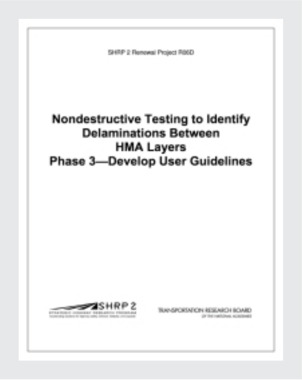

SHRP 2 Renewal Project R06D

Nondestructive Testing to Identify
Delaminations Between
HMA Layers
Phase 3—Develop User Guidelines

SHRP 2

TRANSPORTATION RESEARCH BOARD

Nondestructive Testing to Identify Delaminations Between HMA Layers: Phase III–Develop User Guidelines

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SHRP 2
STRATEGIC HIGHWAY RESEARCH PROGRAM
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SHRP 2 Renewal Project R06D

Nondestructive Testing to Identify Delaminations Between HMA Layers Phase 3—Develop User Guidelines

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Contents

CHAPTER 1
Background

Several types of surface distress in asphalt pavements, such as longitudinal cracking in the wheel path and tearing in the surface, can be attributed to delamination between hot mix asphalt (HMA) layers. Delamination is primarily due to layer debonding or stripping. Debonding occurs when there is improper tack between asphalt concrete (AC) layers or between an AC overlay and concrete pavement. Stripping develops when the aggregates and asphalt binder are incompatible, adhesion is lost, and water separates the asphalt binder from the aggregate.

Delamination is difficult to detect before the surface distress—cracking or tearing—occurs. Currently, coring is often used to measure the depth, type, and severity of delamination after the visual distress appears. This test method is destructive and not suitable for continuous, effective evaluation of long stretches of pavement. Nondestructive testing (NDT) methods are needed to identify the presence, location (depth and area), and severity of delamination in a rapid, effective manner even before the surface distresses occur. They can be applicable to both network-level pavement condition assessment and project-level investigation to select a proper rehabilitation strategy and improve construction quality.

Strategic Highway Research Program 2 (SHRP 2) Project R06D was initiated to evaluate NDT technologies that could detect delamination and to further develop the most promising methods to accomplish construction, project-level, and network-level evaluations. NDT for construction quality assurance should have the ability to detect debonding after placement of an AC lift. NDT for project-level investigation should have the ability to provide a detailed identification of the location and severity of delamination. NDT for network-level assessment should have the ability to detect the presence of delamination with the test equipment operating full lane width at a safe highway speed.

The SHRP 2 Project R06D was initially conducted in two phases; Phase 3 was added later to the project after the first two phases had been completed. Phase 1 identified potential NDT technologies and prepared research programs for developing and evaluating these technologies. Phase 2 conducted the research programs and refined the best candidate NDT technologies. Detailed results of Phases 1 and 2 were presented in a separate report (*1*); a summary of the results is provided in the following paragraphs. Phase III developed guidelines and facilitated the implementation of the selected NDT technologies for evaluating delamination in asphalt pavements. Results of Phase 3 are presented later in this report.

In Phase 1, through a literature search, meeting with NDT vendors, and discussion with a panel of experts, nine NDT technologies, including three ground-penetrating radars (GPR), two mechanical wave techniques, two infrared thermography devices, and two deflection measurement methods were selected for further evaluation in Phase 2.

In Phase 2, the NDT technologies were evaluated in both controlled and uncontrolled conditions. The controlled-condition evaluation was conducted on two delaminated pavement slabs (8 ft × 4 ft × 8 in. thick) in the National Center for Asphalt Technology (NCAT) laboratory and on ten 25-ft intact and delaminated pavement sections constructed on the NCAT Pavement Test Track. The evaluation was performed under warm-dry pavement and cool-wet pavement conditions. Based on the results of the controlled-condition evaluation, the GPR and mechanical wave technologies were identified as most promising for achieving the objectives of the project.

A GPR vendor and a mechanical wave vendor agreed to work with the research team through two seed-money agreements to improve their hardware and software before the uncontrolled-condition evaluation. At the time, the GPR vendor already had a lane-width, air-launched antenna array with the software that could process the raw data into a three-dimensional visual array. Hence, the hardware improvement focused on modifying the vehicle attachment for safe and secure transport between testing sites. Software improvements were done to help users examine the GPR measurements in greater detail and streamline the data analysis.

During the controlled-condition evaluation, the mechanical wave vendor demonstrated a prototype device with two rolling wheels that could conduct impact echo (IE) and spectral analysis of surface waves (SASW) measurements along a longitudinal path. Further development of the hardware focused on increasing the number of wheels to measure the lane width in a single pass. The software was improved to collect more data when more wheels were used and to better analyze data, particularly for SASW measurements.

The improved NDT devices were then evaluated in uncontrolled conditions at delaminated pavement sites in Maine, Kansas, and Florida. Both of the vendors showed significant improvements in their hardware and software. GPR is capable of testing full lane width at moderate testing speed. Mechanical wave methods are limited to testing at less than 5 mph, but this is still a significant improvement over point-test methods. Software is available to analyze data in great detail but requires a trained technician. Further improvement in software is needed to reduce the analysis time.

Both technologies can be used to detect discontinuities in asphalt pavements; however, they cannot be used to conclusively distinguish between types of pavement discontinuities. Coring will be needed to confirm the nature of the discontinuity. GPR can be used to identify variations in the pavement, isolate the depth and area of a discontinuity in the pavement, and provide a relative degree of severity. Severe conditions, like stripping, can be observed with conventional analysis software. Detecting debonding between asphalt layers requires a refined analysis methodology. For the mechanical wave methods, IE can identify variations in the pavement below 4-in. depth, and SASW can identify variations in the top 7 in. of the pavement. However, IE should be conducted on cool and stiff asphalt surfaces, and SASW requires a reasonable value for the pavement stiffness for analysis. Both the IE and SASW methods have limited ability to provide the degree of severity and cannot measure pavement condition below the top of the discontinuity.

GPR and mechanical wave methods were recommended for implementation as project-level tools used independently or in combination to determine the extent and depth of pavement discontinuity to help select the proper rehabilitation strategy. GPR can be conducted without a lane closure and is appropriate for preliminary assessment of pavement condition. IE and SASW will require a lane closure and can be used to supplement GPR results. In addition, continuing improvement in data analysis software is needed to make NDT a network-level tool for detecting delamination in HMA pavements.

Phase 3 Objective and Work Plan

The objective of Phase 3 was to develop user guidelines for the NDT technologies selected in Phase 2, that is, GPR and mechanical wave. Phase 3 was added to the project to help implement the advanced NDT technologies for detecting delamination in HMA pavements. The guidelines would be provided to pavement engineers (users) with an interest in applying NDT for pavement evaluation and project development. The Phase 3 objective was later enhanced to include pilot workshops for interested users.

CHAPTER 2

Developing User Guidelines

The research team developed guidelines for using the NDT technologies improved under SHRP 2 Project R06D to identify delamination between asphalt layers. The guidelines were developed in three steps. First, the research team proposed hardware and software specifications for GPR and mechanical wave methods based on the results of the evaluations in Phase 2 and prepared vendor surveys based on the specifications. Second, the team then sent the specifications and surveys to vendors for review and followed up with a conference call with each vendor to discuss the vendor's comments and responses. Finally, the guidelines were prepared in a generic NDT technology perspective based on the proposed specifications, the vendors' survey inputs, and expected target users. A summary of each step follows.

Proposed Specifications

Proposed Specifications for GPR

Based on the Phase 2 evaluation results, GPR is capable of detecting moderate to severe delamination by observing spatially coherent anomalies in the GPR data at specific depths. It could also identify debonding between asphalt lifts if water was present in the seam. This detection capability was implemented using a multi-antenna array distributed across the width of the pavement. The purpose of the array was to collect equally spaced parallel lines of data simultaneously, so that coherent areas of delamination can be identified and mapped for the full width of a 12-ft wide lane. Data are collected continuously while the system is driven along the surface of the pavement. The data collection is typically triggered using a distance measuring instrument (DMI) mounted to the vehicle wheel or to an external distance wheel. Tables 2.1 and 2.2 show proposed specifications for a GPR system that can be used to evaluate delamination in asphalt pavements.

Table 2.1 Proposed System Requirements for GPR

System Component	Specification
System type	Array of multiple antenna elements lined up transverse to the direction of travel
Frequency Range - Impulse radar systems	Center frequency of pulse > 2.0 GHz; –10 db limits: 0.5 to 5.0 GHz
Frequency Range - Frequency sweep radar systems	Frequency range: up to 3.0 GHz
Lateral spacing of antenna elements	< 1.5 ft
Lateral coverage per pass	12 ft (full lane width)
Longitudinal data collection rate	> 2 scans per foot per antenna element
Travel speed during data collection	> 20 mph
Travel speed during mobilization	Posted speed limit
Real-time display	B-scan for selected antenna elements
System monitoring and control	From within the survey vehicle
Data collection rate	Data collection should be triggered on distance using a DMI
Spatial reference	Vehicle DMI, external distance wheel, or global positioning system (GPS)
Detection Depth Range	2 to 12 in.

Table 2.2 Proposed Data Output and Display Requirements for GPR

Requirements	GPR
Data Output	Output should be a volume of data with amplitude as a function of *x* (longitudinal distance), *y* (transverse offset), and *z* (time)
Data Display	Field operation and playback software should be capable of the following displays: • Direct time domain waveform (A-scan) • Longitudinal profile for a given transverse offset (B-scan) • Time/depth slice for a given time range • Transverse profile for a given location or station

Proposed Specifications for Mechanical Wave Methods

Based on this project evaluation results, SASW and IE methods are capable of detecting delamination by observing spatially coherent anomalies in the data at specific depths. The SASW detection capability was implemented using multiple pairs of motion sensors (displacement transducers) with an impact source in an array distributed across the width of the pavement. The automated IE system is an array of measurement units, each consisting of one impact source and one motion sensor. The purpose of the array is to collect equally spaced parallel lines of data simultaneously so that coherent areas of delamination can be identified and mapped for the full lane width of 12 ft. Data are collected incrementally while the system is moved along the surface of the pavement. The data collection is typically triggered using a DMI mounted to the vehicle wheel or to an external distance wheel. Tables 2.3 and 2.4 show proposed specifications.

Table 2.3 Proposed System Requirements for SASW and IE

System Component	SASW Specification	IE Specification
System type	Array of impact sources and pairs of motion sensors, lined up transverse to the direction of travel	Array of impact sources and motion sensors lined up transverse to the direction of travel
Sensor frequency response	Up to 50,000 Hz	Up to 50,000 Hz
Impact source input frequency	Up to 50,000 Hz	Up to 50,000 Hz
Lateral spacing between sensors	2 ft between center of motion sensor pairs (maximum)	2 ft between motion sensors (maximum)
Lateral coverage per pass	6 ft (half lane width)	12 ft (full lane width)
Longitudinal data collection rate	1 test per foot (minimum)	1 test per foot (minimum)
Travel speed during data collection	1 to 2 mph	1 to 2 mph
Travel speed during mobilization	Posted speed limit	Posted speed limit
Real-time display	Single sensor pair waveforms in time domain at reduced display rate	Waveform and resonant frequency at each sensor
System monitoring and control	Within or outside the survey vehicle	Within or outside the survey vehicle
Data collection rate	Based on speed and sensor spacing on the sensor array	Based on speed and sensor spacing on the sensor array
Spatial reference	Vehicle DMI, external distance wheel, or GPS	Vehicle DMI, external distance wheel, or GPS

Table 2.4 Proposed Data Output and Display Requirements for SASW and IE

	SASW	IE
Data Output Requirements	• Output format should be a volume of data with surface wave velocity as a function of *x* (longitudinal distance), *y* (transverse offset), and *z* (depth)	• Output format should be a two-dimensional array of data with thickness as a function of *x* (longitudinal distance) and *y* (transverse offset)
Data Display Requirements	• Direct time domain waveforms from each of the two receivers • Dispersion curve for each sensor pair • Waterfall plot of dispersion curves collected versus distance covered for each sensor pair	• Direct time domain waveforms from each source-receiver pair • Running amplitude/thickness plot, or equivalent B-scan, for each sensor pair

Survey of Vendors

The proposed NDT system specifications along with questionnaires were sent to GPR vendors and mechanical wave equipment manufacturers. Four GPR vendors and two mechanical wave equipment manufacturers responded. The research team then had a conference call with each vendor to discuss the specification and survey. The questions used in the survey are listed below. The same set of questions were used for both NDT technologies but referred to the applicable NDT technology specification described in the previous section of this report. The vendor responses are summarized in Appendix A.

Question 1	Do you currently supply equipment that can be configured to meet the proposed requirements?
Question 1a	If yes, please describe the components that you would use, and how they would be configured to meet these requirements.
Question 1b	What type of carrying/mounting assembly would you use to meet the target testing speed?
Question 1c	Also, if yes, can you exceed the proposed requirements, and to what degree?
Question 1d	If not, do you have plans to offer equipment that would meet these requirements? When would this equipment become available?
Question 1e	If no, what changes in the requirements would need to be made in order for your equipment to comply?
Question 2	What would be the approximate cost range for the system that you would propose in answer to question 1?
Question 3	Are there modifications to the proposed requirements that you would recommend based on your perception of the overall objectives of this system?
Question 4	Based on your experience, who are the probable buyers for this equipment?
Question 5	Based on your experience, how frequently do you anticipate this system would need to be upgraded, and what would be the cost implications?
Question 6	What are the features of your process that supports data transfer and analysis?
Question 7	What are the features of your analysis software that supports our pavement evaluation objectives?
Question 8	How do you analyze the data and report delamination conditions?
Question 9	What is the level of expertise needed to operate the equipment and analyze the data?
Question 10	What do you consider to be the unique strength of your system in meeting the proposed objectives?
Question 11	Similarly, what do you consider to be potential limitations of your system?
Question 12	What are the weather and pavement condition limitations for your equipment?
Question 13 (GPR only)	Has the equipment that you propose been approved by the Federal Communications Commission (FCC)? If not, is the equipment going through the approval process, and if so, what is the status of this process? Are there any regulatory restrictions to the use of your equipment, and, if so, what are they?

Identify Target Users

Determining the target audience for the guidelines is an important step that precedes preparation of the document. The target audience must have a need for the equipment, funding to purchase the equipment, and a level of technical expertise to operate and analyze the data. An obvious target audience would be the pavement design engineers of state highway agencies. State highway agencies are responsible for most of the moderate- to high-volume routes and are most likely to have resources to purchase NDT equipment. The second likely group is the pavement management engineers responsible for measuring and monitoring the condition of the pavements. The third group would be the consulting engineering firms that provide pavement assessment and design services. Each of the three groups has individuals who operate and maintain testing equipment and individuals who process and analyze pavement data.

Vendor Survey Question 4 asked the vendors about anticipated target users who might purchase the equipment. Their responses confirmed the previous target list. The vendors also identified factors that would influence potential users. Two additional factors are the ability to use the equipment for multiple purposes (such as pavements and bridge decks) and resistance to purchase a device that requires a “black box” to collect and analyze the data.

Guideline Format

The format for the guidelines is based on the research team’s experience from Phases 1 and 2, the information collected from the vendor survey, and knowledge of the target users. The document is intended to be a concise user guide, not a detailed user operation manual. As a tool to foster NDT implementation, the guideline needs to follow a logical sequence of topics. For example, a discussion of the data analysis should follow the discussion of data collection.

The research team elected to prepare separate guidelines for GPR and the mechanical wave technologies. While the general purpose of the equipment is the same (detect delamination in asphalt pavements), the features and operation of each device are unique. The format needs to conform to the scope and objectives of SHRP 2 R06D while recognizing there are multiple vendors. To accomplish this, the format for the body of the guidelines is generic and an additional appendix is included for each vendor to highlight their equipment’s capabilities. The user guidelines for GPR are found in Appendix B1. The user guidelines for SASW/IE are found in Appendix C1.

Both the GPR and mechanical wave guidelines use the following format.

1. General Theory
2. Equipment Specifications
3. Proposed Data Output and Display Requirements
4. Equipment Calibration and Verification
5. Pavement and Climate Conditions for Testing
6. Testing Modes and Required Settings
7. Test Output Data Formats

8. Test Output Data Quality Control Check
9. Data Analysis
10. Test Reporting

CHAPTER 3
Pilot Workshops

The original scope of this Phase 3 implementation effort included a focus on a pilot workshop effort by FHWA. Later, the scope was expanded to have the research team coordinate with FHWA and key NDT vendors (3d-Radar and Olson Engineering) to identify interested users and pilot the NDT capabilities with those users. Each pilot workshop included a presentation of the NDT capability to the user's engineers and pilot testing with the equipment, when the equipment was available, on a field site selected by the user. The following bullets highlight the results of each pilot workshop.

- *FHWA Measures NCAT Pavement Test Track SHRP 2 R06D Research Sections*
  On June 21, 2012, FHWA Turner Fairbanks Highway Research Center travelled to the NCAT Pavement Test Track facility to measure the SHRP 2 delamination test sections with their GPR and MIRA equipment. Results of their measurements and analysis have not been shared with the SHRP 2 research team.
- *NCAT Regional Pilot for Southeast Highway Agencies*
  On December 3, 2012, the research team, with cooperation of 3d-Radar and Olson Engineering, hosted a pilot workshop at the NCAT Pavement Test Track. Ten agencies in the southeast region were invited to attend the half-day program. Twelve representatives from four agencies were able to attend (one representative from the FHWA Resource Center in Atlanta, one representative from the Georgia Department of Transportation [DOT], two representatives from the Florida DOT, and eight representatives from the Alabama DOT). The program included presentations by Dr. Heitzman and Mr. Olson on SASW and IE technologies and presentations by Dr. Maser and Mr. Stevens on GPR technology. After lunch, 3d-Radar and Olson Engineering operated their NDT equipment on the NCAT Pavement Test Track for the participants to observe NDT measurements of test track sections.
- *TRB Vendor and User Contacts*
  During the TRB annual meeting, the research team, Olson Engineering and 3d-Radar, used the opportunity provided by the vendor exhibit hall to solicit additional interest for pilot workshops. A specific conversation was held with Minnesota DOT recognizing the diverse pavement research sections available at the MnROAD Research Facility. Potential dates in April were considered.
- *Minnesota Regional Pilot for North Central Highway Agencies*
  On April 19, 2013, the research team, with cooperation of the Minnesota Department of Transportation, 3d-Radar, and Olson Engineering, hosted a pilot workshop at the MnROAD Research Facility. Five agencies in the north-central region were invited to attend the half-day program. Nine representatives from two agencies were able to attend (one representative from FHWA and eight representatives from the Minnesota DOT).

Poor weather conditions restricted representatives from other DOTs from attending. The program included presentations by Dr. Heitzman and Mr. Olson on SASW and IE technologies and presentations by Dr. Maser and Mr. Stevens on GPR technology. After lunch, 3d-Radar and Olson Engineering operated their NDT equipment on MnROAD Test Sections for the participants to observe NDT measurements of research sections.

- *Indiana Regional Pilot for North Central Highway Agencies*
  Indiana expressed an interest in hosting a pilot but was unable to establish an acceptable date.
- *Connecticut DOT Regional Pilot for North East Highway Agencies*
  Connecticut expressed an interest in hosting a pilot in the northeast region, but was unable to establish an acceptable date.

Workshop Discussion

The participants at the workshop expressed a number of key questions and comments. A summary of those discussions is given below.

Question: Why were these technologies recommended?
Response: Numerous NDT technologies were examined in Phase 1 and 2 of the SHRP2 study. The study reviewed literature on each technology, performed theoretical modeling, and tested each technology against known delamination built into test sections on the NCAT Pavement Test Track. GPR and SASW/IE were the only technologies that demonstrated reasonable potential to meet the SHRP2 study objectives.

Question: The SHRP2 study is recommending both devices. Why are both devices needed?
Response: These NDT technologies use different methods for measuring changes in the pavement. They each have strengths and weaknesses. GPR can assess a large area of pavement very quickly, but the measurement is sensitive to distress severity and the presence of moisture. SASW/IE is not as rapid as GPR and is sensitive to the temperature of the pavement.

Question: What are the differences between the vendors for this equipment?
Response: Each vendor manufactures a uniquely different device. The NDT technology applied is similar, but the features of each device are different. For GPR, three major differences are (1) air-coupled versus ground-coupled antenna configurations, (2) antenna signal frequency, and (3) single antenna units versus units with an array of antennas. For SASW/IE the primary difference is manual point-to-point testing versus automated testing.

Question: How many tests can each device perform?
Response: The density (spatial distribution) of tests is dependent on a number of factors. For GPR, the frequency of testing is an input for the device and influences the speed of testing. If individual antennas are used, then the density of tests is also controlled by the number of passes

made by the device. When an antenna array is used, the density of tests (rows of data) will likely be much larger. For SASW/IE, the density of testing is established by the test grid for manual point-by-point measurements. For the automated SASW/IE device, the density of testing is controlled by the automated frequency in the longitudinal direction and the spacing between the units in the transverse direction.

Question: Is either NDT technology cost-effective to own and operate?
Response: Both technologies can be a valuable tool for pavement forensic evaluations. The cost-effectiveness of each technology depends on the amount of use and the ability to expand the use these NDT technologies for other applications. For example, GPR can be used for numerous types of subsurface evaluations involving soils and drainage. SASW/IE is also used for bridge deck delamination evaluations.

Question: How complicated is the data analysis?
Response: Both technologies require an understanding of the measurement principles associated with the NDT theory so that the testing is done under appropriate conditions to obtain good data. The analysis will require both manual manipulation of the data and analysis software that screens the data for signal changes. Analyses software will continue to evolve as user demand grows.

CHAPTER 4
Summary and Conclusions

Phase 3 of this SHRP 2 study prepared user guidelines for using GPR and SASW/IE NDT technologies to detect delamination in asphalt pavements. The research team solicited input from NDT equipment vendors so the guidelines would accurately reflect the capability of each technology. The target users are highway agency pavement design and pavement management engineers and consultants who provide the same services. The research team prepared separate guidelines for GPR and SASW/IE. Each guideline is a concise overview of the NDT technology that includes general theory on the NDT principles, equipment specifications, output and display requirements, equipment calibration, testing conditions and settings, output data analysis, and reporting formats. The guidelines are not intended to be technician equipment operation or engineer data analysis training documents.

There are five appendices to this report. Appendix A1 and Appendix A2 are a summary of the NDT vendor input for the guidelines. Appendix B1 is the GPR user guidelines. Appendix B2 contains a technical brief from each GPR vendor. Appendix C1 is the SASW/IE user guidelines. Appendix C2 contains a technical brief from each SASW/IE vendor. The vendor technical briefs were solicited from all known vendors, but not all vendors chose to submit a document.

Both types of NDT technologies have functioning hardware and data collection systems. Data analysis is the challenging aspect of the technology, and software to support the analysis is advancing. Skilled technicians and engineers are needed to operate the equipment and analyze the data to identify pavement condition.

The cost-effectiveness of each NDT device is dependent on the level of intended use and the diversity of applications it is applied to. Specific for this SHRP 2 study, both devices are suitable for pavement forensic studies and field investigations for pavement rehabilitation projects. GPR can be used for network-level pavement assessment, but to manage the volume of data and analysis will require further software development. Both devices can be used for field measurements to assess other roadway features, like bridge decks and culverts.

