing during construction, and backcalculation (with associated complications regarding unknown layers/thickness) for evaluation of structural strength.

As part of the study, PSPA testing was conducted in a number of projects, both after reclamation before the top layer was placed as well as after reclamation after the top layer was placed. The results are presented in two sections in the following paragraphs. First, the data from reclaimed sections without HMA layer are presented, followed by the data from sections with HMA covers.

Use of PSPA for Determination of Moduli of Reclaimed Layers During Construction
The seismic modulus data, obtained from the PSPA, for the projects without HMA layers is shown in Table 7. Each set of testing took less than 30 minutes by a single operator. Testing was done behind the reclaimer (for FDR)/paver (for PMRAP) projects and the data was corrected and reduced in terms of temperature and seismic-to-design modulus. Note the very high coefficient of variation (46 %). The variation is also an indicator of the quality of the recycling operation, and any out of the ordinary test data would indicate a potential problem. Since in base recycling with foamed asphalt or emulsion there is sufficient workability of the material to allow for reworking, any deficiency can be corrected before the application of the HMA layer. This method should be followed for continuous monitoring of the pavement during recycling work.

Table 7. PSPA data

Route	Station	Corrected Design Modulus at 25C, MPa
Route 69, Winterport, PMRAP	1	1014
	2	1088
	3	1084
	4	1265
	5	1084
	6	2207
	7	788
	8	762
	9	542
	10	581
	11	691
	12	2482
	13	742
	14	981
	15	929
	16	749
	17	578
	18	1103
	19	1287
	20	1364
	21	1417
average		1082
coefficient of variation, %		46
Route 116, Chester	1	1155
	2	974
	3	974
	4	374
	5	379
	6	430
	7	1223
	8	1383
	9	2253
	10	781
	11	410
	12	959
	13	1205
	14	1155
	15	1676
	16	906
	17	1382
	18	1200
	19	1359
	20	1840
average		1062
coefficient of variation, %		46

Development of a Procedure to Utilize the PSPA to Determine the Modulus of Full Depth Reclaimed Base Layers Underneath HMA

For the tests conducted on reclaimed base with HMA, the scope of the work consisted of testing and analyzing sixteen reclaimed sections in different locations in Maine. These sites are described in Table 8. Nine sites had FA reclaimed bases, whereas the remaining seven were constructed with PMRAP. The locations of these sites ranged from southeast to west to north in Maine. In most cases, these pavement sections were reclaimed by using the existing top 75 mm to 100 mm of HMA and 50 mm to 75 mm of base underneath, to produce a new pavement with a relatively thin HMA layer (60 mm -75 mm) on top of about 150 mm of full-depth reclaimed base, on top of approximately 600 mm of subbase. The subgrade soil types ranged from A-1 to A-4.

The validity of the use of PSPA was evaluated in these projects, with additional testing using the FWD and GPR. The testing and evaluation program consisted of performing FWD tests at five spots, 5 m apart, on a selected uniform section of each route at multiple load levels to produce contact pressures of 414 kPa, 483 kPa, 552 kPa, 690 kPa and 828 kPa (60 psi, 70 psi, 80 psi, 100 psi and 120 psi), respectively. A GPR with a 1.5 GHz antenna was used to check the uniformity of different layers throughout the selected sections. The test sections were at stations for which thickness data for all the different layers were available to Maine DOT. Finally, the PSPA was used to conduct two PSPA tests at each spot, one parallel to the wheelpath and another perpendicular.

TABLE 8. Projects tested in this study

Route	Structure	Subgrade Type	Reclaimed base Type	% Binder	% Cement
115W	100 mm HMA				
	150 mm FA		FA	2.5	1.5
	575 mm gravel				
	subgrade	A-2-4			
302S	100 mm HMA				
	100 mm FA		FA	3.5	3.0
	750 mm gravel				
	subgrade	A-1-b			
138S	38 mm HMA				
	75 mm PMFA		PMFA	NA	NA
	450 mm gravel				
	subgrade	Silt			
32N	75 mm HMA				
	150 mm FA		FA	3.0	---
	25 mm RAP				
	575 mm gravel				
	subgrade	Gravel with silt and sand			
6W	75 mm HMA				
	150 mm FA		FA	2.5	1.5
	25 mm RAP				
	150 mm gravel				
	subgrade	A-4			
10	75 mm HMA				
	150 mm FA		FA	3.5	1.5
	600 mm gravel				
	subgrade	Silt			
27 Eustis	75 mm HMA				
	138 mm FA		FA	2.5	1.5
	50 mm RAP				
	subgrade	A-1-b			
27 COP	63 mm HMA				
	150 mm FA		FA	2.5	3.0
	subgrade	A-1-b			
11S	60 mm HMA				
	150 mm FA		FA	2.5	1.5
	subgrade	Unknown			

--- Not used; NA – Not available

TABLE 8. Projects tested in this study (continued)

Route	Structure	Subgrade Type	Reclaimed Base Type	% Binder	% Cement
27S	75 mm HMA				
	75 mm PMRAP		PMRAP	3.25	1
	575 mm gravel				
	subgrade	A-4			
126E	75 mm HMA				
	75 mm PMRAP		PMRAP	2.75	1.5
	900 mm gravel				
	subgrade	Silt			
219	75 mm HMA				
	75 mm PMRAP		PMRAP	2.5	2.0
	450 mm gravel				
	subgrade	A-4			
3W	175 mm HMA				
	100 mm PMRAP		PMRAP	3.25	1.25
	625 mm gravel				
	subgrade	Brown Silty Clay			
7S	75 mm HMA				
	75 mm PMRAP				
	100 mm RAP				
	800 mm gravel				
	subgrade	Unknown	PMRAP	NA	NA
137W	75 mm HMA				
	100 mm PMRAP				
	675 mm gravel				
	subgrade	Unknown	PMRAP	NA	NA
35N	50 mm HMA				
	150 mm PMRAP			3.75	2.0
	600 mm gravel				
	subgrade	Unknown	PMRAP		

--- Not used; NA – Not available

Seismic Data Collection and Analysis

The modulus versus wavelength plot (dispersion curve) provided by the PSPA is used to estimate the modulus profile versus depth. The actual modulus profile differs from this approximation, and previous researchers have used a backcalculation process to recover this true variation. To eliminate the backcalculation process, an innovative method was developed in this study. A series of simulations was carried out to relate the ratio of the composite modulus (Figure 10) of the top two layers to modulus of the top layer to the ratio of the actual surface wave velocities of the top and second layer. In these simulations, the velocity of the top layer was maintained constant and the velocity of the base was varied from 20% to 100% of the velocity of the top layer. Such a graph is shown on Figure 11 for a pavement with 66 mm of HMA and 154 mm of base (foamed asphalt stabilized layer) underneath the HMA. The best fit curve to this graph can be used to directly estimate the actual modulus of the base, knowing the modulus of the top layer and the composite modulus of the top two layers.

The raw data from PSPA testing are shown in Table 9. The coefficients of variation from testing are low, around 5 % for both HMA and composite (HMA + Base) moduli. This indicates that the test equipment and method are capable of producing consistent test results.

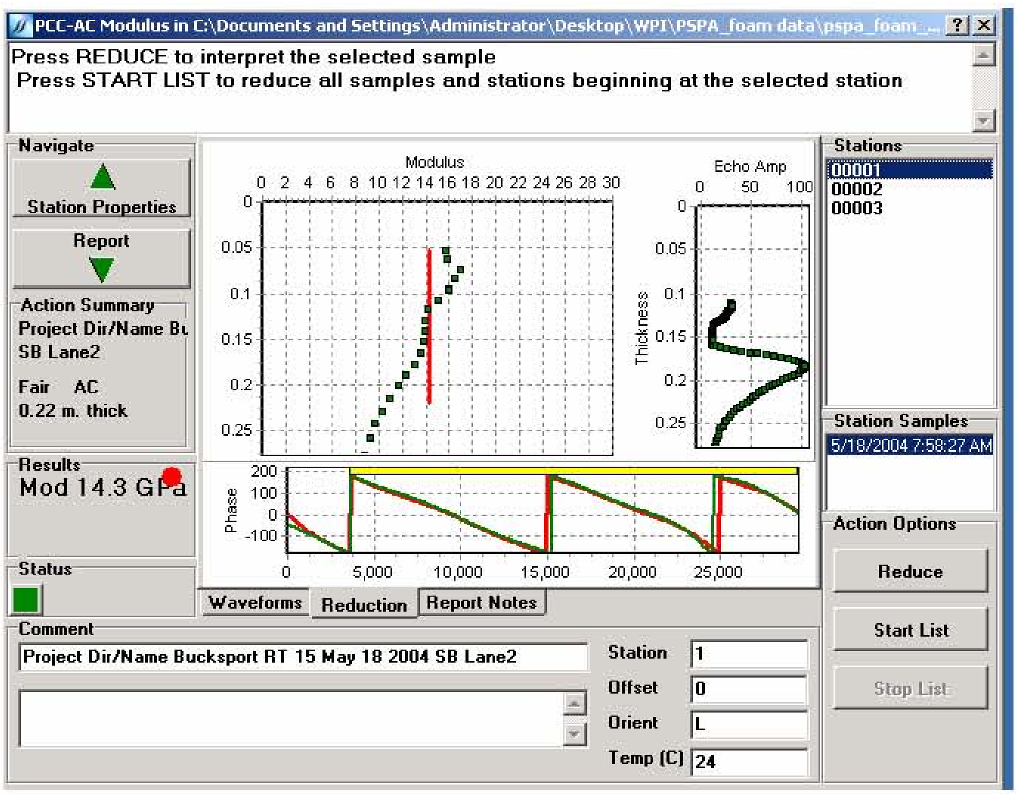


Figure 10. Composite modulus from PSPA tests

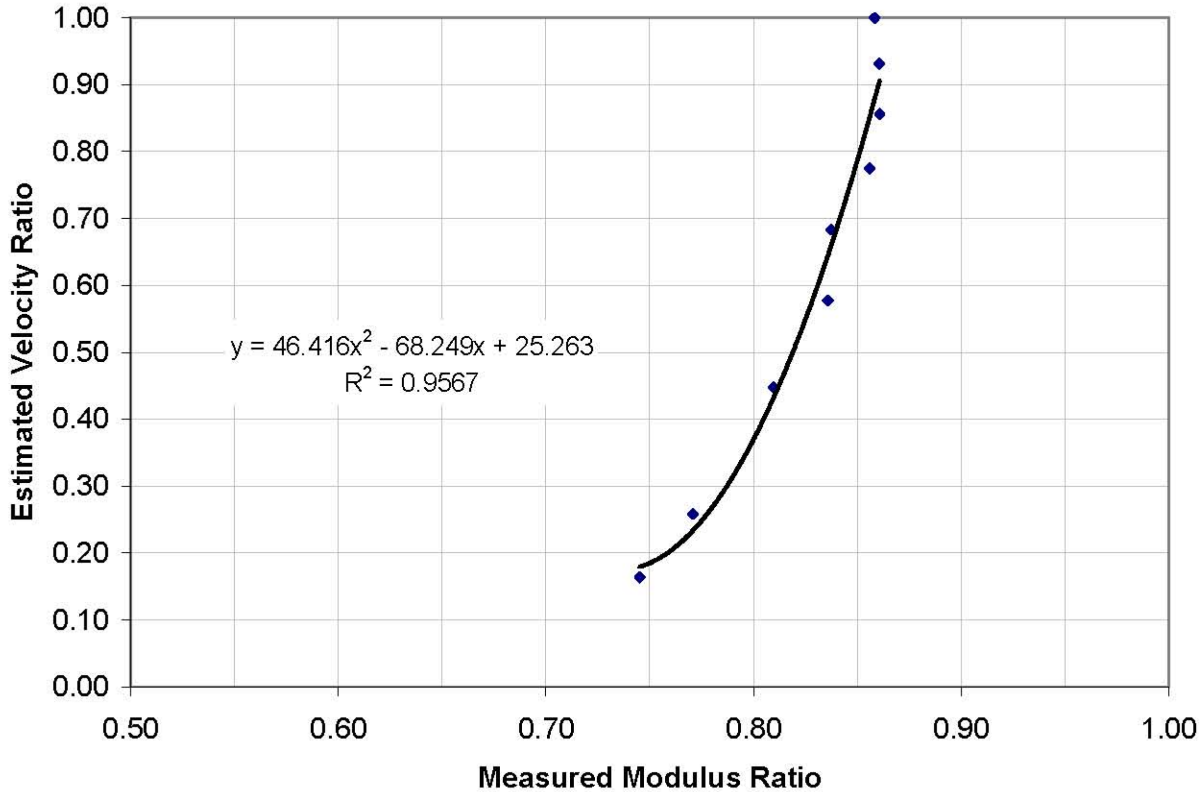


Figure 11 Variation in measured modulus ratio versus estimated velocity ratio

TABLE 9 Raw data from PSPA tests

Roadway	HMA (Seismic) modulus		Composite (Seismic) modulus	
	Average, GPa	Coefficient of Variation, %	Average, GPa	Coefficient of Variation, %
35N	13.9	4.98%	11.54	9.17%
115W	22.3	4.88%	18.1	5.27%
302S	16.9	6.36%	15.8	5.77%
138S	15.5	7.33%	9.4	5.58%
27S	14.7	6.24%	13.2	6.07%
126E	16.5	6.03%	13.4	4.29%
32N	16.3	2.91%	12.7	2.34%
7S	20.3	9.44%	17.0	4.50%
137W	17.3	6.90%	11.1	2.37%
219	11.3	5.07%	9.2	2.44%
3W	15.9	3.96%	15.9	4.66%
6W	15.2	2.87%	11.8	3.74%
10	15.2	5.83%	12.1	2.54%
11S	13.7	11.57%	11.0	14.03%
27 Eustis	15.5	4.32%	13.2	3.54%
27 COP	15.1	6.01%	9.3	4.27%

Note: Average coefficient of variation for HMA seismic modulus = 5.9 %
Average coefficient of variation for composite seismic modulus = 5.0 %

The design moduli of the HMA and reclaimed base layers from PSPA are shown in Table 10.

Table 10. Design moduli for different layers

Route	Test Temperature, C	Design modulus at test temperature, GPa	
		HMA	Base
35N	9	4.3	3.3
115W	10	6.9	5.4
302S	11	5.3	5.1
138S	11	4.8	1.7
27S	12	4.6	4.3
126E	12	5.1	4.0
32N	13	5.1	3.4
7S	13	6.3	5.1
137W	18	5.4	1.3
219	21	3.5	1.7
3W	19	4.9	4.9
6W	16	4.7	2.6
10	19	4.7	3.0
11S	18	4.3	3.4
27 Eustis	19	4.8	4.2
27 COP	19	4.7	0.9

In order to check the accuracy of these PSPA predicted values, two approaches were taken. First, the pavements were modeled as elastic layered systems so that the maximum deflections under the loading plate could be determined with the PSPA predicted moduli, and compared to the actual maximum deflections under different levels of contact stress. The intention was to determine how closely the predicted deflections match the actual deflection. Secondly, the layer moduli were backcalculated with available information and with the PSPA predicted moduli as the seed moduli for the reclaimed layers. The objective in this case was to determine whether a reasonable root mean square (RMS) error could be obtained with these inputs. These two approaches are described briefly in the following paragraphs.

Comparison of predicted and actual maximum deflections

The procedure followed for this task was as follows.

