Primer

# Advanced Methods to Identify Pavement Delamination (R06D)

## NDT to Detect Asphalt Pavement Delamination Guide

April 8, 2019

# Contents

# Acronyms and Abbreviations

- 3D is the abbreviation for three-dimensional
- AC is the abbreviation for asphalt concrete
- DMI is the abbreviation for distance-measuring instrument
- GHz is the abbreviation for gigahertz
- GPR is the abbreviation for ground-penetrating radar
- GPS is the abbreviation for global positioning system
- Hz is the abbreviation for hertz
- IE is the abbreviation for impact echo
- MHz is the abbreviation for megahertz
- mph is the abbreviation for miles per hour
- NDT is the abbreviation for nondestructive testing
- SASW is the abbreviation for  spectral analysis of surface waves
- SHRP2 is the abbreviation for second Strategic Highway Research Program
- User Guidelines refers to Nondestructive Testing to Identify Delaminations between HMA Layers Phase 2—Develop User Guidelines

# Executive Summary

This report provides guidelines for using ground-penetrating radar (GPR) and mechanical wave (spectral analysis of surface waves and impact echo) nondestructive technologies (NDT) to detect delamination between asphalt pavement layers. These technologies comprise the Advanced Methods to Identify Pavement Delamination R06D products, which were developed through the second Strategic Highway Research Program (SHRP2). The Advanced Methods to Identify Pavement Delamination NDT products can be used by transportation agencies to detect the location and severity of delamination before the pavement deficiency causes visible pavement distress. More detail can be found in the R06D Study Phase III task report. The target users are highway agency pavement design and pavement management engineers and consultants who provide the same services. The guidelines identify the hardware and software requirements necessary to achieve measurement across a pavement lane width. Each NDT system can be configured to measure pavement response in a single pass, but current agency-preferred hardware requires two or more passes. Data analysis is challenging, and software to support data analysis is still advancing. Skilled technicians and engineers are needed to operate the equipment and analyze the data to assess pavement conditions and identify delamination.

The cost-effectiveness depends on how much each NDT system is used and where it is applied. Both NDT systems are suitable for forensic studies and project field investigations. GPR can also be used for network-level pavement assessments, but software development is needed to manage the volume of data and analysis. Both NDT systems can also be used to assess other roadway features, such as bridge decks. The NDT companies continue to improve their systems as demand for the technology expands.

Stand-alone user guidelines for both technologies are included as Appendixes A and B. The guidelines include general theory, equipment specifications, data output and display requirements, equipment calibration and verification, testing conditions, data format and quality control, data analysis, and test reporting. Both technologies can be used to detect discontinuities in asphalt pavements; however, they cannot be used to conclusively distinguish between types of pavement discontinuities.

# Background

## What is Delamination?

Delamination is a loss in the continuity between asphalt concrete (AC) layers in the total thickness of asphalt pavement. Delamination can cause several types of surface distress, such as longitudinal cracking in the wheel path and tearing in the surface. Delamination results primarily from debonding between AC layers or stripping within an AC layer. Debonding occurs when there is improper tack between 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.

## How is Delamination Identified?

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

## Nondestructive Testing Technologies Available

The Advanced Methods to Identify Pavement Delamination SHRP2 R06D study was initiated to evaluate NDT technologies that could detect delamination and further develop the most promising methods to accomplish construction, project-level, and network-level evaluations. NDT for construction quality assurance should detect debonding after an AC lift is placed. NDT for project-level investigation should provide a detailed identification of the delamination location and severity. NDT for network-level assessment should detect the presence of delamination with the test equipment operating full-lane width at a safe highway speed.

NDT technologies were evaluated in both controlled and uncontrolled conditions. The controlled evaluation included ten 25-foot control and delaminated pavement sections constructed on the National Center for Asphalt Technology Pavement Test Track. The NDT systems were evaluated under warm-dry and cool-wet pavement conditions. Based on the results of the controlled evaluation, ground-penetrating radar (GPR) and mechanical wave technologies were identified as most promising for achieving the study objectives.

GPR and mechanical-wave vendors agreed to work with the research team through seed-money agreements to improve their hardware and software before further evaluation. The GPR vendor manufactures a lane-width, air-launched antenna array with software that processes the raw data into a three-dimensional (3D) visual display. The hardware improvement focused on modifying the vehicle attachment for safe and secure transport between testing sites. Software improvements were developed to help users examine the GPR measurements in greater detail and streamline the data analysis. 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 cannot be achieved with the current analysis methodology.

The mechanical-wave vendor demonstrated a prototype device with two rolling wheels that conduct impact echo (IE) and spectral analysis of surface waves (SASW) measurements along a longitudinal path. Further hardware development focused on increasing the number of wheels to measure a 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. IE can identify variations in the pavement below 4-inch depth, and SASW can identify variations in the top 7 inches of the pavement. However, IE should be conducted on cool and stiff asphalt surfaces, and SASW analysis requires a reasonably accurate input value for pavement stiffness. 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.

Both GPR and mechanical-wave vendors made improvements in their hardware and software. GPR can conduct field tests full lane width at moderate testing speed without a lane closure and is appropriate for preliminary assessment of pavement condition over a project length. Mechanical wave methods are limited to testing at approximately 1 mile per hour (mph), but this is still a significant improvement over manual point-test methods. IE and SASW will require a lane closure and can be used to supplement GPR results to better define the boundaries of pavement damage. Software is available to analyze data in great detail but is predominantly a manual process requiring a trained technician. Further improvement in software is needed to reduce the analysis time to make NDT an effective tool for detecting delamination in AC pavements.

Both technologies can be used to detect the location and depth of discontinuities in asphalt pavements; however, they cannot be used to conclusively distinguish between types of pavement discontinuities. Coring or other NDT methods will be needed at critical locations identified by NDT to confirm the nature of the discontinuity so that engineers can select the proper pavement maintenance, preservation, or rehabilitation strategy.

## User Guidelines

Most of this guide is extracted from the SHRP2 Advanced Methods to Identify Pavement Delamination study Phase III task report, Nondestructive Testing to Identify Delaminations between HMA Layers Phase 3—Develop User Guidelines (user guidelines; Heitzman et al., 2015). The user guidelines are intended to be a concise overview, not a detailed user operation manual. The user guidelines are a tool for interested pavement engineers that follow a logical sequence of topics. Both the GPR and mechanical-wave guidelines use the following format and a separate user guide was prepared for GPR and SASW/IE and are found in Appendixes A and B:

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

## Target Audience

The target audience must have a need for these NDT products, funding to purchase and maintain the equipment, and a level of technical expertise to operate the equipment and analyze the data. The primary target audience is pavement design engineers of state highway agencies. State highway agencies are responsible for most moderate- to high-volume routes and are most likely to have resources to purchase NDT equipment. The second target audience is pavement management engineers responsible for measuring and monitoring the pavement network condition. The third target audience is consulting engineering firms that provide pavement assessment and design services. Each target audience has individuals that operate and maintain testing equipment and process and analyze pavement data.

