GPR-RU4474

Demonstration of Ground Penetrating Radar (GPR) (NJDOT Statewide GPR Pilot Project)

FINAL REPORT
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16. Abstract

As a part of the Pavement Management Systems (PMS) project, ground penetrating radar (GPR) surveys were conducted at locations throughout New Jersey. Interpretations of the survey information were conducted for both network-level pavement management and design-level (project management) purposes. The objective of the work was to provide NJDOT with useful information obtained by the GPR survey regarding pavement structure and layer properties (thickness, dielectric, etc…), useful at the pavement management level for decision-making, and at the design level for improvement of FWD backcalculation or characterization of pavement thickness variability over potential project sections.

The project included field surveys, associated data analysis, and reporting on approximately 600 lane-miles (test miles) of pavements designated as network level investigations, as well as 25 to 50 lane-miles of project (design)-level pavement. Pavements consisted of all pavement types (flexible, rigid and composite), as well as a few sample ramp pavements; with approximately 375 test miles of Interstate, 125 test miles of State Highway System (SHS), 75 test miles on road sections selected for FWD testing for project scoping, and the test sites used for the seasonal variation and model refinement sub-tasks. Some of the test miles included the testing of multilane sections that have been the subject of widening and/or realignment.

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INTRODUCTION

As a part of the Pavement Management Systems (PMS) project, ground-penetrating radar (GPR) surveys were conducted at locations throughout New Jersey. Interpretations of the survey information were conducted for both network-level pavement management and design-level (project management) purposes. The objective of the work was to provide NJDOT with useful information obtained by the GPR survey regarding pavement structure and layer properties (thickness, dielectric, etc…), useful at the pavement management level for decision-making, and at the design level for improvement of FWD back-calculation or characterization of pavement thickness variability over potential project sections.

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Table 1. Interstate highway sections surveyed for network level.

Route	Direction	From	To	Passes	GPR test miles	Testing Date
I-76	E	0.0	2.0	1	2.0	09/04/02
	W	0.0	2.0	1	2.0	09/04/02
I-80	E	18.8	68.5	1	49.7	08/21/02
	W	0.0	68.5	1	68.5	08/21/02
I-95	N	0.0	8.8	1	8.8	09/03/02
I-195	W	0.0	9.0	1	9.0	08/22/02
	E	12.0	34.2	1	22.2	08/27/02
	E	0.0	9.0	1	9.0	08/27/02
I-280	E	0.0	17.7	1	17.7	08/21/02
I-287	N	0.0	67.5	1	67.5	09/08/02
	S	0.0	67.5	1	67.5	09/08/02
I-295	N	0.0	32.0	2	64.0	09/03/02
	S	0.0	32.0	2	64.0	09/03/02
	S	32.0	67.9	1	35.9	09/03/02
I-676	N	0.0	3.6	1	3.6	09/04/02
	S	0.0	3.6	1	3.6	09/04/02
Total network level interstate highway test miles					**495.0**	

Table 2. U.S. and state highway sections surveyed for network level.

Route	Direction	From	To	Passes	GPR test miles	Testing Date
US-9	N	62.4	68.0	1	5.6	08/26/02
	S	62.4	68.0	1	5.6	08/26/02
US-30	E	40.5	52.0	1	11.5	08/26/02
	W	40.5	52.0	1	11.5	08/26/02
NJ-36	S	10.0	16.0	1	6.0	08/22/02
NJ-55	N	20.0	33.2	1	13.2	08/26/02
	S	20.0	33.2	1	13.2	08/26/02
US-130	N	41.0	51.0	1	10.0	08/27/02
	S	43.6	50.6	1	7.0	08/27/02
US-130	N	56.5	67.2	1	10.7	08/27/02
	S	56.5	67.2	1	10.7	08/27/02
Total network U.S. and state highway test miles					**105.0**	

Table 3. State, U.S., and interstate highway sections surveyed for project level.

Route	Direction	From	To	Passes	GPR test miles	Testing Dates
NJ-55	N	36.0	39.0	1	3.0	09/05/02
NJ-55	S	58.0	61.0	1	3.0	09/05/02
NJ-55	N	56.0	59.0	1	3.0	09/05/02
US-130	N	13.0	15.0	1	2.0	09/05/02
I-195	W	9.0	16.0	1	7.0	09/05/02
I-195	E	9.0	16.0	1	7.0	09/05/02
Total project level test miles					**25.0**	

BACKGROUND

A GPR antenna transmits high-frequency EM (Electro-Magnetic) waves into the ground. A portion of the energy is reflected back to the surface from the interface of two adjacent (usually layered) materials with different electrical properties and it is received at the antenna. Schematic of a single GPR measurement and its idealized record for flexible and rigid pavement profiles are shown in Figure 1. To construct a GPR profile, several measurements are made along the survey line and the reflected wave amplitudes for each scan are plotted with different colors to construct a GPR profile. A typical GPR profile is shown in Figure 2. In most ground-coupled antenna surveys, high-amplitude, hyperbolic reflections (arch-shaped features) are generally observed in GPR records over buried metallic objects such as pipes and tanks, but these “hyperbolas” are commonly seen when the antenna passes over point targets such as rounded boulders or even PVC (usually water-filled, but sometimes gas) utilities.

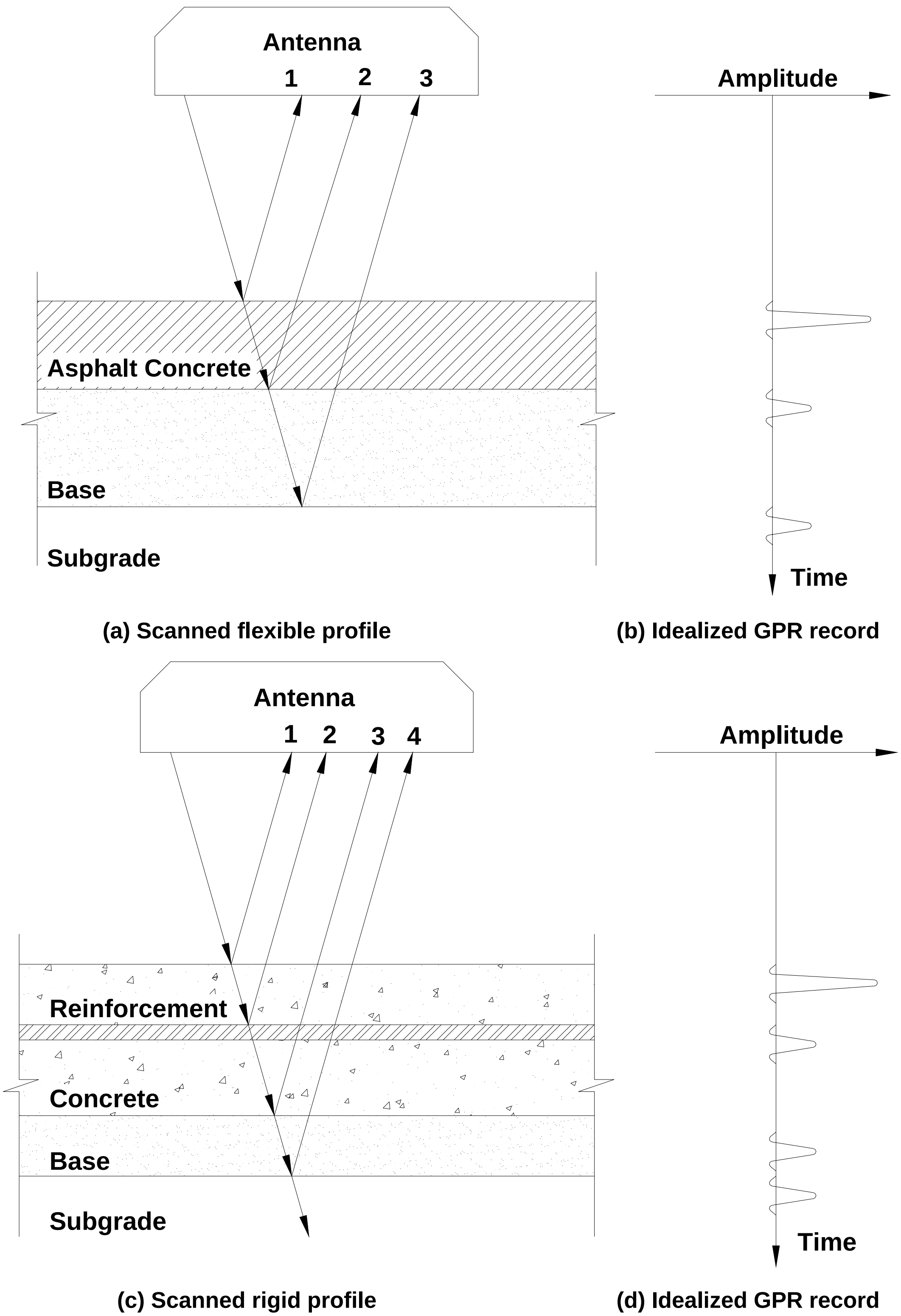


Figure 1. Schematics of a GPR measurement and its idealized record for flexible and rigid pavement profiles.