1. Consider each pavement and each FWD drop.
2. Use HMA modulus (E_{AC}) from PSPA testing at FWD temperature.
3. Use the reclaimed base moduli (E_{Base}) from PSPA at FWD temperature.
4. Ignore the unstabilized RAP layer; or if a layer was suspected, group it with the reclaimed layer
5. Assume the modulus of the subbase layer from experience/past studies
6. Determine the subgrade modulus, E_{SG} (in psi), according to the relation given below *(7)*:

   $$E_{SG} = (0.24\ P) / (d_r\ r) \tag{2}$$

   where, P = applied load, lb, d_r = deflection at a distance r from center of the load , inch.
7. Using the load used for each FWD location (average of the last three drops, for each of the five stress levels, 414 kPa, 483 kPa, 552 kPa, 690 kPa and 828 kPa), determine the center deflection using layered elastic analysis software BISAR.
8. Compare these deflections with the deflections observed during FWD tests.

The results of this analysis are compared with the actual deflections in Figure 12. Most of the data points lie on or close to the line of equality. The disagreement between the predicted and actual deflections may very well be due to the nonlinear responses from some of the pavements. The impact of load-induced nonlinearity has been investigated and presented later in this report.

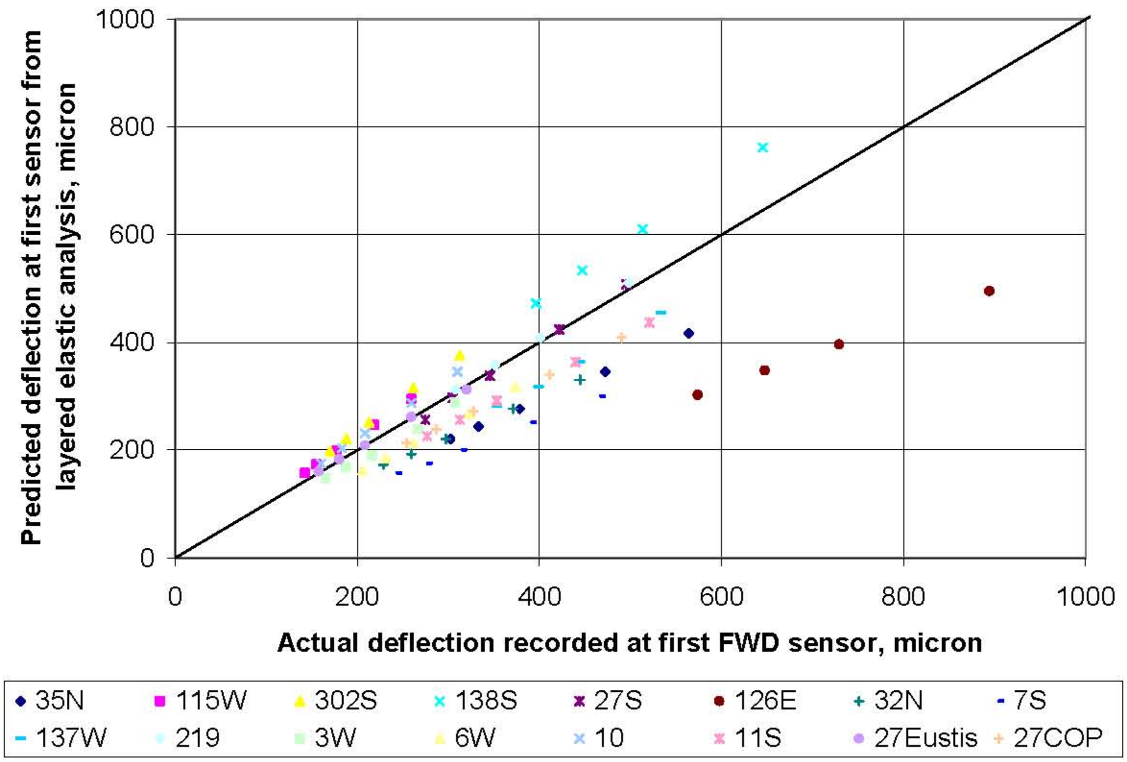


Figure 12. Plot of actual versus predicted deflections

Backcalculation of layer moduli

The backcalculation of the layer moduli for each pavement was conducted with the Evercalc software (***8***). In the backcalculation process the following items were considered:

1. The depth to a stiff layer was calculated and considered.
2. The moduli of the HMA layers less than or equal to 75 mm were "fixed" to the corresponding moduli determined from tests conducted earlier on similar HMA.
3. The initial or seed moduli of the reclaimed layers were based on the results of testing conducted with the PSPA.
4. The moduli of the subbase gravel layers for all pavements were considered to be the same as obtained from Maine DOT.
5. The modulus of the subgrade was determined with the use of the deflection at the seventh sensor and formula presented in Reference (*7*).

The backcalculation RMS errors, along with the moduli estimated with PSPA and the backcalculated FWD moduli are shown in Table 11. The RMS errors (considering all projects except 2) ranged from approximately 2% to 11%. The RMS errors from Rt 126 and 7S projects were 21% and 17%, respectively. The pavement on Rt 126 was found to be exhibiting significant load-induced nonlinear behavior (discussed later), and the pavement on Rt 7S consisted of approximately 100 mm of RAP with unknown properties underneath the reclaimed layer (this 100 mm layer was considered as part of the reclaimed layer during backcalculation). These factors could at least be partially responsible for the high mismatch errors in the backcalculation at those two sites. For the other pavements, the PSPA predicted and the backcalculated moduli are reasonably close to one another. The backcalculation process would not have been successful (i.e. yielded relatively small RMS errors) without the use of proper "seed moduli" obtained from the seismic tests.

TABLE 11 Comparison between PSPA predicted and backcalculated moduli

a) Foamed Asphalt

Project	PSPA predicted Modulus, GPa	Backcalculated Modulus, GPa	Root Mean Square Error, %
6 W	2.6	2.1	6.46
10	3.0	3.2	2.19
27 COP	0.9	1.3	10.89
27 Eu	4.2	4.2	3.14
32 N	3.4	2.4	8.17
115 W	5.4	5.0	2.71
302 S	5.1	6.1	2.4
138 S	1.7	2.4	9.4
11S	3.4	2.1	2.3

b) PMRAP

3 W	4.9	6.0	8.74
27 S	4.3	3.4	1.93
126 E	4.0	2.8	21.81
291 E	1.7	1.8	1.65
7S	5.1	4.	16.7
137W	1.3	1.1	3.3
35N	3.3	2.1	8.8

Checking for Linear Elastic Response

The data acquired from the FWD testing was analyzed to determine the nature of the response (linear or nonlinear) from the subgrades. The surface modulus was calculated for each project for the data obtained at 552 kPa contact stress. The surface modulus is the "weighted" mean modulus of the half space calculated from the surface deflection using Boussinesq's equation (*9*):

$$E_0(0) = 2*(1-\mu^2)*\sigma_0*a/d(0), \text{ and} \tag{3}$$

$$E_0(r) = (1- \mu^2)* \sigma_0*a^2/(r*d(r)) \tag{4}$$

where: $E_0(r)$ = surface modulus at distance of r from the center of the loading plate, μ = Poisson's ratio, considered as 0.35, σ_0 = contact stress under he loading plate, a = radius of the loading plate, d(r) = deflection at distance r.

Figure 13 shows the plots of surface modulus versus distance, r, which is plotted as depth, since the surface modulus at distance *r* approximately denotes the surface modulus at the same equivalent depth (***9***). Only two (6W and 115W) out of the sixteen projects actually indicate almost linear elastic subgrade (denoted by almost vertical lines). All other sites show nonlinear subgrades. This information is important for considering the errors obtained in the backcalculation process.

The deflections obtained under the loading plate, at different contact stresses, were also used for determining the load-response (***10***) of pavements (linear elastic, deflection hardening or deflection softening). Considering a linear response between stress and deflection (at the center of the loading plate), the intercept (at zero stress) and the correlation coefficient were determined for each fitted regression line. The results are shown in Figure 14 and Table 12. The criteria used for classification of the load-response behavior are (***10***):

1. If $R^2 \geq 0.99$ and intercept between -10 μm and +10 μm, the response is elastic
2. If $R^2 \geq 0.99$ and intercept greater than +10 μm, the response is deflection hardening
3. If $R^2 \geq 0.99$ and intercept below -10 μm, the response is deflection softening
4. If $R^2 < 0.99$, fit a line through data points from the two highest stresses; if the intercept is above +20 μm, the response is deflection hardening, and if the intercept is below -20 μm, the response is deflection softening

Figure 14 shows that only three pavements (Rt 10, 27 COP and 32 N – all foamed asphalt projects) out of the sixteen can be classified pavements with the "elastic response." The remaining sites show "deflection hardening" response. The plot for the PMRAP pavement on 126E shows the highest intercept (86 μm). The observations of nonlinear response should explain part of mismatch between the predicted and actual deflections (noted in Figure 12) and the relatively high RMS errors in backcalculation (shown in Table 12).

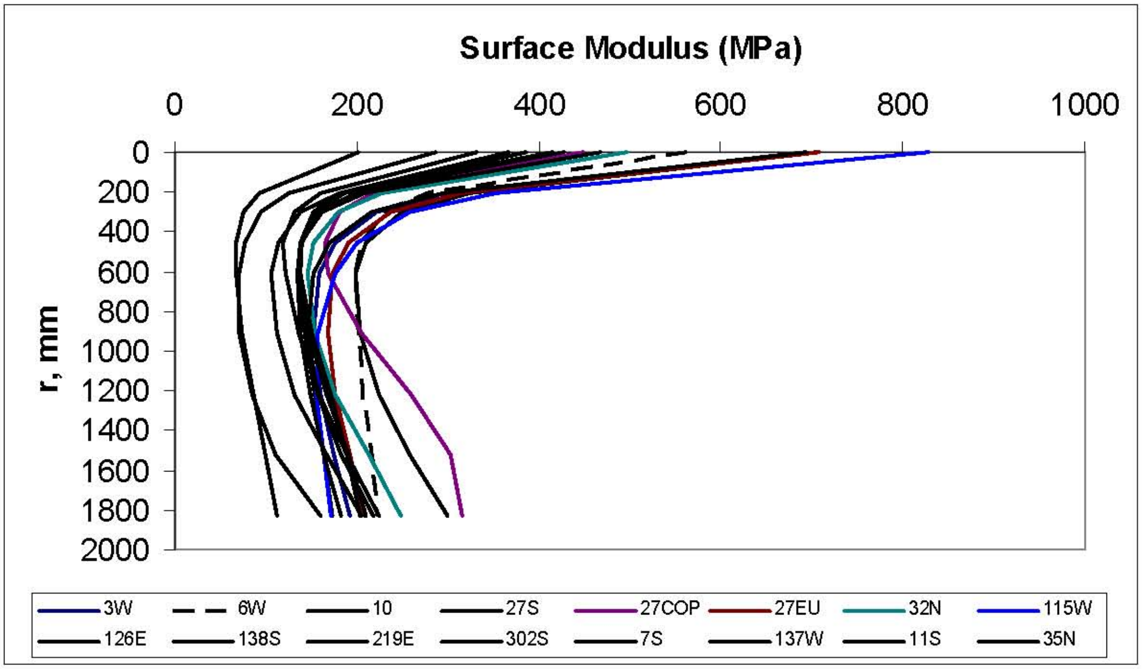


Figure 13. Plot of surface modulus versus distance from center

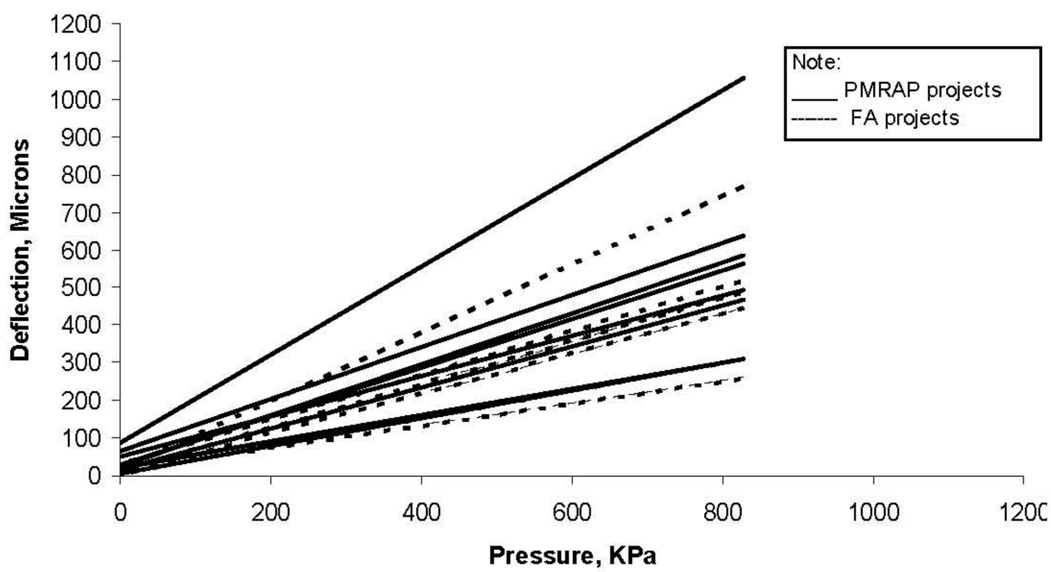


Figure 14. Plot of deflection at Center of load plate versus pressure

Table 12. Interpretation of behavior of pavements from FWD deflections

Project	R^2	Y-Intercept, µm	Response*
3 W	0.998	19.136	Deflection hardening
6 W	0.9987	31.664	Deflection hardening
10 ST	0.9998	6.6605	Elastic
27 S	0.9993	48.261	Deflection hardening
27 COP	0.9996	6.2291	Elastic
27 EU	0.999	13.359	Deflection hardening
32 N	0.9992	5.9355	Elastic
115 W	0.9981	16.675	Deflection hardening
126 E	0.9993	86.28	Deflection hardening
138 S	0.9963	14.769	Deflection hardening
219 E	0.9977	25.942	Deflection hardening
302 S	0.9983	20.446	Deflection hardening
7S	0.99	14.74	Deflection hardening
137W	0.99	64.37	Deflection hardening
11S	0.99	30.75	Deflection hardening
35N	0.99	26.96	Deflection hardening

Prediction of Design Moduli

The estimated seismic moduli with the PSPA were adjusted for temperature using the following equations:

For HMA : $E_{25} = E_t / (1.35 - 0.014\,t)$ (5)

For foamed asphalt: $E_{20} = E_t / (1.68\text{-}0.034t)$ (6)

where, E_{20} = Modulus at 20°C, E_{25} = Modulus at 25°C , E_t = Modulus at t°C, t = specific test temperature, °C.

Table 13 shows the average temperature adjusted moduli for the FA and PMRAP. The HMA moduli range from 3.3 GPa to 5.8 GPa, the FA moduli range from 0.9 GPa to 4.1 GPa and the PMRAP moduli range from 1.8 GPa to 4.8 GPa. Based on past experience, these values are consistent with expected values of moduli for these materials.