Two factors that influence the target user's level of interest are the ability to use the equipment for multiple purposes (for example, pavements and bridge decks) and understanding that these NDT systems require a "black box" to collect and analyze the data.

The cost-effectiveness of each NDT device depends on the level of intended use and the diversity of applications to which it is applied. Specific for these SHRP2 Advanced Methods to Identify Pavement Delamination products, both systems are suitable for pavement forensic studies and field investigations for pavement rehabilitation projects. GPR could be used for network-level pavement assessment but managing the volume of data and timely analysis will require further software development. Both systems can be used for field measurements to assess the condition of other roadway features, such as bridge decks.

The SHRP2 Advanced Methods to Identify Pavement Delamination study established and confirmed that NDT technologies can be important tools for assessing pavement condition and identifying the presence of pavement distress. 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.

## Ground Penetrating Radar

### Test Overview

GPR detects moderate to severe delamination by observing spatially coherent anomalies in the GPR data at specific depths. GPR also identifies debonding between asphalt lifts if water is present in the seam between the layers. This detection capability was advanced using a multiple antenna array distributed across the pavement width. The antenna array collects parallel lines of data to identify and map areas of delamination in the pavement under the width of the antenna array while the system passes over the pavement surface.  The number of passes driven to measure an entire 12-foot-wide lane depends on the width of the antenna array. The data collection is typically triggered using a distance-measuring instrument (DMI) mounted to the vehicle wheel or to an external distance wheel.  Geospatial location of the measurement is collected by tying the testing to a global positioning system (GPS).

### Technology Theory

GPR operates by transmitting short pulses of electromagnetic energy into the pavement using an antenna. These pulses are reflected back to an antenna with an arrival time and amplitude that are related to the location and nature of the subsurface materials. These radar waveforms contain 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. The dielectric constant of the material and velocity of wave propagation are affected by both the presence of moisture and air voids.

## Equipment

A GPR system can be implemented using one or more antennas, with four or more antennas considered a multiple antenna array. The purpose of an array is to collect equally spaced parallel lines of data simultaneously so that coherent areas of pavement discontinuity can be identified and mapped. Data is collected continuously while the system is driven along the pavement surface. Tables 1 and 2 show proposed specifications for a GPR system that can be used to evaluate delamination in asphalt pavements.

Assemblies for mounting an antenna array vary between GPR users. The general guidelines for designing mounting hardware are 48 inches between the vehicle bumper and antenna, 12 to 18 inches between the antenna and pavement surface, the frame is composed of non-ferrous metals (aluminum) or plastic composites, and the frame includes diagonal bracing to minimize antenna bounce or sway.

**Table 1. System Requirements for GPR for Detecting Delamination**

| System Component | GPR 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 more than 2.0 gigahertz (GHz); -10 decibel limits: 0.5 to 5.0 GHz |
| Frequency range—frequency sweep radar systems | Frequency range: typically from 200 megahertz (MHz) up to 3.0 GHz |
| Lateral spacing of antenna elements | Less than 1.5 feet |
| Lateral coverage per pass | Controlled by antenna array width, recommend a minimum 6 feet to achieve full lane-width coverage in two passes |
| Longitudinal data collection rate | More than 2 scans per foot per antenna element |
| Travel speed during data collection | More than 20 mph, recommend posted speed |
| Travel speed during equipment mobilization to test location | Posted speed limit |
| Real-time display | B-scan for selected antenna elements |
| System monitoring and control | From within the test vehicle |
| Data collection rate | Data collection should be triggered on distance using a DMI |
| Spatial reference | Vehicle DMI, external distance wheel, or GPS |
| Detection depth range for pavement delamination | 2 to 12 inches |

**Table 2. Data Output and Display Requirements for GPR**

| Requirement | 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 have the following displays:<br>• Direct-time domain waveform (A-scan)<br>• Longitudinal profile for a given transverse offset (B-scan)<br>• Time and depth slice for a given time range (C-scan)<br>• Transverse profile for a given location or station |

### Test Procedure

Data collection is typically triggered using a DMI mounted to the vehicle wheel or to an external distance wheel. The array of measured signals produces a 3D dataset of the amplitude of the GPR signal, Amplitude (x,y,z), where x is longitudinal distance, y is transverse offset, z is GPR time in nanoseconds (which is converted to depth).

### Data Analysis

Testing conducted under SHRP2 Advanced Methods to Identify Pavement Delamination Study using actual measured GPR arrays showed that debonded asphalt layers with trapped moisture and stripped asphalt layers, will produce detectable reflections not normally measured with intact pavement layers. Semi-automated software procedures to detect these reflections and map the areas of potential damage were developed and demonstrated under this study. Only limited commercial analysis software is currently available. Two methods of measuring these damage-related reflections were Method 1, using variations in waveform amplitudes in the time domain, and Method 2, using a delamination detection algorithm in the frequency domain. Other methods of automated analysis were examined during the Implementation Assistance Program.

## Impact Echo and Spectra Analysis of Surface Waves

### Test Overview

SASW and IE methods can detect delamination by observing spatially coherent anomalies in the data at specific depths. Lane-width SASW detection capability was demonstrated using multiple pairs of motion sensors (displacement transducers) with an impact source in an array distributed across the pavement width. The automated IE system is an array of measurement units, each consisting of one impact source and one motion sensor. The system array collects parallel lines of data simultaneously to identify and map areas of delamination across the full width of a 12-foot wide lane, while the system is moved along the pavement surface. The data collection is typically triggered using a DMI mounted to the vehicle wheel or to an external distance wheel. Under the SHRP2 study, the capability to measure full-lane width was demonstrated, but the evolution of the NDT system is a single test cart making multiple passes to measure the target pavement area in question.

## Technology 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 material surface to generate three primary elastic waves—R-, P-, and S-waves—and then measuring the waves propagating to some distance(s) from the source impact.

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. The dispersion curve changes when a pavement material discontinuity occurs.

In the IE test, an impact source is used to transmit a high-frequency mechanical (sound) wave into the pavement, and a receiver measures 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. The frequency changes when a pavement discontinuity is encountered.

## Equipment

Currently, most commercially available portable devices for conducting SASW and IE tests on pavements are point-test devices. To improve the testing efficiency, testing equipment mounted on rolling wheels was 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 slow walking speed. Tables 3 and 4 show proposed specifications for an array of three testing units to cover a half-lane width as demonstrated for the R06D study. Currently, a single test unit is the only continuous measure NDT system being developed. The specification for the "continuous" SASW and IE testing equipment with rolling wheels can travel at a modest 1 mph, taking measurements every 6 inches, and completing 3 tests per second.