The research team and key vendors held workshops in Alabama and Minnesota. In addition to the host state highway agency, neighboring agencies were invited to attend. A total of seven states participated in the workshops and gained a better understanding of the potential of GPR and SASW/IE technologies for asphalt pavement condition assessment.

The execution of this study established and confirmed that NDT technologies have the ability to be important tools in the assessment of pavement condition and identification of pavement distress. The companies developing the equipment and software will continue to improve the capability of their systems if there is a reasonable potential for a profitable market. Improvements in the technologies will progress as demand for the technology expands.

Reference

1. Heitzman, M., K. Maser, N. Tran, R. Brown, H. Bell, S. Holland, H. Ceylin, K. Belli, and D. Hiltunen. *Nondestructive Testing to Identify Delamination Between HMA Layers, Volume 1*. SHRP 2 Report S2-R06D-RR-1, 2013, p. 58.

Abbreviations, Acronyms, Initialisms, and Symbols

AC	asphalt concrete
AI	GPR Activity Index
CMP	common midpoint
DMI	distance measuring instrument
DOT	Department of Transportation
FCC	Federal Communications Commission
FHWA	Federal Highway Administration
GPR	ground-penetrating radar
GPS	global positioning system
GSSI	Geophysical Survey Systems, Inc.
HMA	hot mix asphalt
IE	impact echo
NCAT	National Center for Asphalt Technology
NDT	nondestructive testing
PSPA	portable seismic pavement analyzer
SASW	spectral analysis of surface waves
2-D	two-dimensional
3-D	three-dimensional

Appendix A1
GPR Vendor Survey Responses

Feedback from Vendor Survey for GPR

Question 1	*Do you currently supply equipment that can be configured to meet the proposed requirements?*
3d-Radar	Yes
GSSI	Yes
MALA	Yes
IDS	Yes
Question 1a	*If yes, please describe the components that you would use, and how they would be configured to meet these requirements.*
3d-Radar	GeoScope Mark 4 data acquisition and radar unit; Model VX3341 antenna (3.3 m wide antenna array with 41 channels, 7.5 cm spacing). Older system (3231) had 10 cm spacing. Power source, DMI, GPS, cables, software. Data is now stored on the laptop. Minimum laptop requirements include adequate disc space with solid state drive or 7800 rpm hard disc, and minimum I-5 processor with adequate memory. Power requirement - 12V power source. Can run off of vehicle power. Recommend 12V deep cycle marine battery (70 amp hour, good for one day).
GSSI	GSSI would use two synchronized SIR-30 data acquisition and control units. Each unit would run 4 antennas, so the total would be 8 antennas. Then 8 antennas, when spaced 1.5 feet apart, would cover the full 12 foot lane width. The two units would be controlled by the operator using a single touch screen monitor and an optional keyboard and mouse. Data acquisition would be controlled using a DMI, and GPS data would be directly acquired and merged with the GPR data using a standard GPS receiver. There are two antenna options: (a) 2-Ghz horn antennas (typically 20" × 20" × 8" wide); and (b) 2.6 GHz ground coupled antennas (typically 7" × 4" × 2" high). The horn would permit unlimited driving speeds to meet the stated data collection requirements. The ground coupled is less expensive, but is limited to approx. 20 mph.

Feedback from Vendor Survey for GPR

MALA	MALA has 2.3 GHz antenna, and can run 6 antennas at a time with ProEx system using multichannel expansion. Each expansion module runs 2 antennas. MALA also has a 16 antenna array of 1.3 GHz antennas, called MIRA. The swath width of the array is 1.5 m. It is a true array, in that it can transmit from one antenna and receive by others. Example: can go from T1 to R8 (1 meter apart). Firing sequence, T1 to R1-R4. set up pairs. Number of pairs? MIRA can go 12 MPH. Can run multiple, operate independently. Run with total station for high precision.
IDS	IDS has a multichannel control unit, powers up to 8 antennas. Up to four Control units can be connected together in order to power up 32 antennas. Can connect 8 horn antennas to a single control unit. 1st antenna connected to the control unit. Other antennas connected to each. (chain connection). HI-PAVE - 1GHz and 2 GHz antennas, Multichannel control unit, customizable. Can use multiple controllers to increase speed.
Question – 1b	*What type of carrying/mounting assembly would you use to meet the target testing speed?*
3d-Radar	Use a portable car charger to raise/lower the system. Could use a hand winch. Need at least 2 people to set up on vehicle. Would be nice to fold antenna. Will consider.
GSSI	The deployment would depend on the antenna type. For the horn antenna array, each horn antenna would be cantilevered from a mounting structure. One option is to have all 8 antennas mounted behind the rear of the vehicle. Another is to have 4 in front and 4 in the rear, offset appropriately. The primary challenge is safely deploying the antennas that are outboard of the vehicle footprint. This would clearly need some design work. The ground coupled antennas are smaller and might be easier to deploy. They would ride on a replaceable skid plate which would drag on the ground.
MALA	MIRA Array has a cart. Cart can be mounted to a vehicle. There is also a road cart for 2.3 GHz. MALA has also put together a 6 antenna road cart as a special order for a client.
IDS	Nothing off the shelf for 8 antennas. Need to evaluate effect of proximity. Currently have setup for 4 antennas.

Feedback from Vendor Survey for GPR

Question 1c	*Also, if yes, can you exceed the proposed requirements, and to what degree?*
3d-Radar	Design goal is true highway speed. Mark 4 has 2 receiver boards. Transmit from one and receive from 2 at the same time. This will be included in the next release of firmware. With this upgrade, Task 7 5 mph test could now be at 15 mph. New antennas have GPS chip which will allow GPS data to be embedded with the GPR data.
GSSI	The system proposed as Option (a) in Question 1a, with horn antennas, can generate 10 scans/foot travelling at 50 mph. The system with the ground coupled antennas, while limited to 20 mph, can also generate 10 scans per foot at that speed.
MALA	With 2.3 GHz, can do 55 mph at 2 scans/foot, or 4 scans/foot at 35 mph.
IDS	Data collection rate - 8 antennas - 32 kmh with 10 cm data spacing, 30 cm spacing at 100 kmh. With 2 control units double the spacing. Can use up to 4 control units. 100 kph 7.5 cm is the maximum rate using 4 control units.
Question 1d	*If not, do you have plans to offer equipment that would meet these requirements? When would this equipment become available?*
3d-Radar	Question does not apply.
GSSI	Question does not apply.
MALA	Researching higher frequency and speed, details unspecified.
IDS	Question does not apply.
Question 1e	*If no, what changes in the requirements would need to be made in order for your equipment to comply?*
3d-Radar	Question does not apply.
GSSI	Question does not apply.
MALA	Lower the frequency to 1.3 GHz. Or, use 2.3 with 2 foot lateral spacing.
IDS	Question does not apply.
Question 2	*What would be the approximate cost range for the system that you would propose in answer to question 1?*
3d-Radar	Estimated costs: Geoscope: $155,000 3 meter Antenna: $100,000 3-DR Examiner: $14,200 3-years support: $5400 Total: ~$270,000 1.8 meter Antenna alternative - requires 2 passes - $43,000

Feedback from Vendor Survey for GPR

GSSI	Including all mounting hardware, estimated cost is $200K for the horn system and $150K for the ground-coupled system.
MALA	Pro-EX $125K max; MIRA has never been sold - strictly a research system.
IDS	Rough estimate of horn, 8 antennas plus control unit. $150K
Question 3	*Are there modifications to the proposed requirements that you would recommend based on your perception of the overall objectives of this system?*
3d-Radar	Agree with requirements
GSSI	With the horn antenna system, you can increase the speed requirement to 40–50 mph. This would make the system more suitable for highway work and would eliminate the need for a rolling closure.
MALA	None
IDS	IDS would suggest considering the alternative Hi BrigHT system with 16 antennas at 2 GHz, ground coupled, spacing 3 to 4 inches between antennas obtain delamination results. Speed 6 to 7 km/h.
Question 4	*Based on your experience, who are the probable buyers for this equipment?*
3d-Radar	DOT's, larger consultants for network-level survey and for multiple uses.
GSSI	Most likely large companies providing pavement evaluation services.
MALA	For MIRA it would have to be DOT. For pro-ex it could be DOT's or consultants who work for DOT's.
IDS	Engineering companies involved in asphalt pavement evaluation. Road authority, but often don't have expertise.
Question 5	*Based on your experience, how frequently do you anticipate this system would need to be upgraded, and what would be the cost implications?*
3d-Radar	Depends on routine SW upgrade, bug fixes. New SW release every 6 months. Also depends on how frequently customer wants to upgrade. Also firmware support - biannual basis. New models and enhancements.
GSSI	Hardware should not require upgrade. Software is typically upgraded once a year, and these updates are provided free of charge to equipment owners. Equipment has a two-year warrantee. Extended warrantees are available for a fee.
MALA	Hardware - 5 years; Software - 3 years; SW negligible cost. Mounting might need repair.
IDS	Multichannel arrangement since 2004, and don't plan to change hardware. Would expect a software upgrade every 2 years. SW upgrades are free for customers. Extended warrantee and support. Typically 7%. of purchase price.

Feedback from Vendor Survey for GPR

Question 6	*What are the features of your process that supports data transfer and analysis?*
3d-Radar	System uses a fast solid state hard drive. Viewing the data with Examiner for processing can be time consuming due to IFFT and background removal. Data volumes can exported. Examiner has an open door. Anyone can create an algorithm as a task using C++. Examiner provides a software development kit to facilitate this process.
GSSI	Data is recorded directly to a solid state hard drive built into the system. Pure raw data is recorded, and settings (filters, gains) are recorded separately. The advantage is that if there are operator errors in field settings, the proper data can be recovered during processing. Also, programs for real time data analysis can be built into the system. Data can be downloaded after the survey using a standard ethernet connection or a conventional USB external drive. User can mark various features in the data (during collection and during processing) using programmable function keys (F1–F10).
MALA	Laptop runs system. Data transfer is Ethernet standard.
IDS	Data goes directly to laptop. All data is raw (unfiltered). Acquisition parameters saved. 16 bits per sample.
Question 7	*What are the features of your analysis software that supports our pavement evaluation objectives?*
3d-Radar	Prototype delamination detection software has been developed, and needs some further testing. Software worked on the test track, but needs more correlation with ground truth in other situations. Examiner has 3D layer tracking. Can output the time, point by point, and thickness. It also has an algorithm for calculating the dielectric constant for each layer. This can be done by setting up the Geoscope for periodic common midpoint (CMP) array measurements. These measurements produce a second data cube, which is analyzed by Examiner to get a map of dielectric. Accuracy of this process degrades with depth.
GSSI	RADAN Software can do time-depth slices of the data. These slices can be converted to bitmaps with GPS coordinates so that they can be displayed on Google earth. Slices must be done on the entire data file - not easy to break it down into smaller length units.
MALA	No analysis tools. 3D imaging. 3D migration. 6 antennas gives 6 data files, individual profiles.

Feedback from Vendor Survey for GPR

IDS	RIS Hi-Pave layer tracking, filtering, can represent cores, like RADAN. Can also represent video data and GPS. The Post processing platform can work with 8 horn antennas but currently is mainly dedicated to bridge deck evaluation. Can be optimized for road evaluation. IDS requires non-disclosure agreement to allow outside groups access to their data. Is possible to post process IDS data with other proprietary software.
Question 8	*How do you analyze the data and report delamination conditions?*
3d-Radar	Prototype software - marks areas where it thinks there is delamination An export function could be included. Also, algorithm can do some distinguishing levels. Maybe/probably/definitely
GSSI	RADAN provides Time-depth slices and automatic layer picking for detecting asphalt layering. The layer picking information is saved as text files which can be reported in spreadsheets or plots.
MALA	MALA has no special software for this function.
IDS	Currently only done with bridge decks. Would have to develop adaptation for horn antennas. Maps and depth slices, contour plots.
Question 9	*What is the level of expertise needed to operate the equipment and analyze the data?*
3d-Radar	Operate equipment - not much expertise. Field technician – 2 to 3 weeks training. Need automatic tools for self-diagnostic. Analyzing data - need more expertise.
GSSI	Field work requires a field technician who can do repetitive work but has enough knowledge to handle potential problems and troubleshooting. Analysis requires more training and experience.
MALA	Field Technician for data collection.
IDS	Data acquisition is relatively easy. Post processing need experience, but don't need to be engineer or geophysical expert for pavement thickness. Delamination detection is semi-automatic in our post processing platform we need to evaluate if the algorithm have to be changed using horn instead of ground coupled antenna.
Question 10	*What do you consider to be the unique strength of your system in meeting the proposed objectives?*
3d-Radar	Full coverage, high speed, high bandwidth.
GSSI	Data collection speed, system flexibility, ease of use, software widely used, company experience with pavement applications, large installed customer base, and customer support.

Feedback from Vendor Survey for GPR

MALA	MIRA Array - true multipath array. ProEx has speed capability. Each antenna can have separate settings.
IDS	Modularity, speed, number of antennas. Good quality data.
Question 11	*Similarly, what do you consider to be potential limitations of your system?*
3d-Radar	Ground bounce issues revealed in Task 7 data; price
GSSI	None discussed
MALA	Ground-coupled, collision with objects.
IDS	Will need customization for putting together 8 horn antennas. Post processing software needs new parameter for delamination analysis.
Question 12	*What are the weather and pavement condition limitations for your equipment?*
3d-Radar	Severely damaged pavement making antenna bounce - bit of rain okay. Water on pavement okay. Get false positive from wet pavement due to local scattering. Water spray not a problem due to the shielded shape.
GSSI	Rain
MALA	Rain is a limitation, since the components are not weather proof. Heavy road salt presence could be a problem. Array is encased.
IDS	Same limitation of others, not during rain or snow.
Question 13	*Has the equipment that you propose been approved by the FCC? If not, is the equipment going through the approval process, and if so, what is the status of this process? Are there any regulatory restrictions to the use of your equipment, and, if so, what are they?*
3d-Radar	3d-Radar has a waiver for a step frequency system that has the characteristics of the system that they are selling. They want to make a change to the waiver - it currently prescribes a fixed frequency step size. They would like to make it a minimum step size. Equipment configuration will be tested for FCC approval over the next 2 months. Right now, 3d-Radar has a 1-year permission to operate the equipment for marketing purposes.
GSSI	All equipment has been FCC approved except for the "smart" version of the 2.6 GHz ground-coupled antenna. (52600S). With this version, the SIR-30 automatically detects the antenna type and optimizes the allowable system speed for that antenna. Since the "non-smart" version of this antenna is FCC approved, approval of this new version is considered routine.
MALA	Pro-Ex is FCC approved. MIRA is not, and MALA is not pursuing FCC approval for this system.
IDS	Currently IDS 2 GHz horn is FCC certified, along with control unit.

APPENDIX A2

SASW/IE Vendor Survey Responses

Feedback from Vendor Survey for Mechanical Wave Methods

Question 1	*Do you currently supply equipment that can be configured to meet the proposed requirements described in the GPR specifications?*
Olson	YES
Geomedia	NO – The current single-point portable pavement seismic analyzer (PSPA) system cannot meet the testing collection rate. However, the company is working on three projects to develop similar systems for concrete, including automated software (Air Force), light-weight equipment (tunnels), and a transverse measurement array for robotic testing (Rutgers), that would achieve incremental steps toward an NDT system that may meet the proposed requirements for asphalt pavement delamination. These projects are in early development stages and are not ready for public sale.
Question 1a	*If yes, please describe the components that you would use, and how they would be configured to meet these requirements.*
Olson	Olson Engineering is receptive to selling the system and could have a commercial model available by 2013. The system consists of: • Array of three sensor wheel pairs. Each wheel is capable of independent IE measurement. Each pair measures SASW. Spacing between the impact source and motion sensors is fixed for pavement delamination, but the spacing between the motion sensors could be adjustable for other NDT applications. • Control module. Handles the test sequencing between multiple wheel pairs. • Mounting hardware. The hardware is full lane width (approximately 10 ft) and allows for any transverse spacing of the wheel pairs. • Data acquisition system. The Freedom Data PC is standard commercially available Olson equipment for numerous Olson Instruments NDT systems. • Data analysis software. The software is still at an applied research stage of development but has been advanced since the AL, FL, and KS HMAC field tests.

Feedback from Vendor Survey for Mechanical Wave Methods

Geomedia	The equipment that is currently under development is an array of eight impact sources and fourteen motion sensors split onto two 3-ft beams with the capacity to measure IE every six inches transverse across the six-foot array. The sensors have a capacity of 42 kHz. The source has a range of 17 to 30 kHz to cover a range of pavement temperatures. The 6-ft transverse array can collect the eight sets of data in two seconds. The array can be folded for easy transport to pavement sections. All data collection and analysis are continuous and achieved on a single laptop computer. Other parties are building the testing vehicle with the DMI to carry and position the measurement array. The software developed for PSPA has all the needed analysis and mapping functions and will be upgraded to display all eight (four?) signal traces from the array.
Question 1b	*What type of carrying/mounting assembly would you use to meet the target testing speed?*
Olson	The mounting hardware is fixed to the vehicle and can accommodate any transverse location of the sensors. The target testing speed is controlled by the sensors mounted on the wheels.
Geomedia	The test vehicle is under development by others (Rutgers) for bridge deck applications. Conceptually, a rolling system could be developed at a later time to improve testing speed.
Question 1c	*Also, if yes, can you exceed the proposed requirements, and to what degree?*
Olson	The wheel pairs can test every six inches in the direction of travel. An equipment configuration with six independent wheels can provide full lane-width testing at 2-foot spacing for IE measurements. An equipment configuration with six wheel-pairs could be provided for single pass, full lane-width testing at 2-foot spacing between adjacent wheel pairs for SASW.
Geomedia	The system under development will exceed the proposed lateral spacing for testing. The IE layout is a six-inch lateral spacing and the SASW layout is nine inches. Once the software is ready, the flexural analysis will exceed the capability of the SASW and IE.
Question 1d	*If not, do you have plans to offer equipment that would meet these requirements? When would this equipment become available?*
Olson	Question does not apply.
Geomedia	The current three projects will take 12 to 18 months. Further development on HMA testing may be ready in late 2014.

Feedback from Vendor Survey for Mechanical Wave Methods

Question 1e	*If no, what changes in the requirements would need to be made in order for your equipment to comply?*
Olson	Question does not apply.
Geomedia	See response 1.
Question 2	*What would be the approximate cost range for the system that you would propose in answer to question 1?*
Olson	The commercial price for a six pair system is estimated to be in the range of $100,000 to $150,000.
Geomedia	The approximate cost of a 6-ft array with software is anticipated to be $80,000 to $90,000. The density (spacing) of the sensors ($5000 per set) will directly affect the total price.
Question 3	*Are there modifications to the proposed requirements that you would recommend based on your perception of the overall objectives of this system?*
Olson	In the long term, when technology is available, increase the array from three wheel-pairs to six wheel-pairs for full lane-width, single-pass testing. Add video logging to tie the field measurement location (series of video frames for slow speed). Include a GPS location system since the wheel-based calibrated DMI can accumulate error over long distances. Develop a unit to automate lifting/lowering the test system OR trailer assembly. Include an infrared temperature sensor (for adjusting material modulus to a target analysis temperature). Place a laser surface texture ahead of the motion sensors (to identify rough/raveled surface).
Geomedia	The proposed requirements are appropriate for SASW and IE, but a new analysis approach, based on the flexural properties of the pavement, has the potential to exceed the capability of SASW and IE to identify delamination. It is possible that the 50 kHz frequency range is too high and could be reduced to 42 kHz with a substantial savings in hardware cost and no loss of measurement quality. It should be noted that the energy source pins should be capable of multiple frequencies to account for changes in pavement stiffness as temperature changes.

Question 4	*Based on your experience, who are the probable buyers for this equipment?*
Olson	Past DOT customers for NDT testing were DOT bridge maintenance. Probable customers for the new array system included both pavement and bridge departments for project development. Sales to consulting firms depend on the quantity of units. These sales would create competition with Olson Engineering consulting service. If the market is large, consulting sales would be okay.
Geomedia	The first tier buyers will be research consultants. The second tier buyers will be highway agencies with active pavement management programs. Purchase of this technology is generally limited by the resistance to “black box” perception.
Question 5	*Based on your experience, how frequently do you anticipate this system would need to be upgraded, and what would be the cost implications?*
Olson	Purchase of a system would probably include an option for a software maintenance agreement at a cost of approximately $1000 to $2000 per year. The hardware technology is maturing and will not require major changes.
Geomedia	Software will need to be upgraded every 3 years as base-software changes ($1,000 to $2,000). Hardware will need to be upgraded every 5 to 10 years as computer hardware upgrades ($5,000?). Sensors and source technology is mature and will not require upgrading.
Question 6	*What are the features of your process that supports data transfer and analysis?*
Olson	The SASW/IE data files are not large and download to windows “on the fly.” Field data is 50 Kbyte per foot (about 25 MByte per mile). The field data is easily moved to a laptop for analysis. The field data is archived as it is downloaded to the laptop.
Geomedia	All data is transferred by USB. Ethernet is not cost-effective at this time.

Question 7	*What are the features of your analysis software that supports our pavement evaluation objectives?*
Olson	Automation of the analysis software as primarily advanced through bridge deck studies. IE data analysis is well automated. The more complex SASW data analyses needs further automation. The SASW software can automatically locate the surface wave portions of the signal. Automatic masking to locate cycle 1 is complete. Pattern recognition of the phase data will be implemented in the near future. It is planned to implement a modeling algorithm to match up with the experimental phase data to more fully automate SASW data analyses. The results of theoretical modeling will be the actual compression wave velocity profiles (depths) of the pavement.
Geomedia	The SASW software is robust and current development to automate the analysis will strengthen it. The IE software is not as strong because it has more limitations for HMA delamination detection. The developing flexural mode analysis is expected to exceed both SASW and IE and should be reported in 2013.
Question 8	*How do you analyze the data and report delamination conditions?*
Olson	In general, a significant drop of surface wave velocity (from the SASW tests) in the dispersive curve is a great indication of asphalt debonding. When asphalt is cold, the Impact Echo test can detect the delamination deeper than 4 inches. Currently the surface wave velocities are plotted on a gray scale by slice depth. The analysis software generates 2D color-scale slices at depths and tabulates the planar summary values. A plot of each depth is presented side by side so that comparison of velocities can be made and delamination can be visually located. Locations/areas of delamination are also reported in tables that can be read into spreadsheets.
Geomedia	Current focus is on PCC testing. Further development for HMA is still in concept only.

Question 9	*What is the level of expertise needed to operate the equipment and analyze the data?*
Olson	The technician and engineer need Windows-PC and digital data processing skills similar to operating GPR NDT technology. Training will be required for field testing. The engineer needs physics, geotechnical, and materials understanding for data analysis. Both the field technician and analysis engineer need to recognize “bad” data. Development of expertise should be similar to expertise development during the implementation of the falling weight deflectometer.
Geomedia	The military is training young (high school graduates) technicians to operate the equipment. The analysis is automated. More expertise is needed to review the quality of the results.
Question 10	*What do you consider to be the unique strength of your system in meeting the proposed objectives?*
Olson	The system can identify delamination reasonably well in the top 6 inches of the pavement based on the accuracy from testing at the NCAT Test Track. SASW technology has the potential to give more information, like material properties (moduli vs. wavelength/depth) and crack development.
Geomedia	The test protocol and analysis are firmly guided by a deep understanding of the theory. The tight lateral spacing of the sensors exceeds the requirements.