TABLE 13 Temperature adjusted design moduli for different layers

a) Foamed Asphalt (FA) Reclamation Projects

Route	Design Modulus, GPa	
	HMA at 25C	Base at 20C
35N	3.6	2.4
115W	5.8	4.1
302S	4.4	4.0
138S	4.1	1.3
32N	4.4	2.8
6W	4.2	2.4
10	4.4	3.0
11S	3.9	3.2
27 Eustis	4.5	4.1
27 COP	4.4	0.9

b) Plant Mixed Recycled Asphalt Pavement (PMRAP) Reclamation Projects

Route	Design Modulus, GPa	
	HMA at 25C	Base at 20C
27S	3.9	3.4
126E	4.4	3.1
7S	5.5	4.1
137W	4.9	1.2
219	3.3	1.8
3W	4.6	4.8

c) Statistical Information

Modulus, GPa	HMA	FA	PMFA	PMRAP
Average	4.3	2.9	1.3	3.1
Range	3.3-5.8	0.9-4.1	-	1.8-4.8

On the basis of this study the following conclusions can be made:

1. The seismic testing and a proposed analysis method can provide reliable estimates of moduli of reclaimed layers in HMA surface pavements.
2. The process is fast and hence can be used to collect a large number of data – something that is very important for layers which exhibit a large variation in properties.
3. The predicted moduli can be used effectively in mechanistic empirical design of pavement structures.
4. The seismic method presented in this study should be used on a regular basis to develop a large database of in-place layer moduli for pavements with thin HMA surface for use in mechanistic-empirical design methods.

RECOMMENDED PROCEDURE FOR THE USE OF PORTABLE SEISMIC PAVEMENT ANALYZER (PSPA) FOR DETERMINATION OF ELASTIC MODULUS OF RECLAIMED BASE LAYERS

Test Equipment

The Portable Seismic Pavement Analyzer (PSPA) marketed by Geomedia (www.geomedia.us) or any similar equipment is suggested for use. The Geomedia equipment consists of an impact source and two receivers packaged into a hand-portable unit and is operated through a computer. Preliminary data acquisition and reduction software is preloaded in the computer.

Test Procedure

The following method is suggested for obtaining seismic modulus of recycled layers. As an example, consider a pavement with 66 mm of HMA and 154 mm of foamed asphalt stabilized layer underneath the HMA.

1. Set the layer thickness to 66 mm to determine the modulus of the HMA layer, E_{AC},
2. Set the layer thickness to 220 mm (66+154) to determine the composite modulus of base and HMA layers, Ecomp.
3. Determine the measured modulus ratio (Ecomp/E_{AC})
4. Using the measured modulus ratio, estimate the actual velocity ratio from appropriate graph and estimate the approximate modulus of the base layer, E_{Base}.
5. Adjust E_{AC} and E_{Base} from Steps 1 and 4 to a frequency equal to FWD load dominant frequency. As a first approximation, the adjustment is achieved by dividing PSPA modulus by 3.2.
6. For predicting the HMA or base modulus at 25°C, E_{25}, use the following equation: $E_{25} = E_t / (1.35 - 0.014\,t)$, where E_t is the modulus at field temperature t°C.

Test Frequency and Data Analysis

Repeat this test at five spots on wheelpath, 20 ft apart for the length of the project that has the same mix design and underlying structure. Take the average of the seismic moduli and the standard deviation. Consider the value that is (Average – 1.5* standard deviation) for structural design. If either one of those (mix design and underlying structure) changes within the project length, select another five-spot area and conduct the tests.

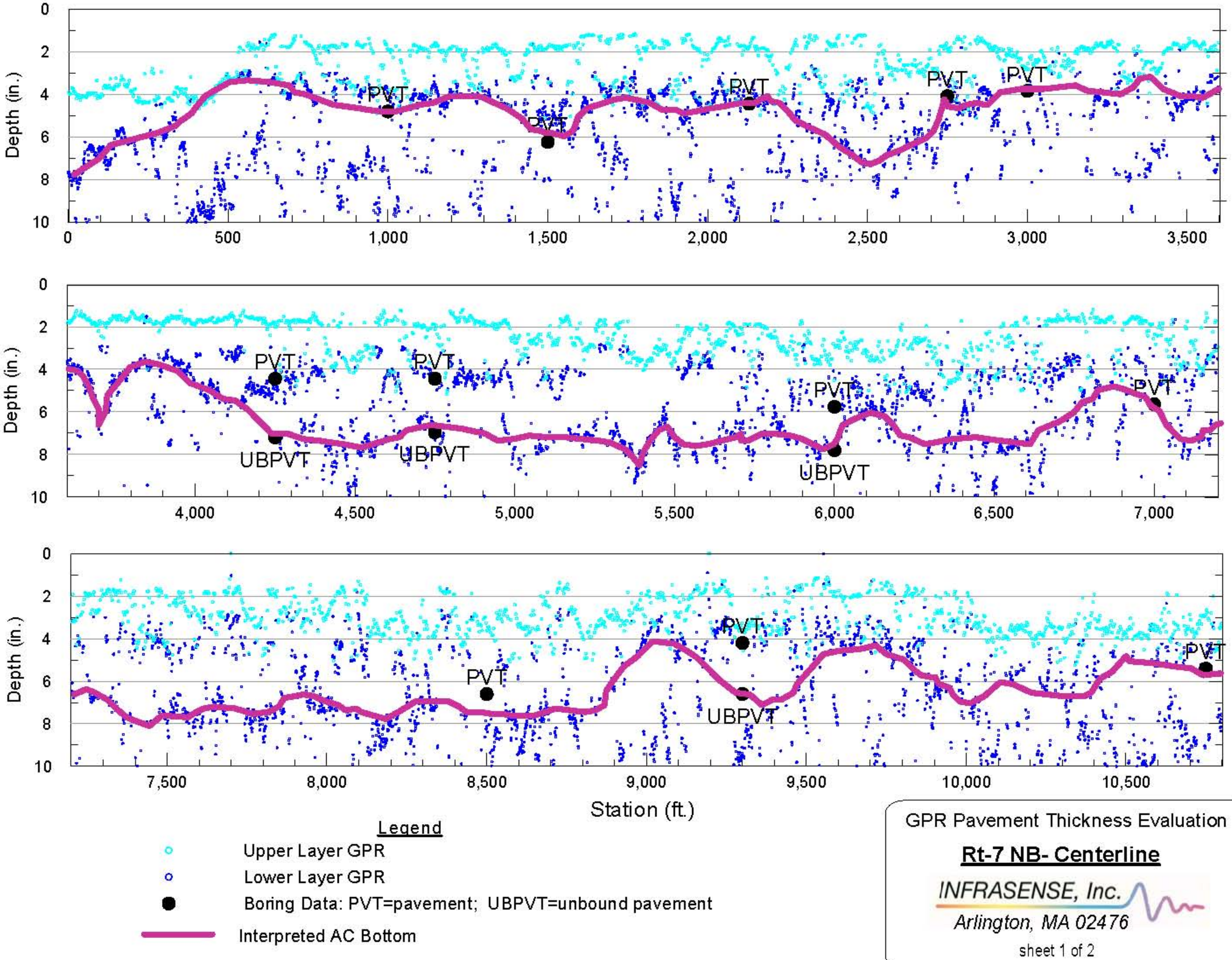
Recommended Future work

The validity of this rational and fast nondestructive seismic-based procedure for the determination of moduli of reclaimed layers with HMA surface layers has been illustrated. The next step is to make this process available to the highway agencies and the industry to make its full use of it. Currently the equipment is available, but the post processing of the data has to be done manually. This task can be automated with the help of the artificial neural networks (ANN). The moduli of the top layer (HMA) and the composite modulus of base and HMA can be determined almost instantaneously. However, to obtain the modulus of the base from these two moduli, a number of simulations had to be carried out for separately for each site. If a large number of simulations are carried, an ANN model can be developed and incorporated in the PSPA analysis so that the modulus of the base can be determined instantaneously by any operator. Such work has been done with seismic testing successfully in the past.

ACKNOWLEDGEMENTS
The authors are grateful to Brian Marquis, Tim Soucie, Wade McClay, Rick Bradbury and Dale Peabody of Maine DOT for funding this study and their help in conducting the field tests. The authors thank Ethan Ray, Julie Bradley, Jaime MacFall and Donald Pellegrino of Worcester Polytechnic Institute for their help in conducting the field and laboratory tests.

REFERENCES

1. An Overview of Recycling and Reclamation Methods for Asphalt Pavement Rehabilitation. Asphalt Recycling and Reclaiming Association (ARRA), Annapolis, Maryland, 1992.
2. Marquis, B., D. Peabody, R. Mallick and T. Soucie. *Determination of Structural Layer Coefficient for Roadway Recycling Using Foamed Asphalt.* Final Report Submitted to the Recycled Materials Resource Center, University of New Hampshire, December 2003.
3. Maser, K. R., Holland, T. J., and Roberts, R., "Non-Destructive Measurement of Layer Thickness on Newly Constructed Asphalt Pavement". *Proceedings of the Pavement Evaluation Conference 2002,* Roanoke, VA, October 21-25, 2002.
4. Nazarian, S., K. H. Stokoe II, and W. R. Hudson. Use of Spectral Analysis of Surface Waves for Determination of Moduli and Thickness of Pavement Systems. In *Transportation Research Record, No. 930,* TRB, National Research Council, Washington, D. C., 1993, pp. 38-45.
5. Nazarian, S., and K. H. Stokoe II. Nondestructive Testing of Pavements Using Surface Waves. In *Transportation Research Record, No. 993,* TRB, National Research Council, Washington, D. C., 1984, pp. 67-79.
6. Nazarian, S., M.R Baker, and K Crain. Fabrication and Testing of a Seismic Pavement Analyzer. *SHRP Report H-375.* SHRP, National Research Council, Washington, D.C. 1993.
7. American Association of State Highway and Transportation Officials (AASHTO). *AASHTO Guide for Design of Pavement Structures.* Washington, DC, 1993.
8. Sivaneswaran, N, L.M. Pierce and J.P. Mahoney. Evercalc® Pavement Backcalculation Program, Materials Laboratory, Washington State Department of Transportation, Version 5.20, March 2001.
9. Ullidtz, Per., *Pavement Analysis,* ELSEVIER, 1983
10. ERES Consultants, Introduction to Mechanistic Empirical Pavement Design, *ASCE Reference Manual,* June 2004



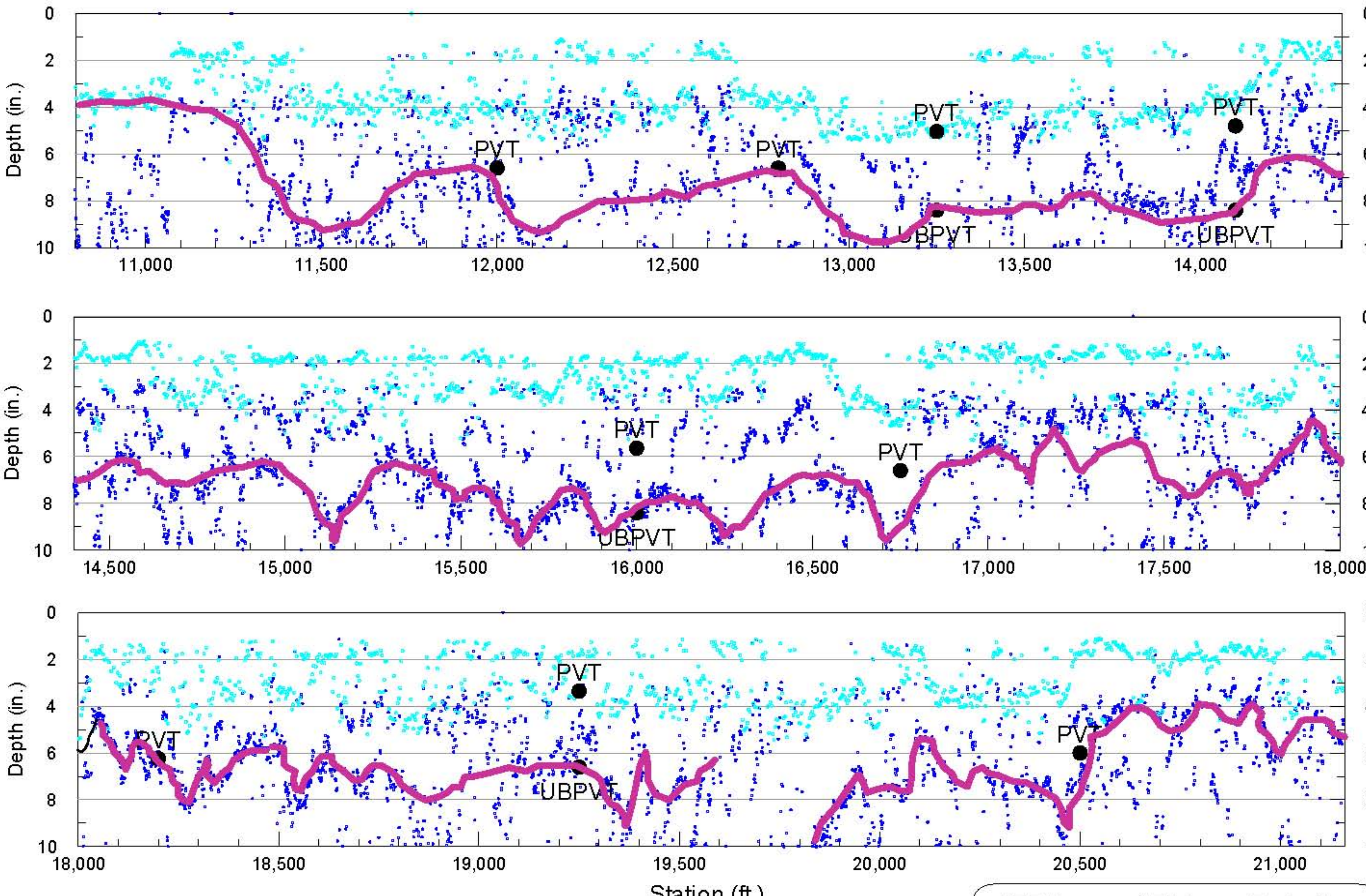
GPR Pavement Thickness Evaluation

Rt-7 NB- Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 1 of 2



Legend

- Upper Layer GPR
- Lower Layer GPR
- Boring Data: PVT=pavement; UBPVT=unbound pavement
- Interpreted AC Bottom