**Table 3. System Requirements for SASW and IE for Detecting Delamination**

| System component | SASW specification | IE specification |
|---|---|---|
| System type | Array of impact sources and pairs of motion sensors, lined | Array of impact sources and motion sensors, lined up |

**Table 3. System Requirements for SASW and IE for Detecting Delamination**

| System component | SASW specification | IE specification |
|---|---|---|
| | up transverse to the direction of travel | transverse to the direction of travel |
| Sensor response frequency | Up to 50,000 hertz (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 feet between center of motion sensor pairs (maximum) | 2 feet between motion sensors (maximum) |
| Lateral coverage per pass | 6 feet (half-lane width) | 12 feet (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 a single 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 4. Data Output and Display Requirements for SASW and IE**

| Requirement | SASW | IE |
|---|---|---|
| Data Output | 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 | • Direct-time domain waveforms from each of the two receivers<br>• Dispersion curve for each sensor pair | • Direct-time domain waveforms from each source-receiver pair<br>• Running amplitude (thickness) plot, or equivalent b-scan, for each sensor pair |

**Table 4. Data Output and Display Requirements for SASW and IE**

| Requirement | SASW | IE |
|---|---|---|
| | • Waterfall plot of dispersion curves collected vs. distance covered for each sensor pair | |

## Test Procedure

The primary differences between SASW and IE hardware are the impact source configuration and the number and location of receiver sensors. SASW typically has two receiver sensors spaced away from the impact source. The spacing between the receiver sensors should be adjusted for the pavement thickness. The optimum spacing depends on the pavement thickness, condition, and material stiffness. IE has one sensor spaced relatively close to the impact source. The spacing between the units in the array must consider the desired level of measurement density and signal interference from adjoining units. 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. Data collection speed is influenced by this sequence, primarily the time for the receiver sensors to collect the impact response.

In general, the SASW and IE testing works better on stiff materials that have high moduli. Testing asphalt pavements at colder temperatures is preferable. To get good signal measurements, the SASW and IE techniques require good contact between the tip of each transducer and 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).

## Data Analysis

Both SASW and IE analyses rely 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.

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 are 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 3D array of material response measured as wave velocity. Each x, y, and z coordinate has a computed wave velocity. The wavelength component is related to pavement depth.

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 are processed, the output data file converts the response wave frequency into a measured pavement thickness. The final output data file is a 3D array of the contour of the bottom of the pavement. When the test encounters a debonded area, the computed pavement thickness reflects the depth of the delamination. 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.

## References


Heitzman, M., N. Tran, and K. Maser. 2015. Nondestructive Testing to Identify Delaminations between HMA Layers Phase 3—Develop User Guidelines. Second Strategic Highway Research Program, Transportation Research Board, Washington DC.

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

# Appendix A

# Use of Ground Penetrating Radar for Identifying Asphalt Pavement Delamination

1. General Theory
2. Equipment Specifications
3. Proposed Data Output and Display Requirements
4. Equipment Calibration and Verification
5. Climate and Pavement Conditions for Testing
6. Testing Modes and Required Settings
7. Test Output Data Formats
8. Test Output Data Quality Control Checks
9. Data Analysis
10. Test Reporting

## 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 (such as, air/asphalt or asphalt/concrete and reinforcing steel). The reflected energy is received in 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 asphalt concrete layers where the deterioration was at a moderate or advanced stage. Stripped asphalt concrete 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 (3D) database, Amplitude (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 at those spatial coordinates.

Testing conducted under SHRP2 R06D using antenna 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 was developed and tested under the R06D study.

Two methods of measuring these damaged-related reflections were explored in the study. 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:

$$AI_{(x,y)} = {A_{(x,y)}} \Big/ {A_{\left(x \pm \frac{L}{2}, y\right)}} \qquad \textbf{Equation A1}$$

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.

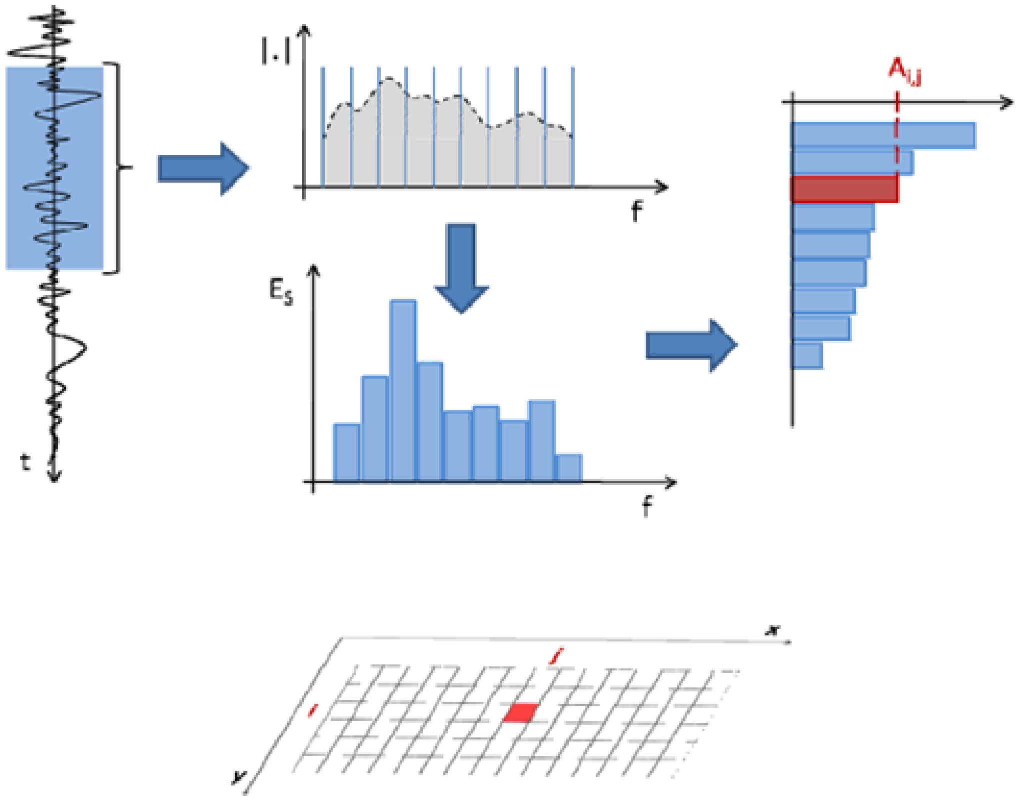
Another key parameter in the AI computation is the depth range over which this scan amplitude is calculated. The depth range should be selected to highlight the depth in which delamination or moisture damage is believed to be occurring. If this is not known, then a larger range can be used. Once cores 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 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 National Center for Asphalt Technology (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 3D radar data.