Question 11	*Similarly, what do you consider to be potential limitations of your system?*
Olson	There is noise at the sensor pavement contact due to rolling wheel movement and the size of the sensor contact area. Olson has recently built and successfully tested a pair of sensor wheels on an extremely rough asphalt overlaid bridge deck for the Colorado DOT and the new sensor design greatly reduced the rolling sensor contact noise. It is difficult to control the speed of the tow vehicle at slow speeds of 1 to 2 mph. Reasonably uniform testing speed is important for smoother rolling of the sensor wheels. Area of coverage is about 25% in transverse direction. A dirty road surface influences impactor and sensors contact. It may be possible to brush the surface ahead of the wheels and/or use compressed air to blow dirt away. The data acquisition system had limited speed. This limitation has been addressed with a better data controller. Currently the three wheel-pair axles are not tied together to maintain a 1-inch testing offset sequence which results in occasionally testing at a 1-ft interval instead of the 6-inch interval.
Geomedia	Energy wave propagation is a complex subject. The analysis and confidence in the results will improve with a greater density of measured data.
Question 12	*What are the weather and pavement condition limitations for your equipment?*
Olson	Temperature of the pavement is critical. High material temperature (100F) reduces the test response resolution. This is more of a problem with IE. A higher material temperature also impacts the SASW measurement because it reduces the wave velocity change at the delamination interface. More field experience on warm to very hot asphalt pavements is anticipated this summer to further understand operating temperature limits. The hardware system could be waterproofed to permit field testing in rain conditions. SASW and IE can be operated on wet pavement. Tests on a raveled pavement surface would likely need to filter out the excessive roughness.
Geomedia	PSPA can be operated in 20F to 120F and is not affected by wet conditions. The flexibility of the array frame will allow up to 1-inch vertical (rutting) difference.

APPENDIX B1
GPR User Guidelines

Use of Ground-Penetrating Radar (GPR) for Identifying Asphalt Pavement Delamination: User Guidelines

Prepared by the SHRP R06D Research Team

1 General Theory

Ground-penetrating radar (GPR) operates by transmitting short pulses of electromagnetic energy into the pavement using an antenna attached to a mobile platform or survey vehicle. These pulses are reflected back to the antenna with an arrival time and amplitude that are related to the location and nature of discontinuities in the material (air/asphalt or asphalt/concrete, reinforcing steel). The reflected energy is received in the form a series of pulses that are referred to as the radar waveform. The waveform contains a record of the properties and thickness of the layers within the pavement.

GPR measures changes in the dielectric properties of pavement layers and the velocity of wave propagation within those layers. In a study on Texas highways, Scullion and Rmeili (1997) found that GPR technology was effective for detecting stripping in HMA layers where the deterioration was at a moderate or advanced stage. Stripped HMA typically has higher moisture contents or higher air voids, or both. The dielectric constant of the material is affected by both moisture content and air voids, as is the velocity of wave propagation.

A GPR system can be implemented using one or more antennas, with four or more antennas considered a multi-antenna array. The purpose of an array is to collect equally spaced parallel lines of data simultaneously so that coherent areas of delamination can be identified and mapped. Data is collected continuously while the system is driven along the surface of the pavement. The data collection is typically triggered using a distance measuring instrument (DMI) mounted to the vehicle wheel or to an external distance wheel. The array produces three-dimensional data, $Amp(x, y, z)$, where x is longitudinal distance, y is transverse offset, z is GPR time in nanoseconds (equivalent to depth), and Amp is the amplitude of the GPR signal.

Testing conducted under SHRP 2 R06D using actual or simulated arrays has shown that debonded asphalt layers with trapped moisture and stripped asphalt layers will produce detectable reflections not normally seen with intact pavement layers. Semi-automated software to detect these reflections and map the areas of potential damage has been developed and tested under this project.

Two methods of measuring these damage-related reflections were explored. Method 1 uses variations in waveform amplitudes in the time domain, while Method 2 uses a delamination detection algorithm in the frequency domain.

Method 1: Activity Index (time domain)

A GPR indicator defined as the GPR activity index (AI) has been explored to identify the anomalies associated with wet delamination interfaces and moisture damage. This approach is based on the increased reflections from affected layers producing localized reflection anomalies within otherwise homogeneous layers. It is this additional reflection activity that the method seeks to quantify. Because these deterioration processes tend to occur non-uniformly in the pavement, a measure of the homogeneity of the electromagnetic properties was found to be useful in segmenting the roadway into features which can subsequently be used to plan more localized seismic testing and coring, as well as defining areas of deterioration. As a GPR indicator, the AI can be defined as the normalized average absolute amplitude of the GPR scan as follows in Equation 1:

$$AI_{(x,y)} = A_{(x,y)} \Big/ \overline{A}_{\left(x\pm\frac{L}{2},y\right)} \qquad (1)$$

where A is the average absolute reflection amplitude for the scan at (x, y) and L is the normalization length. When compared to the values from neighboring locations, the index shows changes in reflection activity, which, if sufficient, may be related to delamination or moisture damage.

Normalization allows for an AI that varies around 1.0 and thus permits lane-to-lane and site-to-site comparison without concern for the absolute values. For the initial site screening and segmentation, the normalization length can be selected as the entire project length. For detailed mapping of areas with potential moisture damage, a smaller normalization length may be appropriate to highlight local variability. Where scan magnitude variation occurs, the scan is scaled before AI normalization by dividing A by the amplitude of the direct coupling or end reflection of the scan.

Another key parameter in the AI computation is the depth range over which this scan amplitude is calculated. The depth range should be selected to highlight the depth in which delamination or moisture damage is believed to be occurring. If this is not known, then a larger range can be used. Once cores are obtained and other data are available, this range can be reduced and the index recalculated. The depth range is bounded in the GPR scan, with the upper boundary defined by the interface between the air and the road surface, and the lower boundary layer as the interface at the bottom of the asphalt. To avoid including the amplitude of the reflection caused by the layer boundaries, the analyzed trace section should begin below the upper boundary layer and above the lower boundary layer.

Method 2: Delamination detection algorithm (frequency domain)

A delamination detection algorithm was prototyped based on the data collected at the NCAT facility. The algorithm concept incorporates the fact that delamination can occur at a relatively wide range of depths and show a variety of amplitude characteristics in the recorded data. An energy-based study of frequency intervals was performed in areas of known delamination in the three-dimensional radar data.

As represented in Figure B1.1, the time window of interest is extracted from every trace and converted to the frequency domain. The frequency spectrum is then divided into frequency intervals, or bins. The energy contained in each bin is calculated and the bins are sorted by energy values.

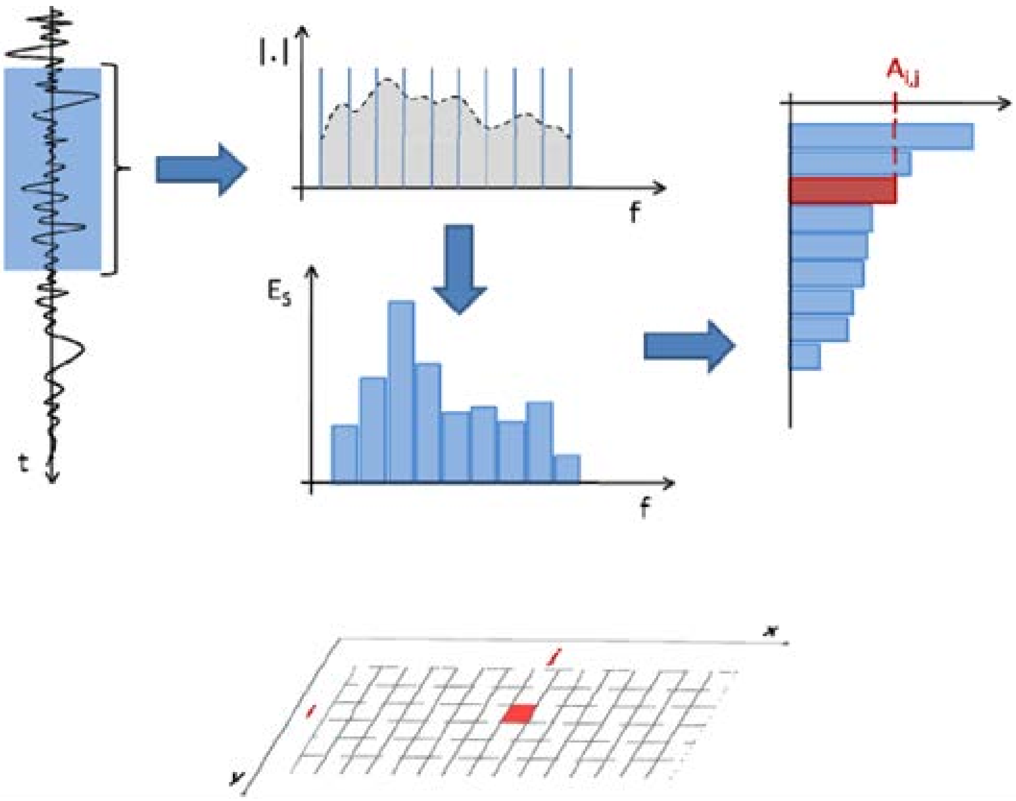


Figure B1.1. Representation of the delamination detection algorithm: operations on the trace at position *x* = j, *y* = i.

When an area is damaged, the waveform propagates in a different way through the roadway structure. This change can be used to generate a damage detection procedure. Because the analysis takes place in the frequency domain, every sample will carry information about the whole depth range to be analyzed. Sorting the energy values takes into account the varying amplitudes of signatures due to delamination. The operator chooses the bin of interest (e.g., bin 3, the red bin in Figure B1.1), the minimum size of delamination width and the cutoff threshold for the energy value that represents delamination, to produce a plot of the damaged areas (Figure B1.2). The rectangles in the picture delineate areas of delamination based on the final output of the algorithm and the statistical analysis based on parameter inputs.

Figure B1.2. Areas of delamination based on final algorithm and statistical analysis.

2 Equipment Specification

Table B1.1. GPR Equipment Specifications

Component	Specification
System type	Array of multiple antenna elements lined up transverse to the direction of travel
Frequency range: Impulse radar systems	Center frequency of pulse > 2.0 GHz –10 db limits: 0.5 to 5.0 GHz
Frequency range: Frequency sweep radar systems	Up to 3.0 GHz
Lateral spacing of antenna elements	< 1.5 feet
Lateral coverage per pass	12 feet (full lane width)
Longitudinal data collection rate	> 2 scans per foot per antenna element
Travel speed during data collection	>20 mph
Travel speed during mobilization	Posted speed limit
Real-time display	B-scan for selected antenna elements
System monitoring and control	From within the survey vehicle
Data collection rate	Data collection should be triggered on distance using a DMI
Spatial reference	Vehicle DMI and/or global positioning system (GPS)
Detection depth range	2 to12 in.

3 Proposed Data Output and Display Requirements

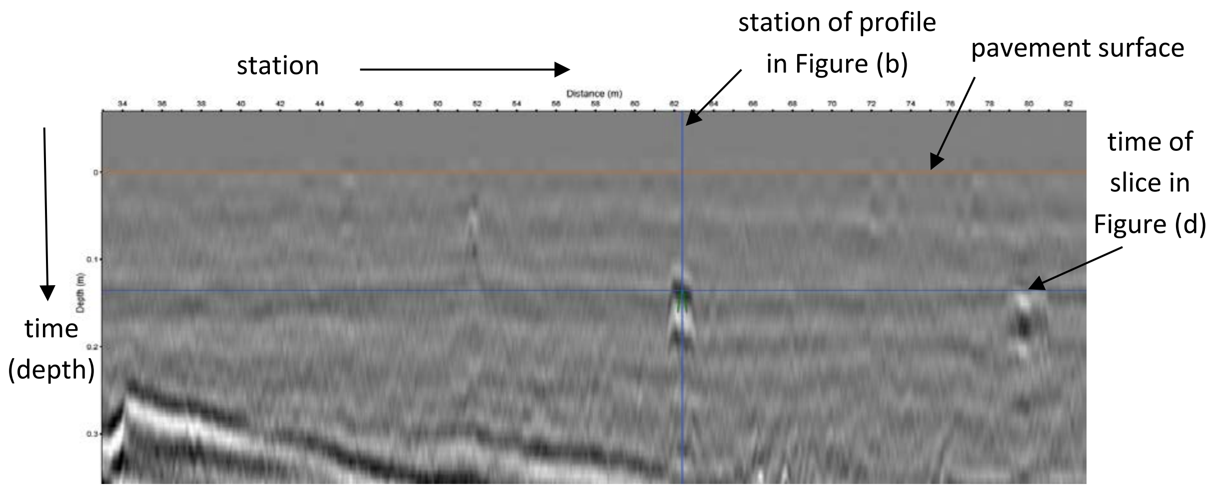
The field operation and playback software should be capable of the following displays:

- Direct time domain waveform (A-scan);
- Longitudinal profile for a given transverse offset (B-scan);
- Time/depth slice for a given time range; and
- Transverse profile for a given location or station.

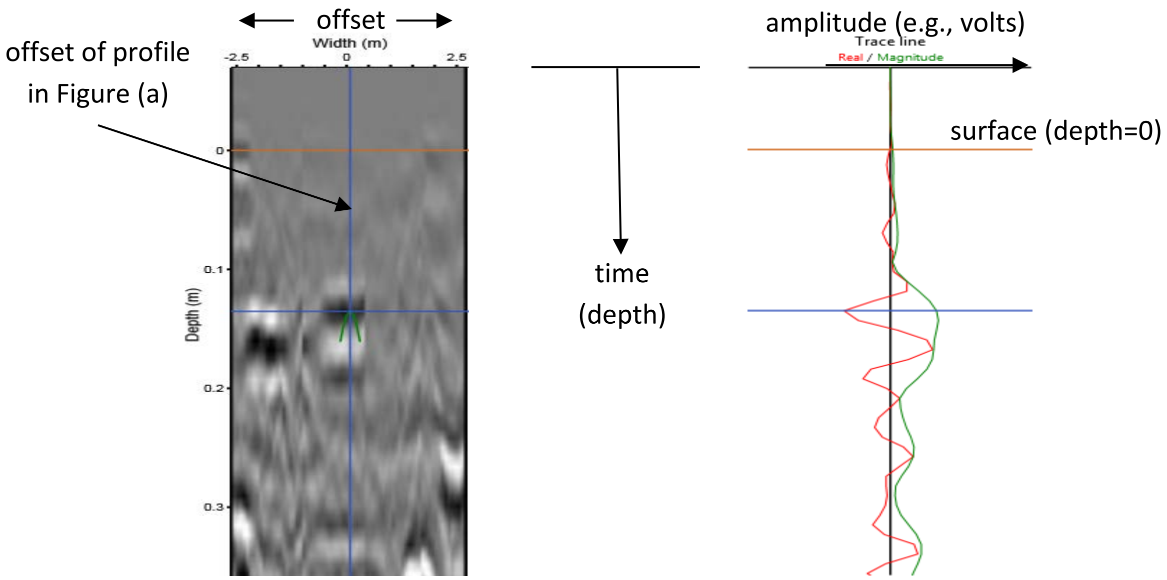
Examples of these displays are shown in Figure B1.3.

Output Format

Output should be a volume of data with amplitude as a function of *x* (longitudinal distance), *y* (transverse offset), and *z* (time).

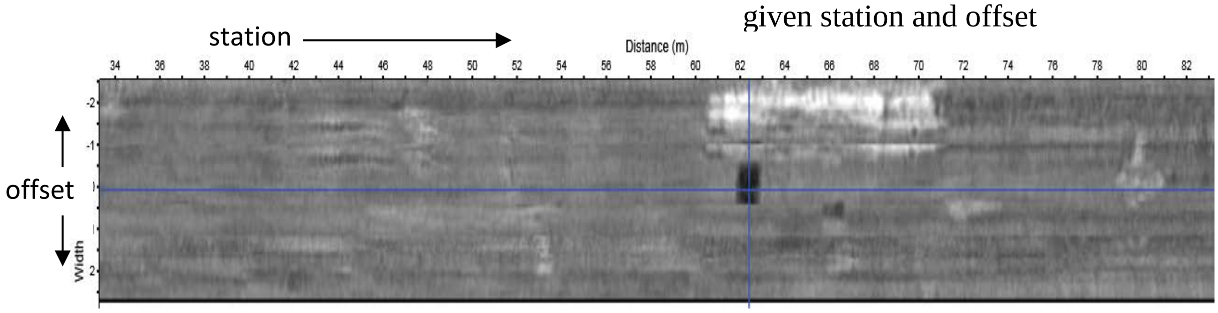


(a) longitudinal profile for a given offset ("b-scan")



(b) transverse profile for a given station

(c) time domain waveform (a-scan) for a given station and offset



(d) time/depth slice (c-scan)

Figure B1.3. Example GPR system output displays.

4 Equipment Calibration and Verification

4.1 DMI Calibration

All systems will use some sort of DMI to control the data collection rate and to record linear distance. The DMI will either be attached to the wheel of the survey vehicle, or to a separate wheel associated with the antenna array. In either case, the DMI needs to be calibrated at regular time intervals to ensure accurate distance measurement. The DMI is calibrated by running the system over a pre-measured distance (usually ranging from 1,000 feet to one mile). The measured distance expressed by the DMI is compared to the known distance, and the DMI calibration factor is adjusted so that the two will agree. It is advisable to repeat the calibration after the calibration factor has been adjusted to confirm that the calibration has been carried out correctly. The measured distance should be within a foot (0.1% accuracy) of the pre-measured distance after the repeat calibration run.

4.2 Radar System Calibration

The manufacturers of GPR systems do not provide user calibration procedures. If there are any concerns about the signal and receiver antenna system, the system should be returned to the manufacturer for evaluation.

Field verification of radar system function will depend on the type of equipment system. Horn antenna systems usually require initial base-line measurement using a metal plate “bounce” test to provide data for calculating dielectric properties and pavement thickness. Other systems, such as the 3d-Radar array and ground-coupled antenna systems, do not use a metal plate. These systems require other means for calculation of dielectric properties and thickness. Consult with the manufacturer for acceptable methods of field verification.

4.3 Verification of Radar Operation

Awareness of problems in the GPR electronic signal is something that generally improves with the experience of the operator. Some simple checks are suggested below.

One type of verification is to ensure that the signal is properly positioned; that is, the surface of the road is near the beginning of the signal (shortly beyond zero time). For a horn antenna or any other air-launch antenna, this can be quickly checked by sliding a metal plate onto the pavement under the antenna. The signal from the top of the pavement should increase to a very large value, highlighting the location of the pavement surface. For ground-coupled antennas, the same effect can be produced by lifting the antenna a few inches off of the pavement. In either case, the observed signal change should be located within 2 to 3 nanoseconds of time zero.

Sometimes, when the equipment is set up in the vicinity of strong radio transmission sources, the data display will have the appearance of malfunctioning equipment. This problem generally disappears when the equipment is driven to a location away from the radio transmission source. Degree of radio transmission sensitivity will vary with the type of antenna system.

A practical method to check the radar operation would be to have an identified pavement test section of well-documented asphalt thickness and possibly with well-defined flaws, similar to that built at NCAT under this project. Periodically, the equipment can be brought to this section for data collection, to ensure that the results of the analysis are consistent with previous analyses and known conditions.

5 Climate and Pavement Conditions for Testing

All pavement temperatures above freezing are acceptable for this type of system. Below freezing, the moisture in the pavement can freeze. Since frozen water has dielectric properties very similar to asphalt, the anomalies that are normally produced by moisture infiltration and moisture damage would not be present.

Radar measurements on wet pavement are not recommended. The water will produce anomalous reflections which might interfere with the subsurface condition detection process.

Testing in rain is not recommended since (a) the water can accumulate on the antenna elements and distort the GPR signal and (b) the wet pavement can produce a distorted signal as discussed in the previous paragraph. All other conditions are acceptable.

6 Testing Modes and Required Settings

For a given array setup, with a given number of antennas at a set spacing, the variables to consider for the testing setup include time range (in nanoseconds), the number of samples per scan, and data rate (scans per foot of travel). Other settings such as gains and filters tend to be specific to the equipment, and the operator should have experience with these settings.

The time range relates directly to the depth of detection. The specified 2- to 12-in. detection depth range translates to a time range of approximately 6 nanoseconds (ns) for the typical range of asphalt properties. For an air-launched system the time to reach the pavement surface must be added, so a minimum time for that type of system would be 10 ns. The stepped frequency systems specify a frequency range, not a time range, and the operator has less direct control over the resulting time range.

The number of samples per scan defines the resolution in time. Typically a 10- to 20-ns waveform will be digitized into 256 or 512 samples, resulting in resolutions ranging from 12.8 and 51.2 samples per ns. Higher sampling rates show more detail and may facilitate processing, but there is a point beyond which there is no benefit. Based on past experience, rates on the order of 20 samples per ns should be sufficient for this application.

The data rate determines the spatial resolution of the detected subsurface features. The more scans per foot, the more scans there will be in delaminated areas. This greater density usually increased the rate of detection. On the other hand, the speed of most systems is affected by the data rate; the more scans per foot collected, the slower the system has to go.

For project-level work, which generally demands greater detail, data can be collected with a moving closure, and therefore one should use the maximum practical data collection rate for that arrangement. Network-level applications, where the required results are usually less detailed, can get by with a reduced data rate, one which would be suitable for driving speed data collection.

6.1 Non-Array GPR Systems

While this guideline recommends an array of antennas spaced laterally across the pavement, many organizations own single or dual antenna systems which they may wish to apply for this delamination application. This is possible by collecting multiple passes of data, so that the resulting series of data lines is equivalent to that which would be generated using an array. For example, if an organization has a single antenna system, they would need to collect, for a given lane, data lines at 1.0, 2.5, 4.0, 5.5, 7.0, 8.5, 10.0, and 11.5 feet offset from the shoulder line. Some arrangement needs to be made to ensure the accuracy of these offsets, and the ability to collect data while maintaining each line parallel to the shoulder line.

The above data collection protocol would generate eight data files which can be combined to create the data volume discussed in Section 1 and in the following sections.

7 Test Output Data Formats

The goal of the GPR field data collection is to produce a three-dimensional volume (x, y, z) of reflection amplitudes, with x (distance) as the direction of vehicle travel, y (distance) the offset between antennas, and with z (time) being the arrival time of the GPR pulse reflections. x and y can be obtained from field specifications or from attached GPS coordinates. The format of this data volume will vary with each equipment manufacturer.

In some array systems, each antenna will generate a data file, and then these individual files will be combined to create the three-dimensional volume described above. In this case, each file will represent x and z for one particular value of y (the offset of the antenna). Software provided by the supplier can generally be used to combine these files into the 3-D volume. In other array systems, the 3-D volume will be generated directly during data collection.