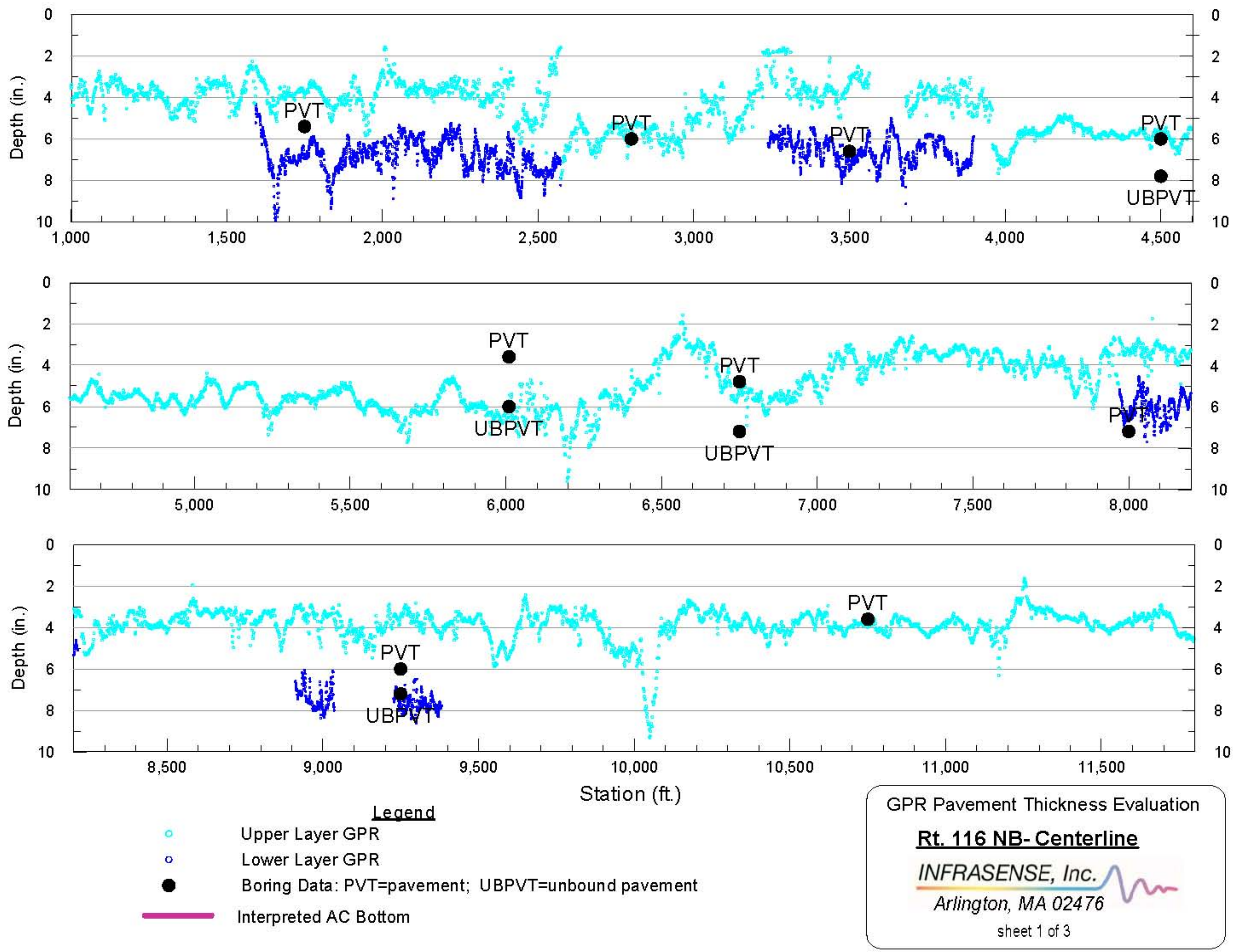
GPR Pavement Thickness Evaluation

Rt-7 NB- Centerline

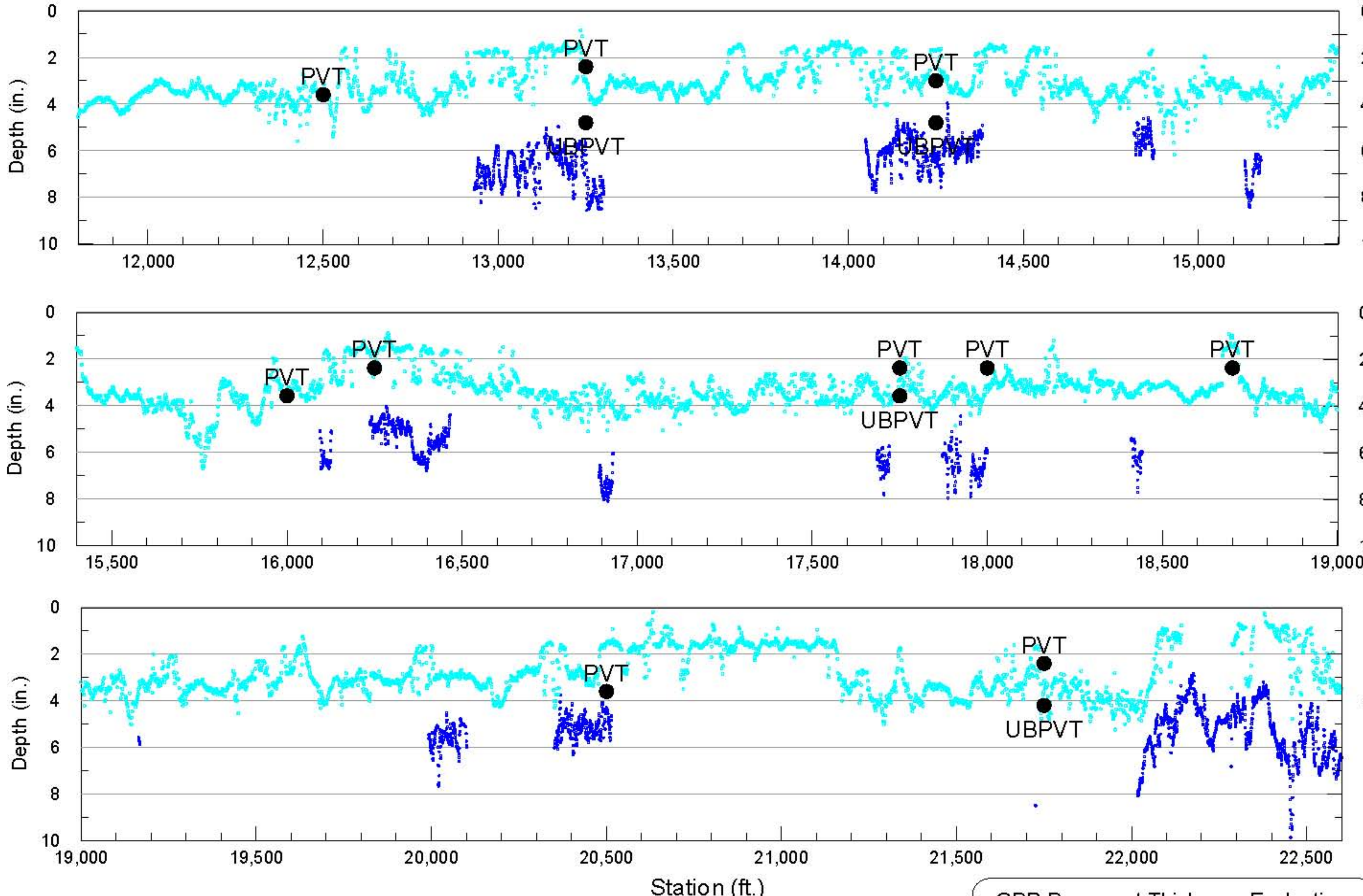
INFRASENSE, Inc.

Arlington, MA 02476

sheet 2 of 2



Depth (in.)
PVT
UBPVT
Station (ft.)
Legend
Upper Layer GPR
Lower Layer GPR
Boring Data: PVT=pavement; UBPVT=unbound pavement
Interpreted AC Bottom
GPR Pavement Thickness Evaluation
Rt. 116 NB- Centerline
INFRASENSE, Inc.
Arlington, MA 02476
sheet 1 of 3



Legend

- Upper Layer GPR
- Lower Layer GPR
- Boring Data: PVT=pavement; UBPVT=unbound pavement
- Interpreted AC Bottom

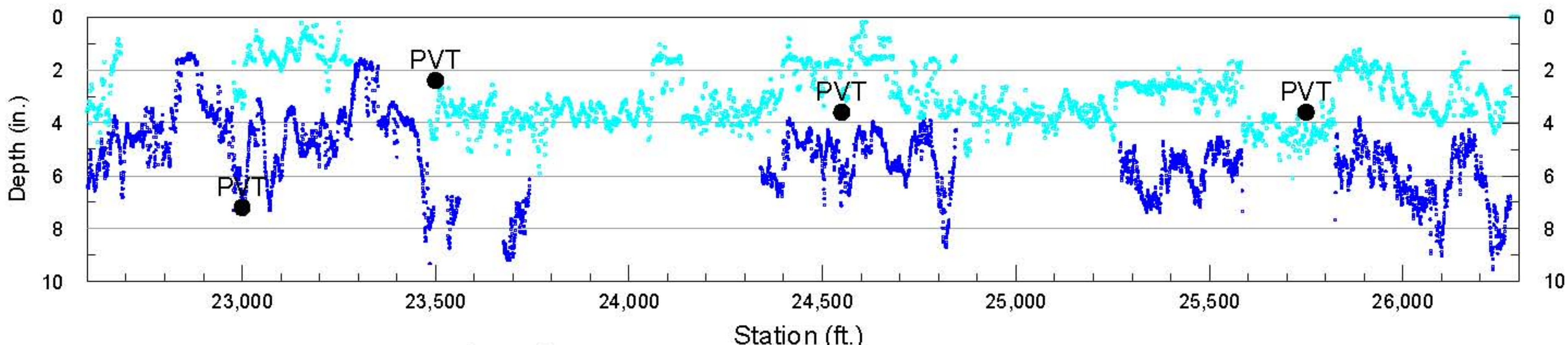
GPR Pavement Thickness Evaluation

Rt. 116 NB- Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 2 of 3



Legend

- Upper Layer GPR
- Lower Layer GPR
- Boring Data: PVT=pavement; UBPVT=unbound pavement
- Interpreted AC Bottom

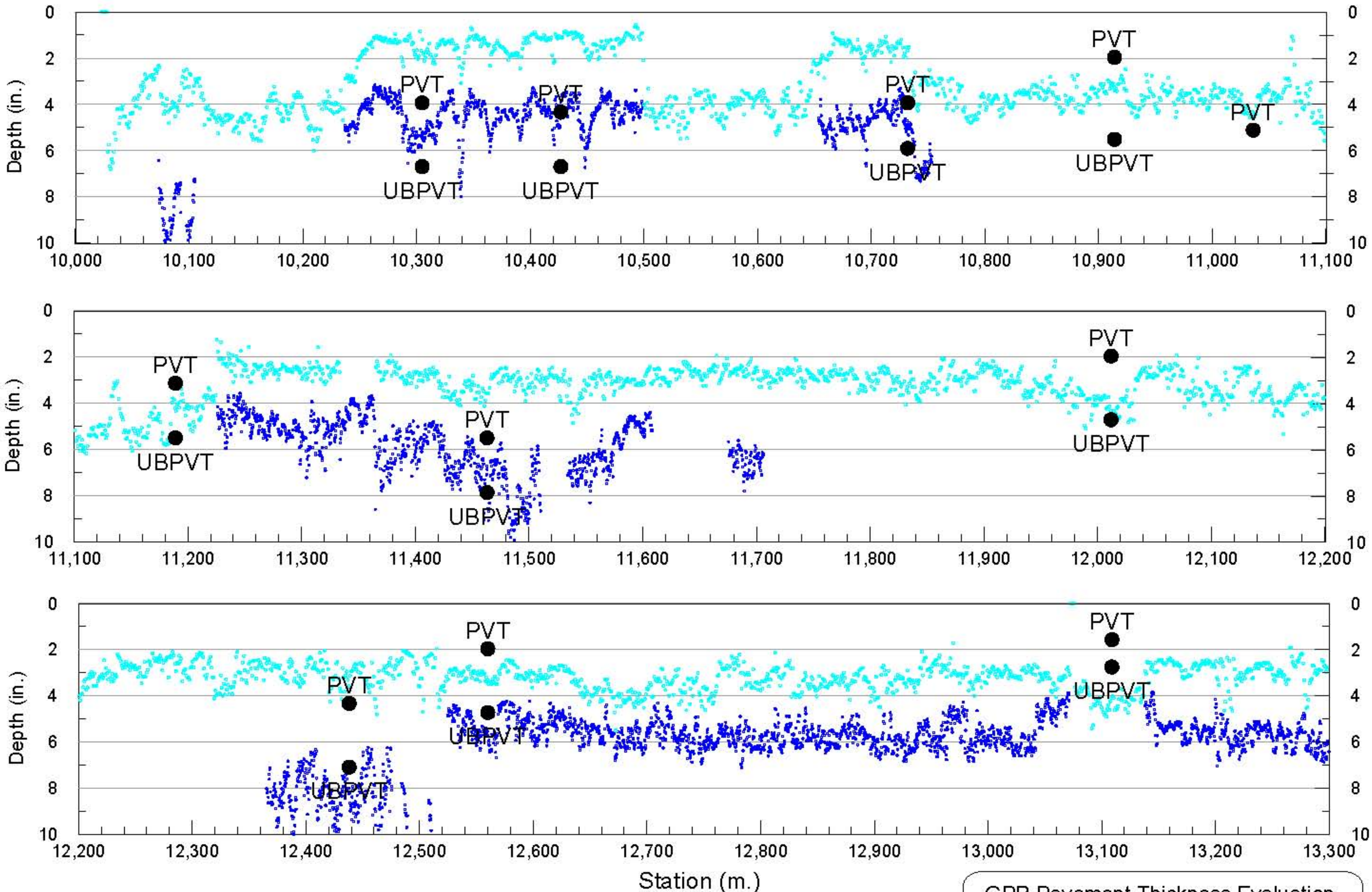
GPR Pavement Thickness Evaluation

Rt. 116 NB- Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 3 of 3



Legend

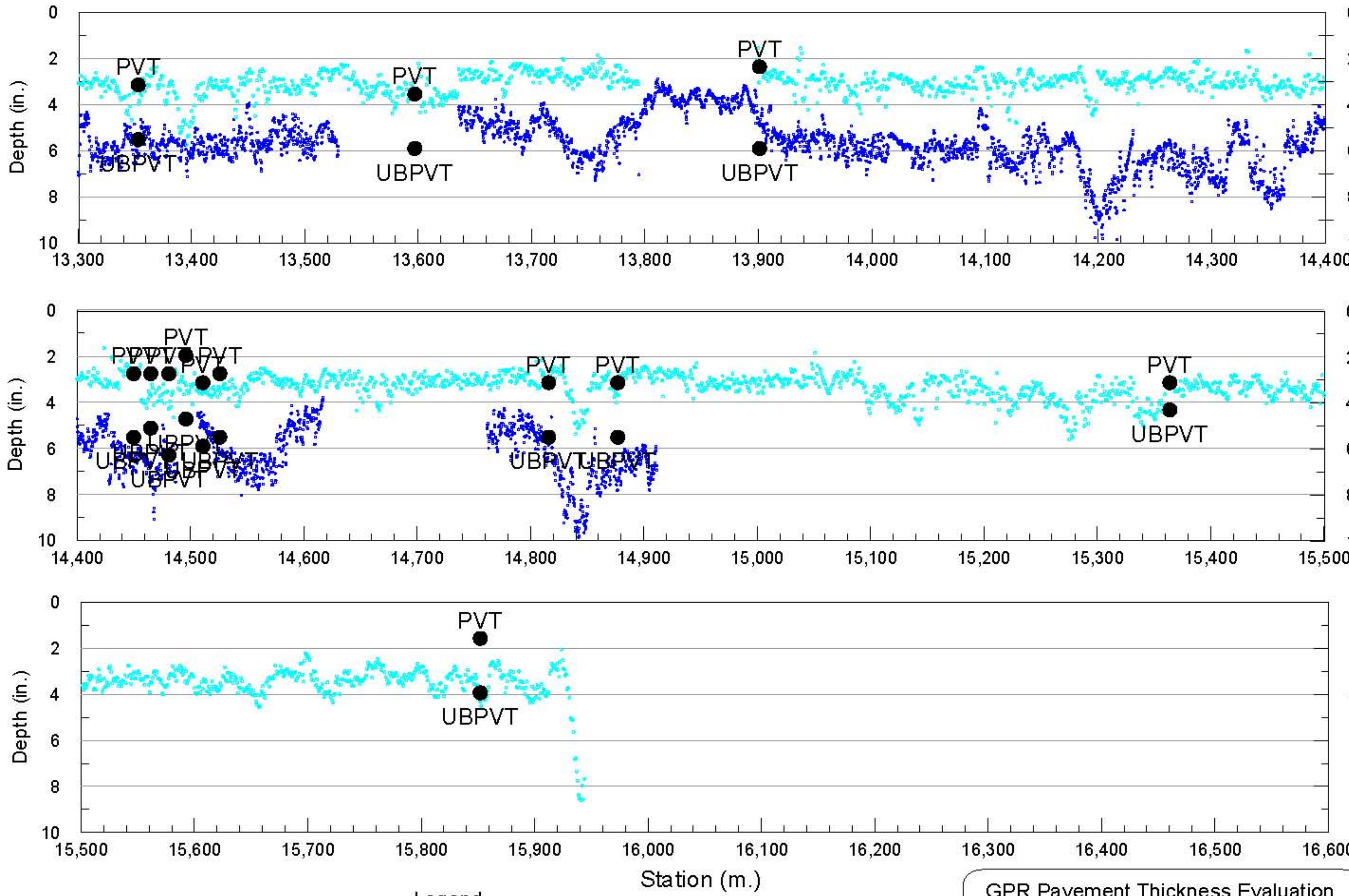
- Upper Layer GPR
- Lower Layer GPR
- Boring Data: PVT=pavement; UBPVT=unbound pavement
- Interpreted AC Bottom