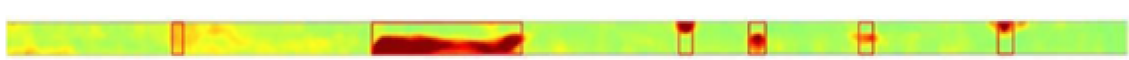
As represented in Figure A.1, the time window of interest is extracted from every trace and converted to the frequency domain. The frequency spectrum is then divided into frequency intervals, or “bins”. The energy contained in each bin is calculated and the bins are sorted by energy values.

**Figure A.1**




When an area is damaged, the wave form 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 (for example, bin 3 - the red bin in Figure A.1), the minimum size of delamination width and the cutoff threshold for the energy value that represents delamination, to produce a plot (Figure A.2) of the damaged areas. 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 A.2**



Additional automated analysis concepts were explored by some of the agencies during the Implementation Assistance Program phase of R06D. New Mexico Department of Transportation (DOT) commissioned Dr. Majeed Hayat to develop anomaly detection algorithms for a single horn antenna system, but the limited research effort was too small to be expanded to the analysis of a 3D database. One of Minnesota DOT's in-house GPR experts, Dr. Shongtao Dai, examined acoustic emission and energy ratio theories, which successfully identified delamination distress patterns from the NCAT Test

Track. Both Minnesota DOT and Florida DOT hired Dr. Ken Maser from Infrasense (a member of the R06D study team) to apply the AI, Method 1 above, to analyze pavement test sections.

## 2. Equipment Specifications

**Table A.1. GPR Equipment Specifications for Detecting Pavement Delamination**

| Component | Specification |
|---|---|
| System type | Array of multiple antenna elements lined up transverse to the direction of travel. |
| Frequency Range<br>-Impulse radar systems | Center frequency of pulse > 2.0 gigahertz (GHz)<br>-10 decibel limits: 0.5 to 5.0 GHz |
| Frequency Range<br>-Frequency sweep radar systems | Typically from 200 megahertz (MHz) up to 3.0 GHz |
| Lateral spacing of antenna elements | Less than 1.5 feet |
| Lateral coverage per pass | Controlled by antenna array width, recommend a 6-feet minimum |
| Longitudinal data collection rate | More than 2 scans per foot per antenna element |
| Travel speed during data collection | More than 20 mph, recommend posted speed |
| Travel speed during equipment mobilization to test location | 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) system |
| Detection Depth Range for pavement delamination | 2 to 12 inches |

Assemblies for mounting the antenna array to a test vehicle vary between GPR users. The general guidelines for designing the mounting hardware are 48 inches between the vehicle bumper and antenna, 12 to 18 inches between the antenna and pavement surface, the frame is composed of non-ferrous metals (aluminum) or plastic composites, and the frame includes diagonal bracing to minimize antenna bounce or sway.

Another critical equipment component is the power source for the antenna operation. Most portable power supplies that create electric current, such as portable generators, cause signal noise within the GPR data.  Clean power is obtained by using a battery source or placing a filter between the generator and the antenna system.

## 3. Proposed Data Output and Display Requirements

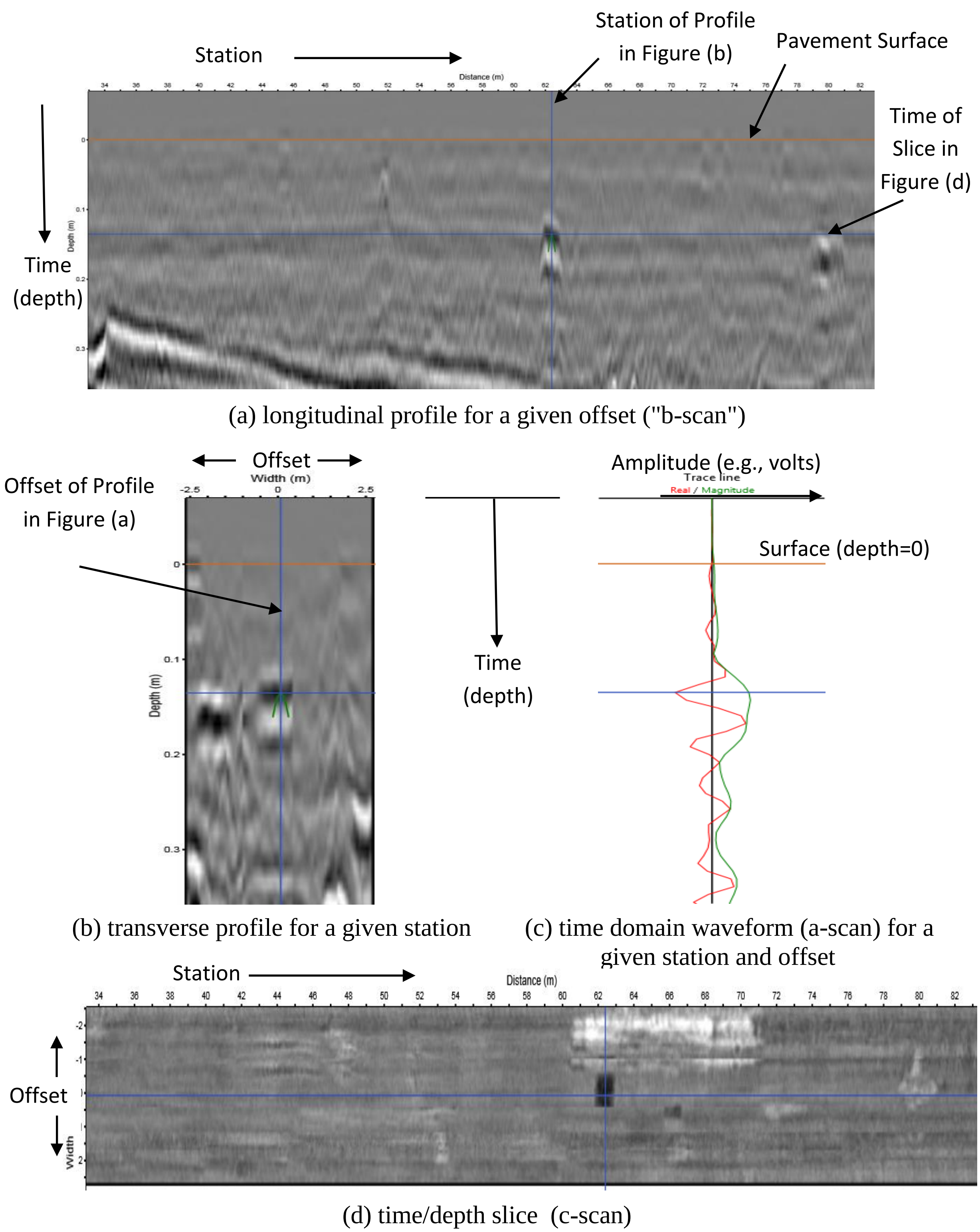
The field operation and playback software should be capable of the following displays:

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

Examples of these displays are shown in Figure A.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 A.3. Example of GPR system output delays**

## 4. Equipment Calibration and Verification

### Distance-Measuring Instrument 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 1 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 values 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 0.1% accuracy of the pre-measured distance after the repeat calibration run.