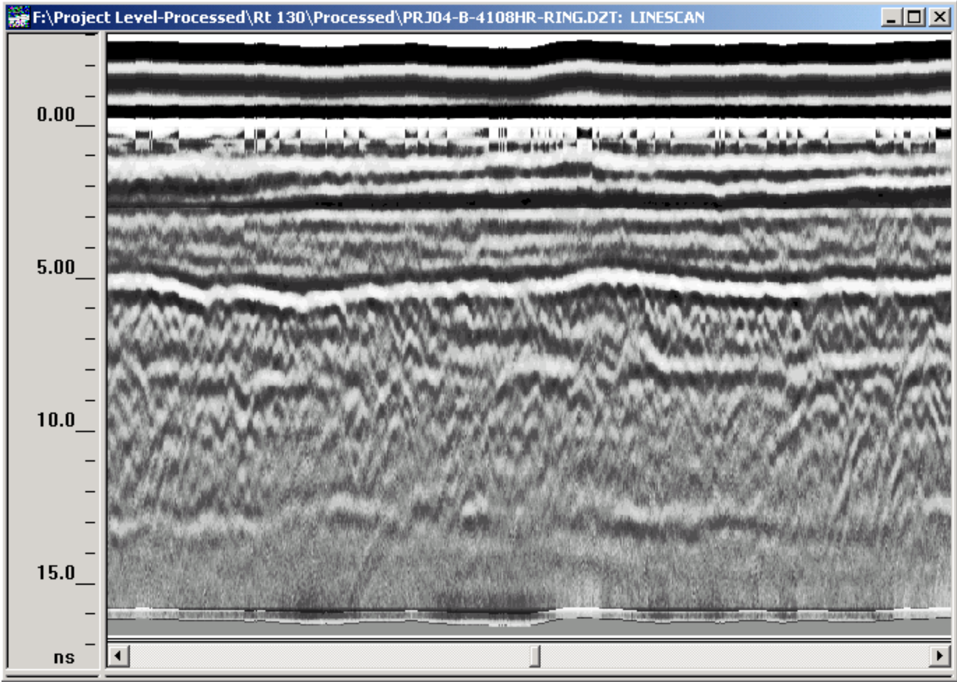


Figure 2. A typical GPR profile.

When horn (air-coupled) antennas are used for high-speed pavement or bridge deck surveys, however, the most likely high-amplitude reflections existing in the data occur from man-made interfaces such as pavement layers, pavement overlays on concrete bridge decks, steel mesh or reinforcing mats, and bridge deck bottoms. Other common interfaces seen in the data include reflections from asphalt or concrete pavement and the base material beneath it, the base/subbase interfaces, and subbase/subgrade contacts within a pavement system. The measured time of arrival of each of these signals and its amplitude are used to measure and estimate (by way of calculation using a calibrated data collection technique) subsurface "target" depths, GPR propagation speed, and often, subsurface structural condition.

GPR has been used with varying degrees of success to solve a variety of subsurface investigation problems. Its use in pavement and transportation infrastructure assessments or quality assurance (QA) inspections has recently grown, and it is rapidly becoming an accepted (and recommended) non-destructive evaluation (NDE) technology in this field. In recent years, improvements in systems, sensors (antennas) and computing capability have allowed experienced GPR service-providers to both (a) collect and process data in a rapid fashion, and (b) accurately assess the condition of both existing structures (in-service inspections) and new construction (Quality Assurance—QA).

SURVEY EQUIPMENT

Equipment setup for project and network level surveys are shown in Figure 3 and 4. As shown in these Figures, GPR equipment consisted of a Geophysical Survey Systems Inc. (GSSI) SIR-20 two-channel data acquisition unit controlled by a rugged-ized portable laptop; a 1000 MHz (1 GHz) air-coupled (horn) antenna designed for high-speed, non-contact surveys over pavements and bridge decks; a 1500 MHz (1.5 GHz) ground-coupled antenna; a portable (shippable) antenna deployment frame with an attached survey wheel; vehicle mounted Nu-metrics® distance-measuring instruments (DMI); digital video camera mounted on the vehicle and additional laptop computer for image capturing.

(a) Setup for network level surveys **(b) Setup for network project surveys**

Figure 3. Equipment setup for (a) network level and (b) project level surveys

(a) SIR-20 data acquisition unit **(b) Laptop computers for GPR and video data collection**

Figure 4. SIR-20 data acquisition unit and laptop computers for data collection.

All the GPR equipment used in the survey is manufactured by Geophysical Survey Systems, Inc. (GSSI), and represents the latest in highway GPR systems. All the network level data were collected using SIR-20 (SIRveyor model) two-channel, high-speed data acquisition unit and Model 4108 transceiver TEM horn antennas (1 GHz), at speeds requiring no traffic control. GSSI Model SIR-20 Data Acquisition System is the only GPR unit capable of data collection at rates at, or in excess of, 300 scans/second, as specified in section 4.1 of the RFP. Precision and bias of the GPR system conforms to ASTM D 4748-98; the antenna was shielded from interference due to other sources of electromagnetic radiation such as mobile phones and radio during data collection; and the system was capable of collecting data at scan intervals of 1 to 10 ft at the appropriate vehicle speed. In addition to the 1 GHz horn antenna, a 1.5 GHz ground-coupled sensor was also used for project-level surveys and data was collected simultaneously on both channels. Simultaneous use of ground coupled and air coupled antennas for project level surveys provide better resolution and consequently more accurate interpretation of GPR data. GSSI provides a certificate of calibration which verifies that the system has undergone the testing, specified in the RFP, for (1) reflection tests (metal plate and end reflection), (2) noise to signal ratio (SNR) test, (3) long-term signal stability test, (4) signal stability test, and (5) concrete penetration test.

The GPR vehicle was equipped with two distance-measuring instruments (DMI), each of a precision higher than 1 ft per mile (0.0189% of measured distance) at an operating speed of 65 mph. The Nu-Metrics® DMI was capable of automatically displaying the distance and vehicle speed. The higher-resolution, encoder-based DMI provided higher quality GPR data, yet does not have a capability for displaying vehicle speed. Field calibration of both the GPR system and the DMI was performed in accordance to the specifications set forth in section 4.2 of the RFP. Initial network level GPR surveys (I-280 & I80) was conducted using Nu-Metrics® DMI as data acquisition trigger, however due to higher resolution of encoder-based DMI rest of the surveys was conducted using survey wheel as data acquisition trigger.

During all surveys, there was digital camera recording of the pavement with live audio feed from operator marking special pavement features and indicating milepost. A separate laptop computer controlled the camera and images were streamed to computer simultaneously during surveys.

METHODOLOGY & DATA QUALITY

Data from the antenna were collected while surveying at posted speeds averaging between 50 and 60 mph on highways and expressways, and 30-50 mph on local roads on the network level. On the project level, data were collected at speeds less than 15 mph. Due to low speeds; mobile traffic control was required during project level surveys. However, the network level surveys were performed without any traffic control.

During the initial part of network level GPR data collection (I-80 and I-280), vehicle mounted DMI was used to record data on a distance based rate of 1 scan/foot with system generated scans at a time based rate of 125 scans/second). However, due to higher resolution and better results of encoder-based survey wheel, the wheel was set to record data to the hard drive at a distance-based rate of 2 scans/foot for rest of network level surveys (while the system generated scans at a time-based rate was increased to 250 scans/second). Both DMI and the encoder-based survey wheel were calibrated over a distance of 300 feet prior to any survey.

Projects level data were collected using two antennas with survey wheel on a distance based rate of 6 scans/foot. To optimize the performance of SIR-20 in terms of speed and quality of signal, system generated scans were set to the rate of 200 scans/second.

The SIR-20 data acquisition unit can collect data at rates of up to 800 scans/second. If transmit frequency is set above 500 KHz the unit provides optimum data quality as a result of more sample-averaging (to improve signal-noise ratio) which occurs at the higher transmit rates. However at excessively high transmit rates slightly degraded signal is also generated. The slight gain in signal quality from more sample averaging (at the >500 kHz rate) does not compensate for the decrease in quality that also occurs at that rate. Since at network level surveys, high survey speeds was critical and there was not a need to sample in a spatially dense (many scans/foot) fashion, the balance of moderately high transmit rate of 450 KHz (400 KHz for I-280 and I-80) and moderate scan rate of 250 scans/second (125 scans/second for I-280 and I-80) with 2 scan/foot data output (1 scan/foot for I-280 and I-80) produced extremely high signal quality. This translates into GPR data whose amplitude and time measurements (the only two things GPR actually measures).