GPR Pavement Thickness Evaluation

Conant Road EB- Centerline

INFRASENSE, Inc.
Arlington, MA 02476

sheet 1 of 2



<u>Legend</u>

- Upper Layer GPR
- Lower Layer GPR
- Boring Data: PVT=pavement; UBPVT=unbound pavement
- Interpreted AC Bottom

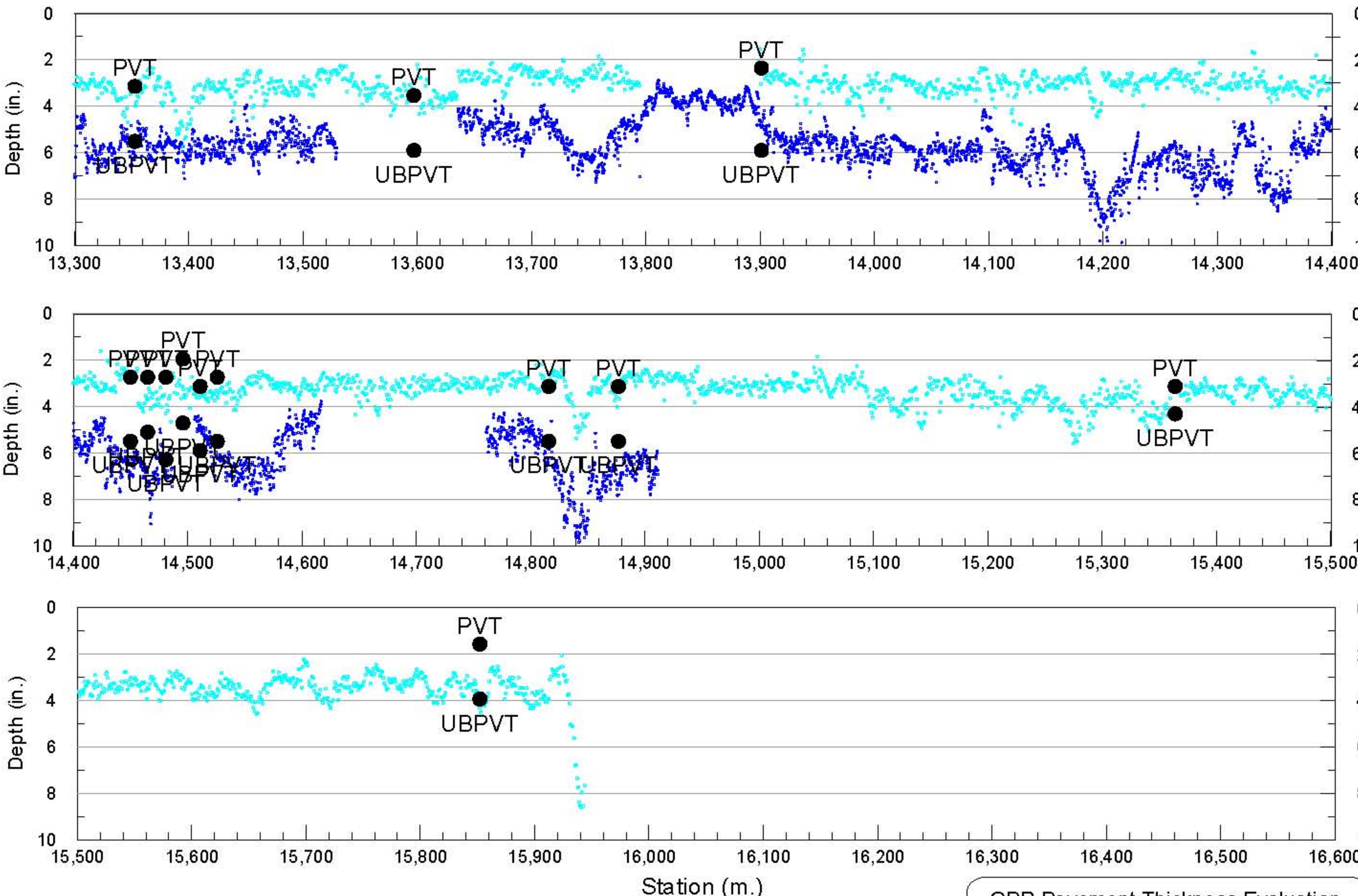
GPR Pavement Thickness Evaluation

<u>Conant Road EB- Centerline</u>

INFRASENSE, Inc.

Arlington, MA 02476

sheet 2 of 2



Legend

Upper Layer GPR

Lower Layer GPR

Boring Data: PVT=pavement; UBPVT=unbound pavement

Interpreted AC Bottom

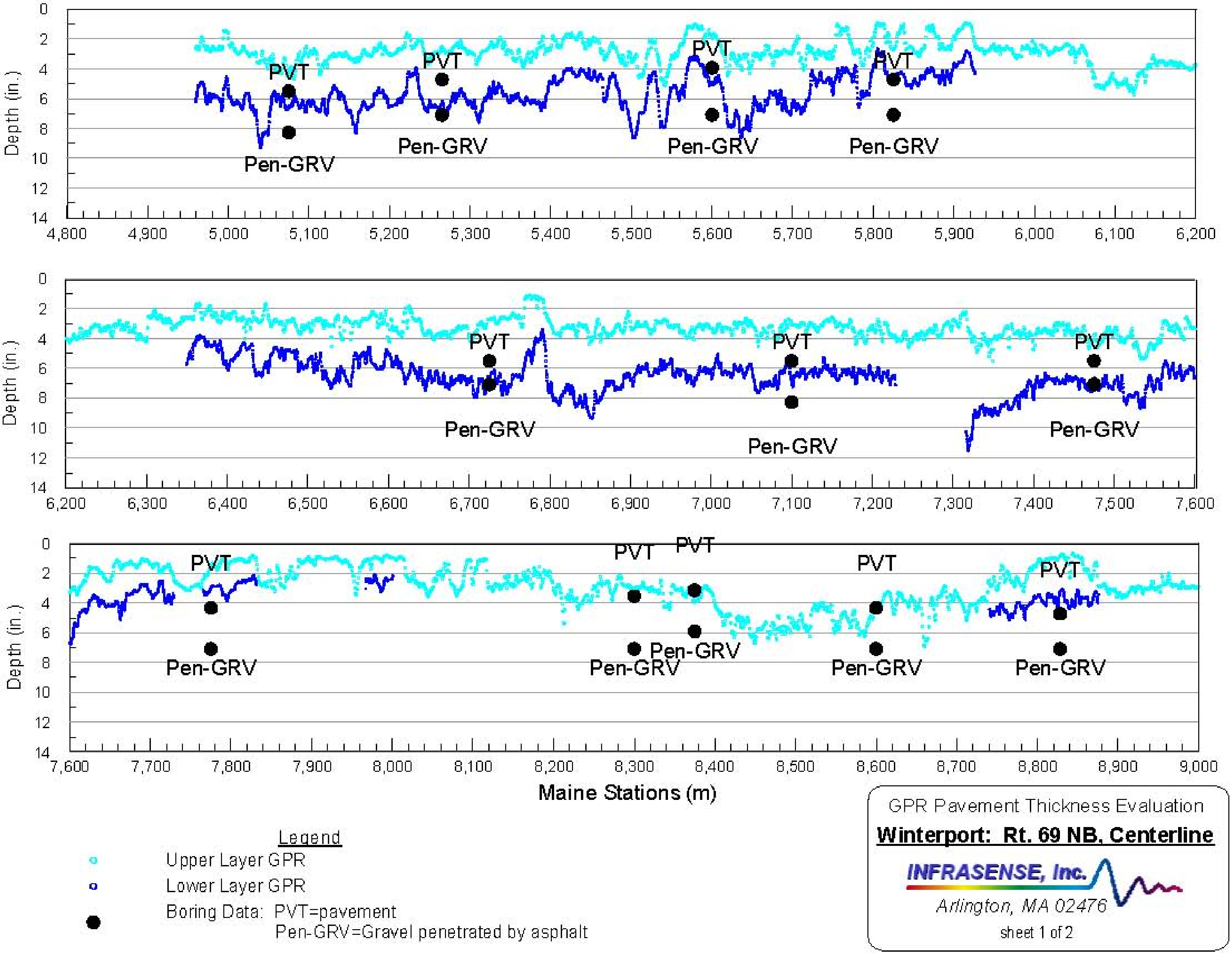
GPR Pavement Thickness Evaluation

Conant Road EB- Centerline

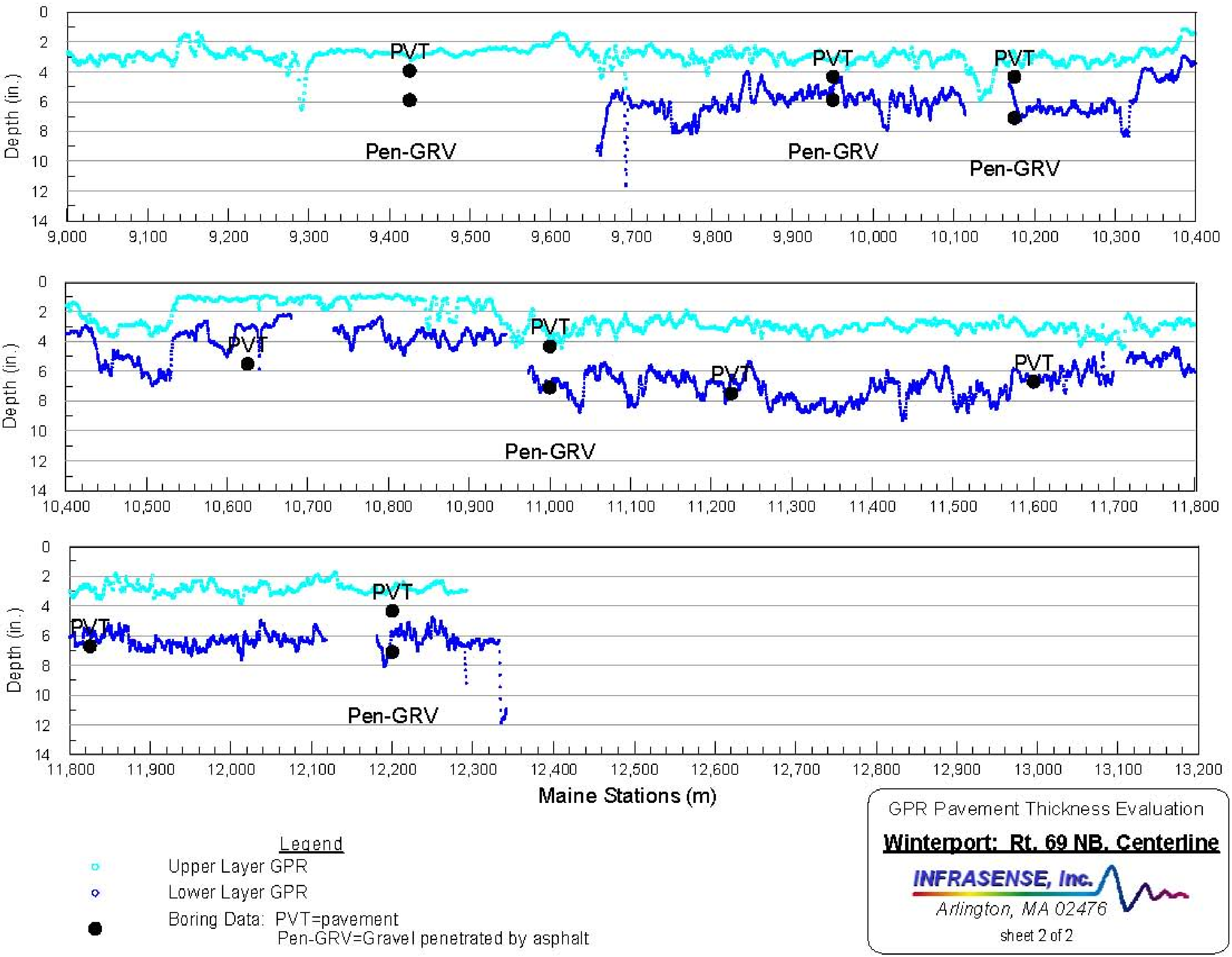
INFRASENSE, Inc.