### Radar System Calibration

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

Field calibration of radar signal for determining pavement thickness will depend on the type of equipment system. Horn antenna systems usually require initial baseline measurement using a metal plate "bounce" test to provide data for calculating dielectric properties. A set of baseline tests were developed for the stepped-frequency array antenna by Dr. Kyle Hoegh at Minnesota DOT that consider increasing sample frequency and extracting the air wave through air and metal plate tests. Ground-coupled antenna systems have not used a metal plate and require other means for calculation of dielectric properties and thickness. Consult with the manufacturer for acceptable methods of field verification.

### Verification of Radar Operation

Awareness of problems in the GPR electronic signal is something that generally improves with the experience of the operator. Users should monitor antenna signal stability as outlined in AASHTO R37 Standard Practice for Application of Ground Penetrating Radar to Highways. Test procedures for measuring noise-to-signal ratio, signal stability, variation in time-calibration factor will vary for single frequency horn antennas, ground coupled antennas and step-frequency antennas. 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 the NCAT Pavement Test Track under the initial R06D study. Periodically, the equipment can be brought to the verification pavement 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-inch 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.

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.

Non-Array Ground-Penetrating Radar Systems

While this guideline recommends an array of antennas spaced laterally across the pavement, many organizations own single or dual antenna system which they may wish to apply for this delamination application. This is possible by collecting multiple passes of data so that the results 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 that 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 3D 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 3D 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 3D volume. In other array systems, the 3D volume will be generated directly during data collection.

Note that this application will generate very large data volumes. Consider, for example, a 1 mile survey, with an 8-antenna array collecting 2 scans per foot at 512 samples per scan. This collection will result in a file size of 8 x 2 x 512 x 2 (bytes/sample) x 5280 = 43 megabytes, 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 gigabytes 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 no problems with the data.
- 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. This section discusses the results of the R06D Study. The results of the Implementation Assistance Program (IAP) are discussed in the R06D final IAP report.

A 3D volume of amplitude data can be obtained by extracting the reflection amplitude values from a 3D 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 dielectric properties. The thickness of each pavement layer can be computed according to Equation 2:

$$h = {}^{c \times (\Delta t)}\!\big/_{2\sqrt{\varepsilon}}$$

Where h is the layer thickness, triangle t is the two-way travel time of the electromagnetic pulse wave through the layer, is the speed of light in free space (c = 3x 108 m/s or 11.8 in/ns), and e is the dielectric constant of the layer.

As part of the R0D Study, 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 inches (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 AI 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 AI analysis were chosen by picking the layers of interest in the 3D 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, then utilized at both the test site and field sites by using time slices through the C-scan at distinct intervals.

## 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 3D 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.

National Center for Asphalt Technology Site

Activity was determined in two 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 A.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 A.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.