This is essential for a GPR pavement thickness survey, where material dielectric properties (and GPR propagation speeds through the pavement) are calculated from the measured data at each scan location, and dielectric properties are used to convert measured travel time to depth (and thickness) values for the layers in the pavement system. Additionally, increased signal-noise ratio (GSSI SIR-20 provides the cleanest signal among all GSSI systems) allows for slightly greater penetration—all other things equal (antennas)—in situations where GPR penetration is difficult, i.e. many concrete pavements.

During the project level surveys spatially dense data collection with two antennas were required. To optimize the quality of data with the considerations mentioned in previous paragraph, the transmit rate was reduced to 300 KHz to be able to collect good quality data with both air coupled and ground coupled antennas simultaneously.

Data collection setting and parameters, including scans/second, scans/ft, and ft/mark are user-specified inputs that affect respectively how many scans of GPR data are collected in any given second, how many scans are written to the data file based on distance traveled, and how often a visual mark will be placed in the data at a user-specified distance interval. Other user defined parameters such as time Range (ns), samples/scan and bits/sample all affect the “depth sample” and resolution of the data, and can affect whether a high-quality signal is recorded as such. The values for these parameters and other settings for network and project level surveys are shown in Figure 5 and 6.

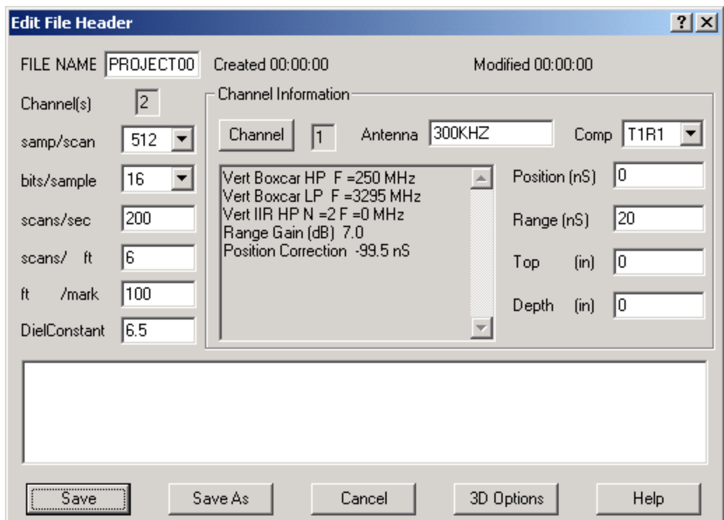
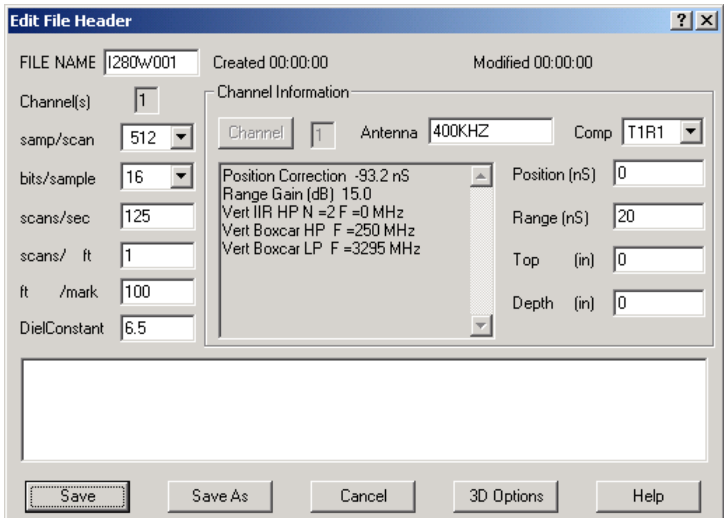


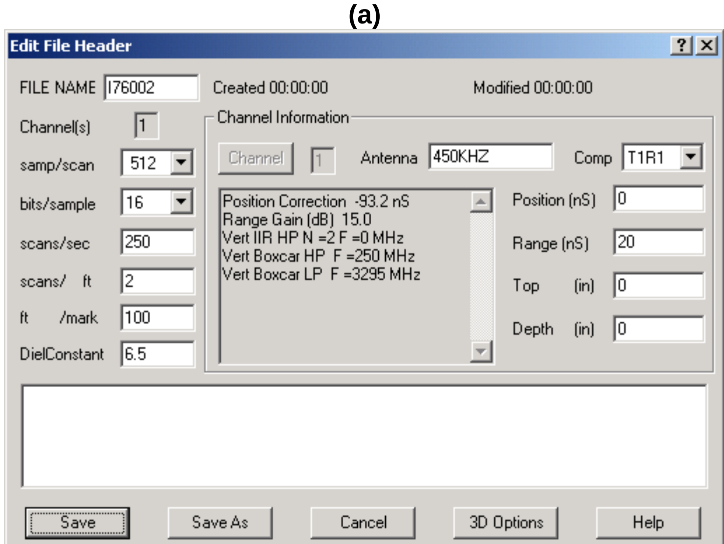
Figure 5. Data collection setting and parameters for project level surveys.

In all of the pavement surveys, required scan density (for reporting and/or data collection) was maximized—more scans/foot were collected than required by specification—so that better interpretations could be made. Very often, increased spatial density makes all the difference between an accurate and an inaccurate pavement layer interpretation. Often, horizontal stacking or “smoothing” the data from a sample with greater spatial sampling can minimize local aberrations (electronic artifacts) in the measured signal that are not representative of true subsurface properties. The end result is that there is greater flexibility, when required, to post-process the data and accurately interpret it when signal response is less than desirable. After interpretation is completed, it is routine practice to reduce the data output to the client’s specified reporting interval (0.01 Mile for network level data and 3 feet for project level data).

Each GPR scan produces information about the layer interfaces. These scans, interpreted for layer properties such as thickness or layer dielectric constant, provide a “depth sample”. A “depth sample” simply refers to the fact that the GPR signal, at every scan location, provides information about all the pavement layers in a vertical sequence. When evaluating pavement variation along its length, including layer structure variation and thickness of the various pavement components, GPR’s high spatial scan density can be thought of as being equivalent to a like number of core samples. If 2 scans/foot of data are collected, this profile information is quite comparable (though not as exact) to extracting cores every six inches along the pavement's length—or slicing a continuous vertical section, 2 to 3 feet in depth, along the entire GPR survey path



(a)



(b)

Figure 6. Data collection setting and parameters for (a) initial part of network level surveys and (b) rest of network level data collection.

Figures 7 and 8 show typical GPR profiles. In Figure 7 GPR profile of flexible pavement with interpreted pavement layer structure is shown. Upper panel shows GPR profile data (roughly 350', or 700 GPR scans). Layers are picked and overlaid on the upper panel, where travel time and amplitude of each point is measured; calculated depths (in inches) are then shown on the lower panel. Several primary layer systems can be seen in this profile: (a) Yellow dots, or "picks", define the bottom of a thin asphalt (b) green and blue boundaries contain multiple granular layer sequences which might correspond to base and subbase layers or even different lifts in the same material (c) considering their depth, brown “picks” are possible the layering in the subgrade material of the surveyed site.

In Figure 8 a horizontal asphalt layer (yellow dots) lies above a sequence of (apparently) dipping asphalt layers. Top of concrete (red dots forming a boundary) is deeper on the left of the image, but is beneath the horizontal asphalt overlay that continues, till where the yellow and red boundaries meet. To the right of this junction, everything above the red boundary is the same asphalt overlay seen above the yellow boundary. Within the entire image, the concrete pavement is immediately beneath the red boundary. The wavy, black/white boundary that is actually a part of the GPR image—with a herringbone pattern beneath it—is the reinforcement (most likely wire mesh, as evidenced by its undulating pattern). In this image, the concrete bottom is much more difficult to interpret. It was properly identified, though, after reviewing GPR data from adjacent profiles it can be identified.