Arlington, MA 02476

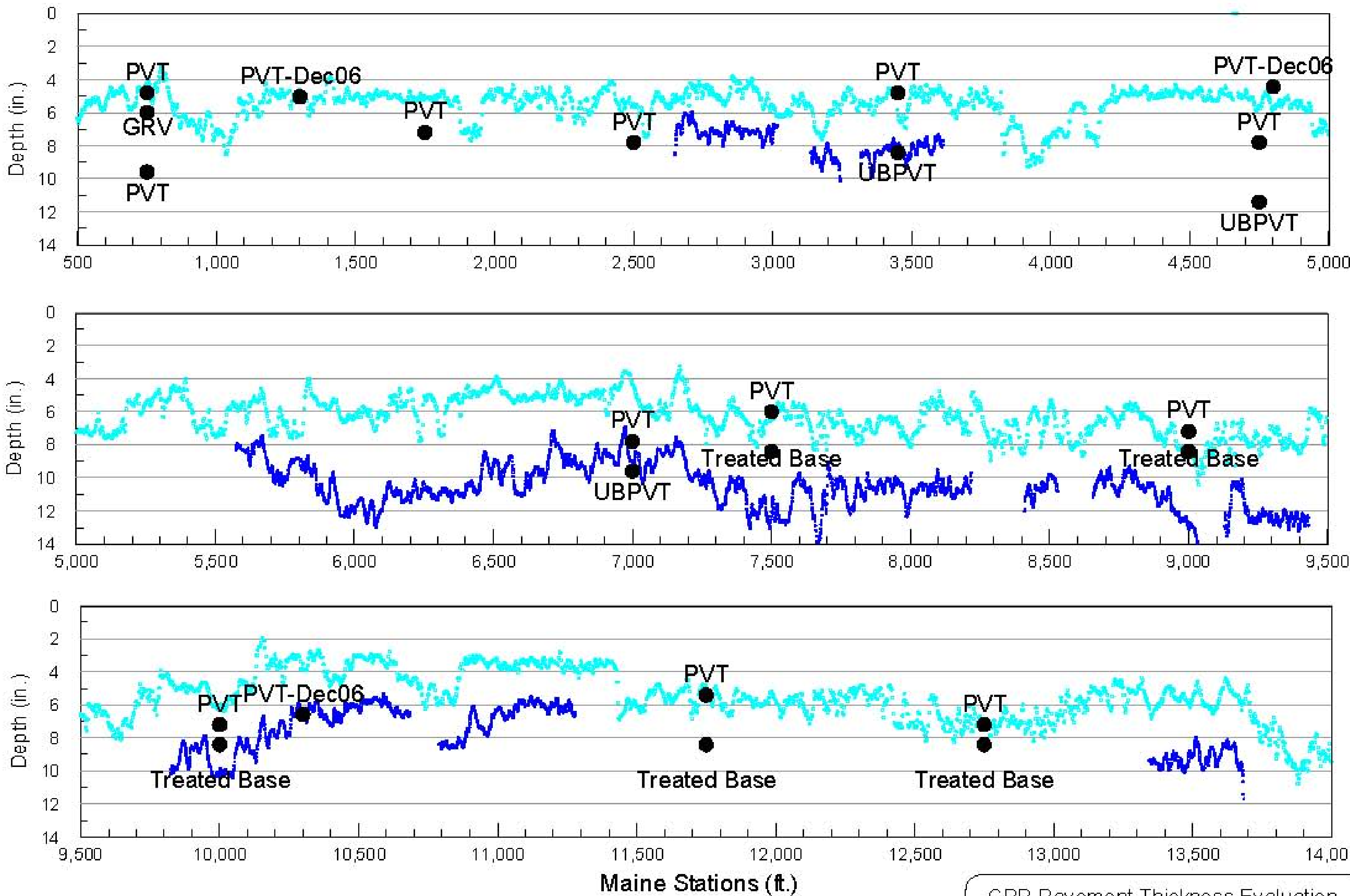
sheet 2 of 2



Depth (in.)
PVT
Pen-GRV
Maine Stations (m)
Legend
Upper Layer GPR
Lower Layer GPR
Boring Data: PVT=pavement
Pen-GRV=Gravel penetrated by asphalt
GPR Pavement Thickness Evaluation
Winterport: Rt. 69 NB. Centerline
INFRASENSE, Inc.
Arlington, MA 02476
sheet 1 of 2



Depth (in.)
PVT
Pen-GRV
Maine Stations (m)
GPR Pavement Thickness Evaluation
Winterport: Rt. 69 NB. Centerline
INFRASENSE, Inc.
Arlington, MA 02476
sheet 2 of 2
Legend
Upper Layer GPR
Lower Layer GPR
Boring Data: PVT=pavement
Pen-GRV=Gravel penetrated by asphalt



Legend

Upper Layer GPR

Lower Layer GPR

Boring Data: PVT=pavement (cored Aug 2004, unless Dec 2005 noted)
UBPVT=unbound pavement

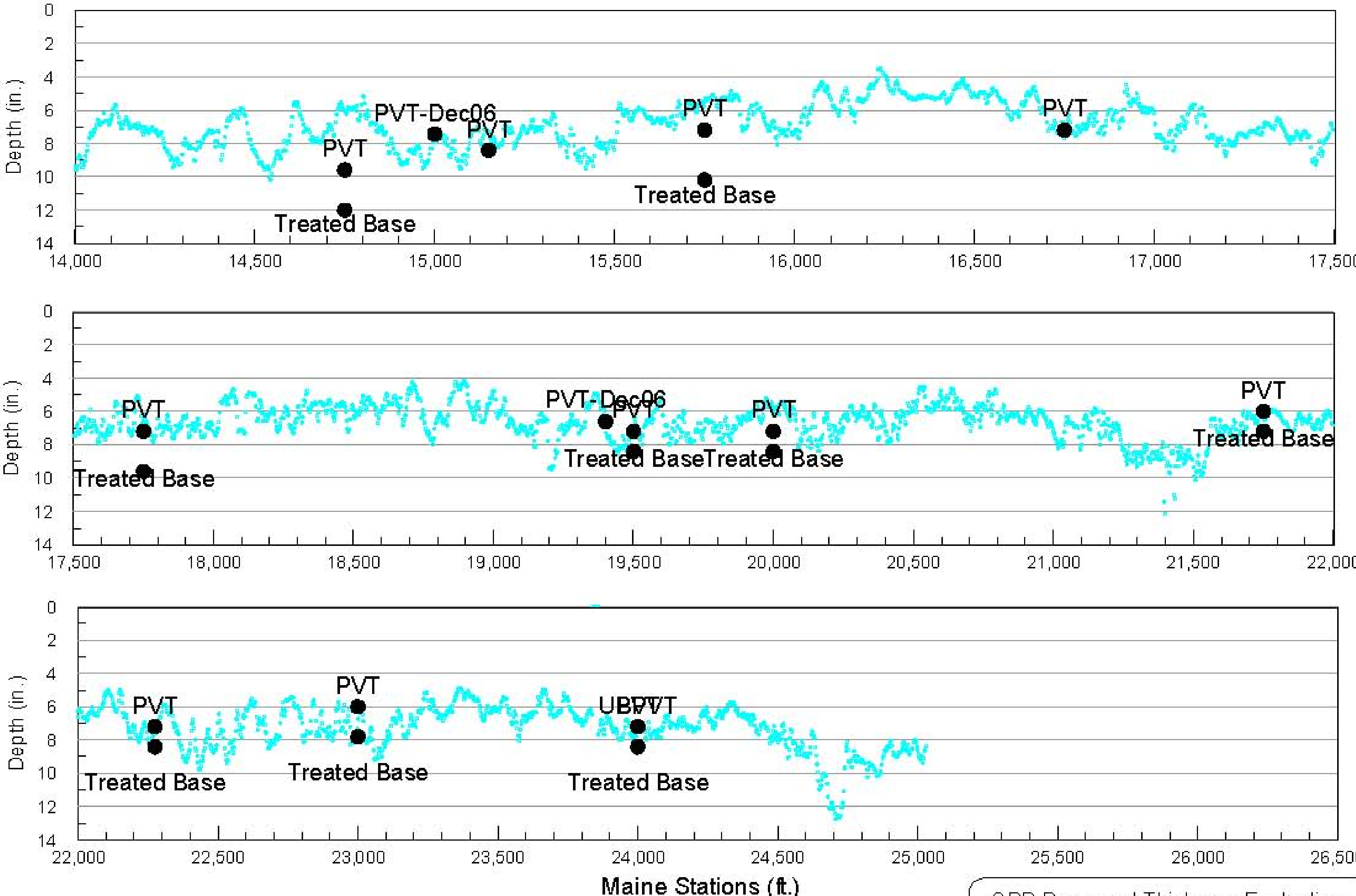
GPR Pavement Thickness Evaluation

Rt. 226 NB- Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 1 of 2



Legend

Upper Layer GPR

Lower Layer GPR

Boring Data: PVT=pavement (cored Aug 2004, unless Dec 2005 noted)
UBPVT=unbound pavement

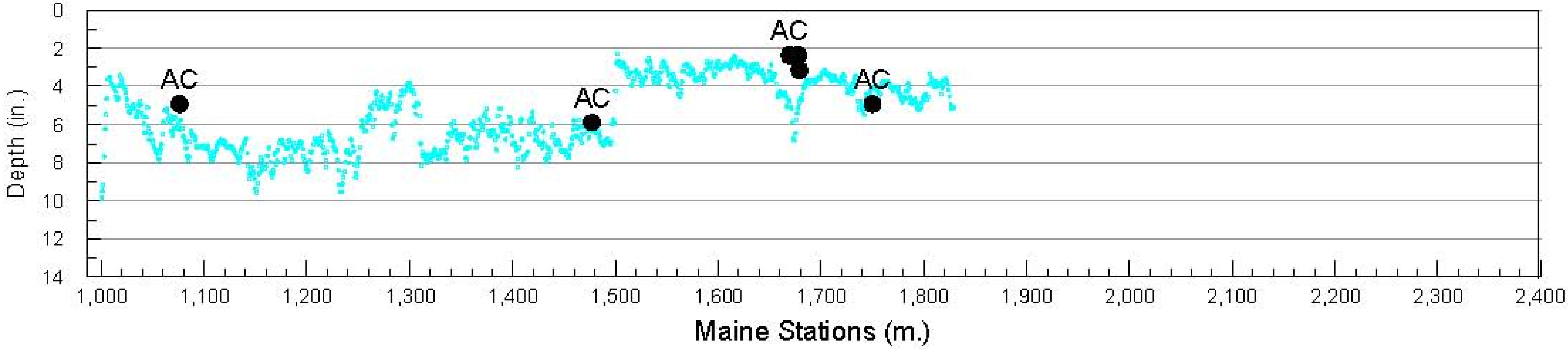
GPR Pavement Thickness Evaluation

Rt. 226 NB- Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 2 of 2



Legend

Upper Layer GPR

Lower Layer GPR

Boring Data: AC= asphalt

GPR Pavement Thickness Evaluation

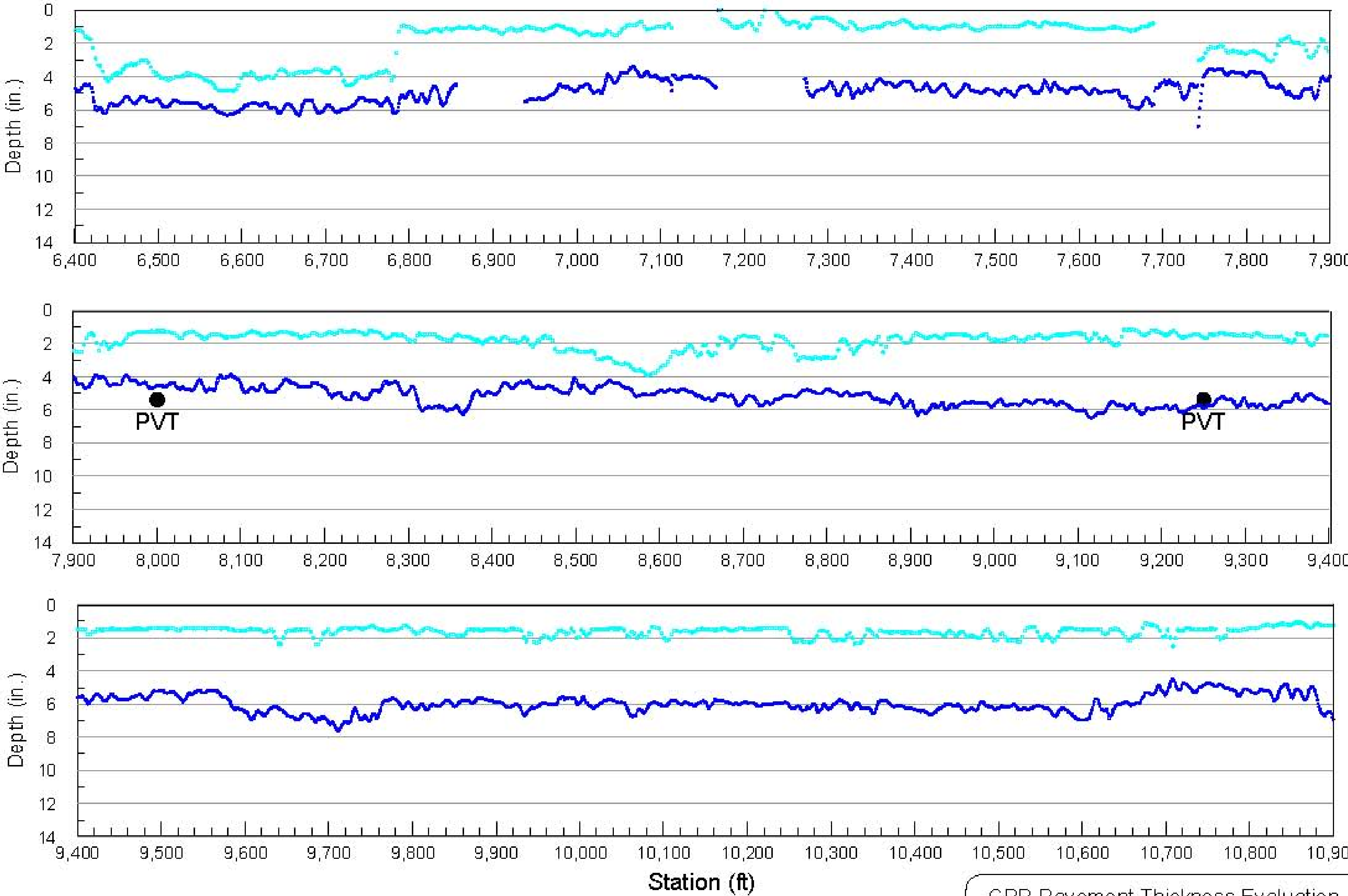
Waldoboro: Jefferson St. NB

Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 1 of 1



Legend

- Upper Layer GPR
- Lower Layer GPR
- Boring Data: PVT=pavement

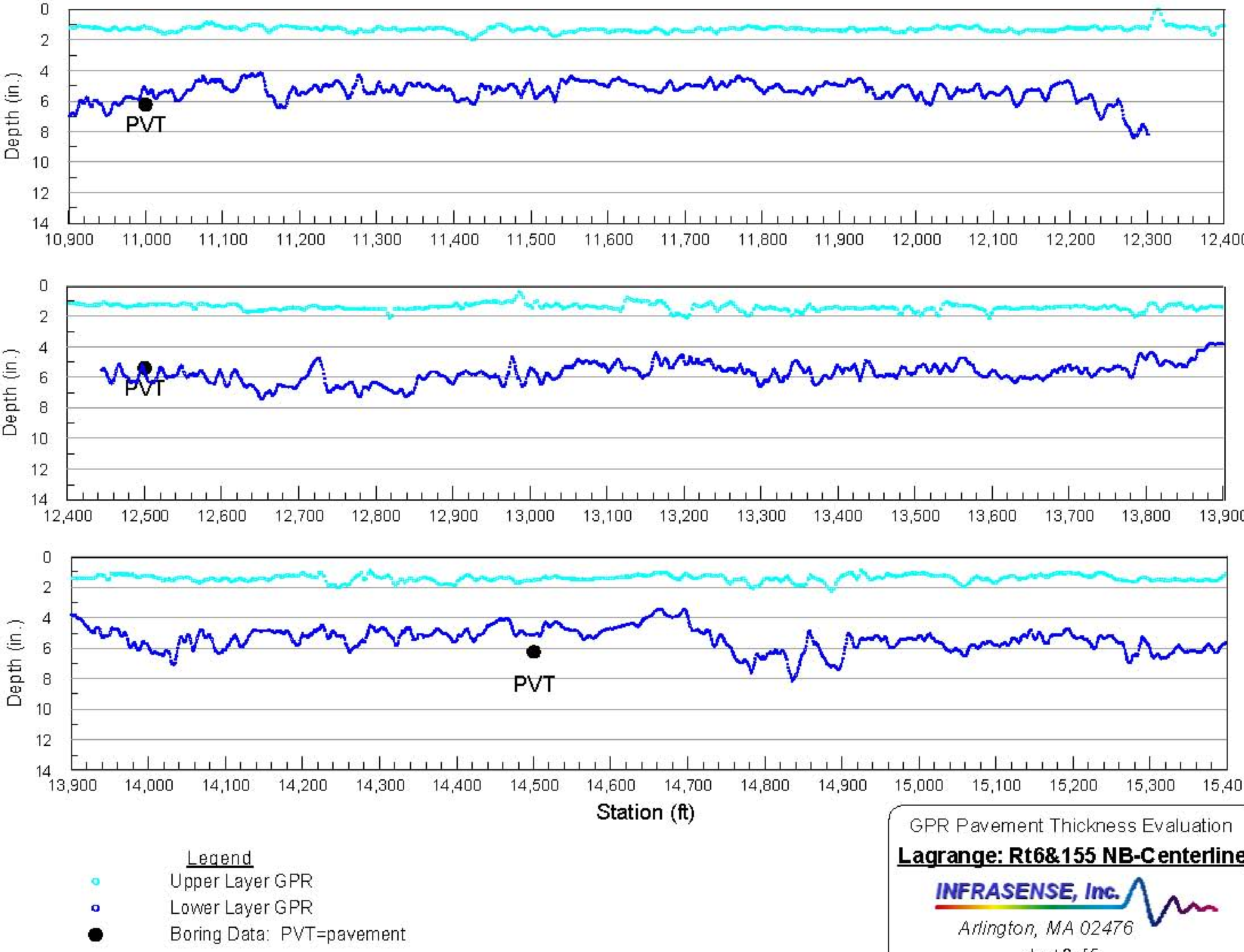
GPR Pavement Thickness Evaluation

Lagrange: Rt6&155 NB-Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 2 of 5