Note that this application will generate very large data volumes. Consider, for example, a one-mile survey, with an eight-antenna array collecting two scans per foot at 512 samples per scan. This collection will result in a file size of 8 × 2 × 512 × 2 (bytes per sample) × 5,280 = 43 MB, a size that is well within the range of standard jump drives. Use of more antenna elements, more scans per foot, and more bytes per sample can produce data files on the order of 4 to 5 GB per mile. At this high end, data storage and transfer can become a problem, and accommodations need to be made to deal with this.

8 Test Output Data Quality Control Checks

It is highly desirable to check the quality of the data prior to demobilizing from the field site. Quality control can be carried out during lunch breaks or other pauses in the normal data collection process. Such checks should include

- Checking all of the recorded data files to confirm that their size is consistent with the amount of data collected;
- Correlating the field notes with the data files to ensure that all noted files actually exist;
- Scrolling through each data file to ensure that the data looks reasonable and that there are no problems with the data; and
- Checking the length of each file (recorded distance) and confirming that it agrees with the intended length.

If problems are encountered or there are data of questionable quality, the data collection should be repeated.

9 Data Analysis

Data analysis can be performed by both automated and manual methods. The goal of both methods is the same: to define areas of increased scan activity and thus delineate areas of potential deterioration.

A 3-D volume of amplitude data can be obtained by extracting the reflection amplitude values from a three-dimensional radar file or by collating the data stored in files collected by individual antennas. The surface reflection and bottom of asphalt reflections are identified in each trace. If the analysis will be by depth slices, the individual GPR traces at each *x*, *y* location need to be adjusted so that the surface is horizontal. *z* can be converted to depth by GPR dielectric calculation using GPR data, or by estimation, of the material's dielectric properties. The thickness of each pavement layer can be computed according to Equation 2:

$$h = {c \times (\Delta t)} \Big/ {2\sqrt{\varepsilon}} \tag{2}$$

where h is the layer thickness, Δt is the two-way travel time of the electromagnetic pulse wave through the layer, c is the speed of light in free space ($c = 3 \times 10^8$ m/s or 11.8 in./ns), and ε is the dielectric constant of the layer.

Three sites were analyzed for damaged areas using the AI measure of radar activity and the delamination detection algorithm discussed in Section 1. A control site, the NCAT test track, was manufactured with two lifts. The lower lift was 3 in. thick, and the upper lift was 2 in. thick. A layer of unbound asphalt (1 in. thick) was placed in small areas on the lower lift, creating areas of low density to represent moisture-damaged (stripped) asphalt. Measurements at the control site were used to develop algorithms which were applied at two field sites (Kansas and Florida).

The activity index at the test site was determined by using time slices through the C-scan at regular, overlapping intervals. At the two field sites, the scan sections for activity analysis were chosen by picking the layers of interest in the three-dimensional view and exporting the results to be used as bounding regions. At these sites, the ground surface and asphalt bottom layers were picked to constrain the time slices. The delamination detection algorithm was developed at the test site; it was then utilized at both the test site and field sites by using time slices through the C-scan at distinct intervals.

9.1 Data Analysis: Automated Tools

Method 1: activity index (time domain)

To automate analysis of the activity index, slices can be extracted from a cube of 3-D radar data. The depth and thickness of each slice needs to be defined for each location based upon the depth of pavement and area of interest.

NCAT Site

Activity was determined in 2 overall slices and in multiple overlapping slices between 2.1 and 5.5 ns from the start of the scan. These times represent locations at the air/surface interface and below the asphalt/base interface (from 0 in. to 8.5 in. from the ground surface). Figure B1.4 shows activity analysis results for depth slices at various depths below the ground surface at the NCAT test area with manufactured voids. Areas with increased reflection are shown in green (lower) to blue (higher). The *x* axis is distance in the direction of travel, the *y* axis is the offset distance, and the color shading represents the AI for the layer depth interval. These slices are roughly equivalent to the following depth intervals.

- Activity 18–26 (0 to 2.4 in.)
- Activity 21–30 (0.9 to 3.6 in.)
- Activity 25–34 (2.1 to 4.7 in.)
- Activity 29–38 (3.3 to 5.9 in.)
- Activity 33–42 (4.4 to 7.1 in.)
- Activity 38–46 (5.9 to 8.3 in.)

Note that the damaged areas were placed at 1-in. to 2-in. depths. However, when a void is encountered in damaged pavement, the signal below the damaged area will reverberate and show a ringing pattern. High activity in the 29–38 (3.3 to 5.9 in.), 33–42 (4.4 to 7.1 in.), and 38–46 (5.9 to 8.3 in.) plots shows the effect that ringing beneath the void causes in AI calculation. This reverberation can cause confusion as to the actual depth extent of the voids. The ringing pattern is also noted in Figure B1.5, in the radar image below the void located at approximately 3 ns below the ground surface.

As with the delamination detection algorithm, this method suffers in field application due to variation in pavement structure. For example, when defining slice intervals at the test track, we are able to define slices based upon knowledge of the layer depths. It is possible to slice through the boundary between layers and map the boundary activity, or to create slices which are the thickness of the material between adjacent boundaries to examine the activity in each layer. In real world conditions, layer boundaries vary in depth, and it is necessary to avoid the layer reflections in creating the slice interval. Otherwise, slicing through a dipping layer produces reflections at the boundaries which appear to be areas of increased activity.

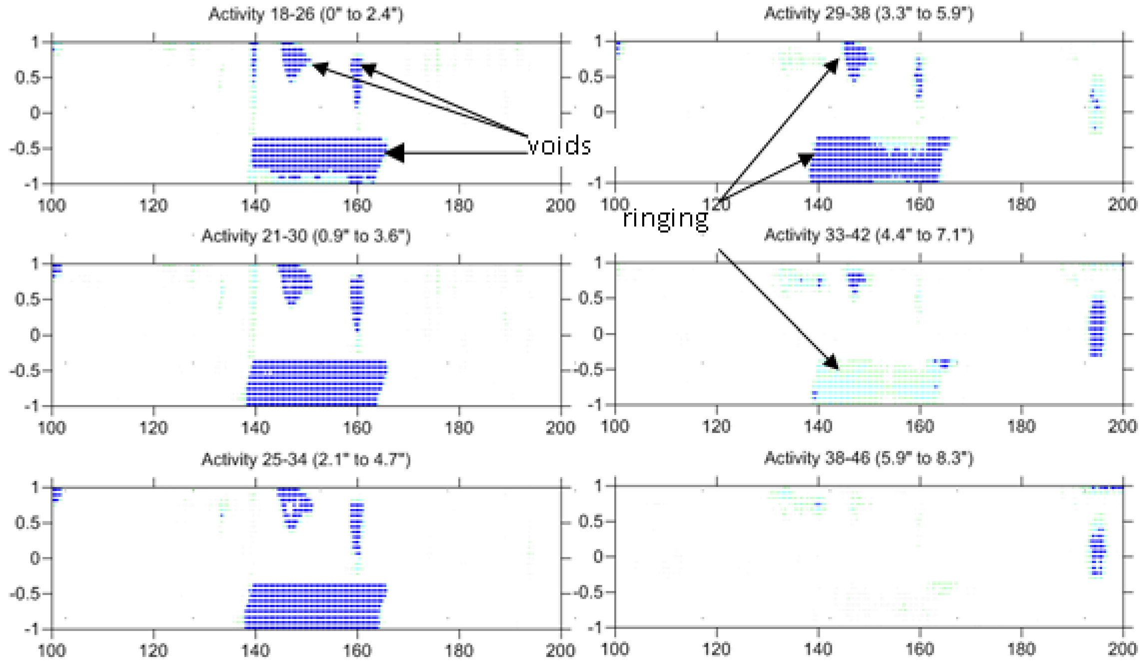
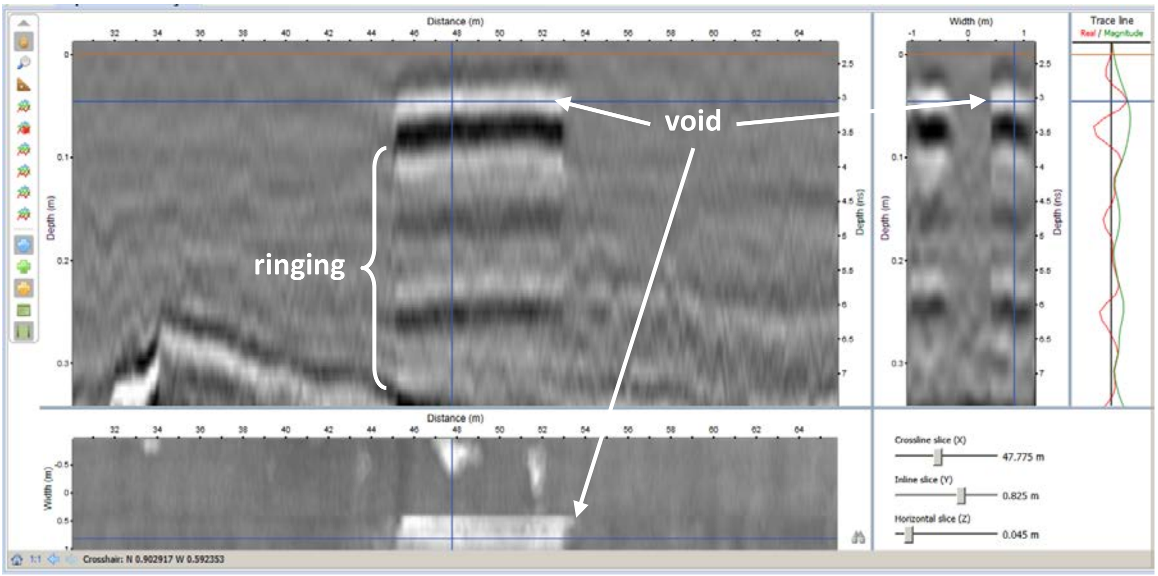


Figure B1.4. Activity index for various slices from the NCAT test track.



Crossline slice (X) 47.775 m

Inline slice (Y) 0.825 m

Horizontal slice (Z) 0.045 m

Crosshair: N 0.902917 W 0.592353

Figure B1.5. Three-dimensional radar representation of NCAT site showing "stripped" asphalt layers at 3 ns (1 to 2 in. below the ground surface).

Method 2: Delamination detection algorithm (frequency domain)

The delamination detection method provides a way to automate the delineation of damaged areas using frequency domain radar data. This method is particularly convenient for stepped frequency GPR systems, since the raw data is in the frequency domain format and conversion to time domain can be skipped. The operator chooses the bin of interest (Figure B1.1), the minimum size of delamination, and the cutoff threshold for the energy value that represents delamination. Results are a plot of the damaged areas as seen in Figure B1.2.

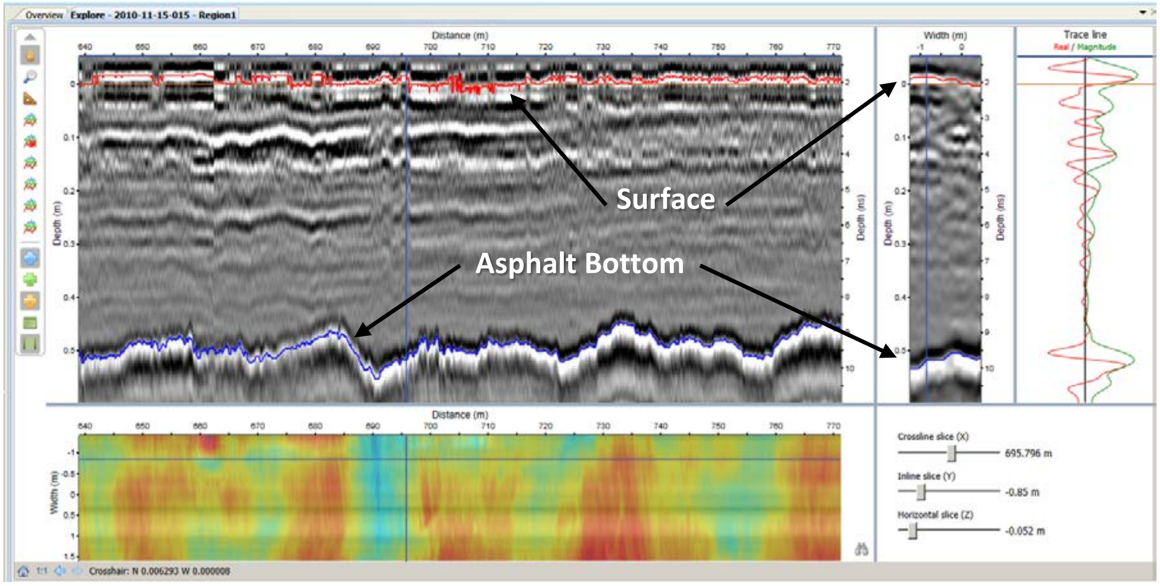
However, this method was not found to be reliable in field investigation. Differences in pavement layers and surface variation served to thwart the method. Since the algorithm was developed based on the experience at the NCAT facility, where simulated delamination provided solid and clean characteristics, further study of the data collected in real situations, combined with ground truth, is needed to refine the signature given by delaminations, both qualitatively and quantitatively. Further enhancement is necessary to factor in characteristics of the road substructure where variation in depth of targeted layers and lateral discontinuities are present.

9.2 Data Analysis: Manual (Semi-automated) Manipulation

Since actual pavement layer boundaries vary in elevation, software was developed to extract depth slices from the 3-D radar model between asphalt layer interfaces. First, each layer is picked in the 3-D radar program and exported to a text file (*x*, *y*, *z*). These text files are used to bind the region of interest. To avoid including the amplitude of the reflection caused by the layer boundaries, the analyzed trace section began 0.5 ns below the upper layer and 0.5 ns above the lower layer.

Figures B1.6 and B1.7 show the picked surface reflection and bottom of asphalt reflection. The upper part of Figure B1.6 shows the longitudinal and transverse profile and the waveform defined earlier in Figure B1.3. The red and blue trace lines in the profile plots represent layer interfaces that were defined as limits for the activity analysis. For this example, the top of the pavement was selected as the upper boundary and the bottom of the asphalt was selected as the lower boundary. The lower part of Figure B1.6 is a color-shaded area representation of the depth of the asphalt bottom. The orange shades represent a shallower asphalt bottom and the light blue shades represent a deeper asphalt bottom (see 3-D version in Figure B1.7).

For the 3d-Radar system data collected during this project, these layers can be picked using the 3d-Radar system Examiner software (3dr-Examiner). The layer depths are exported and then used as boundaries in the activity index calculation for the layer slices. When individual antennas are used, the individual GPR files are combined (as shown in Figure B1.8); the layers are picked in each antenna pass and again used as boundaries in the activity index calculation. Figure B1.9 shows a contour plot of the activity index that was calculated for the region between the picked layers.



Crossline slice (X) 695.796 m

Inline slice (Y) -0.85 m

Horizontal slice (Z) -0.052 m

Crosshair: N 0.006293 W 0.000008

Figure B1.6. Three-dimensional radar analysis.

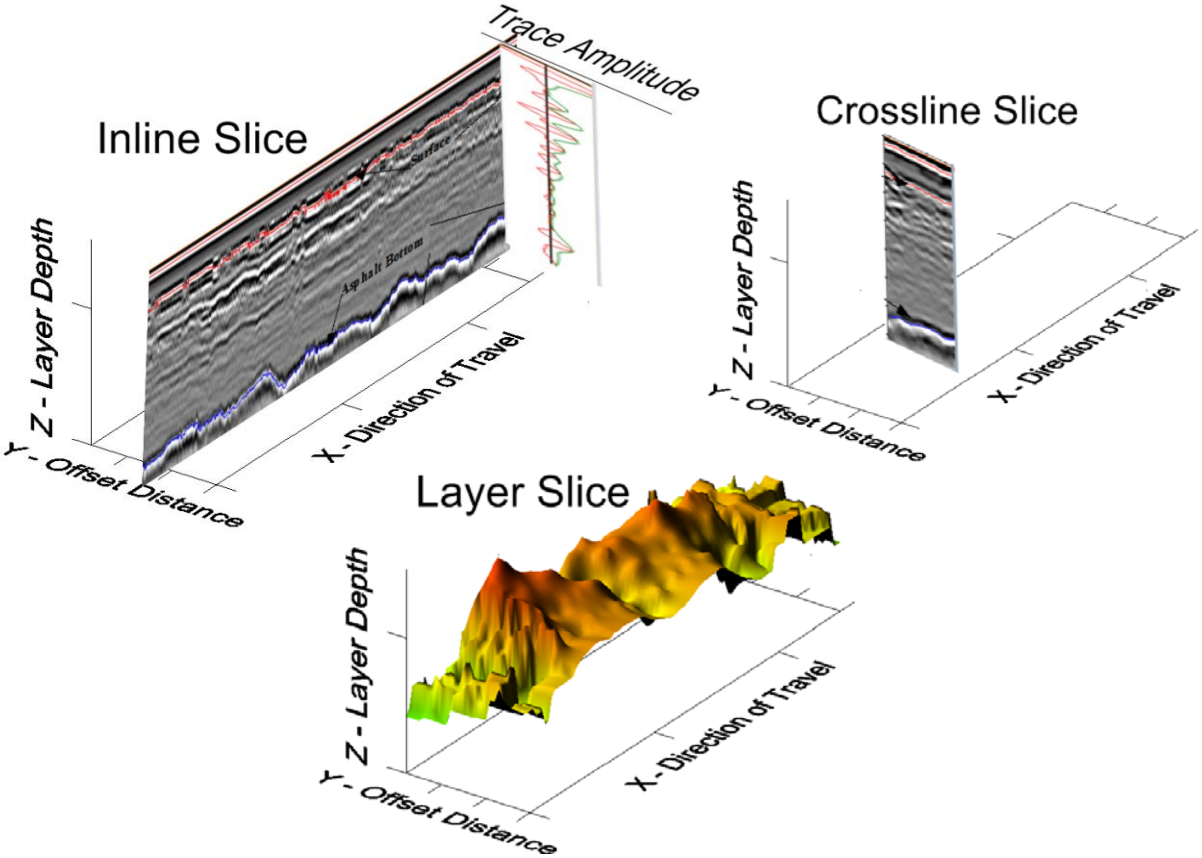
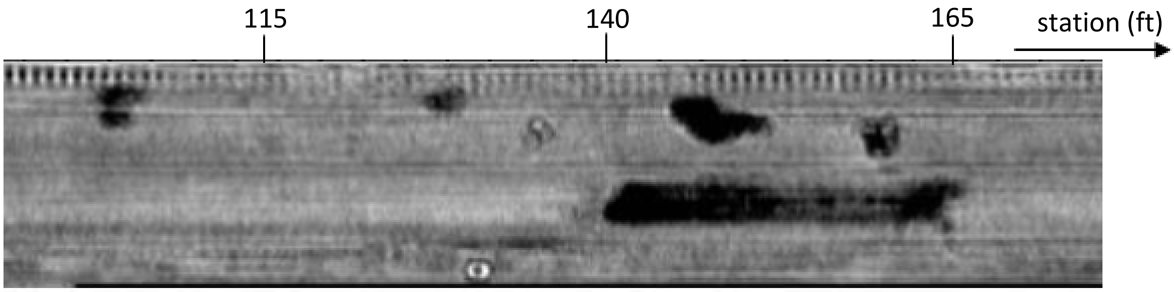
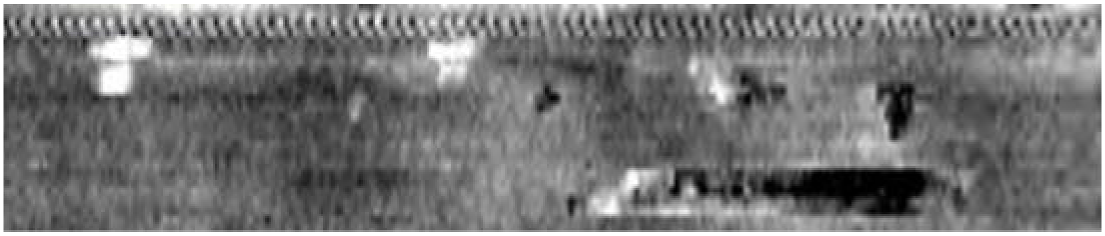


Figure B1.7. Three-dimensional radar analysis sections.



(a) 3d-Radar array



(b) Depth slice data created from combined data from individual radar antenna scans

Figure B1.8. C-scan time/depth slices from NCAT test section.

Note that to create the 3-D cubes of radar data at the test track, the 3d-Radar system used five parallel passes with a 5.5-foot-wide, 21-channel swept-frequency antenna array (140 to 3,000 MHz), and the individual antenna system used 25 parallel passes with a single 3 GHz antenna.

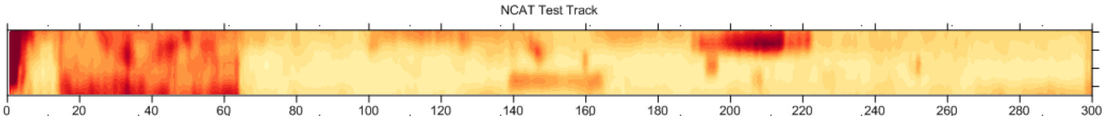


Figure B1.9. Contour plot of activity index between the two asphalt layer boundaries at NCAT.

9.3 Data Analysis Samples from Field Sites

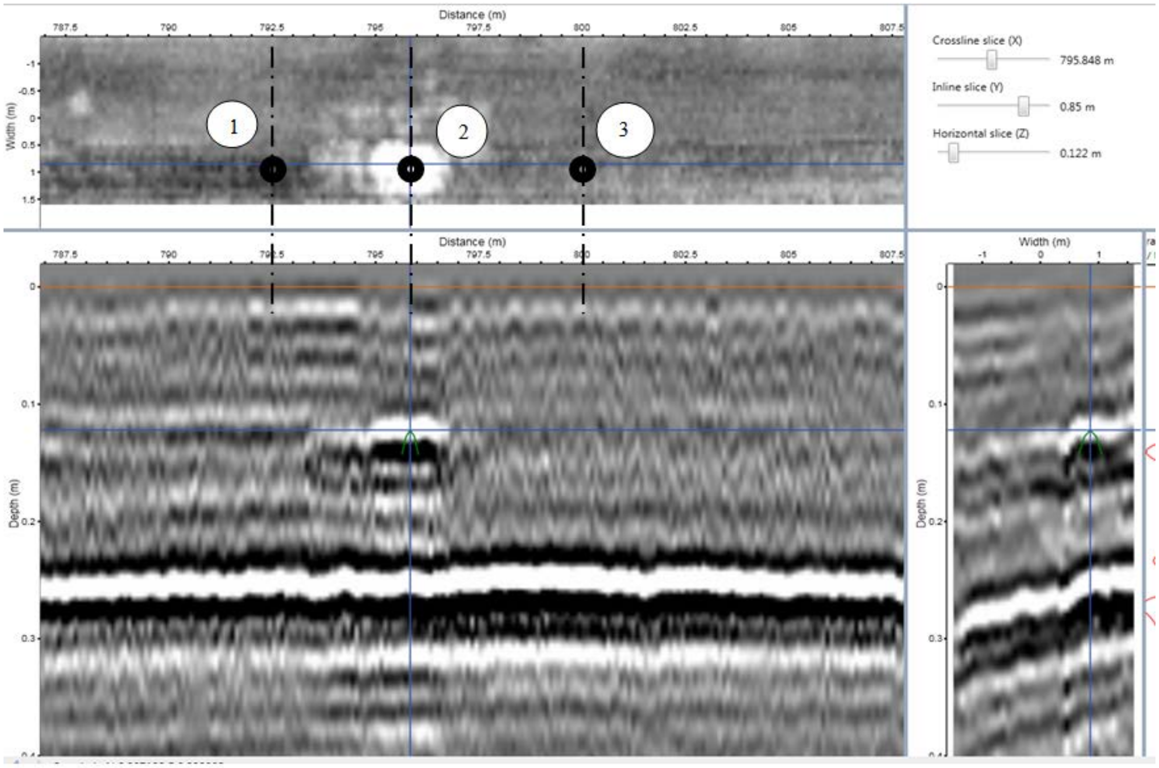
Florida Site

At the Florida field site, the activity index was determined by performing calculations between the picked layers. The upper layer was the interface between the air and the road surface, and the lower layer was the interface at the bottom of asphalt. To avoid including the amplitude of the reflection caused by the layer boundaries, the analyzed trace section began 0.5 ns below the upper layer, and 0.5 ns above the lower layer.