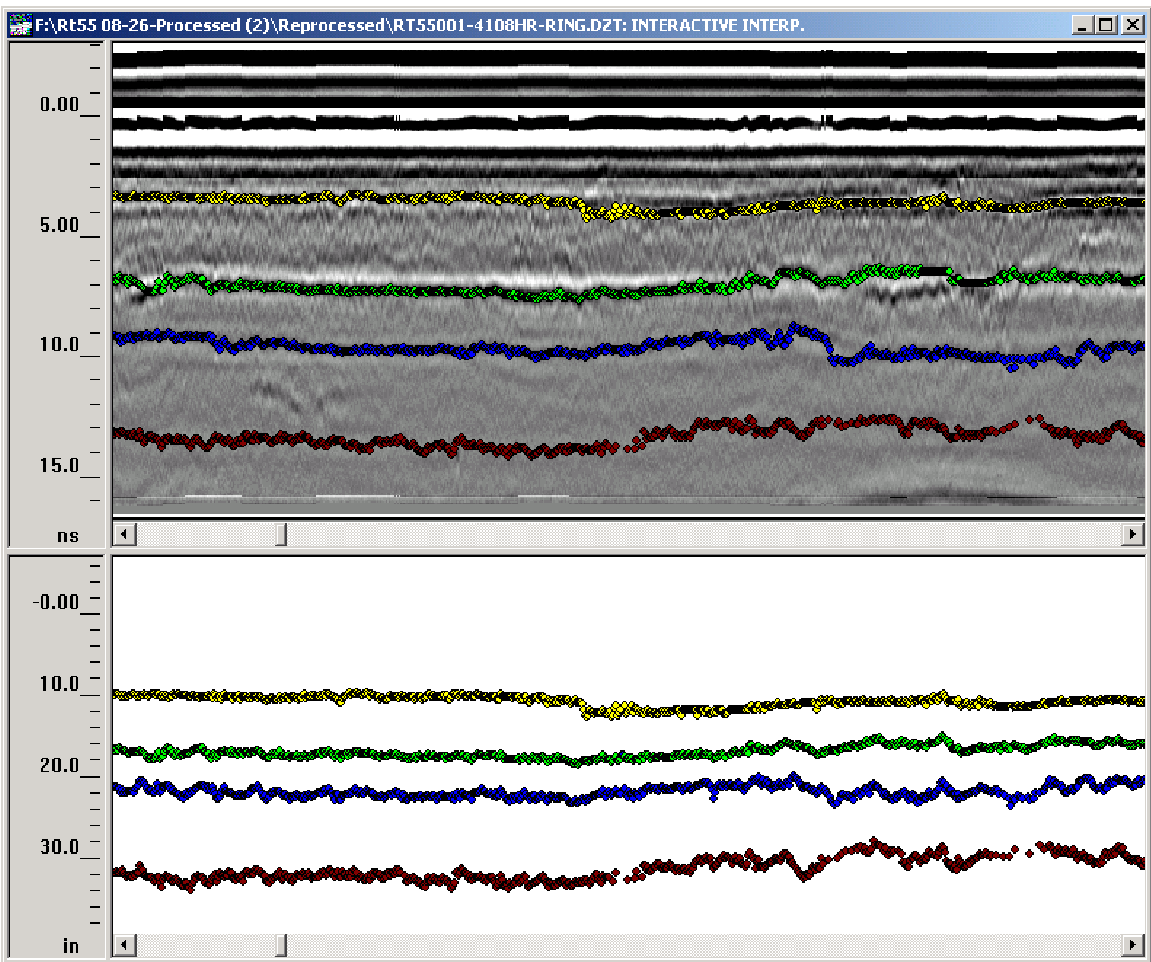


Figure 7. Typical GPR profile of a flexible pavement (NJ-55 network level survey).

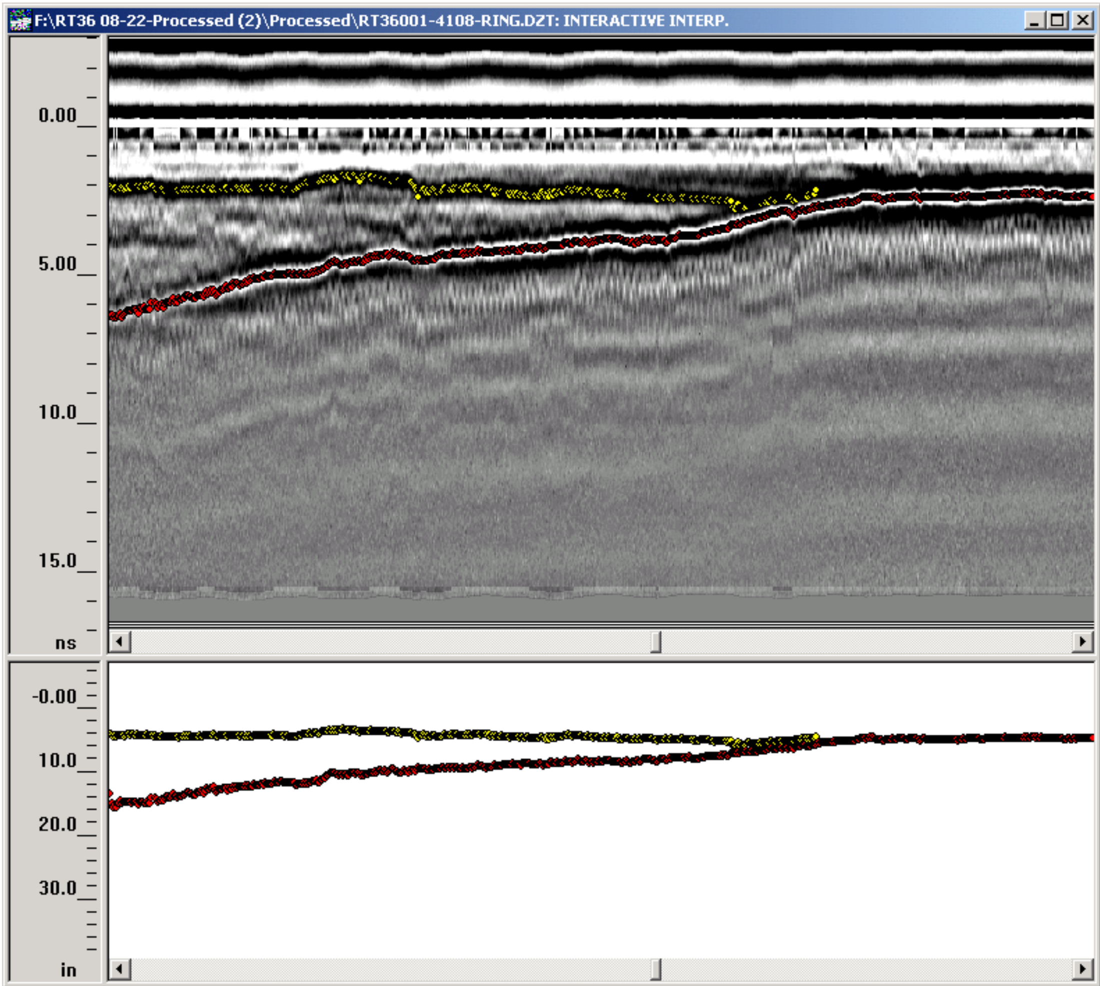


Figure 8. GPR profile with horizontal asphalt layer (yellow dots) lies above a sequence of (apparently) dipping asphalt layers above concrete pavement (NJ-36 network level survey).

There was simultaneous acquisition of digital video data (Figure 9). The captured images were used during interpretation, and reporting to determine details such as survey lane ID and its changes during survey or help to interpret special visually visible pavement features. The video images were also used to verify interpreted pavement structure to the extend possible from visual inspection (i.e. first paving layer type, and possibly verification of composite pavements). The video images can be provided at a later date on the same distance-based format for both the GPR and FWD (if available) data, using Road Doctor™. Road Doctor™ is software, which can read, link, and output various survey datasets (including GPR, FWD, Video, and data already stored in PMS databases). The software can both processes GPR data and link it to any other distance- or coordinate-based pavement data, including a PMS. A typical Road Doctor™ view of linked GPR, video, and roadway map is shown in Figure 10. A sample Road Doctor™ project, linking GPR, video and map has been prepared for NJ-36 S, surveyed as a part of network level surveys, which can be provided.

Figure 9. Typical pavement digital video image (NJ-36 SB at milepost 13.5).