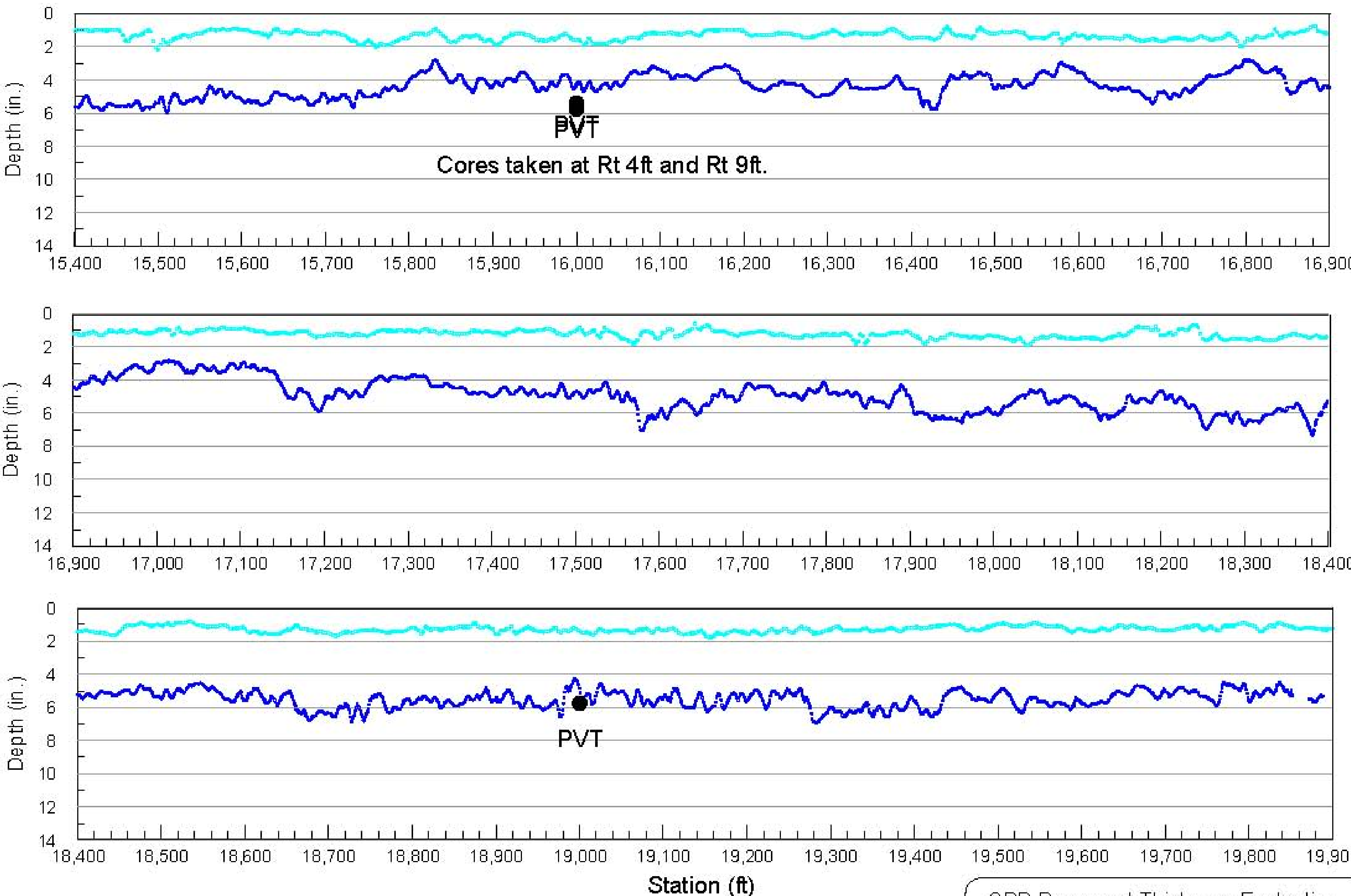
GPR Pavement Thickness Evaluation

Lagrange: Rt6&155 NB-Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 3 of 5



Legend

- Upper Layer GPR
- Lower Layer GPR
- Boring Data: PVT=pavement

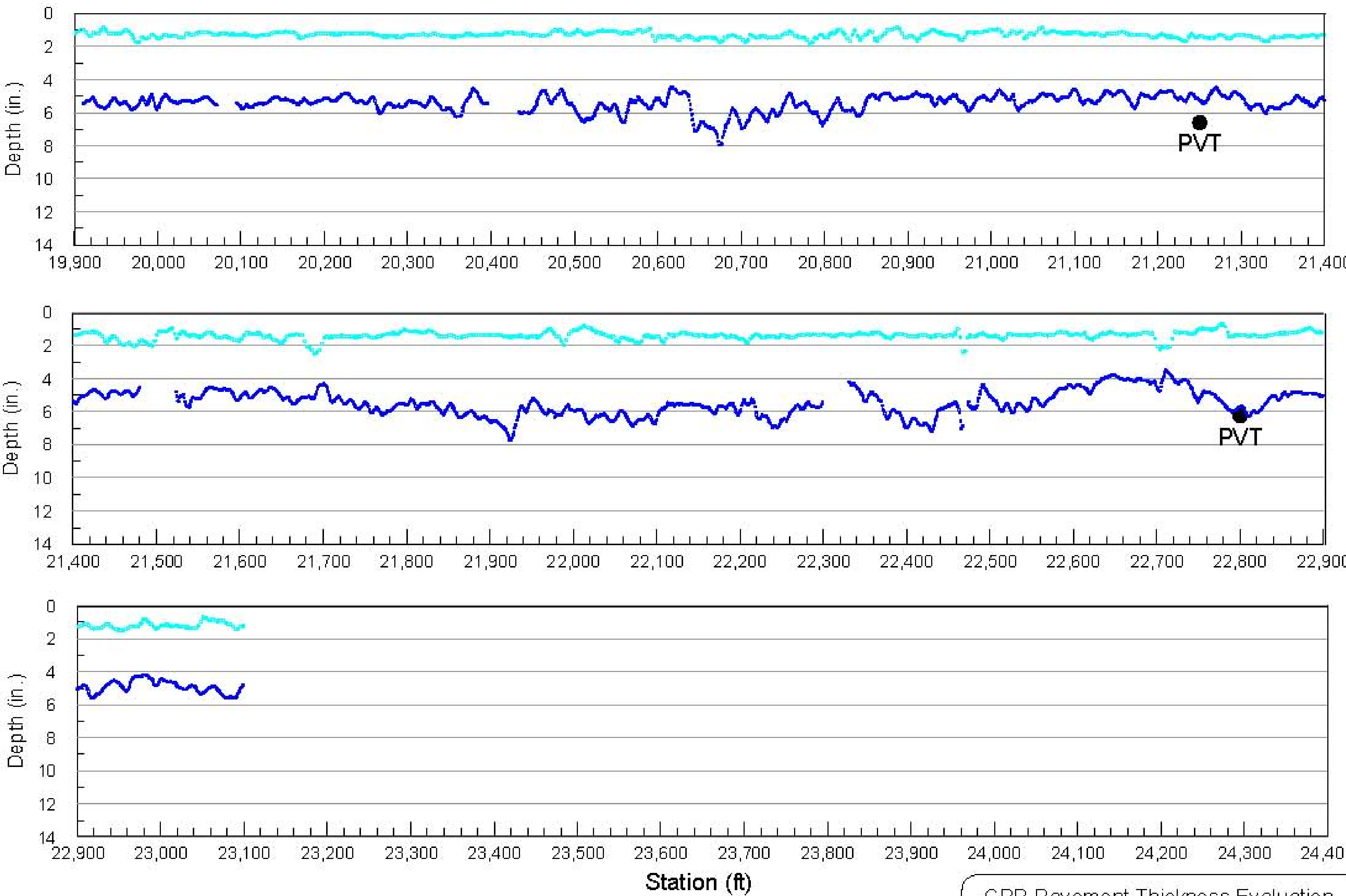
GPR Pavement Thickness Evaluation

Lagrange: Rt6&155 NB-Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 4 of 5



Legend

- Upper Layer GPR
- Lower Layer GPR
- Boring Data: PVT=pavement

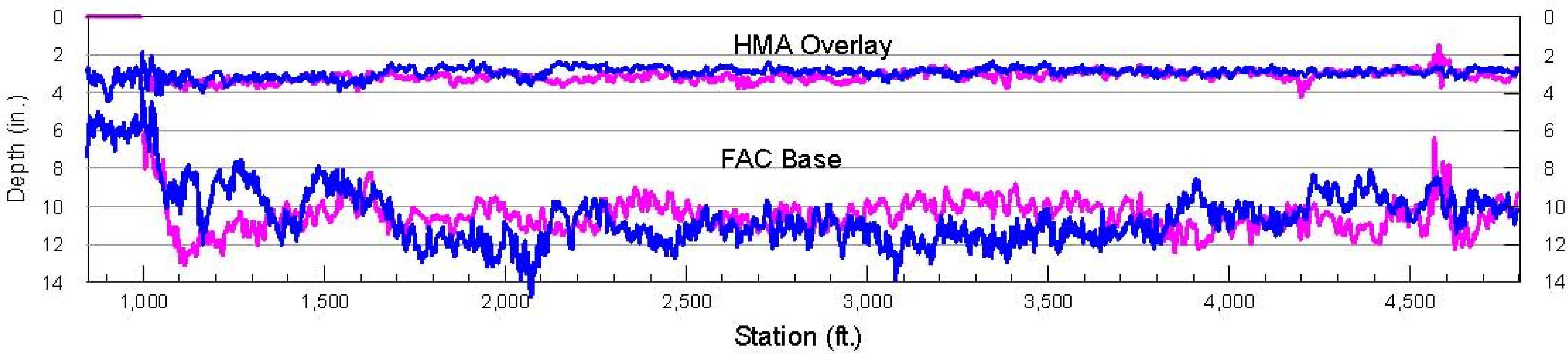
GPR Pavement Thickness Evaluation

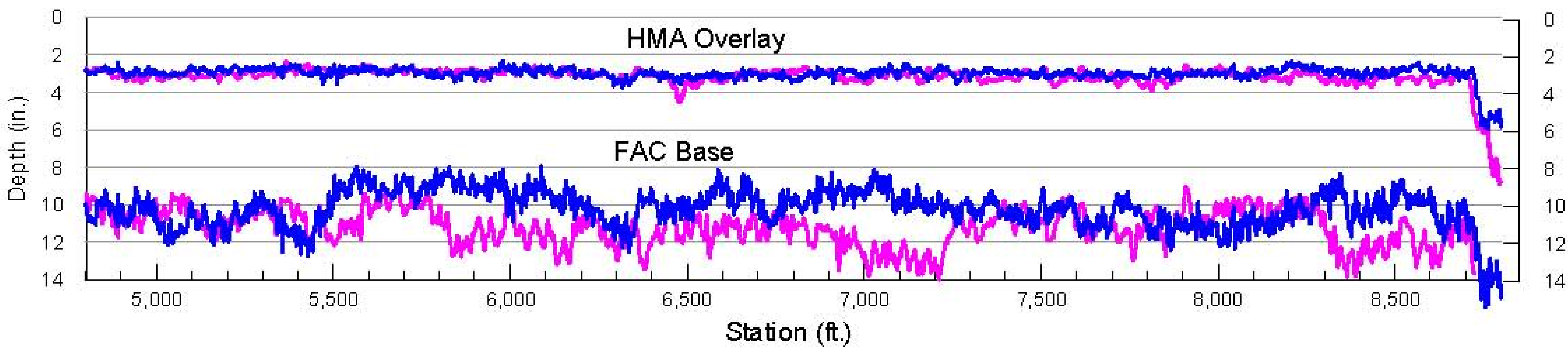
Lagrange: Rt6&155 NB-Centerline

INFRASENSE, Inc.