The end reflection was picked for this site, but it had an abnormal appearance, and normalization of the amplitudes by the end reflection did not work.

Activity index results on either side of the roadway centerline were statistically different from one another, so each side was normalized by the average mean positive amplitude for that side before the activity index was calculated.

Figure B1.10 shows a 3-D radar sample from the Florida site, and Figure B1.11 shows activity index plots for this data. For the activity index plot, a threshold of 20% above the mean is established; below this threshold, no colors are shown. Therefore, the only the areas that show color on the plot are those that represent potential delamination and moisture damage.



Crossline slice (X) 795.848 m

Inline slice (Y) 0.85 m

Horizontal slice (Z) 0.122 m

Figure B1.10. Florida radar data at the location of Cores 1, 2, and 3.

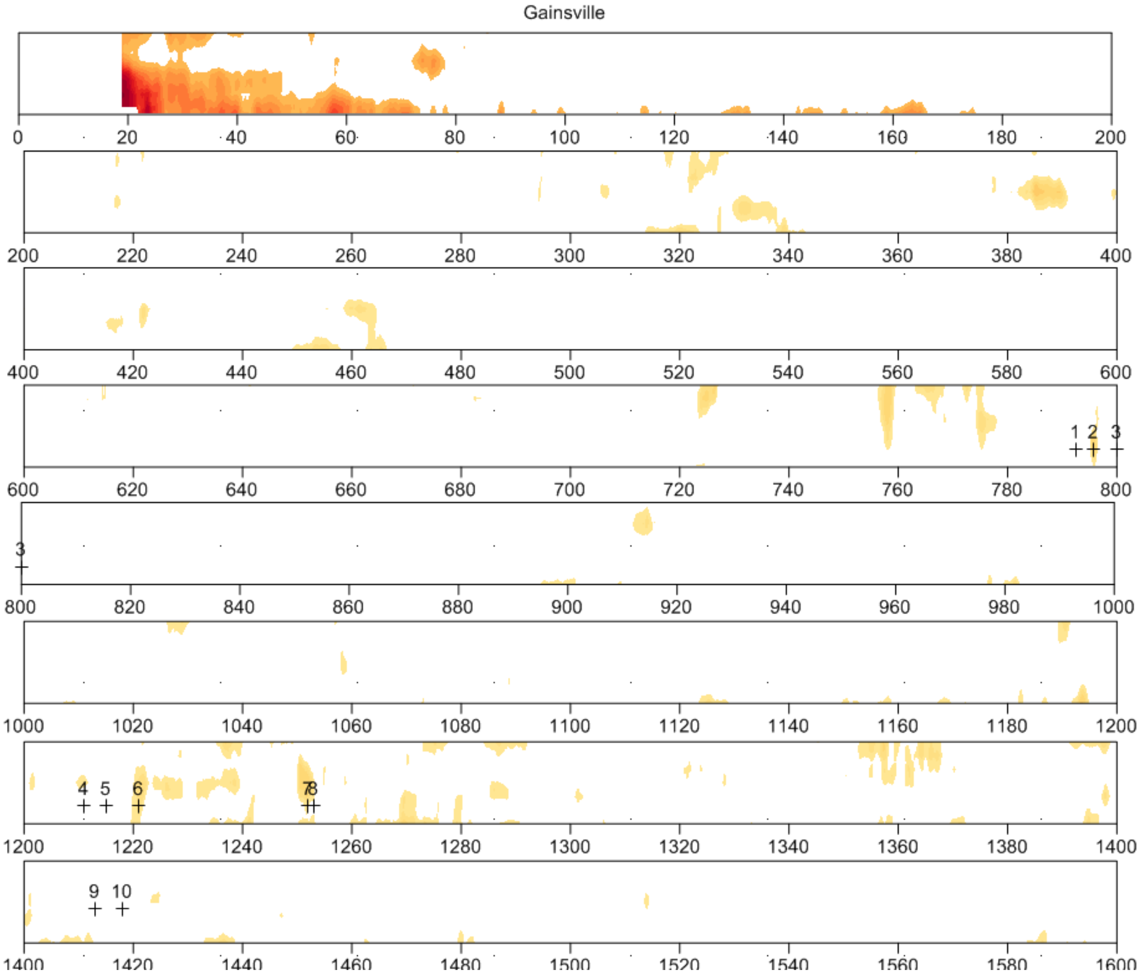


Figure B1.11. Florida site activity index plot of region between picked layers.

Kansas Site

At the Kansas field site, activity was determined by performing calculations between the picked layers. The upper layer was the interface between the air and the road surface, and the lower layer was the interface at the bottom of asphalt. To avoid including the amplitude of the reflection caused by the layer boundaries, the analyzed trace section began 0.5 ns below the upper layer, and 0.5 ns above the lower layer for each waveform. The end reflection was picked for this site, and the amplitudes were normalized by the end-reflection amplitude before the activity index was calculated. This step assures that the energy in each scan is identical.

Figure B1.12 shows a GPR sample from the Kansas site.

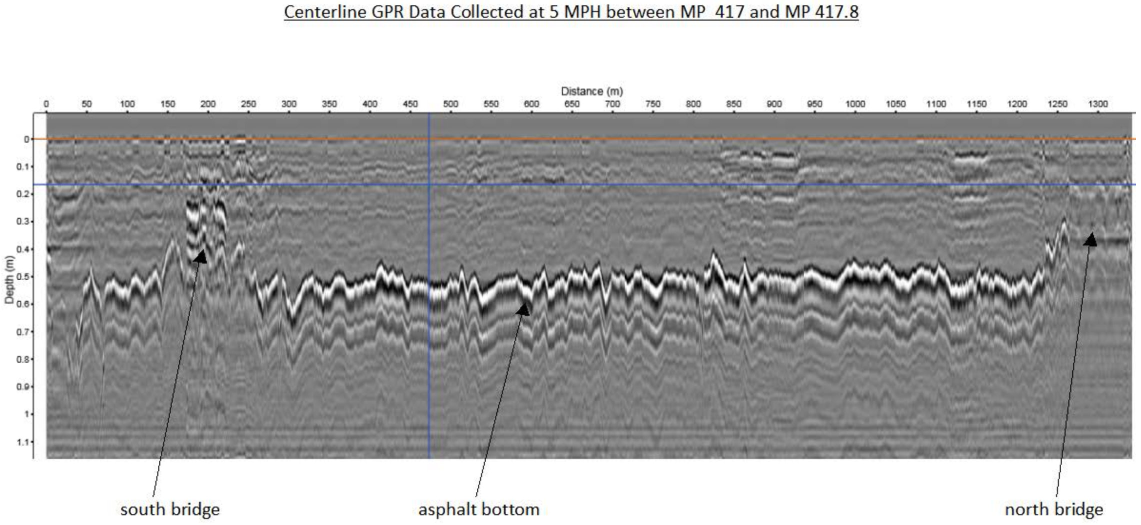


Figure B1.12. GPR radar data from the Kansas site.

10 Test Reporting

Reporting of the GPR test results can take place at various levels of detail, ranging from raw data to summary descriptions of the processed data. The level of detail should be dictated by the information needs. Based on the data presented in these guidelines, the following options are available:

1. Depth and profile slices of raw data

This is the most detailed level of reporting. Examples of this type of reporting can be found in Figures B1.3, B1.4, B1.8, and B1.10. This type of output is useful for examining local detail of potential delamination conditions and for locating cores for confirmation of delamination conditions. It provides both the spatial location and depth of potentially delaminated areas.

2. Contour/area plots of delamination indicators, such as activity index

Figures B1.2, B1.5, B1.9, and B1.11 show examples of this type of reporting. This presentation gives the user a quick visual assessment of the extent and location of delamination conditions, and is particularly suitable for project-level evaluation. It provides location but not necessarily depth of delaminated areas. Depending on the scale of the plot, this representation is suitable for project lengths of 1 to 10 miles.

3. Line plot of delamination indicators

Figure B1.13 shows an example of a line plot that presents a delamination indicator, such as activity index, versus milepost. In this presentation, the areas where the activity index exceeds 1.0 are designated as areas where delamination is likely, and these are shaded blue. This presentation presents a concise summary over many miles, and can be useful at the network level to identify areas for future investigation.

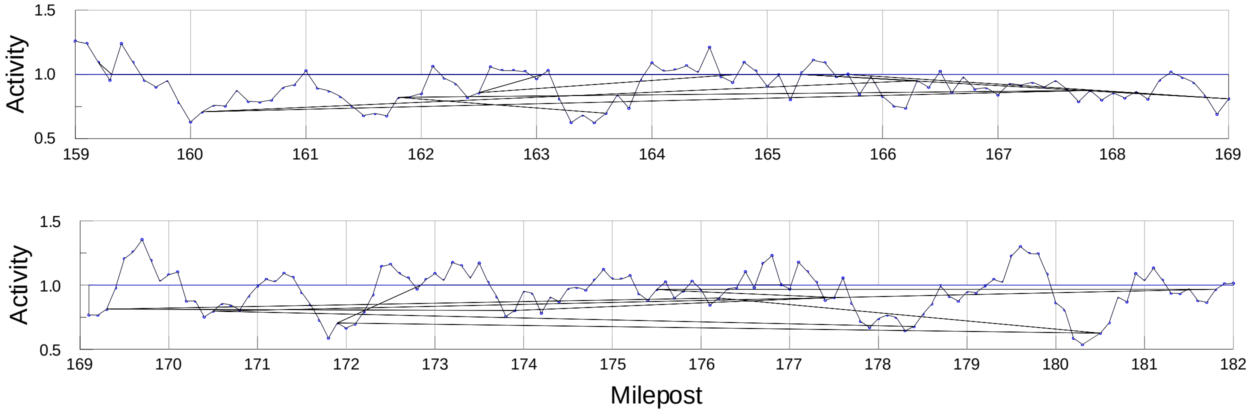


Figure B1.13. Line plot showing delamination indicators versus milepost (blue fill = delamination).

4. Tabular summary of delamination indicators

At the network level, a tabular summary of delamination conditions would also be appropriate for pavement management applications. This data can be imported into the pavement management system along with other variables for each pavement segment and can be incorporated into the rehabilitation planning process. A sample of such a tabular summary is shown in Table B1.2.

Table B1.2. Example Tabular Output at the Network Level

MP	Likelihood of Delamination (%)
159	100
159.1	100
159.2	94
159.3	92
159.4	100
159.5	94
159.6	92
159.7	100
159.8	93
159.9	72
160	55
160.1	47
160.2	44
160.3	52
160.4	31
160.5	48
160.6	59
160.7	100
160.8	100
160.9	100

Reference

Scullion, T., and E. H. Rmeili. *Detecting Stripping in Asphalt Concrete Layers Using Ground-Penetrating Radar*, Research Report 2964-S. Texas Transportation Institute, College Station, TX, 1997.

APPENDIX B2
GPR Vendors' Features

3d-Radar
High Speed, Full Coverage Ground-Penetrating Radar Solutions

(prepared by 3d-Radar, February 2013)

3d-Radar provides ground penetrating radar hardware and software for data collection across an entire swath width at high speeds with high resolution at all resolvable depths. Below are the key components of the system.

1. Equipment – Hardware
GeoScope™ Mk IV

The Geoscope Mk IV generates the waveform and sends this continuous electromagnetic wave to the antenna for transmission and measures the return. It enables high-density high speed 3-D data capture with a combination of deep subsurface penetration coupled to high resolution.

GeoScope Mk IV

Features

- *Resolution at all depths:* Step-frequency technology enables the users to achieve good resolution at each investigation depth. Penetration and high resolution are simultaneously achieved with one single antenna array. No need to employ different frequency antennas to adapt to different depths.
- *Area survey speed (work rate):* Very high scan rates and an efficient sampling method enable the GeoScope Mk IV to provide full resolution 3-D imagery at highway speeds.
- *High resolution 3-D sub surface imagery:* 7.5 cm channel spacing in the antenna array combined with 3 GHz bandwidth enables high-density sampling as required by utility mapping, military applications, and archaeology prospecting.
- *Wide range of antenna arrays with uniform response across the elements:* The GeoScope Mk IV is compatible with all 3d-Radar VX and DX Series antenna arrays ranging up to 330 cm in width.

The GeoScope Mk IV connects to any laptop via a standard GBit Ethernet connection and the primary interface is via a web browser. No software needs to be installed on the host computer to communicate with the system. Via an impedance matched antenna cable, the GeoScope Mk IV connects to 3d-Radar antennas to complete the communications path between the user and collected GPR data.

DX Series Antenna

3d-Radar DX Series antenna arrays allow scanning of up to 41 channels of GPR data over a continuous 200 MHz to 3 GHz frequency range. Near surface signal fidelity with the DX antenna is enhanced by orienting the sending and receiving antenna elements in opposite directions, minimizing antenna ringing while delivering high resolution imagery in collected GPR data.

The air-coupled antenna design offers clear impulse response with low ringing and high suppression of the direct wave from transmitter to receiver. Operated with the GeoScope Mk IV step-frequency radar, the DX Series antennas are capable of collecting 3-dimensional GPR data with dense line spacing, allowing 3-dimensional data processing. The antenna has support for multi-offset recording and CMP, and has a built in GPS receiver.

DX1821 antenna, trailer mounted.

The DX Series of antennas can be used for applications such as road/bridge deck inspection, utility mapping, archaeology, railway ballast inspection and military uses, the DX Series of antennas are available in 1.8, 2.1, 2.4, and 3.3 meter widths.

Accessories

While it is recommended that the antenna is mounted semi-permanently to the front or rear of the survey vehicle, a trailer with an integrated DMI (distance measurement instrument) is available for lower speed data collection.

Equipment – Mounting and Climate Restrictions

3d-Radar step frequency antennas require no warm-up or settling time in cold weather. Operational in both subfreezing and hot climates, the antennas are sealed from the elements and can be exposed to snow and rain without damaging the electronics.

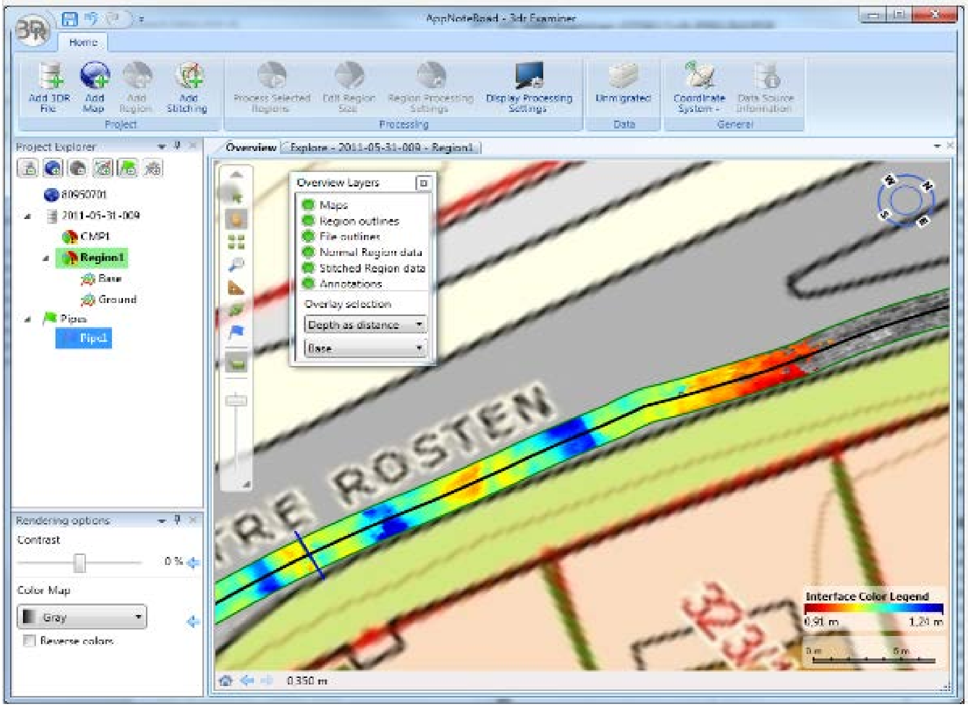
The GeoScope Mk IV should be kept dry at all times. If at all possible the instrument should be housed and operated in an environment no colder than 32°F (0°C).

2. Software – Data Processing

3dr-Examiner

3dr-Examiner is a software application that enables users to process, analyze, and inspect data from 3d-Radar ground penetrating radar systems. 3dr-Examiner is configured to handle large amounts of high resolution data on normal PCs.

High resolution radar surveys result in large amounts of data, which can make them difficult to process, navigate, and analyze. 3dr-Examiner includes techniques and tools to utilize the speed of modern PCs. The software is able to process radar data as fast as it can be collected, enabling surveyors to analyze in 3-D an area while still in the field.

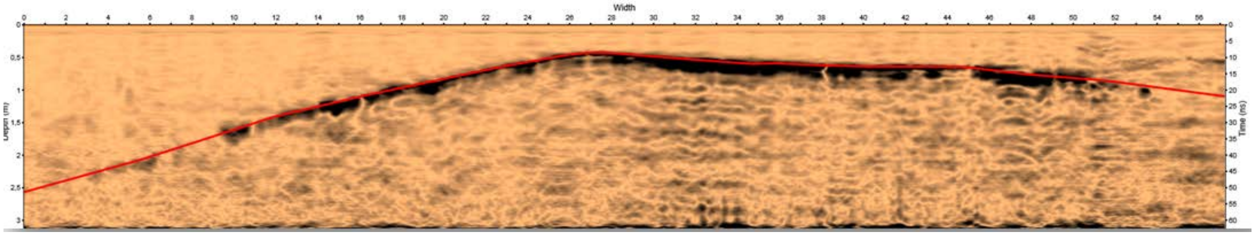


3dr-Examiner—Overview mode.

3dr-Examiner converts data collected from the frequency to time domain, applies filtering and tuning and can migrate in a self-contained, menu-driven environment. As the data are processed, they can be viewed in three dimensions, with the ability to compare processing settings to determine how to optimize the collected data.

3. Software – Data Analysis

Displayed data can be annotated with user-defined groups. Pipes, subsurface variations, and other structures can be mapped, displayed, and moved inside the data. Layers can be traced semi-automatically and displayed in 3dr-Examiner or along with annotations, exported to .kmz format for display in Google Earth, .dxf for AutoCAD, or to other user-defined formats.



Annotated pipe varying in depth from 50 to 2.5 m depth.

4. Field Data Output and Displays

During data collection, collected data are displayed on a controlling laptop in any web browser. As objects are seen during data collection, they can be marked for future review when post-processing in 3dr-Examiner.

Because it can take advantage of quad-core processors 3dr-Examiner can be used between data collection while in the field to quickly process a subsection for QA and onsite analysis.

5. Analysis Data Output and Displays

3dr-Examiner can view any data captured with a 3d-Radar system in two modes, an Explore view and an Overview mode. Overview can be integrated with drawings or satellite imagery while the more traditional Explore view enables the data to be viewed in an inline, cross-line, or horizontal slice simultaneously.

6. Equipment Calibration and Field Validation

At the factory, antennas are calibrated and this information is stored in firmware inside the antenna itself. No further calibration is necessary in the field. To insure the system is functioning properly before data collection, the system can be initially configured to capture data on time triggers instead of distance. This enables stationary data collection to ensure good data is captured before the actual survey starts.

7. Equipment Upgrades and Service

As improvements to 3d-Radar hardware and firmware are implemented, firmware upgrades to both the GeoScope Mk IV and DX Series antennas can be downloaded from 3d-Radar over the Internet.

Future Equipment Developments

New antenna designs will be compatible with the GeoScope Mk IV, ensuring that continuous improvements will be available for only a fraction of the purchase price of the original system.

Geophysical Survey Systems, Inc.
GPR System Specification
(prepared by GSSI, February 2013)

Geophysical Survey Systems, Inc.
12 Industrial Way
Salem, NH 03079

System Type

Specification: Array of multiple antenna elements lined up transverse to the direction of travel
Response: The GSSI RoadScan 30 system, based on the SIR-30 Multichannel Radar Controller, can support up to 4 antennas, oriented transverse to the direction of travel. The system can be extended by adding a second SIR-30 controller (operating as a slave controller) to support up to 4 additional antennas, for a total of up to 8 antennas.

Model 42000S Horn Antenna, Model SIR-30 Multichannel Radar Controller

Frequency Range (impulse radar systems)

Specification: center frequency of pulse > 2.0 GHz, –10 db limits: 0.5–5.0 GHz
Response: The RoadScan 30 system is based on the model 42000S, an air-launched antenna that is suitable for determining asphalt thickness, delamination, and void detection. The 42000S has a center frequency of 2.0 GHz and a bandwidth of 0.6–2.8 GHz @ -10 dB.

Frequency Range (frequency swept radar systems)

Specification: up to 3.0 GHz
Response: Not applicable

Lateral spacing of antenna elements

Specification: <1.5 feet
Response: The minimum lateral spacing for the Model 42000S antenna is 0.75 feet.

Lateral coverage per pass

Specification: 12 feet (full lane width)
Response: Using eight 42000S antennas with a lateral spacing of 1.7 feet, RoadScan 30 will provide full lane coverage of 12 feet.

Longitudinal data collection rate

Specification: >2 scans per foot per antenna element
Response: RoadScan 30 is capable of a longitudinal data collection rate in excess of 2 scans per foot per antenna. The scan density at 23 mph (@ 512 samples per scan) is specified at 12 scans per foot. The scan rate is not affected by the number of antenna elements employed.

Travel speed during data collection

Specification: >20 mph
Response: RoadScan 30 can collect data at speeds in excess of 20 mph. The maximum data collection speed (@ 4 scans per foot and 512 samples per scan) is 70 mph.

Travel speed during mobilization

Specification: posted speed limit
Response: RoadScan 30 can be mobilized at posted speed limits without requiring a mechanical adaptation to the system.

Real time display

Specification: B-scan for selected antenna elements
Response: The RoadScan 30 system can be configured to display a B-scan in real-time.