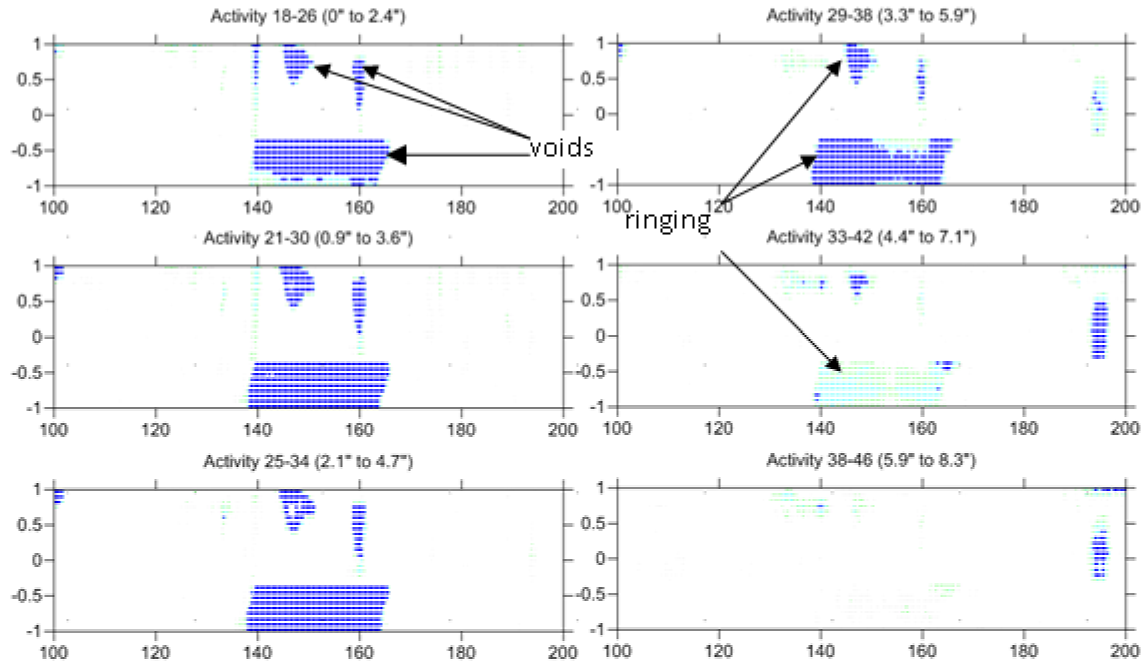



**Figure A.4, Activity Index for various slices from the NCAT test track**

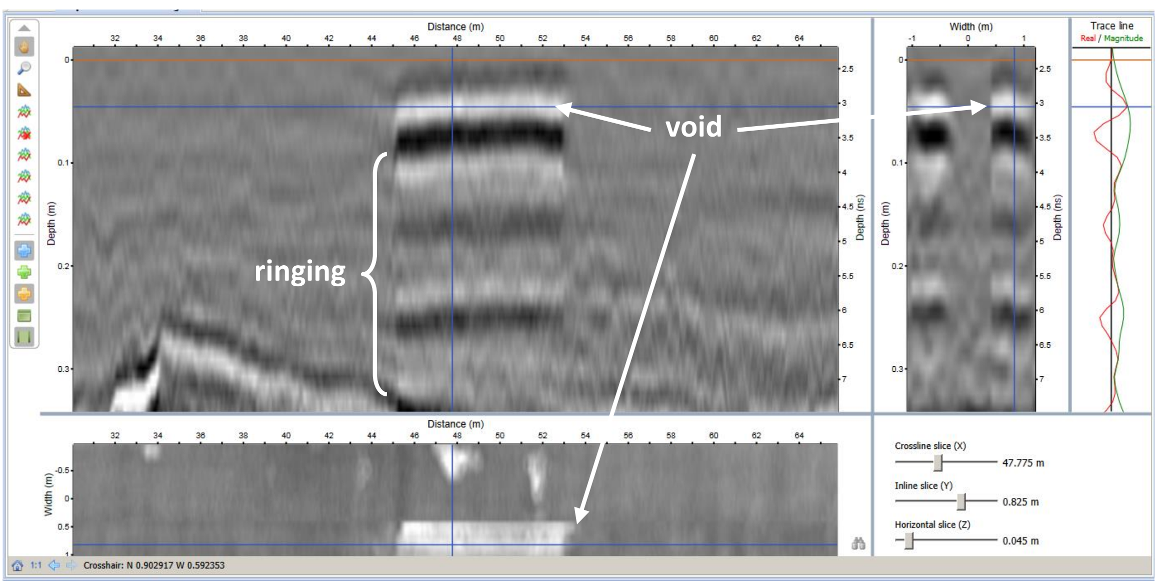



**Figure A.5, 3D radar representation of NCAT site showing "stripped" asphalt layers at 3 ns (1 to 2 in. below the ground surface)**

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 A.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 A.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.

## Data Analysis – Manual (Semi-Automatic) Manipulation

Since actual pavement layer boundaries vary in elevation, software was developed to extract depth slices from the 3D radar model between asphalt layer interfaces. First each layer is picked in the 3D radar software and exported to a text file (x, y, z). These text files are used to bound 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 A.6 and A.7 show the picked surface reflection and bottom of asphalt reflection. The upper part of Figure A.6 shows the longitudinal and transverse profile and the waveform defined earlier in Figure A.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 A.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 3D version in Figure A.7).

For the 3D-Radar system data collected during this R06D study, these layers can be picked using the 3D-Radar system “Examiner” software. 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 A.8), the layers are picked in each antenna pass and again used as boundaries in the activity index calculation. Figure A.9 shows a contour plot of the Activity Index that was calculated for the region between the picked layers.