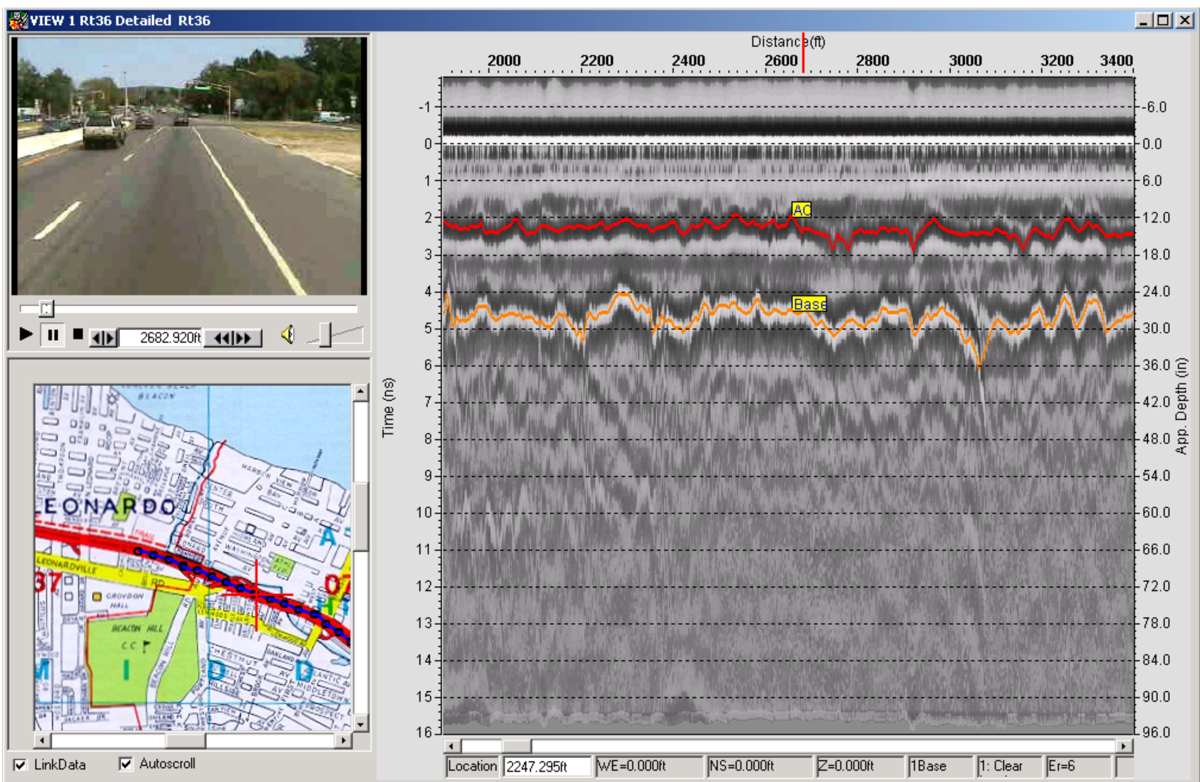


Figure 10. Typical Road Doctor™ view of linked GPR, video, and roadway map (NJ-36 SB at milepost 15.5)

DATA COLLECTION (FIELD) PROCEDURES

GPR Data Collection was collected with carefully designed and consistent procedures to ensure the quality of the data. These quality control/quality assurance (QA/QC) procedures are:

- At least 25 to 30 minutes of system/antenna warm-up, prior to collecting either calibration data or field data was assigned to ensure that antenna electronics have stabilized so that a consistent signal is generated throughout the duration of survey.

- Both DMI and survey wheel were calibrated carefully over a 300 feet interval prior to any surveys.

- Horn antenna mounted on fiberglass rails, extended at least 3 feet distance from the back of the survey vehicle. Cross section of any nearby metallic objects was minimized to minimize unwanted reflections in data. Ratchet straps are used to stabilize the antenna and minimize vibration as well as to fine tune antenna deployment height to about 20 inches (the optimal deployment height for peak performance). Finally, antenna cable is secured to minimize unwanted signals and prevent any damage to antenna connections.

- Metal plate calibration scans with the same survey setting were collected at each day of testing. During long testing (more than app. 6 hours), two metal plate calibration scans were collected.

- Network level surveys where conducted at 50-60 mph on highways and expressways and at 30-50 on local roads. The project level surveys were conducted at less than 15 mph. Lane closures were not necessary for the network level survey, while mobile traffic control units were used in project level testing. Due to safety precautions, all surveys were performed with yellow strobes and work lights.

- The vehicle was driven in a constant position with respect to the lane’s width, i.e. it was driven to “center” the vehicle midway between the lane stripes while driving. Extreme care was taken (including surveying as close to mentioned speeds as traffic would allow) to remain in that lateral position throughout the length of each GPR profile line during testing. When lanes merged, or divided (as often occurs when the travel lane becomes the exit lane for a ramp near an exit) or lanes had to be changed, a quick lane change was made to possibly maintain the “lane ID”. The recorded survey video is used to verify any locations where this may have occurred and the changes are reported in final Excel sheet results.

- As the data profiles were collected, the continuously streaming GPR record was viewed by the GPR operator on the laptop's monitor to ensure recording of good quality data.

- The location (milepost) of the test data are marked manually on GPR data with markers and clearly marked on video through audio input of operator at interval ranging between 0.1 ~2 mile based on the availability of mile markers on the road. These marks were used later during processing and reporting to correct any possible errors in distance measurements with DMI or survey wheel.

- Upon completion of each day of testing all gathered data were backed up immediately for future processing.

DATA PROCESSING

Data were processed using GSSI's **RADAN®** (**RA**dar **D**ata **AN**alyzer) software with Road Structure Assessment (RSA) Module. Following processing steps applied to the GPR data during both data collection (gain & filters) and post-processing:

(a) During Data Collection

- Vertical filter IIR HP N=2 F=0 MHz (vertical filtering of samples in a single scan, in time domain)
- Vertical Boxcar HP F =250 MHz (vertical filtering of samples in a single scan, in time domain)
- Vertical Boxcar LP F =3295 MHz (vertical filtering of samples in a single scan, in time domain)
- Static Stacking N=1 (horizontal filtering of scans in spatial (distance) domain)
- Range Gain (dB) 15.0 (constant signal amplification throughout)

(b) During Post-Processing of Data

- Position Correction –93.2 ns
- Reflection Picking and calibration Scan Subtraction
- Ring-down removal filtering when required.

Figure 11 shows typical data collection and processing settings for typical GPR survey.

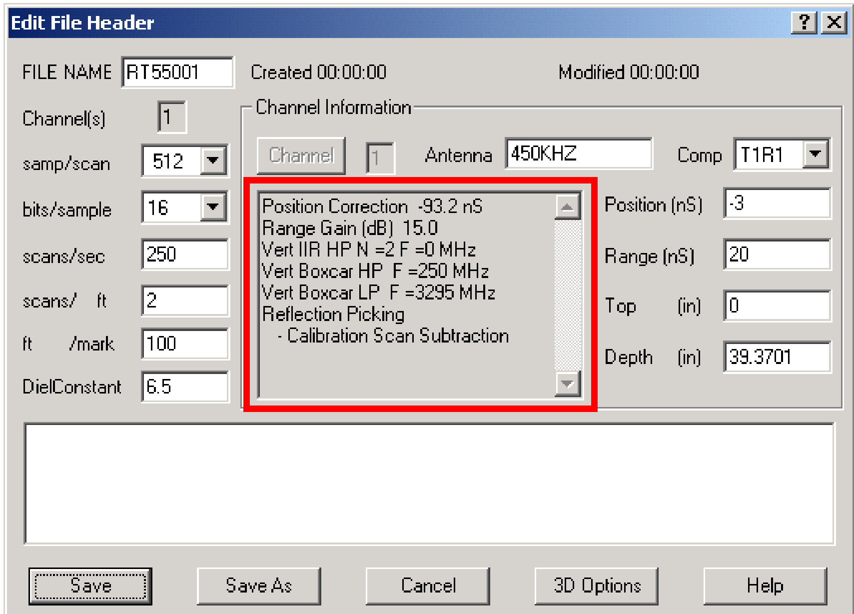


Figure 11. Data collection and processing setting and parameters for typical network level data.

Using RADAN's RSA Module, a metal plate calibration file (collected in the field with the raw data, using the same data collection parameters, filters, etc…but no distance-based scanning, and a different (lower) gain) was processed so that the following could be achieved:

- Amplitude normalization of the data, relative to antenna deployment height during collection of each scan as the survey progressed.

- Removal of clutter (reflections between the pavement surface, the antenna transmitter and receiver, the deployment frame and the back end of the survey vehicle—all constant (or nearly so) at each specific calibration file height) from each scan, again depending on deployment height of the antenna during each scan.

- Calculation of velocity (GPR propagation speed) through pavement, based on relative reflection equation which compares the metal plate reflection amplitude at any given deployment height to the normalized surface reflection amplitude for each scan collected during the entire survey at that same deployment height. Each scan, then, is assigned a velocity, computed from these amplitude values and the measured travel time to the layer in question within that scan.

- Calculation of a pavement depth (asphalt thickness), based on the velocity and the travel time (calculated using the one-way, not two-way travel time from time "zero"—the pavement surface—to the arrival of the "picked", or identified, Layer 1 reflection).

- As the pavement bottom is identified, and the distance, travel time, amplitude (measured values), and related (calculated) variables such as velocity and depth are determined, the information can be stored to ASCII files as master files, or as output files with specified parameters selected by the user. User-specified interval output data were used to generate data for plotting, within intervals of 3 feet along the pavement length… where maximum depth of all identified layer "picks" in each 3-foot interval was output to the spreadsheet, then later plotted.