System monitoring and control

Specification: from within the survey vehicle
Response: The RoadScan 30 system provides monitoring and control from within the survey vehicle via a monitor and keyboard, or laptop computer.

Data collection rate

Specification: data collection should be triggered on distance using a DMI
Response: The RoadScan 30 system is configured with a standard DMI used to trigger data collection based on traversed distance.

Spatial reference

Specification: vehicle DMI and/or GPS

Response: The RoadScan 30 system supports a vehicle-mounted DMI and/or a GPS for spatial referencing.

Detection depth range

Specification: 2–12 inches
Response: The RoadScan 30 system, configured with the 42000S 2 GHz air-launched antenna, has a detection depth range from less than 1 inch up to 20 inches, depending on the dielectric properties of the medium under test. An advantage to RoadScan 30 is that the air-launched antenna calibration is performed once prior to data collection (using a metal plate), eliminating the need for repeated coring to determine the radar propagation velocity (and by computation, the depth) in the medium under test.

Additional Information

System Hardware, Environmental Specifications

RoadScan 30 consists of the following:

- SIR-30 Multichannel Radar Controller w/transit case
- Model 42000S Horn Antenna
- Wheel-mounted Distance Measuring Instrument (DMI)
- 7-meter Control Cable
- SIR-30 Mounting Kit
- AC Adaptor
- User Manual

Additional antennas, control cables, and radar controllers can be added to the base RoadScan 30 system.

Operating Temperature: –10^{o}C to 50^{o}C
Relative Humidity: <95% noncondensing

Mounting Hardware

The model FGVFHM-SL is a permanent multiple antenna mount that can support up to 3 antenna arm mount assemblies. The FGVFHM-SL is permanently mounted to the data collection vehicle. One model FGVFHM-SARM antenna arm mount assembly is required for each 42000S horn antenna deployed.

System Software, Data Processing/Analysis

The system software embedded in the SIR-30 mainframe provides full instrument control: data acquisition, positioning, and data storage and output. Data is stored on an internal solid state drive in 32-bit RADAN .dzt format, compatible with GSSI's RADAN 7 post processing and data analysis package.

The SIR-30 system software provides data acquisition control over

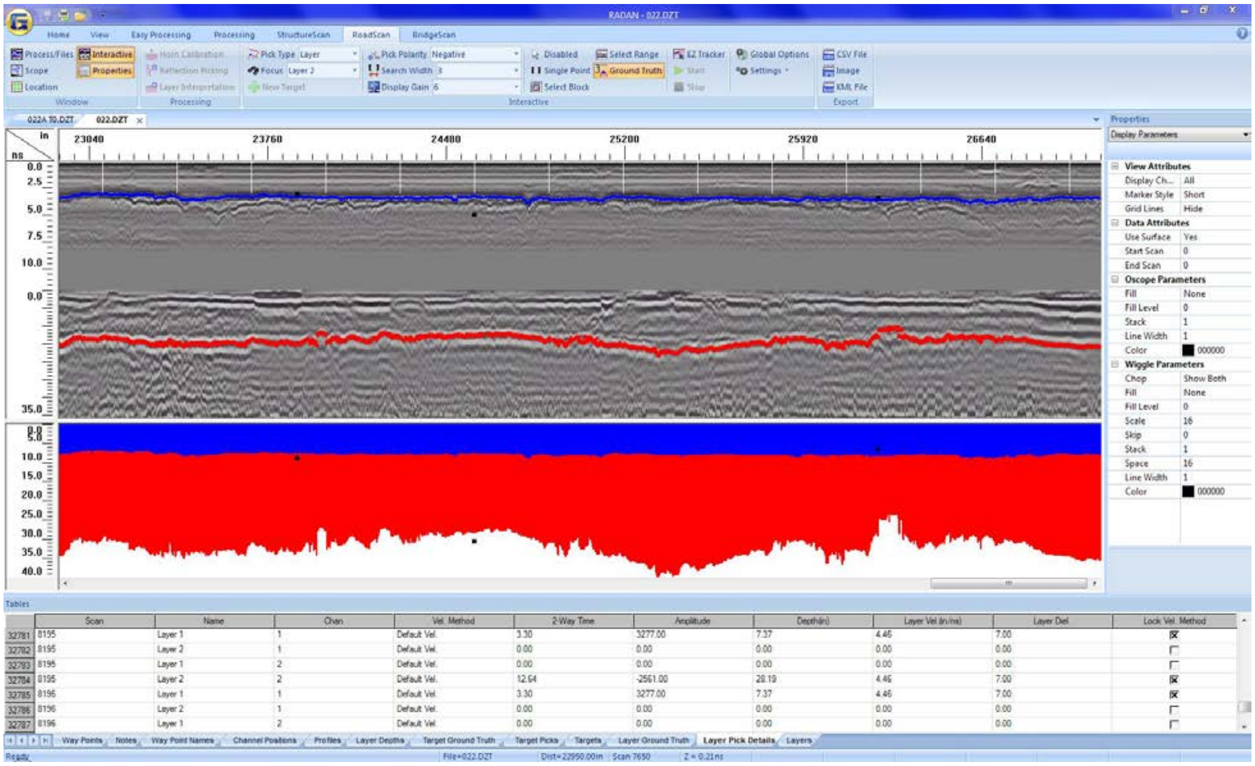
- Scan rate;
- Number of samples/scan; and
- Real-time filters.

The SIR-30 system software is compatible with all GSSI antennas and provides automatic recognition and setup of GSSI Smart antennas.

RADAN 7 is a data processing and analysis package designed for use with GSSI 32-bit data acquisition systems. RADAN 7 is modular and allows users to add functionality based on a specific application. Configured for operation under Windows 7, RADAN 7 provides GPR post-processing functionality under a Windows-based user interface.

The RoadScan Module is optimized for road asphalt layer and bridge deck structure and deterioration assessment and is capable of semi-automated layer picking and target mapping to the basic RADAN 7 module.

The following dataset was collected with RoadScan 30 and two antennas: a 42000S 2GHz horn antenna and a 50400S 400 MHz antenna. Processed in RADAN 7, the data depict asphalt overlay and sub-base layer information.



Properties

Display Parameters

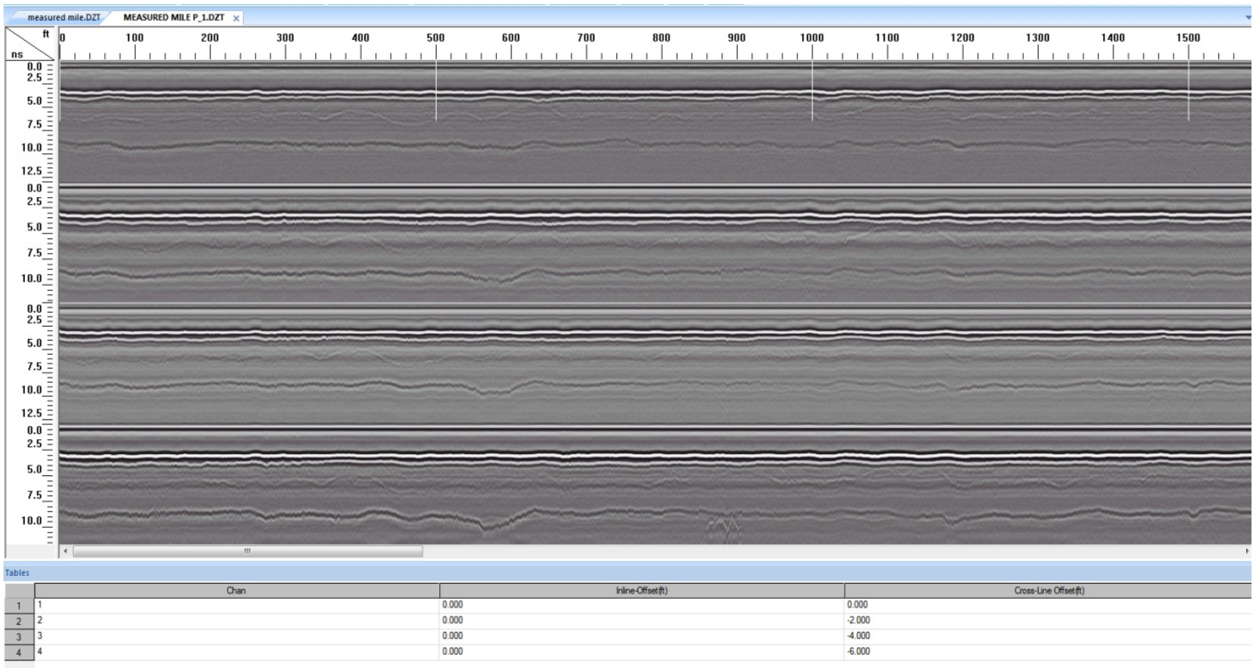
View Attributes	
Display Ch...	All
Marker Style	Short
Grid Lines	Hide
Data Attributes	
Use Surface	Yes
Start Scan	0
End Scan	0
Oscope Parameters	
Fill	None
Fill Level	0
Stack	1
Line Width	1
Color	■ 000000
Wiggle Parameters	
Chop	Show Both
Fill	None
Fill Level	0
Scale	16
Skip	0
Stack	1
Space	16
Line Width	1
Color	■ 000000

	Scan	Name	Chan	Vel. Method	2-Way Time	Amplitude	Depth(in)	Layer Vel (in/ns)	Layer Diel	Lock Vel. Method
32781	8195	Layer 1	1	Default Vel.	3.30	3277.00	7.37	4.46	7.00	☒
32782	8195	Layer 2	1	Default Vel.	0.00	0.00	0.00	0.00	0.00	☐
32783	8195	Layer 1	2	Default Vel.	0.00	0.00	0.00	0.00	0.00	☐
32784	8195	Layer 2	2	Default Vel.	12.64	-2561.00	28.19	4.46	7.00	☒
32785	8196	Layer 1	1	Default Vel.	3.30	3277.00	7.37	4.46	7.00	☒
32786	8196	Layer 2	1	Default Vel.	0.00	0.00	0.00	0.00	0.00	☐
32787	8196	Layer 1	2	Default Vel.	0.00	0.00	0.00	0.00	0.00	☐

Ready File=022.DZT Dist=22950.00in Scan 7650 Z = 0.21ns

Data Example

The following dataset was collected using RoadScan 30 with four 42000S antennas and processed using RADAN 7. The data depict asphalt layer information across a full lane.



	Chan	Inline-Offset(ft)	Cross-Line Offset(ft)
1	1	0.000	0.000
2	2	0.000	-2.000
3	3	0.000	-4.000
4	4	0.000	-6.000

Calibration, Field Validation

The only calibration required by RoadScan 30 is the metal plate calibration used to determine the radar propagation velocity of the medium under test. This calibration is performed daily prior to data collection.

There is no other calibration required by the system.

System Upgrades, Service

Should service be required, the system can be returned to the GSSI Factory Service Center, located in Salem, New Hampshire.

As a matter of routine, hardware and/or firmware updates that address known performance issues are completed when a system is returned to GSSI for repair or for preventative maintenance.

IDS

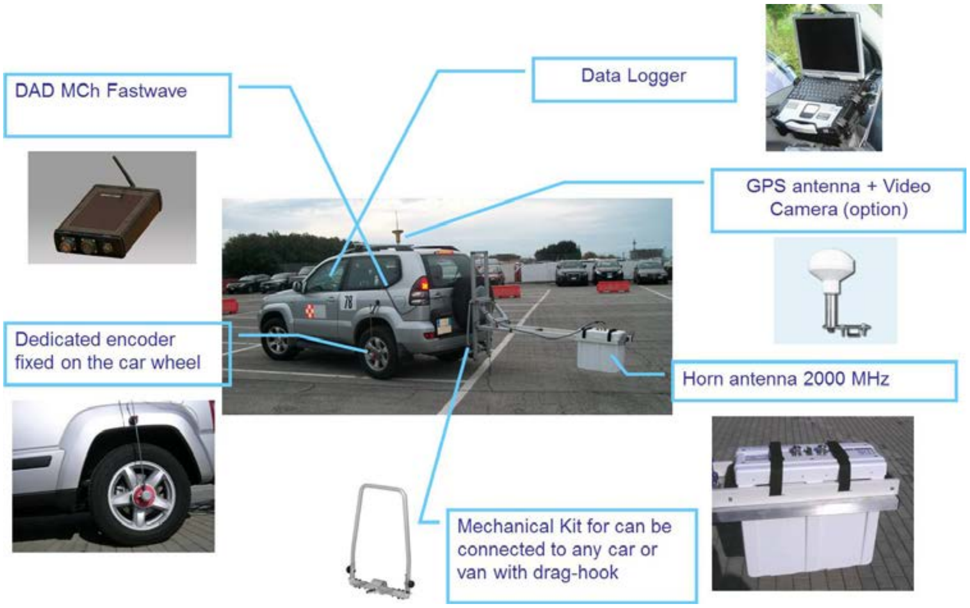
RIS Hi-Pave System: A Dedicated Solution for the Survey of Pavements

(prepared by IDS, February 2013)

RIS Hi-Pave is a ground-penetrating radar solution designed for high-speed Road Assessment Surveys. The system is able to operate with several antennas at the same time, providing a complete assessment of road conditions, such as pavement thickness measurement; surface, base and sub-base road course assessment; detection of cavities and voids; location of cracks; airport runway condition assessment.

Hi-Pave system is based on a multi-channel, high performance radar technology. The architecture of this system enables the following features:

- **High Speed:** the system using only one antenna can achieve up to 180 mph;
- **Multichannel:** up to 8 antennas can be recorded simultaneously with one single control unit;
- **Chain architecture:** antennas are added to the system in a “chain” connection in “plug and play” mode;
- **Data quality:** antenna design allows it to record very clean signals and a proprietary processing algorithm permits an efficient removal of background noise; and
- **Additional features:** integrated video-camera, GPS, data exportation.



RIS Hi-Pave system composition.

Hi-Pave Configuration and Mounting

The RIS Hi-Pave configuration can be configured with horn antennas with frequency values of 1 GHz and 2 GHz mounted on the vehicle; this solution is particularly suitable when an easy-to-remove installation is required. It is also possible to connect additional ground-coupled antenna (standard TR antenna) for deeper investigation.

In this specific configuration the system will be provided with 8 2GHz antennas. The Horn antennas will be connected in chain with only one cable connecting the DAD with Horn antennas, avoiding the use of many cables and additional control units. The Horn antennas are light (6.5 kg–14 lb), and a mechanical frame must be adapted in order to host all the antennas. The off-the-shelf solution from IDS provides a mechanical kit able to bring 2 Horn antennas in parallel and can be adapted to store more antennas.

The maximum survey speed with 8 antennas due to the proprietary IDS chain connection technology is reported in the table below:

	Survey speed with 8 antennas	
Number of DAD MCH Fast-Wave	(with 512 samples and 2 scans per foot)	(with 512 samples and 5 scans per foot)
1	58.4 mph	29.2 mph

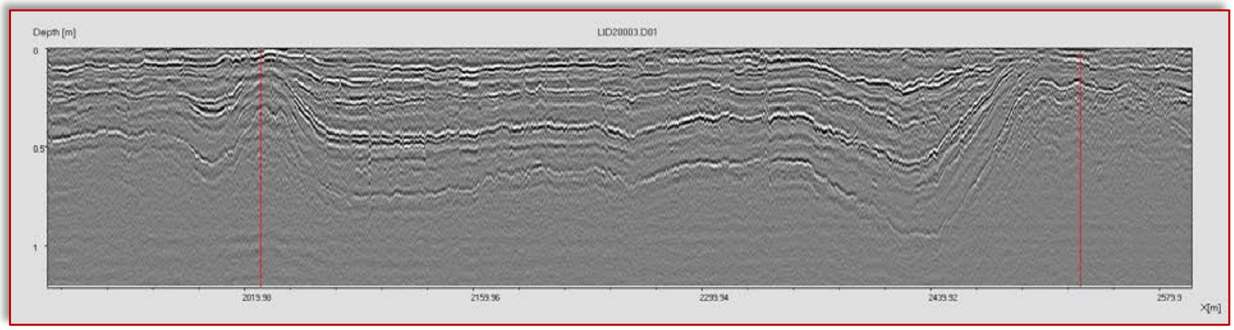
RIS Hi-Pave with two-antenna configuration.

RIS Hi-Pave System Specification

System Specification	
Recommended Laptop:	Panasonic CF-19 Tough-Book
Max. acquisition speed:	260 kmh (150 mph)
Positioning:	Survey wheel and/or GPS
Number of control unit:	DAD 1CH FW - DAD MCH FW
Scan rate: (@ 512 samples/scan)	362 scans/sec or 724 scans/sec.
Scan Interval:	10 scans/mt.
Power Supply:	SLA Battery 12VDC 12 AH
Antennas Specification:	
Environmental:	IP65
Antenna FootPrint:	51 × 22 cm
Number of hardware channels:	from 1 to 8
Antenna Central Frequencies:	2 GHz or 1 GHz
Antenna Polarization:	Horizontal (HH)
Antenna type:	Air launched

K2 Fastwave Acquisition Software

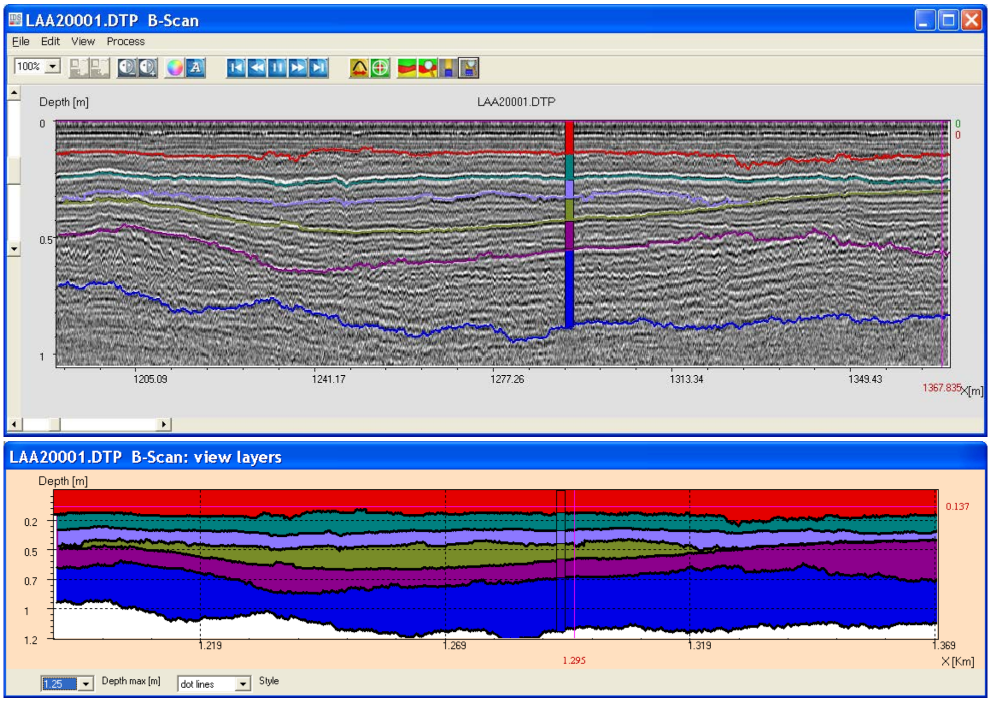
This software operates both with single GPR sections and with sets of homogeneously acquired single or multi-channel profile data; the radar maps can be viewed simultaneously and the sections run using automatic scrolling. It is possible to apply filters as well as to put marks directly on the radargram. The acquired radargrams are stored in raw files that can be opened with GRED HD software. Data can be exported in several formats.



Radargram acquired with K2 Fastwave acquisition software.

GRED HD 3D Post-processing Software (Data Processing)

GRED HD 3D is processing software designed to be an interface for the IDS RIS GPR family of products. The code can identify the various layers using both automatic and manual procedures. The radar Processing Software picture shows a radar map with several layers automatically identified on the radar map and reported in dedicated layers windows; the layers' thicknesses are confirmed by the core sample data inserted in the GRED HD 3D windows. Data interpretation can be done also with GPR-Slice and Reflex software or alternatively IDS can be available to share proprietary information about the data format.



Radar processing software.

System Calibration

The calibration is done automatically by the software. Having a template of the coring can be helpful to estimate with precision the propagation velocity that leads to real layer thickness. The software has a feature to introduce coring data and relate those with the layers in the radargrams in the post-processing phase.

Data Export

Data can be exported in several formats, including Excel, ASCII, CAD, and GIS with GIS coordinates.

GPS Compatibility

The GPS device can be connected to the RS232 port of the data logger computer and GPS data saved together with radar profiles for knowing the position of each scan in absolute coordinates; the software can accept the GPS streaming from any device compatible with the NMEA standard. The GPS positions can be easily loaded on software like Google Earth.

GPR track acquisition loaded on Goggle Earth map.

APPENDIX C1

SASW/IE User Guidelines

Use of Spectral Analysis of Surface Waves (SASW) and Impact Echo (IE) for Identifying Asphalt Pavement Delamination: User Guidelines

Prepared by the SHRP R06D Research Team

This document provides guidelines for using nondestructive testing (NDT) methods that utilize the spectral analysis of surface waves (SASW) and impact echo (IE) technologies to identify delamination in asphalt pavements. This guideline is applicable to all the SASW and IE devices for evaluating delamination in asphalt pavements. Users are advised to understand both SASW and IE because the test equipment may have the ability to measure both. Selection of which data has the highest level of accuracy and confidence will depend on the understanding of each technology and the field-testing conditions.

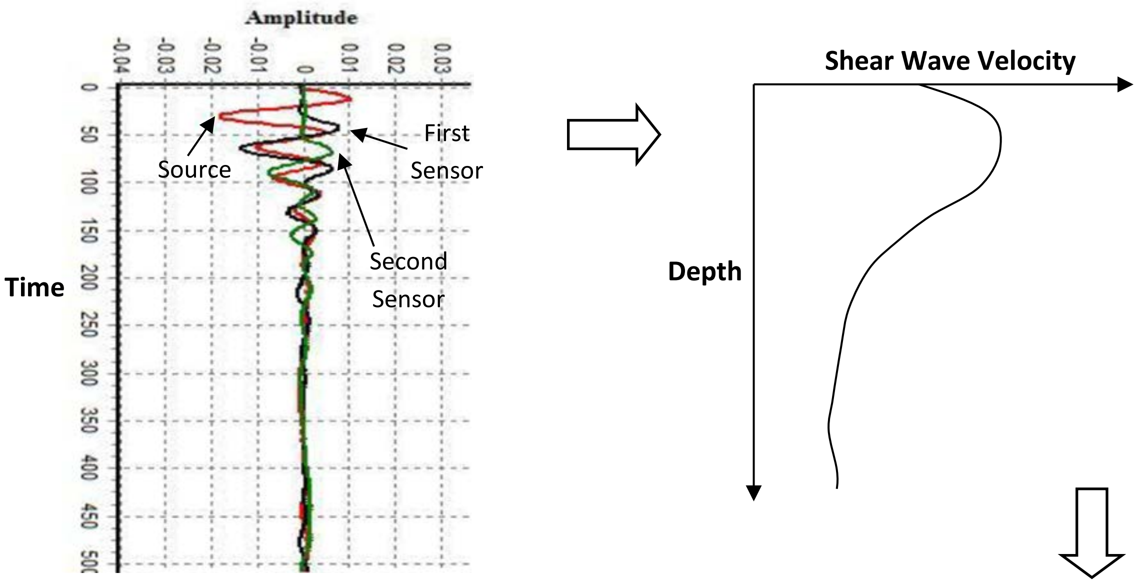
1 General Theory

The SASW and IE methods are used for determining material properties and detecting defects based on the principles of elastic wave propagation. The methods are conducted by impacting the surface of a material to generate three primary elastic waves, including R-, P-, and S-waves and then measuring the waves propagating to some distance from the source impact. The SASW measures the changes in surface wave (i.e., R-wave) dispersion characteristics and elastic properties to determine the pavement material stiffness (modulus) and the potential for material defects. The IE method measures body-wave (i.e., P-wave) reflections in the material response to determine the thickness of the bound layer or the potential location of a defect in the bound layer. Surface waves propagate closer to the surface and have higher amplitudes than body waves.