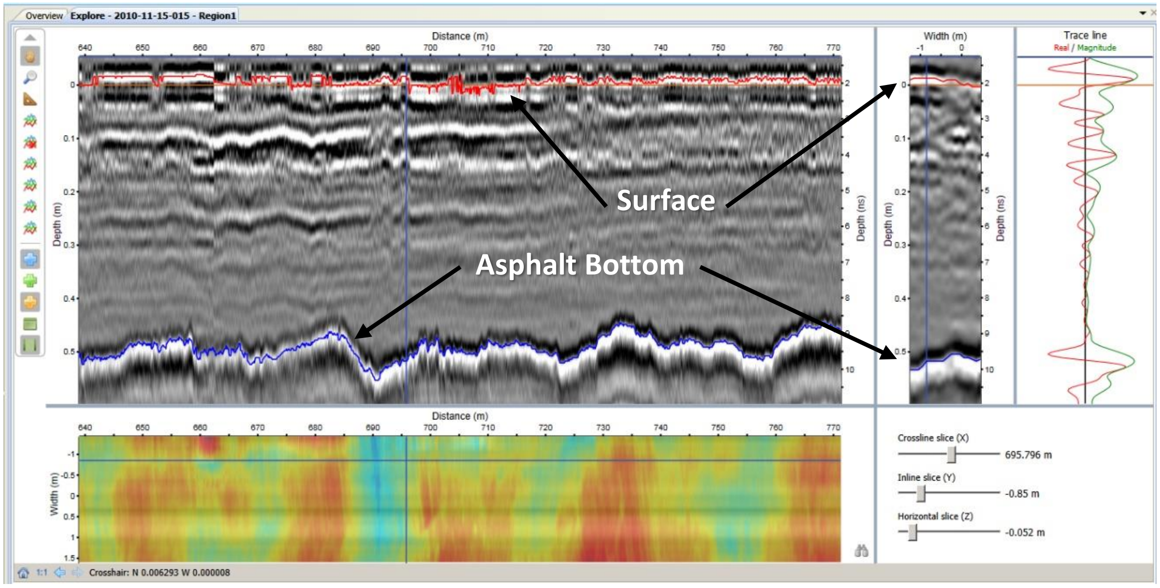



**Figure A.6, 3d radar analysis**

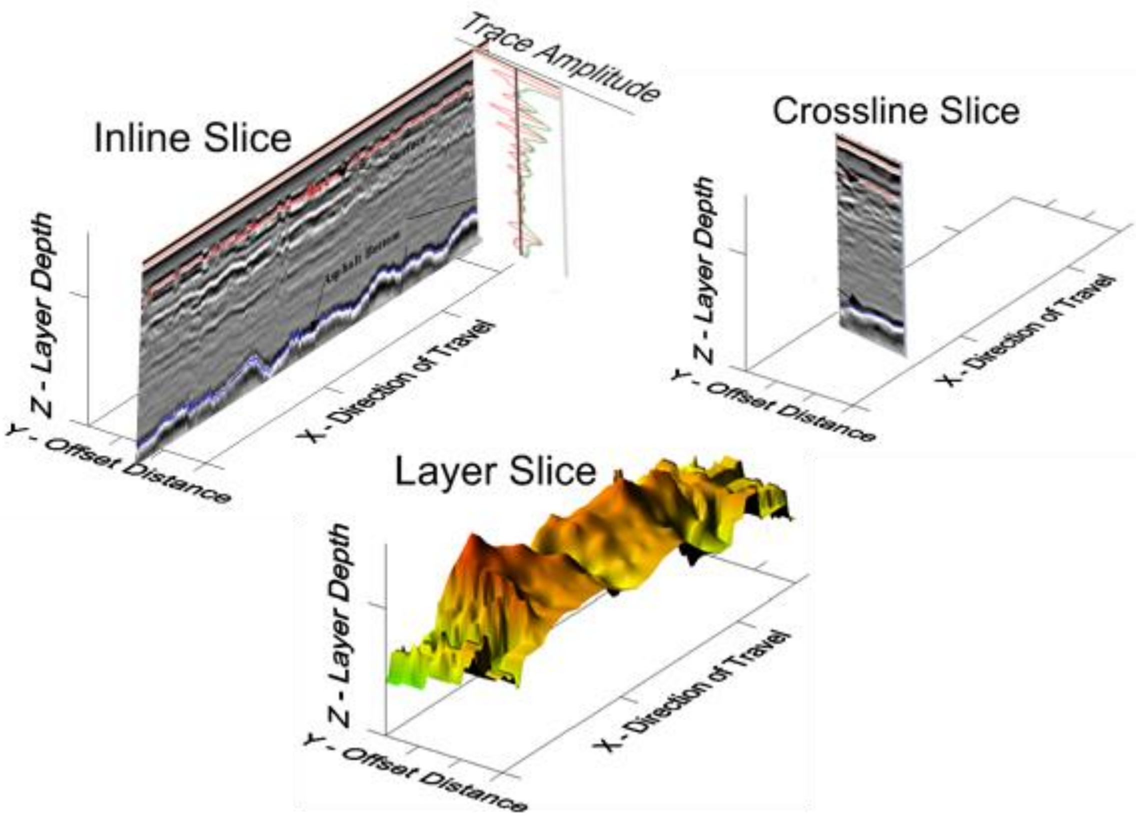
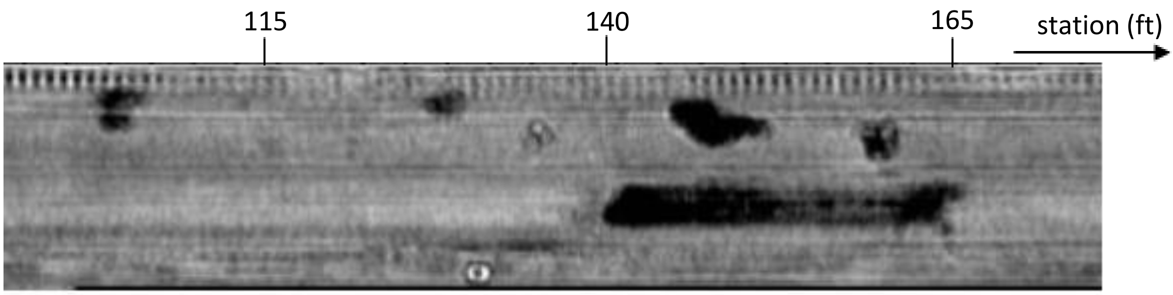
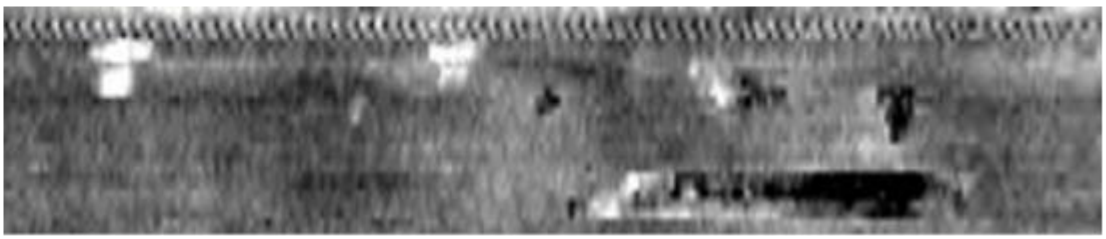



**Figure A.7, 3D radar analysis sections**




(a) 3D-Radar array



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

**Figure A.8, C-scan time/depth slices from NCAT test section**

Note that to create the 3D 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 3.0 GHz antenna.

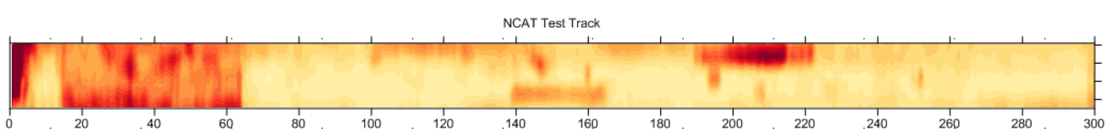



**Figure A.9, Contour plot of activity index between the two asphalt layer boundaries at NCAT**

## Data Analysis Samples from Field Sites

### <u>Florida Site</u>

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 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 A.10 shows a 3D radar sample from the Florida site, and Figure A.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.