(c) During Layer Identification

Several interpretation tools are used to efficiently process the data, accurately identify and mark layers, and record the data in an ASCII file. Interactive interpretation of the data resulted in identification of several pavement layers along surveyed roadways, which is reported in Excel spreadsheets and ASCII files.

RESULTS

Interpretation of the data resulted in identification of several pavement layers and pavement types (rigid, flexible and composite) along surveyed roadways. Figure 12 shows a typical flexible pavement profile. Upper panel shows the GPR profile with interpreted layers picked, while lower panel shows calculated depth for each layer. Several distinct layers are visible in the data. The first layer is the paving layer while the layers picked below are several granular layers, which can be described as base, subbase and subgrade. A typical rigid pavement section is shown in Figure 13. Reinforcements are clearly visible in this image in terms of wavy layer above the first picked layer (red picks), which represents bottom of slab. A granular layer (green picks) can also be identified in GPR profile shown which might be a granular base layer. In a composite profile, as illustrated in Figure 14, reinforcements are identifiable below a surface layer of asphalt (yellow picks). Concrete slab bottom (red picks) and a granular layer (green picks) are also visible in shown picture. As shown in this figure there is considerable variation in slab depth across the scanned path.

GPR profiles also capture several local features of roadways such as utility cuts, pavement repairs, bridges, and culverts… Figure 15 shows GPR profile of a repaired roadway. The figure shows a composite pavement where in the middle of the profile one of the slabs is completely removed and filled with asphalt. Capturing such local variation in pavement structure is quite impossible with usual coring method.

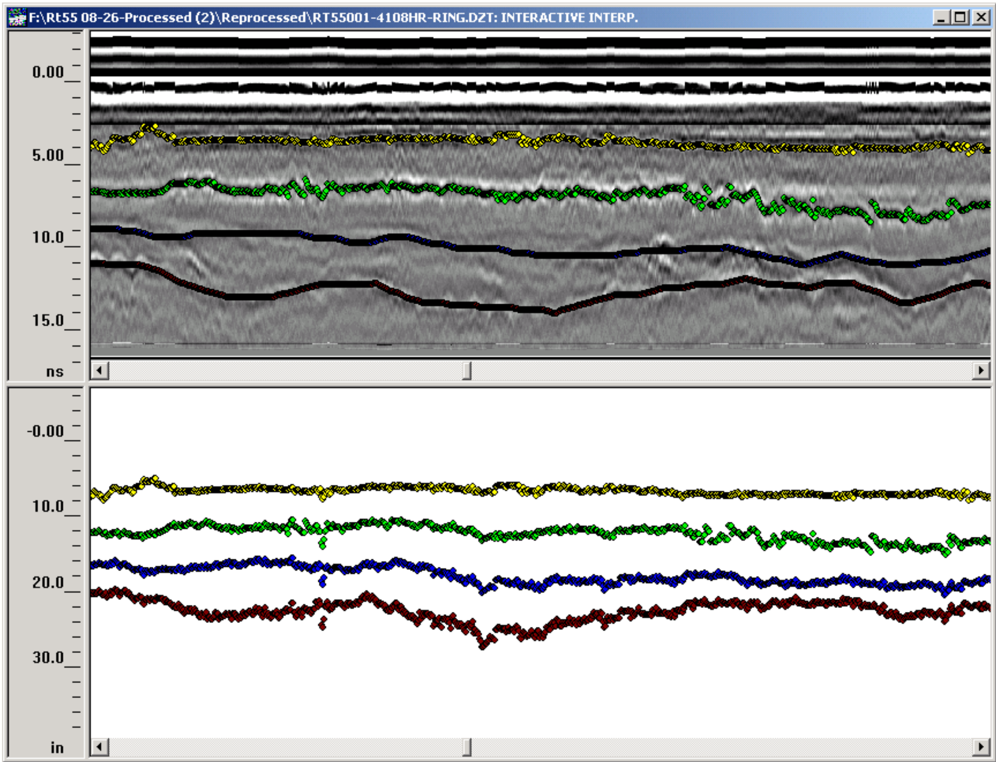


Figure 12. Typical GPR profile of a flexible pavement (NJ-55 NB)

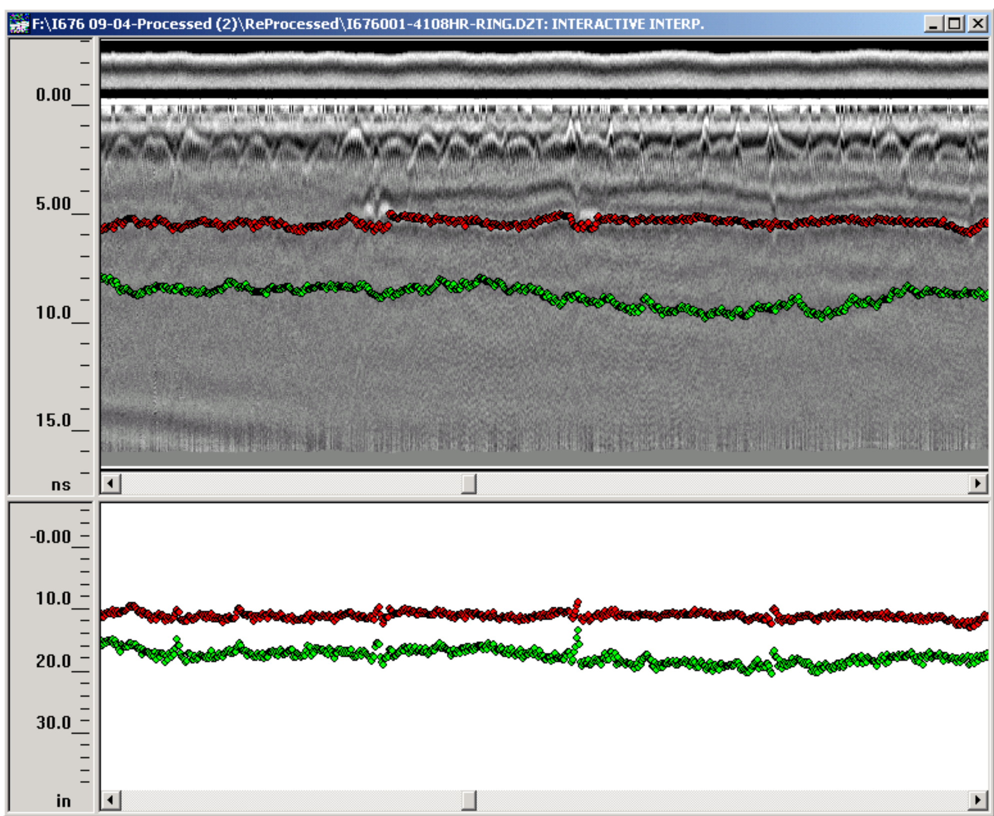


Figure 13. Typical GPR profile of a rigid pavement (I-676 NB)

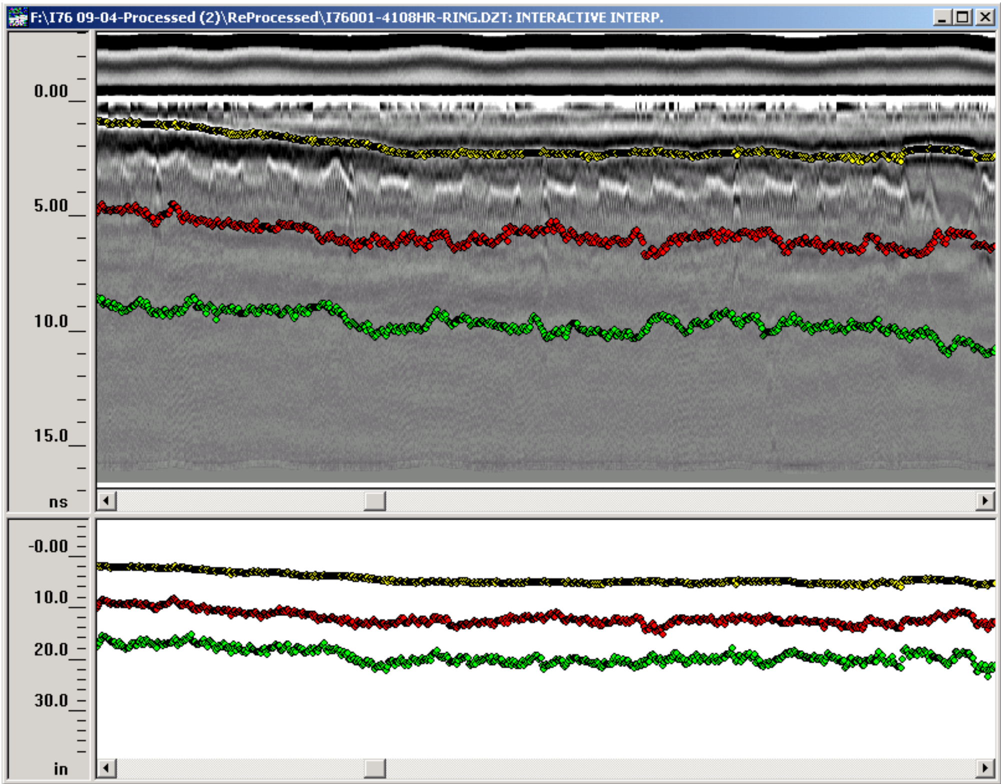


Figure 14. Typical GPR profile of a rigid pavement (I-76 EB)