1.1 Spectral Analysis of Surface Waves

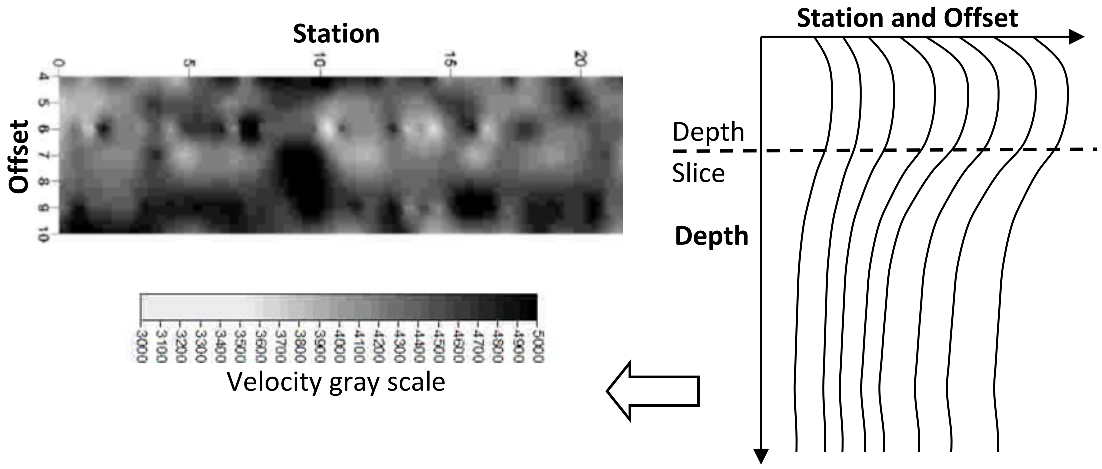
In the SASW test, the pavement is impacted with a short, high-frequency source creating a surface wave that propagates away from the source. Two receivers are spaced at different distances from the source to detect the arriving surface wave. The data from these two locations are used to calculate the wavelength versus velocity (dispersion curve) for the surface wave. Figure C1.1 illustrates the SASW testing and data analysis process.

Since wavelength is related to depth of penetration, and since surface wave and shear wave velocities are very close, this dispersion curve is interpreted as a relationship between shear wave velocity and depth. A sharp drop in velocity at a particular depth is indicative of a discontinuity in the pavement structure which could be associated with delamination and stripping. Figures C1.2 (a) and C1.2 (b) show the dispersion curves for an intact pavement and a pavement with a known delaminated interface at a depth of 5 in. Figure C1.3 is a SASW data analysis screen display. The material modulus determined from the SASW measurements represents low-magnitude (less than 1 micro-strain), high-frequency (greater than 3,000 Hz) values. These material modulus values are higher than modulus values computed from current dynamic modulus tests.



(a) Raw Waveform

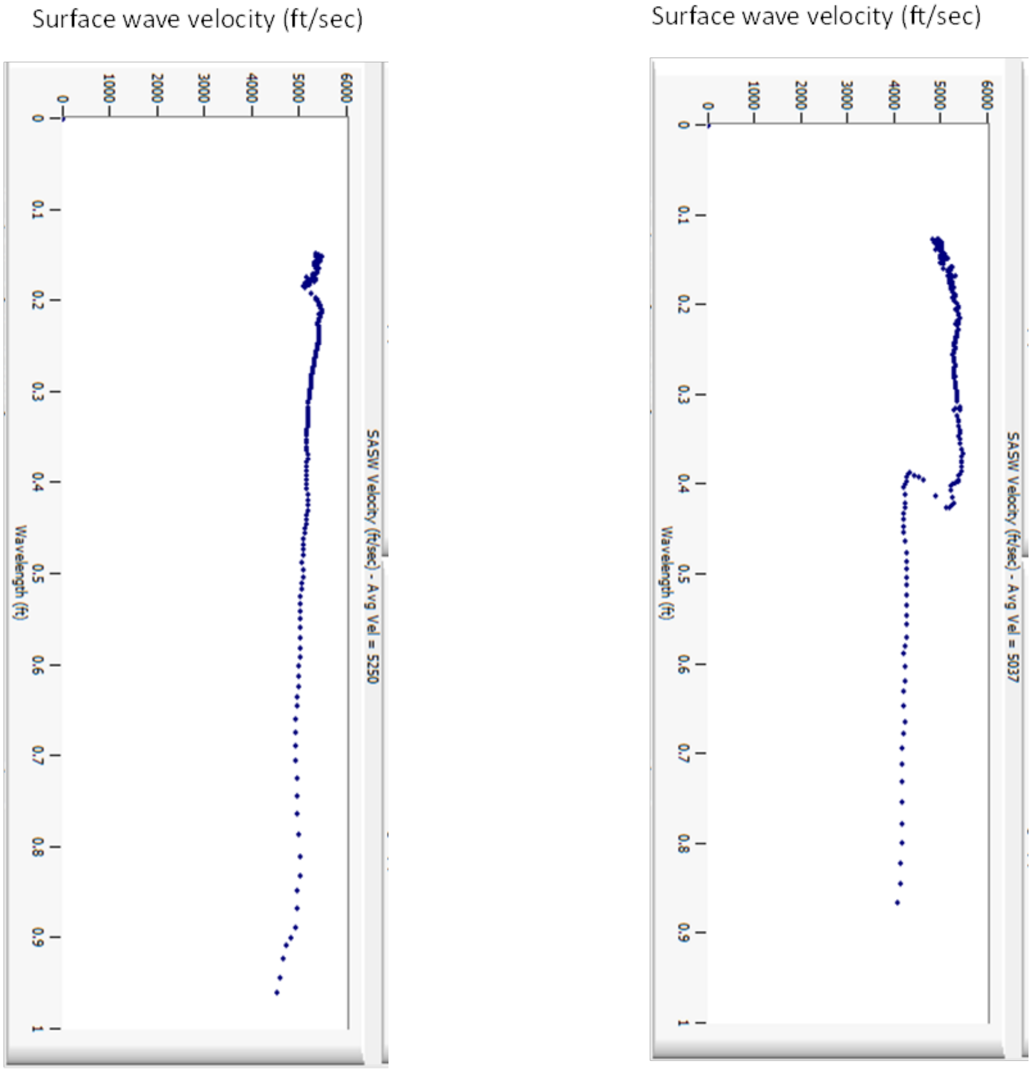
(b) Processed Waveform



(d) Velocity Map at Depth Slice
for an Array of Locations

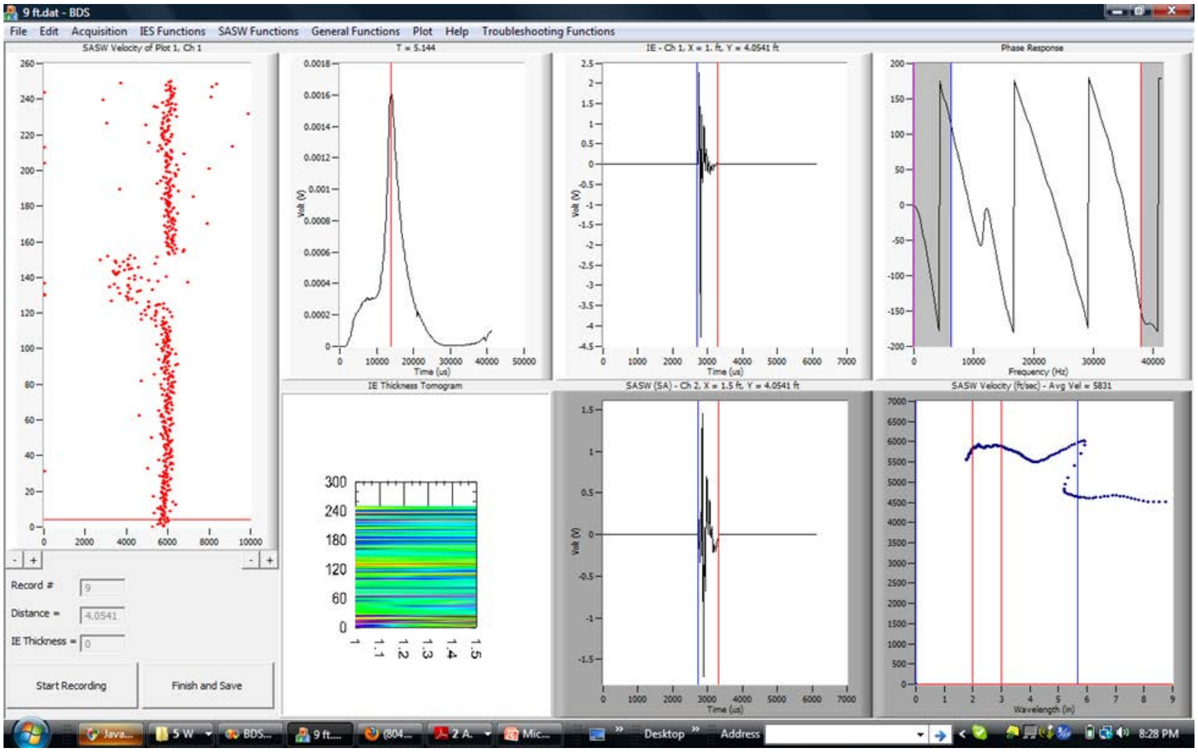
(c) Processed Shear Wave Profiles
at Successive Locations

Figure C1.1. SASW testing and data analysis process.



(a) **(b)**

Figure C1.2. Dispersion curve from an intact pavement (a) and dispersion curve from a pavement with delamination at a depth of 5 in. (b).



Record # 9

Distance = 4.0541

IE Thickness = 0

Figure C1.3. SASW data analysis screen.

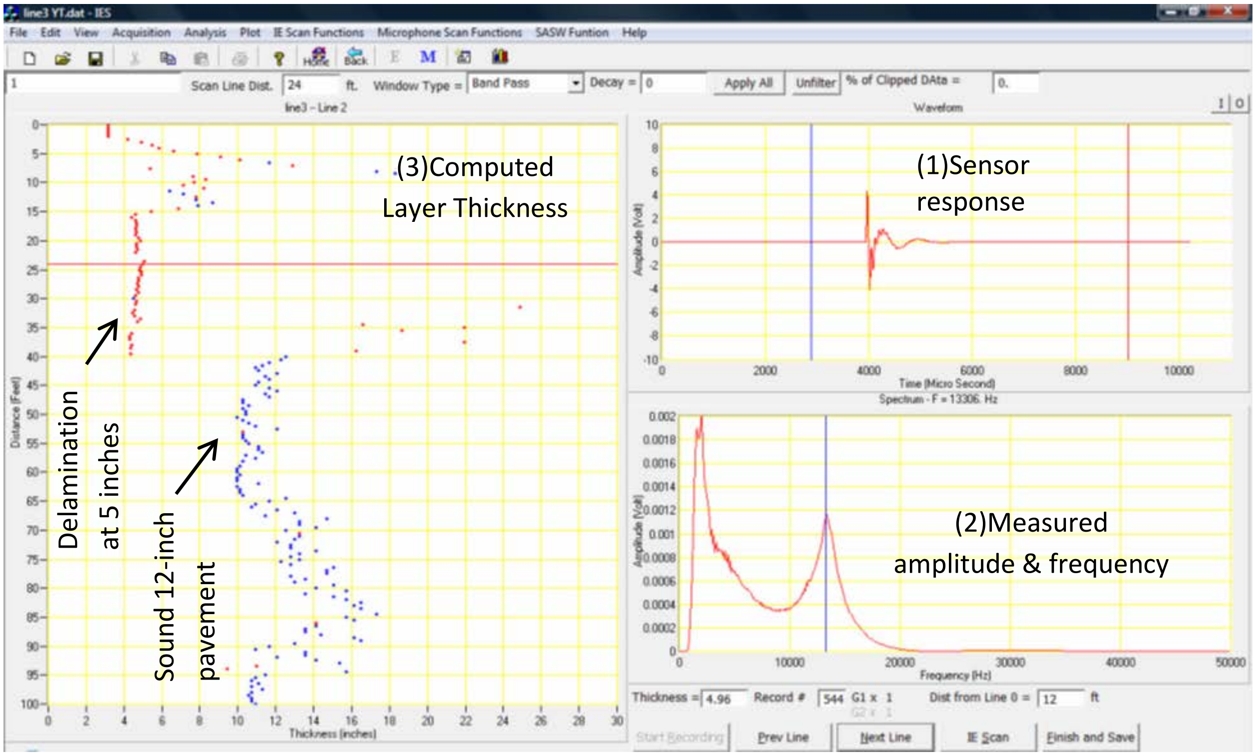
1.2 Impact Echo

In the IE test, an impact source is used to transmit a high-frequency mechanical (sound) wave into the pavement and a receiver is utilized to measure the P-wave reverberation (resonant echo) between the top and bottom surfaces. The impact source and receiver are placed adjacent to each other on the pavement surface. The amplitude of the reverberation detected by the receiver is converted into the frequency domain as amplitude versus frequency. For a homogeneous pavement layer, there is a resonant or dominant frequency directly proportional to the thickness of the pavement layer. This resonant frequency is referred to as the thickness resonance. The frequency data are typically converted to thickness using the following equation with an assumed P-wave velocity that is modified by a beta (β) factor of 0.954 for a Poisson ratio 0.2:

$$T = \beta V/2f \qquad (1)$$

where T = the thickness,
β = a beta factor,
V = the P-wave velocity in the pavement, and
f = the frequency.

For a uniform pavement with no delamination, the calculated thickness resonance will be relatively uniform. However, when there is a shallower delamination, the reverberation will be disrupted and both higher resonant impact echo and lower flexural frequency modes of vibration will occur. This change in frequency will lead to variation in calculated thickness values at delamination locations. For a series of IE tests conducted over an area, the calculated thickness can be plotted (see Figure C1.4), and areas where it changes (i.e., not expected in the pavement structure) are interpreted as delaminated. The change is indicated by a higher-amplitude, low-frequency response due to flexural vibrations for shallow delaminations, or a somewhat deeper but less than full pavement-thickness echo. Figure C1.4, Graph 3 on the left, shows thickness values (horizontal axis) plotted against distance (vertical axis) using the measured resonant frequency in Graph 2 and Equation 1. Note that the calculation requires an assumed velocity, *V*.



Scan Line Dist. 24 ft. Window Type = Band Pass Decay = 0 % of Clipped DAta = 0.

Thickness = 4.96 Record # 544 G1 x 1 Dist from Line 0 = 12 ft

Figure C1.4. IE testing and data analysis.

2 Equipment Specifications

Currently, most commercially available portable devices for conducting SASW and IE testing on pavements are point-test devices, and some of them can conduct both SASW and IE simultaneously. To improve the testing efficiency, prototype testing equipment with rolling wheels has been developed. The device can be pulled behind a vehicle or a push-cart. This equipment allows the SASW and IE tests to be performed continuously at a walking speed. This equipment has the potential to provide full lane-width continuous measurements for project-level investigations.

Table C1.1 shows the specification for the continuous SASW/IE testing equipment with rolling wheels. The continuous testing equipment method can travel at a modest 1 mph using three testing units in an array to cover a half lane width, completing approximately 264 tests per minute over 528 ft^2 (1 test per 2 ft^2). The prototype equipment also demonstrated a test frequency of 1 test per 1 ft^2. The slow rolling continuous test method does not provide for replicate testing at one location. Instead, the density of tests establishes the precision of the computed results. The commercially available point-test SASW/IE testing equipment can be implemented using the testing plan provided in this guide; however, testing will be more labor intensive. For purposes of this guide document, single-point-test devices with replicate measurements can, at best, cover 12 test locations per minute. To cover the same 528 ft^2 for the same test density would take a minimum 22 minutes. A complete array of test results are required to develop a velocity map from SASW testing or a calculated thickness map from IE testing. The maps can be used to identify the potential delamination locations in the evaluated asphalt pavement.

Table C1.1. Equipment Specification for Continuous SASW and IE Testing

System Component	SASW Specification	IE Specification
System type[a]	Array of multiple sets of impact sources and pairs of sensors. The sets are lined up transverse to the direction of travel.	Array of multiple sets of impact sources and sensors. The sets are lined up transverse to the direction of travel.
Sensor frequency response[b]	Up to 50,000 Hz	Up to 50,000 Hz
Impact source input frequency[b]	Up to 50,000 Hz	Up to 50,000 Hz
Lateral spacing between sensors[c]	2 feet between center of sensor pairs (maximum)	2 feet between sensors (maximum)
Lateral coverage per pass[d]	6 ft (half lane width)	12 ft (full lane width)
Longitudinal data collection rate[c]	1 test per foot (minimum)	1 test per foot (minimum)
Travel speed during data collection[e]	1 to 2 mph	1 to 2 mph
Travel speed during mobilization	Posted speed limit	Posted speed limit
Real-time display[f]	Single sensor pair waveforms in time domain at reduced display rate	Waveform and resonant frequency at each senor
System monitoring and control	Within or outside the survey vehicle	Within or outside the survey vehicle
Data collection rate	Based on speed and sensor spacing on the sensor array	Based on speed and sensor spacing on the sensor array
Spatial reference	Vehicle DMI, external distance wheel, or GPS	Vehicle DMI, external distance wheel, or GPS

[a] The primary difference between SASW and IE hardware is the configuration of the impact source and the number and location of receiver sensors. SASW typically has two sensors spaced away from the impact source. IE has one sensor spaced relatively close to the impact source.

[b] The NDT system hardware should include variable frequency sources and sensors so the testing can be effectively performed under diverse climate and material conditions.

[c] The spacing between the units in the array must consider the desired level of measurement density and signal interference from adjoining units. Signal interference must be avoided by controlling the lateral and longitudinal spacing between units and the test sequence. The proposed equipment specification, at the maximum unit spacing and longitudinal collection rate, would generate data for every 2 ft^2. Higher measurement densities of every 1 ft^2 can be achieved with available prototype equipment.

[d] The lane width covered by each pass is a function of the number of testing units in the array. Full lane width during a single pass can be achieved with a sufficient number of measurement units. The purpose of the array is to collect equally spaced parallel lines of data simultaneously so that coherent areas of delamination can be identified and mapped.

[e] The measurement is sent and received in milliseconds, but the entire process includes lowering and seating the source and sensor(s), initiating the source impact, collecting the sensor response, lifting the source and sensor(s) and storing the data. Speed of data collection is influenced by this sequence of tasks.

[f] Real-time data display should be used to monitor the consistency of the measured data. It will provide a preliminary level of pavement uniformity, but more importantly it will show if the NDT system array is operating properly.

3 Proposed Data Output and Display Requirements

The field operation and playback software for SASW should be capable of the following displays:

- Direct sensor time-amplitude waveform; and
- Surface wave velocity–wavelength dispersion curve.

Examples of this display are shown in Figure C1.1, Figure C1.2, and Figure C1.3. The field operation and playback software for IE should be capable of these displays:

- Direct sensor time-amplitude waveform;
- Converted amplitude-frequency curves; and
- Longitudinal thickness profile for a given transverse offset.

An example of this display is shown in Figure C1.4.

Output Format

- SASW output should be a volume of data with velocity as a function of x (longitudinal distance), y (transverse offset), and z (depth).
- IE output should be an area of data with thickness as a function of x (longitudinal distance) and y (transverse offset).

4 Equipment Calibration and Verification

Equipment calibration is critical. Calibration is defined as comparing the response of the test component against a known standard. Bench calibration of each component should follow the manufacturer's recommendations. It is suggested that calibration of the system, or a component, be conducted whenever a verification test shows a problem.

Verification of all the components of the system is recommended prior to the start of testing. Verification is defined as observing the response of the test against a known sample. The user should have a procedure to perform verification where the equipment is normally stored and in the field just prior to testing. A pavement slab constructed in a parking lot with known materials to exact dimensions can provide repeatable verification tests. Testing should only proceed after conducting all the verification steps. The manufacturer should have recommended verification procedures.

A distance measurement instrument (DMI) or global positioning system (GPS) unit is used to record the location of each measurement. It is common to use a DMI to trigger each NDT test. The DMI will either be attached to the wheel of the survey vehicle or to a separate wheel attached to the test equipment. The measurement device should be regularly calibrated as prescribed by the manufacturer and verified by the user prior to the start of testing. The DMI is calibrated by running the system over a pre-measured distance (usually ranging from 1,000 feet to one mile, but may be shorter for smaller manual systems). The measured distance expressed by the DMI is compared to the known distance, and the DMI calibration factor is adjusted so that the two will agree. It is advisable to repeat the calibration after the calibration factor has been adjusted to confirm that the calibration has been carried out correctly. The measured distance should be within a foot (0.1% accuracy) of the pre-measured 1,000 feet distance after the repeat calibration run. Most commercial dashboard DMI units measure in increments less than 1 foot. DMI units for dedicated NDT sensor systems have much finer resolution (typically 0.1 ft). For longer surveys, over 1.0 mile, user marks should be entered into the data at ground control points (mile markers, intersections) for location referencing.

5 Climate and Pavement Conditions for Testing

In general, the SASW and IE testing works better on stiff materials that have high moduli. Testing asphalt pavements at colder temperatures is preferable. SASW testing has been successfully conducted at asphalt surface temperatures of up to 100°F. IE generally requires comparatively cool asphalt for testing, as resonant echo amplitudes decrease with increasing asphalt mixture temperature. Both SASW and IE analysis rely, to some degree, on knowing material properties. IE uses assumed P-wave velocity to calculate thickness; SASW calculates modulus, but needs some seed values to perform the calculation. Better estimates of the material properties can be applied by initially testing a location of sound pavement with a known thickness. The user should recognize that asphalt material modulus is a temperature-depth-dependent gradient. Pavement surface temperature should be monitored and recorded at the time of testing.

Testing should not be affected by the moisture present on the pavement surface. Frozen pavements with high moisture contents and frozen base/subgrade conditions should be avoided. Check with the manufacturer to establish if the equipment is weatherproof.