Arlington, MA 02476

sheet 5 of 5





Legend

Southbound

Northbound

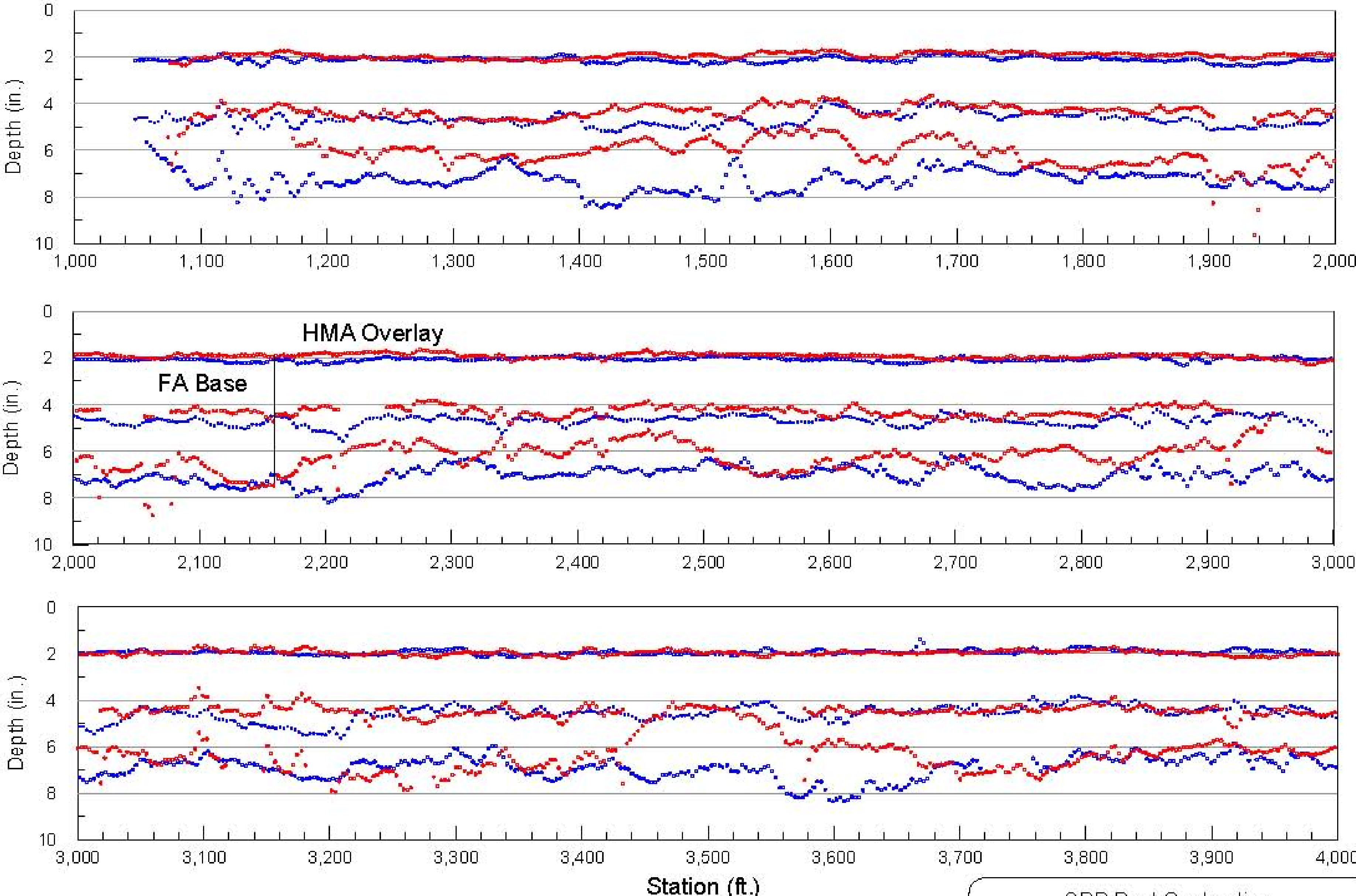
GPR Post Construction
Pavement Thickness Evaluation

Station Road, Easton

INFRASENSE, Inc.

Arlington, MA 02476

sheet 1 of 1



Legend

Northbound

Southbound

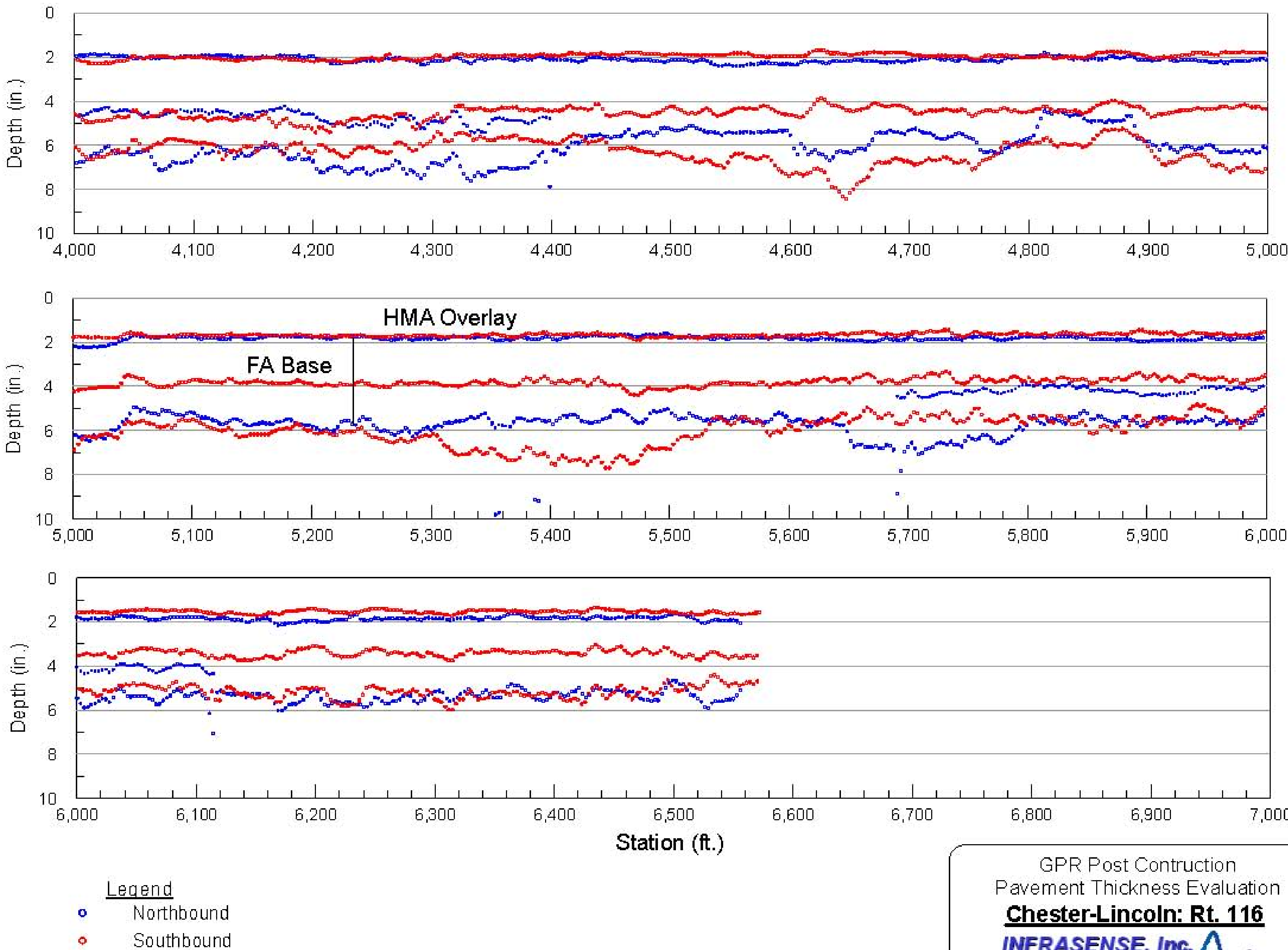
GPR Post Contruction
Pavement Thickness Evaluation

Chester-Lincoln: Rt. 116

INFRASENSE, Inc.

Arlington, MA 02476

sheet 1 of 2



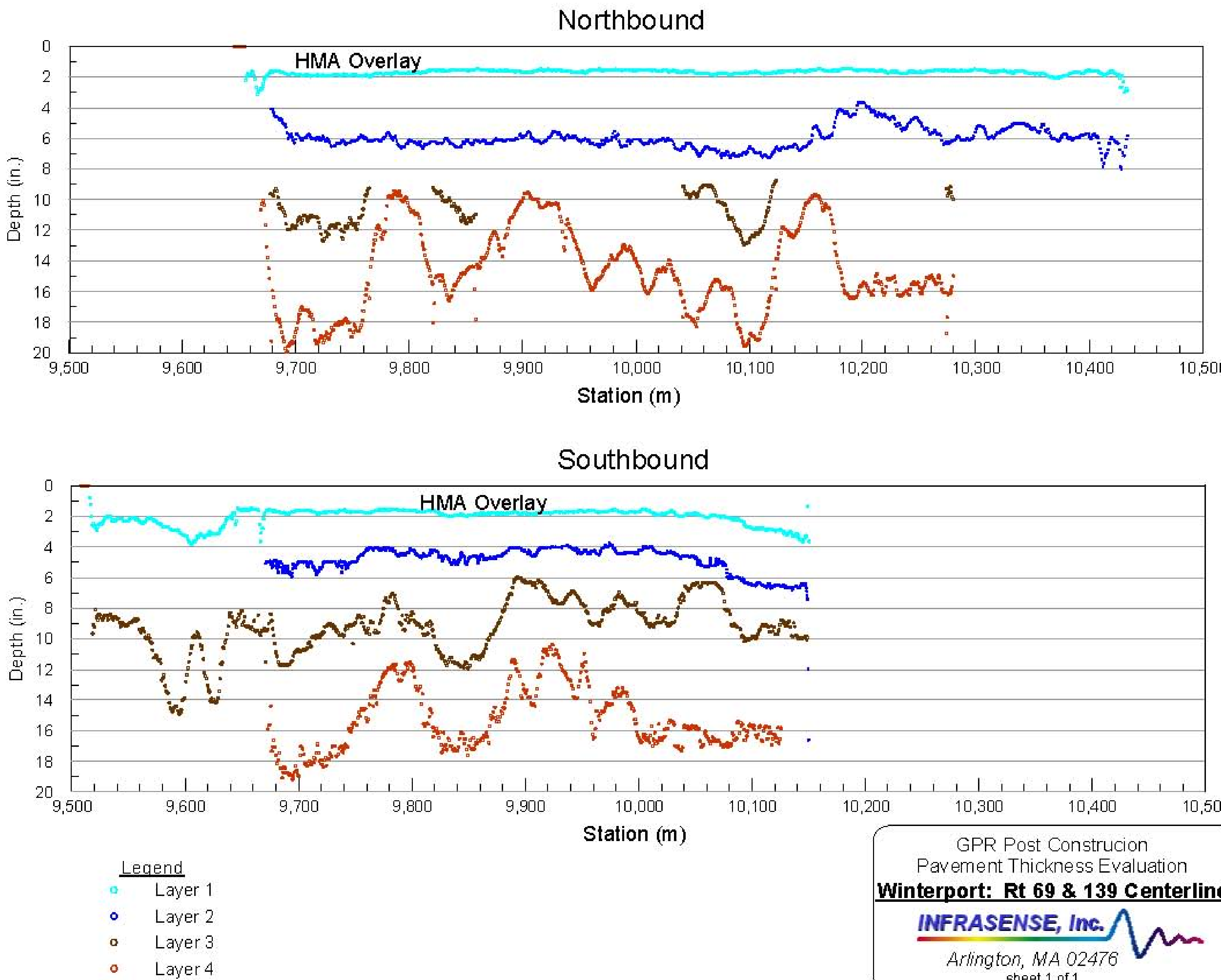
GPR Post Contruction
Pavement Thickness Evaluation

Chester-Lincoln: Rt. 116

INFRASENSE, Inc.

Arlington, MA 02476

sheet 2 of 2



GPR Post Construcion
Pavement Thickness Evaluation
Winterport: Rt 69 & 139 Centerline
INFRASENSE, Inc.
Arlington, MA 02476
sheet 1 of 1

APPENDIX C

Automated Statistical Analysis Results for Pre-Construction GPR Surveys

Route 116

Rt 116	GPR	NB	SB	Cores	
Interval	Layer	Mean	Mean	Type	Mean
1000 to 4000	L1	3.80	3.80		
	L2	5.89	5.65	PVT	6.00
	L3	7.80	7.80		
4000 to 6000	L1	4.00	4.30		
	L2	5.64	5.49	PVT	6.00
	L3	7.95	7.95	UBPVT	7.80
6000 to 7000	L1	3.65	3.65	PVT	4.20
	L2	5.70	4.69	UBPVT	6.60
	L3	8.00	7.82		
7000 to 21600	L1	3.65	3.65	PVT	4.20
	L3	7.64	7.64	UBPVT	6.60
21600 to 25200	L1	3.65	3.65	PVT	3.90
	L2	5.65	5.24	UBPVT	4.20
	L3	7.82	7.58		
25200 to 26230	L1	3.90	3.70	PVT	3.60
	L2	5.65	0.00		
	L3	7.82	7.82		

Route 7

Rt7	GPR	NB	SB	Cores	
Interval	Layer	Mean	Mean	Type	Mean
100 to 5000	L1	4.00	4.10	PVT	4.61
	L2	6.25	7.25	UBPVT	7.08
5000 to 10000	L1	3.51	3.56		
	L2	5.95		PVT	5.55
	L3	7.50	7.50	UBPVT	7.20
10000 to 15000	L1	3.90	3.78		
	L2	6.10		PVT	5.69
	L3	7.90	8.00	UBPVT	8.40
15000 to 21260	L1	3.91	3.91	PVT	5.57
	L2	7.13	8.35	UBPVT	7.50

Route 226

Rt226 Interval	GPR Layer	NB Mean	SB Mean	Cores Type	Cores Mean	Cores SD
500 to 5000	L1	3.20	3.01			
	L2	5.30	0.00	PVT	5.98	1.54
	L3	6.80	6.76			
5000 to 10000	L1	3.28	3.50			
	L2	6.85	6.60	PVT	7.05	0.75
	L3	8.94	8.94	UBPVT	9.60	
10000 to 15000	L1	3.32	3.32			
	L2	6.60	6.60	PVT	7.24	1.37
15000 to 20000	L1	3.08	3.28			
	L2	6.60	6.60	PVT	7.31	0.50
20000 to 25000	L1	3.19	3.35			
	L2	6.50	6.25	PVT	6.72	0.66

Route 69, Winterport

Winterport Interval	GPR Layer	NB Mean	SB Mean	Cores Type	Cores Mean
4960 to 6484	L1	3.20	3.18	PVT	4.72
	L2	6.76	6.95	Pen-GRV	7.28
6484 to 8008	L1	3.15	3.00	PVT	5.22
	L2	6.60	6.98	Pen-GRV	7.38
	L3	8.96			
8008 to 9532	L1	3.03	2.99	PVT	3.94
	L2	6.60	5.89	Pen-GRV	6.61
	L3	0.00	8.10		
9532 to 11056	L1	3.01	2.98	PVT	4.63
	L2	6.17	6.84	Pen-GRV	6.69
11056 to 12690	L1	2.99	2.85		
	L2	6.70	6.35	PVT	6.30
	L3	8.85		Pen-GRV	7.10

Jefferson Street

Jefferson St.	GPR	NB	SB	Cores	
Interval	Layer	Mean	Mean	Type	Mean
100 to 1820	L1	3.80	3.70	PVT	3.54
	L2	7.00	7.37		

Route 6 & 155, LaGrange

Rt6 - LaGrange	GPR	NB	SB	Cores	
Interval	Layer	Mean	Mean	Type	Mean
1900 to 5000	L1	2.30	2.40		
	L2	5.10	5.10	PVT	6.44
	L3	8.30	8.60		
5000 to 10000	L1	2.40	2.30		
	L2	4.50	4.50	PVT	5.40
	L3	8.60	8.50		
10000 to 15000	L1	1.80	2.10		
	L2	5.00	5.00	PVT	5.96
	L3	8.60	9.20		
15000 to 20000	L1	2.00	2.10		
	L2	5.00	5.10	PVT	5.64
	L3	8.50	8.50		
20000 to 23100	L1	2.20	2.20		
	L2	5.00	4.70	PVT	6.42
	L3	8.20	8.00		

Maine Department of Transportation
Bureau of Planning
Transportation Research Division
16 State House Station
Augusta, Maine 04333
tel. 207-624-3305
Fax 207-624-3301

For more information on all of our studies
visit our website at:
http://www.maine.gov/mdot/Trans-Planning.php

Federal Highway
Administration