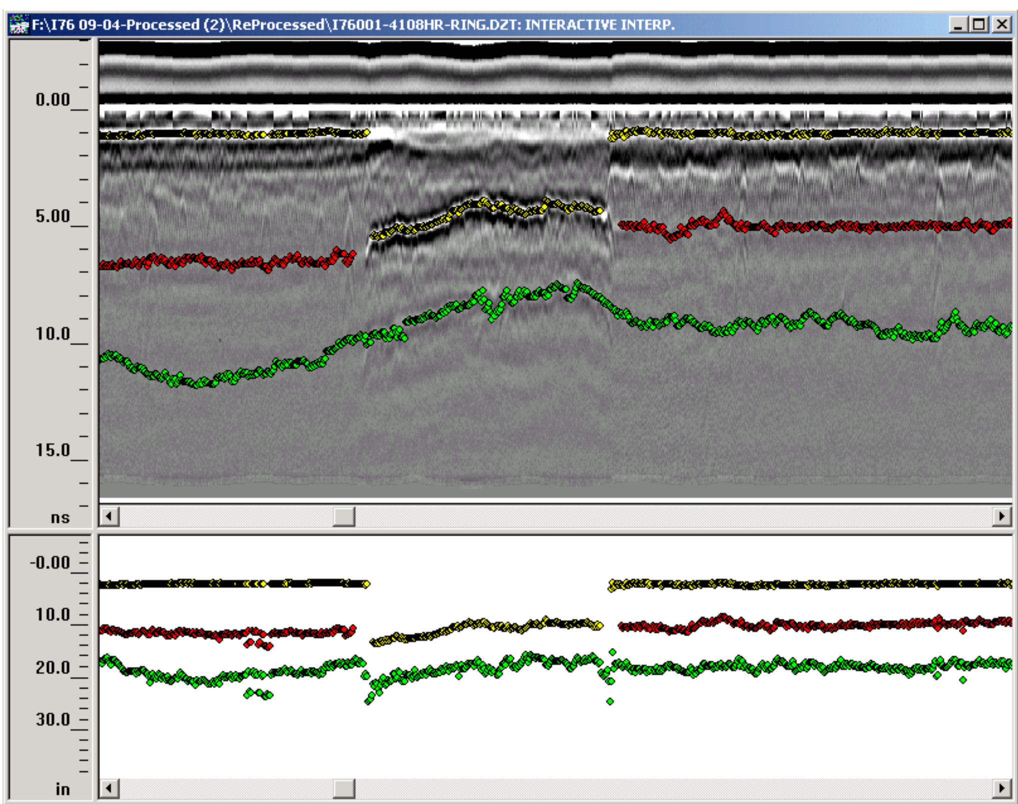


Figure 15. GPR profile of a repaired roadway. (I-76 EB)

Huge amount of collected survey data are processed and interpreted and results are provided in form of RADAN data files (*.dzt) and RADAN interpretations files (*.lay) (about 23 Gigabyte of data). To further facilitate the integration of survey results with PMS applications, survey data for each independent GPR scan path are also provided in specified ASCII and Excel spreadsheet formats, which can be opened in database, or PMS applications

The parameters calculated for each layer are stored along with position of the scan with respect to its distance along the test road (indicated in 1/100 mile increments for network level surveys, and 3 feet for project level surveys.) Figures 16 illustrate the specified file format for data reporting. The columns represent from left to right route number, auxiliary route ID, direction, lane ID, x the distance along survey in project level surveys, milepost, layer ID, average thickness, and average dielectric for all picked layers. Table 4 and 5 indicates the filenames for each of the spreadsheets, as they relate to the pavement test sections described earlier. A summary of pavement types encountered in each surveyed route is also reported in Table 6, and 7.

As have been mentioned earlier, GPR data were marked during survey each time a mile marker sign is observed. These marks were used during data reporting to minimize the errors in distance measurement form DMI devices. To achieve this objective, instead of solely relying on DMI measurement, data collected after each mark were averaged and reported as the representative data for that section till next marker location. For example, if the mark on data were at scan x, which correspond to milepost A, and the next marker corresponds to milepost A+1, the scans x till x+1 mile were averaged and reported as the data for the interval A and A+1 miles. This procedure is repeated for every mile marker on the data to reduce and distribute possible errors in the distance measurements.

This procedure proved helpful specially for the reporting of initial part for network level data, I-280 and I-80 (collected with vehicle installed DMI which had lower resolution). As it discovered later, during the survey, one of the eight metal plates mounted on wheel, which trigger the DMI sensor, was bent (possibly due to impact of debris from pavement) and was not triggering the sensor. This resulted in inaccurate distance measurement (in other words each mile was measured as 7/8 mile). Using the above mentioned procedure and markers in the file, the error from this bent plate were minimized and distributed evenly across the whole route. As has been mentioned earlier, the rest of surveys (network and project level) used survey wheel to measure the distance, which provided better resolution and avoided possible errors from damage to metal plates on the wheel.

There have been some calibration core taken on some roads independent of survey results and used during the interpretation and layer picking to help to verify and/or calibrate the GPR measured thickness and dielectrics.

Table 4. Filename designations for network level result spreadsheet.

Route	Direction	Filename	Route	Direction	Filename
Network level					
I-76	E	I76E.xls	US-9	N	NJ9N.xls
	W	I76W.xls		S	NJ9S.xls
I-80	E	I80E.xls	US-30	E	NJ30E.xls
	W	I80W.xls		W	NJ30W.xls
I-95	N	I95N.xls	NJ-36	S	NJ36S.xls
I-195	W	I195W.xls	NJ-55	N	NJ55N.xls
	E	I195E-MP0-9.xls		S	NJ55S.xls
	E	I195E-MP12-35.xls	US-130	N	NJ130N-MP43-51.xls
I-280	E	I280E.xls		S	NJ130S-MP43-51.xls
I-287	N	I287N.xls	US-130	N	NJ130N-MP56-68.xls
	S	I287S.xls		S	NJ130S-MP56-68.xls
I-295	N	I295N-SLow lane.xls	I-676	N	I676N.xls
	N	I295N-Fast lane.xls		S	I676S.xls
	S	I295S-SLow lane.xls			
	S	I295S-Fast lane.xls			

Table 5. Filename designations for project level result spreadsheets.

Route	Direction	Filename	Route	Direction	Filename
Project Level					
NJ-55	N	NJ55N-Project Level MP36-39.xls			
NJ-55	S	NJ55S-Project Level MP61-58.xls			
NJ-55	N	NJ55N-Project Level MP56-59.xls			
US-130	N	NJ130N-Project Level.xls			
I-195	W	I195W-Project Level.xls			
I-195	E	I195E-Project Level.xls			