To get good signal measurements, the SASW and IE techniques require good contact between the tip of each transducer and the pavement surface. Both SASW and IE test methods have been successfully conducted on older asphalt pavement surfaces with moderate raveling (but no significant loose material on the pavement surface). For cracked asphalt surfaces, the SASW system will generate faulty data when cracks intersect the energy wave passing from the impact point to the transducers. While a point-test system may be carefully placed between the severely failed areas on a pavement surface, it is impractical to adjust the rolling-wheel system, so it will generate irregular data. The rolling-wheel system will work best on dense, low-texture asphalt pavement surfaces.

6 Testing Modes and Required Settings

The testing modes described in this section are prepared for a continuous testing equipment system. The discussion is also applicable to other SASW and IE equipment. The user should be familiar with the capabilities of the equipment they are operating.

The testing mode selected depends on the desired level of pavement condition detail. The permitted speed of data acquisition (travel speed of the equipment during testing) will establish the range of testing modes available. Currently, continuous SASW and IE test equipment is limited to speeds no greater than 5 mph. The slow testing speed limits the use of the equipment to project-level pavement condition evaluation and typically will require a lane closure.

The lane-width coverage depends on the number of measurement units in the array and the desired level of evaluation detail. For IE testing, each single wheel test unit could be spaced at 1- to 2-ft increments. Six units spaced at 2-ft increments would provide full lane-width coverage with measurements at 1, 3, 5, 7, 9, and 11 ft transverse across the lane. If a higher test density is needed, the six units could be spaced every 1 ft to cover half the lane. The measurement units are staggered from wheel to wheel to minimize signal noise from adjacent units.

For SASW testing, each test unit requires a set of two receiver sensors, plus the signal generator. The spacing between the receiver sensors should be adjusted for the thickness of the pavement. The optimum spacing depends on the thickness, condition, and stiffness of the pavement. Testing a thin pavement under cold, stiff conditions will obtain the best signal response with a short spacing. Testing a thicker pavement under warm conditions requires a longer spacing between the receiver sensors. The lateral distance between the receiver sensors is generally 6 to 12 in. Since shallower delamination in the pavement is often a greater concern, the spacing between the sensors is typically 6 in. The distance between the units is typically 2 ft. The SASW test measures the surface waves travelling across the pavement, so it is important that the testing is staggered.

For project-level testing, multiple forms of spatial reference should be employed. In addition to the DMI or GPS system to log the test locations, the data collection software should permit the user to annotate roadway features into the data as the testing proceeds. Mile markers, intersections, bridges, and roadside traffic control signs are good physical references that should be in the data.

The user should prepare a testing plan before starting field testing. The plan should include:

- Proper assembly and verification of the test equipment;
- Start and end of test section;
- Condition of pavement surface;
- Type of test to be used;
- Frequency of measurement (i.e., distances between test points, number of replicates);
- Test speed (i.e., distance covered during continuous testing) or the number of tests conducted per minute for point-test devices;
- Type of output data that will be monitored during the test; and
- Amount of time required to complete the field testing. This includes time to return to the beginning of the test for multiple passes when full lane-width testing is not possible.

7 Test Output Data Formats

The goal of field data collection is to produce a three-dimensional volume of measurements. The *x* distance is defined as the longitudinal direction of vehicle travel in the lane. The *y* distance is the transverse direction, including the spacing between measurement units. The *z* values represent depth as determined from the measured waveform received by the receiver sensors.

SASW tests generate a data file that ties the signal response waves of the impactor and two receivers to the *x* (longitudinal distance) and *y* (transverse offset) test location. Once the data is processed, the output data file converts the response waves into a surface wave velocity as a function of *z* (depth). The final output data file is a 3-D array of material response measured as wave velocity. Each *x, y, z* coordinate has a computed wave velocity.

IE tests generate a data file that ties the signal response wave frequency measured by the receiver sensor to the *x* (longitudinal distance) and *y* (transverse offset) test location. Once the data is processed, the output data file converts the response wave frequency into a measured pavement thickness. The final output data file is a three-dimensional array of the contour of the bottom of the pavement. When the test encounters a debonded area, the measured pavement thickness reflects the depth of the delamination.

The format of this data volume will vary with each equipment manufacturer. The equipment manufacturer’s software will combine these files into the 3-D volume. The wave data analysis may be generated directly during data collection and further refined as a part of post-processing.

SASW field operation and playback software should be capable of the following displays:

- Direct time domain waveforms from each of the two receivers;
- Dispersion curve for each wheel pair; and
- Waterfall plot of dispersion curves collected versus distance covered for each wheel pair.

IE field operation and playback software should be capable of the following displays:

- Direct time domain waveforms from each source-receiver pair and
- Running amplitude/thickness plot, or equivalent B-scan, for each sensor wheel.

8 Test Output Data Quality Control Checks

At the end of testing, the signal data collected from the transducers should be checked for quality according to the manufacturer’s data quality control check procedure. This quality control check should be performed while the equipment is at the pavement site and the traffic control is still in place. If problems are encountered or there are data of questionable quality, the data collection should be repeated.

This process is partially automated but may require considerable user interaction. The quality control process should include:

- Correlating the field notes with the data files to ensure that all noted files actually exist;
- Checking all of the recorded data files to confirm that their size is consistent with the amount of data collected;
- Scrolling through each data file to ensure that the data looks reasonable and that there are no problems with the data: and
- Checking the recorded pavement length of each file (recorded distance) and confirming that it agrees with the intended length.

It is also a good practice to check for the roadway features recorded in the data file to make sure the distance measurement data recorded and lined up with the signal data correctly.

After reviewing the NDT results and other pavement condition survey information, it is recommended that field cores be cut at the locations where potential delamination is identified to verify the delamination condition.

The equipment manufacturer's analysis software should have one or more features to identify data that would be viewed as outliers, based on expected data ranges. This is similar to scrolling through the data as a reasonableness test. This feature is particularly important for continuous tests systems that do not have replicate values and could encounter poor test conditions, like cracks and potholes. The software should highlight all suspect data and allow the engineer to determine the credibility of the values.

9 Data Analysis

Each SASW data set collected during field measurement associates two receiver sensor surface wave traces with a single *x-y* pavement coordinate location. Differences in the time-history of each wave response are analyzed and converted into surface wave velocity versus wavelength, which is referred to as the dispersion curve. The wavelength component is related to pavement depth. The resulting surface wave velocity versus depth curves will be smooth when the test is measuring a sound pavement. See Figure C1.2. When the test encounters material delamination, there is a break and significant drop in the wave velocity. See Figure C1.3.

Once the surface wave velocities versus depth are computed, the 3-D array of velocities can be studied for changes in the wave-velocity pattern. Visual analysis is used to help identify the location and depth of the delaminated area that is associated with a sharp drop in the SASW surface wave velocity. The processed surface wave velocity data is divided into increments of depth (depth slices), and the velocity at each depth is displayed as grayscale or color-coded 2-D maps. Figure C1.5 shows examples of depth slices at different depths. Higher surface wave velocity (dark shade) is an indicator of better pavement condition. Anomalies can be seen as light spots where the velocities are lower. The light-colored areas in the slice at 0.4 ft (4.8 in.) depth represent the constructed delaminated interface at a depth of approximately 5 in. The lower wave-velocity measurement will continue to reflect in the depth slices below the location of the delamination, even though the material below the delamination is sound.

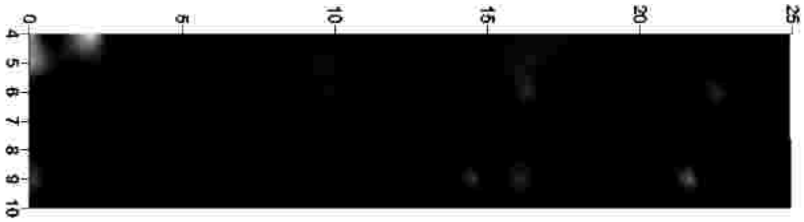
The analysis of IE data is more direct. Each set of IE data measured in the field is a single receiver sensor waveform tied to a single *x-y* pavement coordinate location. The P-wave data is analyzed and the resonant frequency of the wave is determined. The resonant frequency is then converted into the computed thickness of the pavement. The final 2-D display is the computed thickness of the pavement based on the *x-y* locations of the measurements. Figure C1.6 is an example of an IE pavement-thickness display. With a general knowledge of the constructed pavement thickness, IE results that show a thinner (or thicker) pavement thickness are areas with delamination or other significant change in material properties. The IE test analysis does not require the examination of depth slices to locate delamination as is done with GPR and SASW technologies.

10 Test Reporting

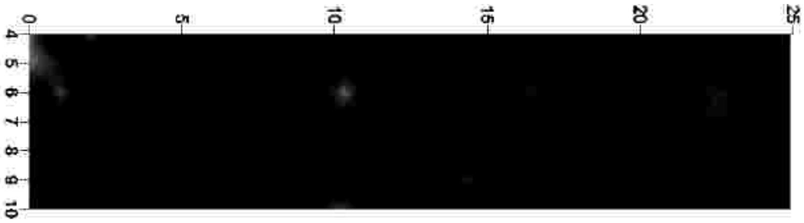
The speed of SASW and IE testing (not over 5 mph) limits the use of these NDT technologies to project-level analysis. As such, common reporting formats used for network-level summary of pavement distress are not applicable to these technologies. This section discusses an alternative method of reporting SASW and IE data for project-level engineering review.

Using color-coded depth slices for visual identification of areas with potential delamination can be labor intensive. There are tabular reporting methods to identify potential delamination based on percentage (or count) of test locations with velocities in specified ranges for each depth-slice increment. The example in Table C1.2 shows the data divided into 0.1 lane-mile increments. In the example, Lane-Sections 35.3 and 35.4 show a significant increase in low-velocity measurements at the 0.5 to 0.75 ft depth. These sections would be highlighted and reviewed in more detail.

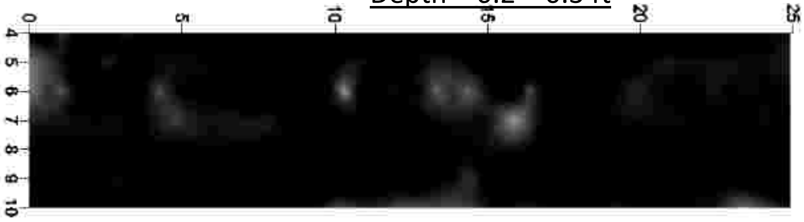
Summary data at 0.1 lane-mile increments gives the engineer a quick method to identify pavement lengths with areas of interest (potential delamination). For typical pavement rehabilitation projects that are 5 to 10 miles long, the 0.1 mile summary data generates 50 to 100 sets of data to examine. Each 0.1 lane-mile increment should generate over 1,000 velocity tests at each depth slice. Simple summary statistics for over 1,000 data points may not identify areas of delamination. The summary data must identify differences in the data by focusing on specific surface wave-velocity ranges.



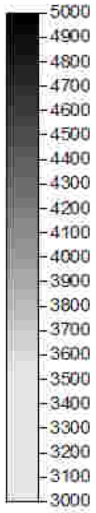
Depth = 0.1 – 0.2 ft



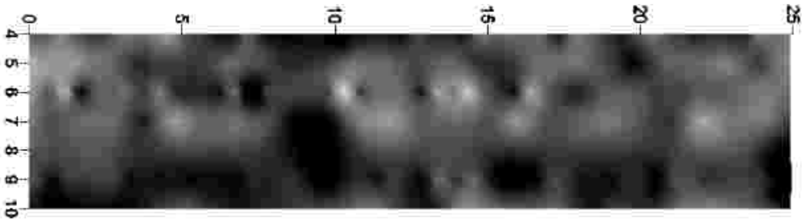
Depth = 0.2 – 0.3 ft



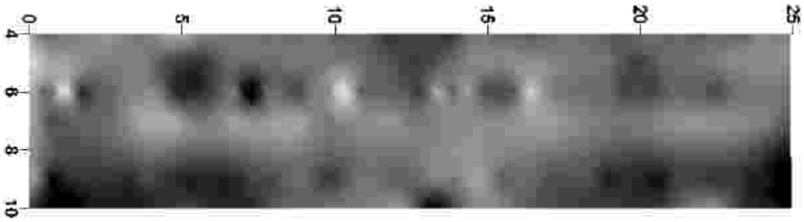
Depth = 0.3 – 0.4 ft



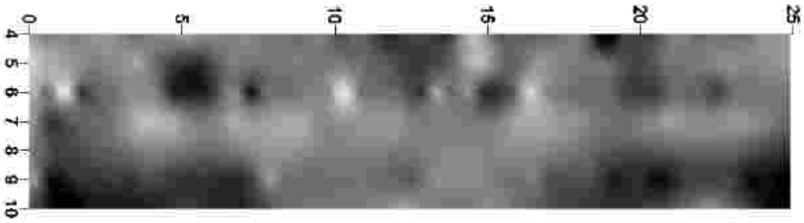
Surface Wave Velocity (ft/sec)



Depth = 0.4 – 0.5 ft



Depth = 0.5 – 0.6 ft



Depth = 0.6 – 0.7 ft

Figure C1.5. Depth slices of the SASW measured surface wave velocity at incremental pavement depths.

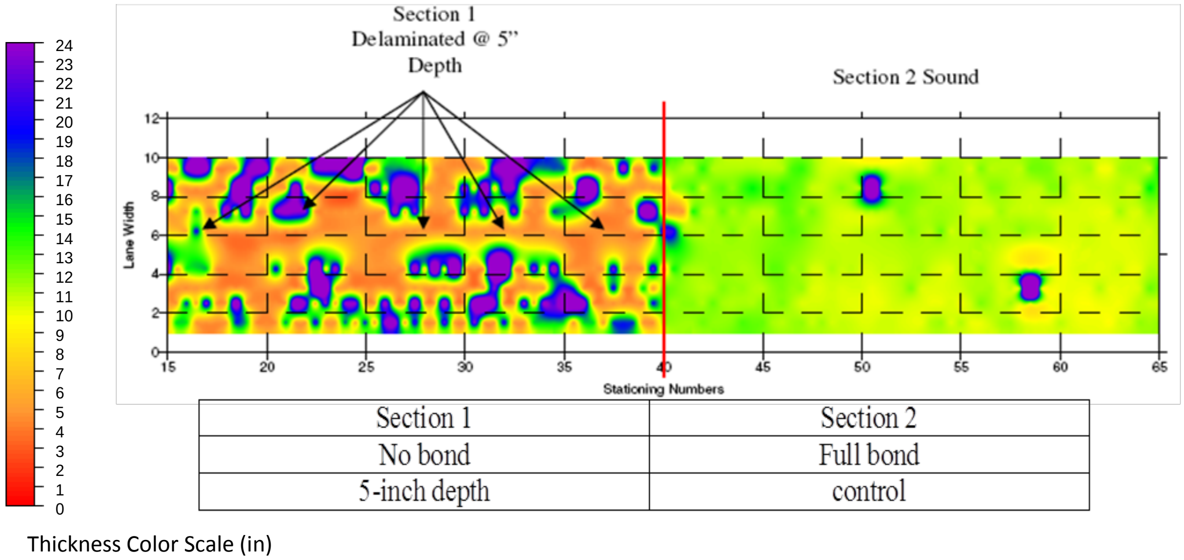


Figure C1.6. Example of impact echo pavement-thickness plot.

Table C1.2. Example Reporting of SASW-Processed Surface Wave Velocity Results

Lane Section	**Depth = <0.25 ft**			**Depth = 0.25 to 0.50 ft**			**Depth = 0.50 to 0.75 ft**		
(MP) (direction)	**Velocity greater than 4,500 fps**	**4,000 to 4,500**	**Less than 4,000**	**Velocity greater than 4,500 fps**	**4,000 to 4,500**	**Less than 4,000**	**Velocity greater than 4,500 fps**	**4000 to 4,500**	**Less than 4,000**
35.1 EB	90	8	2	85	12	3	75	20	5
35.2 EB	92	7	1	86	11	3	77	18	5
35.3 EB	90	7	3	85	13	2	40	40	30
35.4 EB	92	7	1	55	35	10	10	30	60
35.5 EB	91	8	1	86	13	1	76	20	4
35.6 EB	90	7	3	86	11	3	75	19	6

APPENDIX C2
SASW/IE Vendor Features

Olson Engineering, Inc./
Pavement and Bridge Deck Scanner (PBDS) SASW-IE

(prepared by Olson Engineering)

1. **General overview of the system**

   The system consists of a minimum of two transducer wheels and up to six transducer wheels. All transducer wheels are identical. An Olson Instruments computer based data acquisition system (Freedom Data PC) is used to control the transducer wheels. An external distance wheel attached to the moving mechanism is used to record of the location of the tests. The system can be mounted to either a vehicle hitch (if all three pairs of transducer wheels are used) as shown in Figure C2.1 or a scanning cart (if only a pair of transducer wheels are used) as shown in Figure C.2.2. The system performs well on dry and damp surface conditions. The system should not be used while raining or snowing. However, the system can be used immediately after the road is clear.

   Each set of transducer wheels of the BDS system can perform:

   a. Impact Echo (IE) tests on both wheels simultaneously in two scan lines (one scan per each wheel) by offsetting the transducer elements (by approximately 3 inches or 76.2 mm) and having the impactors from both wheels turned on. Note that the spacing between the two adjacent transducer wheels can be set between 6 inches (0.15 meter) and 2 feet (0.61 meter) depending on the scan resolution desired for the testing.

   b. Impact Echo and Spectral Analysis of Surface Waves (SASW) scanning simultaneously by aligning the transducer elements of both transducer wheels. The first transducer wheel (with the impactors on) can be used to perform the Impact Echo test. The second wheel (with the impactors off) can be used as the second transducer to acquire data for the SASW test analysis. Note that both Impact Echo and Spectral Analysis of Surface Waves tests can be performed simultaneously in a single scan.

2. **PBDS Software**
   a. Real-time Display and Processing

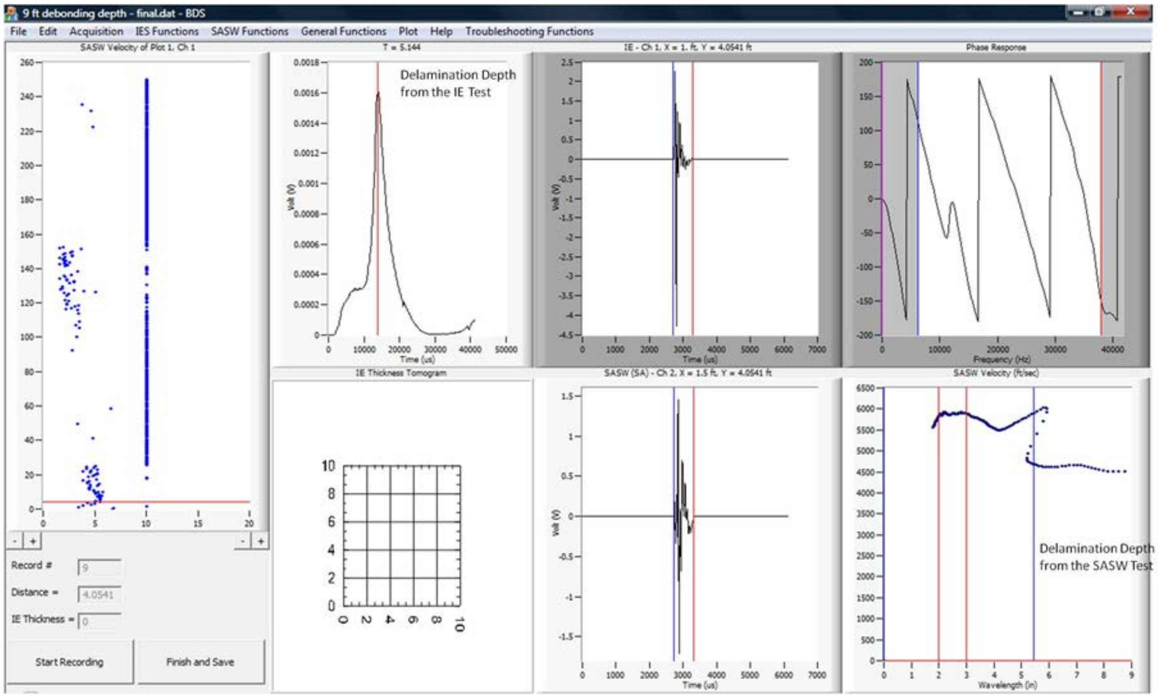
      The software acquires and displays the time domain waveform of each transducer wheel in real-time for both SASW and IE scanning. For the Impact Echo Scanning option, the software calculates the linear displacement frequency spectrum from the Fast Fourier Transform (FFT) of each time domain waveform, displays the displacement spectra, automatically identifies the dominant frequency and calculates the echo thickness associated with the dominant IE resonant frequency. All of these processes are performed real-time. For the spectral analysis of surface waves test data, the software calculates the phase information and dispersion curves (surface wave velocity versus wavelength) for each impact(s). Delamination of the asphalt can be automatically identified from the drop (decrease) of surface velocities in the dispersive curve at wavelengths corresponding to the asphalt lift depth(s).

Figure C2.1. Pavement and bridge deck scanner (PBDS) towed behind a vehicle—3 pairs of wheels at 2 feet (0.61 meter) apart.

Figure C2.2. PBDS system attached to a scanning cart on asphalt overlaid bridge deck—single pair of wheels at 6 inches apart for combined impact echo/surface waves scanning.

b. Data Analysis

The data analysis of the IE tests includes identifying the dominant frequency peak in the spectrum to determine the depth (thickness) of the asphalt (or delamination). The IE tests work best when the asphalt is colder (50°F or less) and therefore its modulus and surface hardness are more concrete-like so that the weaker compressional wave energy resonates (echoes) strong. For the SASW tests, the software automatically calculates the phase data and automatically masks or removes the glitches in the phase data. Based on the processed phase data, the software calculates the dispersive curve. Delamination of the asphalt can be automatically identified from the drop (decrease) of surface velocities in the dispersive curve at wavelengths corresponding to the asphalt lift depth(s). A screen shot of the processed/analyzed data from the NCAT test track over known delamination (debonding) of the asphalt lift is shown in Figure C2.3 below. The analysis is performed automatically by the software.



Record # 9

Distance = 4.0541

IE Thickness = 0

Figure C2.3. A screenshot of the processed/analyzed data.

3. **Final Output**
   Test results (thickness or delamination depth) from each scan line are put together. The final output is a graphical image with color or grayscale plots representing depths of delaminations.

4. **Equipment Upgrades and Service**
   More transducer pairs can be added on to the system (currently up to 3 pairs or 6 transducer wheels).

5. **Future Developments**
   It is planned to further develop the software so that upon completion of scanning a pavement or bridge deck, the data analysis is done and ready for review in a matter of 5 minutes or less. In addition, recent laboratory experiments indicate that the system may be capable of impacting the pavement/deck with the normal strong initial impact and then a second weaker impact at each test location. This will provide for the calculation of coherence (indicator of signal to noise ratio with a value of l.0 being excellent quality data and a value of 0 being very poor quality data) versus frequency (Hz) in SASW tests. The second impact may also improve the quality of the IE data by being able to compare single impacts versus the average of two impacts at each test location. A larger diameter distance wheel is also planned to more accurately measure distance. In addition, GPS may be incorporated to the Freedom Data PC for general test location purposes although it is expected the

distance wheel will be the most accurate measurement of distance. If desired, a video camera could also be incorporated into the PBDS system to provide operators with surface images of each scan.