I95N Revised.xls

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Route #	Aux. ID	Direction	Lane	x(ft)	MP	Layer	Ave. Thickness (in)	Ave. Dielectric	Layer	Ave. Thickness (in)	Ave. Dielectric	Layer	Ave. Thickness (in)	Ave. Dielectric	Layer	Ave. Thickness (in)	Ave. Dielectric
2	95		N	2		0.01	AC	0	0	PCC	0	0	GRAN	0	0	GRAN	0	0
3	95		N	2		0.02	AC	0	0	PCC	0	0	GRAN	0	0	GRAN	0	0
4	95		N	2		0.03	AC	0	0	PCC	0	0	GRAN	0	0	GRAN	0	0
5	95		N	2		0.04	AC	0	0	PCC	0	0	GRAN	0	0	GRAN	0	0
6	95		N	2		0.05	AC	0	0	PCC	0	0	GRAN	0	0	GRAN	0	0
7	95		N	2		0.06	AC	0	0	PCC	0	0	GRAN	0	0	GRAN	0	0
8	95		N	2		0.07	AC	0	0	PCC	0	0	GRAN	0	0	GRAN	0	0
9	95		N	2		0.08	AC	0	0	PCC	0	0	GRAN	0	0	GRAN	0	0
10	95		N	2		0.09	AC	0	0	PCC	0	0	GRAN	0	0	GRAN	0	0
11	95		N	2		0.1	AC	5.55	8.37	PCC	6.32	8.95	GRAN	0	0	GRAN	0	0
12	95		N	2		0.11	AC	5.75	8.37	PCC	6.31	8.91	GRAN	0	0	GRAN	0	0
13	95		N	2		0.12	AC	4.2	8.58	PCC	7.42	9.38	GRAN	0	0	GRAN	0	0
14	95		N	2		0.13	AC	3.91	8.74	PCC	7.93	9.46	GRAN	0	0	GRAN	0	0
15	95		N	2		0.14	AC	4.03	8.4	PCC	8.2	9.38	GRAN	0	0	GRAN	0	0
16	95		N	2		0.15	AC	3.83	7.96	PCC	9.19	8.5	GRAN	0	0	GRAN	0	0
17	95		N	2		0.16	AC	3.53	8.02	PCC	8.87	9.28	GRAN	0	0	GRAN	0	0
18	95		N	2		0.17	AC	4.51	8.18	PCC	7.97	9.07	GRAN	0	0	GRAN	0	0
19	95		N	2		0.18	AC	4.09	8.04	PCC	8.48	9.3	GRAN	0	0	GRAN	0	0
20	95		N	2		0.19	AC	3.95	7.73	PCC	7.73	9.39	GRAN	0	0	GRAN	0	0
21	95		N	2		0.2	AC	3.14	7.35	PCC	6.82	12.21	GRAN	0	0	GRAN	0	0
22	95		N	3		0.21	AC	3.57	8.14	PCC	6.9	10.87	GRAN	0	0	GRAN	0	0
23	95		N	3		0.22	AC	4.5	7.81	PCC	7.36	9.31	GRAN	0	0	GRAN	0	0
24	95		N	3		0.23	AC	5.05	7.61	PCC	6.82	9.55	GRAN	0	0	GRAN	0	0
25	95		N	3		0.24	AC	2.85	7.89	PCC	8.82	9.9	GRAN	0	0	GRAN	0	0
26	95		N	3		0.25	AC	2.61	8.53	PCC	9.15	10.39	GRAN	0	0	GRAN	0	0
27	95		N	3		0.26	AC	4.52	7.96	PCC	8.01	9.44	GRAN	0	0	GRAN	0	0
28	95		N	3		0.27	AC	6.67	7.93	PCC	6.81	8.94	GRAN	0	0	GRAN	0	0
29	95		N	3		0.28	AC	8.1	7.81	PCC	5.85	8.38	GRAN	0	0	GRAN	0	0
30	95		N	3		0.29	AC	8.17	7.8	PCC	6.92	8.03	GRAN	0	0	GRAN	0	0
31	95		N	3		0.3	AC	8.12	7.79	PCC	6.72	8.32	GRAN	0	0	GRAN	0	0
32	95		N	3		0.31	AC	8.15	7.96	PCC	5.63	8.91	GRAN	0	0	GRAN	0	0
33	95		N	3		0.32	AC	8.09	7.98	PCC	5.61	8.82	GRAN	0	0	GRAN	0	0
34	95		N	3		0.33	AC	8.45	7.89	PCC	5.89	8.8	GRAN	0	0	GRAN	0	0
35	95		N	3		0.34	AC	8.13	8.1	PCC	6.29	8.37	GRAN	0	0	GRAN	0	0
36	95		N	3		0.35	AC	8.09	8.31	PCC	6.23	8.99	GRAN	0	0	GRAN	0	0
37	95		N	3		0.36	AC	8.36	8.35	PCC	5.85	8.99	GRAN	0	0	GRAN	0	0
38	95		N	3		0.37	AC	8.36	8.68	PCC	5.41	9.1	GRAN	0	0	GRAN	0	0
39	95		N	3		0.38	AC	7.97	8.56	PCC	5.93	8.8	GRAN	0	0	GRAN	0	0
40	95		N	3		0.39	AC	7.69	8.48	PCC	6.51	8.57	GRAN	0	0	GRAN	0	0

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Figure 16. Typical spreadsheet format of reported results.

Table 6. Percentage of each pavement type in project level surveys.

Route	Direction	From	To	Flexible (%)	Rigid (%)	Composite (%)
NJ-55	N	36.0	39.0	100	0	0
NJ-55	S	58.0	61.0	100	0	0
NJ-55	N	56.0	59.0	100	0	0
US-130	N	13.0	15.0	29	52	19
I-195	W	9.0	16.0	100	0	0
I-195	E	9.0	16.0	100	0	0

Table 7. Percentage of each pavement type in network level surveys.

Route	Direction	From	To	Flexible (%)	Rigid (%)	Composite (%)
I-76	E	0.0	2.0	22	0	78
	W	0.0	2.0	17	0	83
I-80	E	18.8	68.5	64	11	25
	W	0.0	68.5	53	15	31
I-95	N	0.0	8.8	69	0	31
I-195	W	0.0	9.0	100	0	0
	E	12.0	34.2	100	0	0
	E	0.0	9.0	100	0	0
I-280	E	0.0	17.7	35	57	8
I-287	N	0.0	67.5	39	30	31
	S	0.0	67.5	33	36	31
I-295	N-Slow	0.0	32.0	46	27	27
	S-Fast	0.0	32.0	46	22	32
	N-Fast	0.0	32.0	46	27	27
	S	0.0	67.9	37	47	16
I-676	N	0.0	3.6	4	75	21
	S	0.0	3.6	4	75	21
US-9	N	62.4	68.0	1	0	99
	S	62.4	68.0	2	0	98
US-30	E	40.5	52.0	80	0	20
	W	40.5	52.0	76	0	24
NJ-36	S	10.0	16.0	14	0	86
NJ-55	N	20.0	33.2	100	0	0
	S	20.0	33.2	100	0	0
US-130	N	41.0	51.0	45	10	45
	S	43.6	50.6	8	0	92
US-130	N	56.5	67.2	6	29	65
	S	56.5	67.2	17	25	58

DISCUSSION

The following discussion addresses some of the issues which will significantly improves the usefulness of GPR data and its efficient use as a part of comprehensive pavement management system. It is recommended that these issues be considered for implementation in future GPR surveys:

- Capability of GPR continuous profiling in estimation of pavement layer thickness and dielectric is a valuable tool for many pavement management applications. This pilot project has demonstrated the ability of this technology in structure identification. However, for efficient use of this technology a carefully design strategy is required. This strategy may include (a) collecting and analyzing the GPR data, (b) collaborating on appropriate regions and specific locations for ground truth sampling, (c) feedback of ground truth results to be used to in updating and improving interpretations. This cycle of interpretation, ground truth and interpretation will ensure accurate estimation of GPR profiles and increases quality of the final results.

- The ability to link, view, analyze, and report GPR, video, map, and several other pavement related data together, as demonstrated with RoadDoctor™ software, is extremely valuable. Road Doctor™, in particular, has a direct link to ELMOD, which extracts the layer thickness data directly from the GPR interpretation and uses the data in back-calculation. Road Doctor can also provide plots comparing the back-calculated FWD data with the actual deflection measurements (overlaid on each other to show contrast). If significant differences exist at certain FWD drop points, the GPR interpretation and/or FWD data can be investigated to verify whether there is dubious layer structure that could have been interpreted differently. In addition to mentioned capabilities of Road Doctor™, it can also link many other forms of data such as IRI, core data, GPS coordinates, data already stored in databases including PMS systems, and free format data.

- The error in distance measurement is the most dominant cause of discrepancies in GPR measurements. To improve the distance measurements, it is suggested that future GPR surveys be conducted with GPS (global positioning system) to minimize the errors form inaccurate measurement of distance. Since GPS measurements are accurate and independent of vehicle speed and pavement condition (unlike DMI), use of GPS measured coordinates can greatly improve final results of survey. Road Doctor™ is capable of using GPS coordinates to link the data to other data formats such as GPR and Video which can be used in future surveys to integrate GPS, GPR, video and other data format available.

- The captured video images of pavement during testing, if properly linked with other data, are very valuable both in GPR interpretation and pavement management applications. It is suggested that video image of surveyed pavements be captured. Road Doctor™ provides an efficient tool for both capturing and linking these images to other data collected such as GPR.

SUMMARY

GPR's continuous profiling capability, and ability to estimate pavement layer thickness and type without the use of cores, is a valuable precursor to ground-truth, FWD and other evaluation. This capability is clearly demonstrated through out this work, which included network level survey of 600 lane-miles of interstate, U.S., and local highways and project level survey of 25 lane-mile of designated routes. The final results of the work are provided in terms of ASCII and Excel files, summarizing GPR survey results in specified formats and intervals. In addition to summarized results, raw data, processed data, and the interpretation files are also submitted.

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