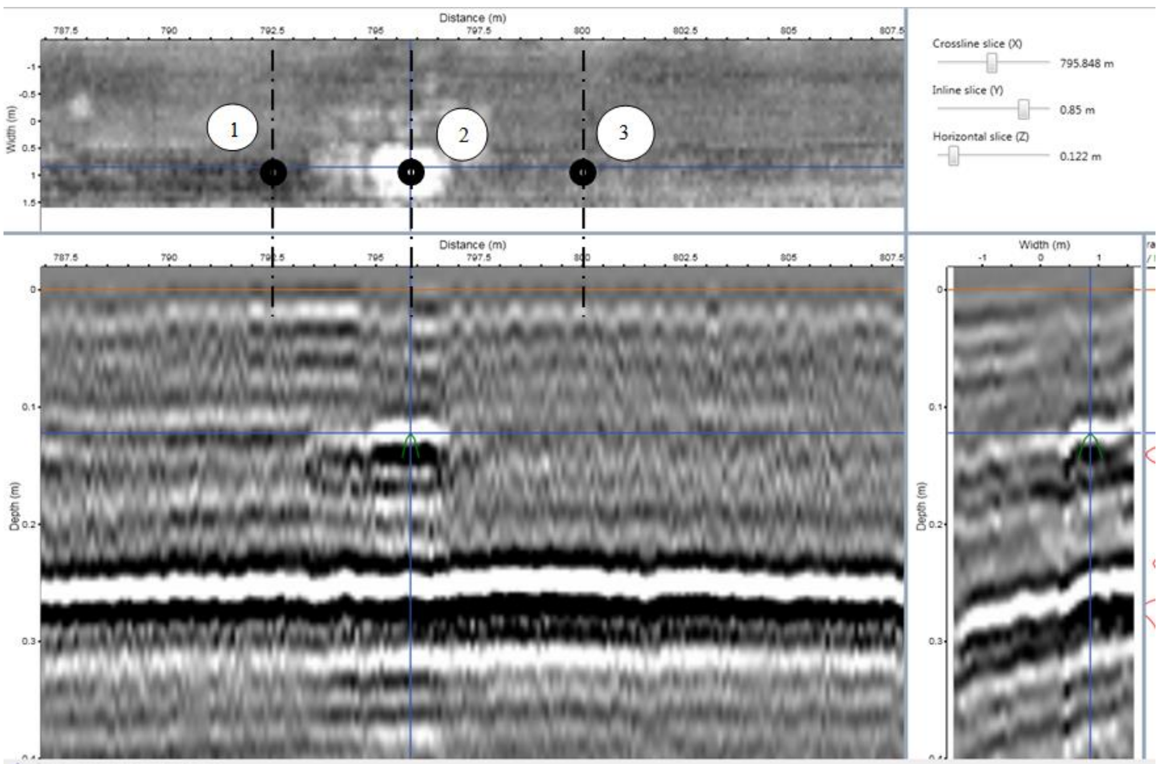



**Figure A.10, Florida radar data at the location of cores 1, 2, and 3**

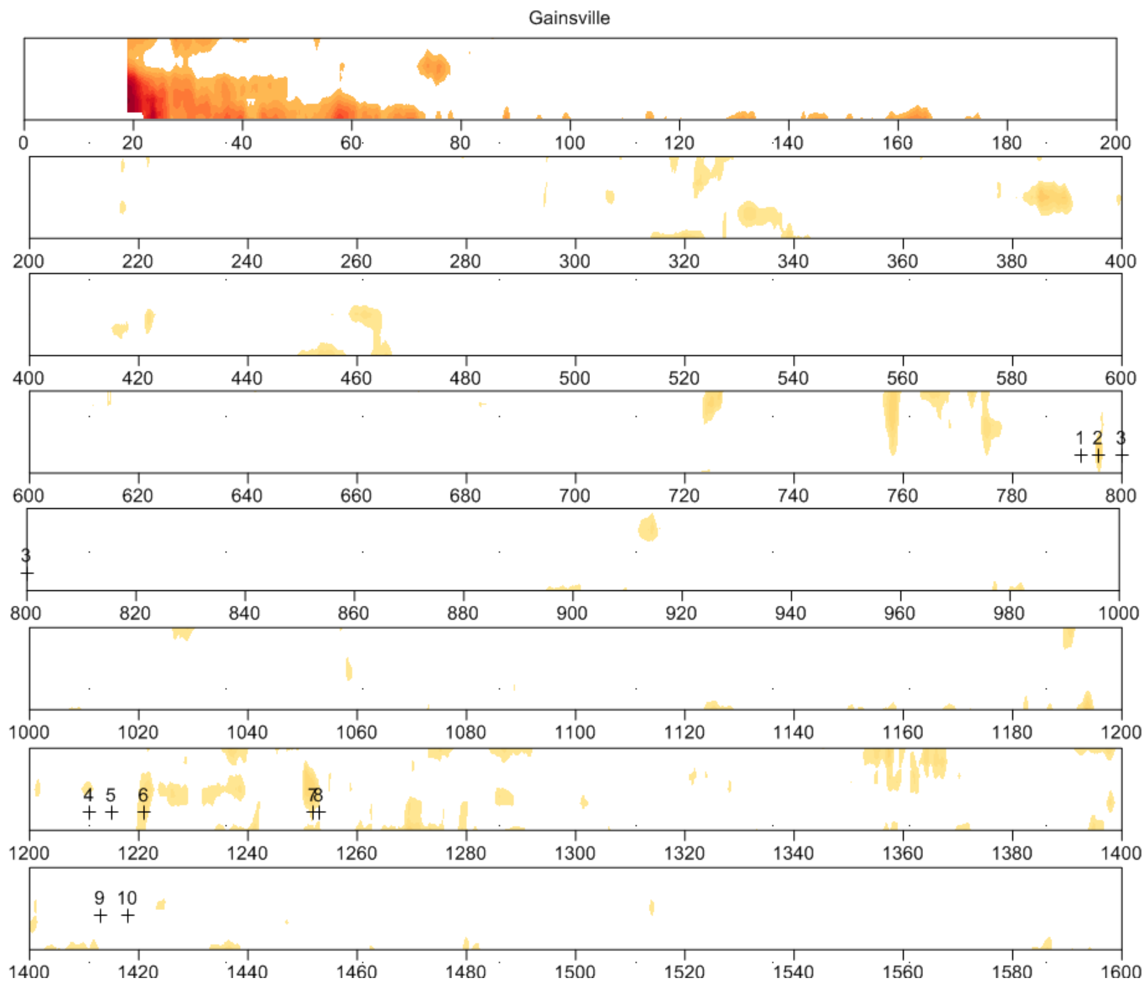



**Figure A.11, Florida site activity index plot of region between picked layers**

**<u>Kansas Site</u>**

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 A.12 shows a GPR sample from the Kansas site.

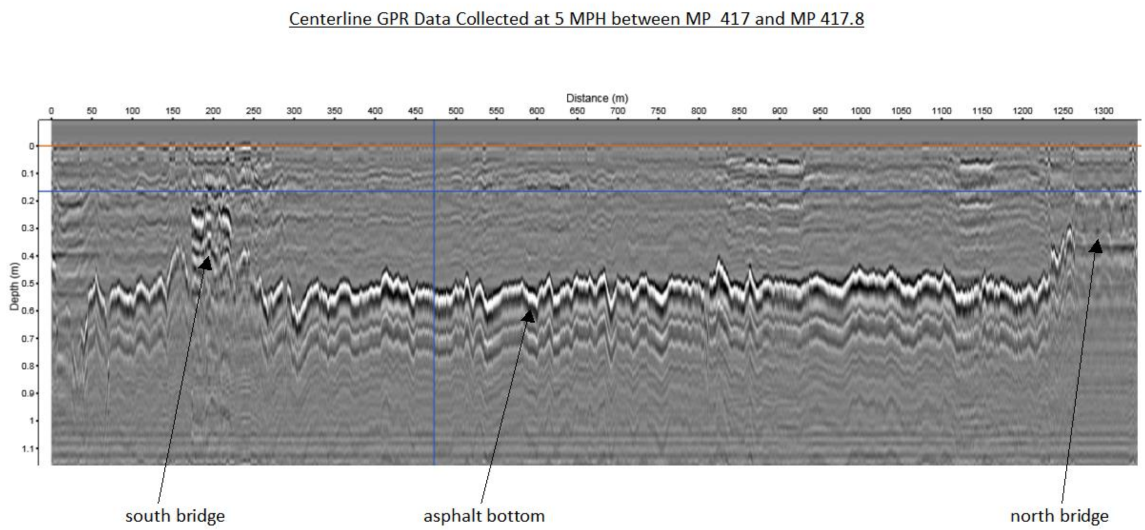



**Figure A.12, GPR radar data from Kansas site**

## 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 agency's information needs. Based on the data presented in these guidelines, the following conceptual reporting formats could be developed:

1. Depth and profile slides of raw data
   This is the most detailed level of reporting. Examples of this type of reporting can be found in Figures A.3, A.4, A.8 and A.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
   Figure A.2, A.5, A.9, and A.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 A.13 shows an example of a line plot that presents a delamination indicator, such as activity index, vs. 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.

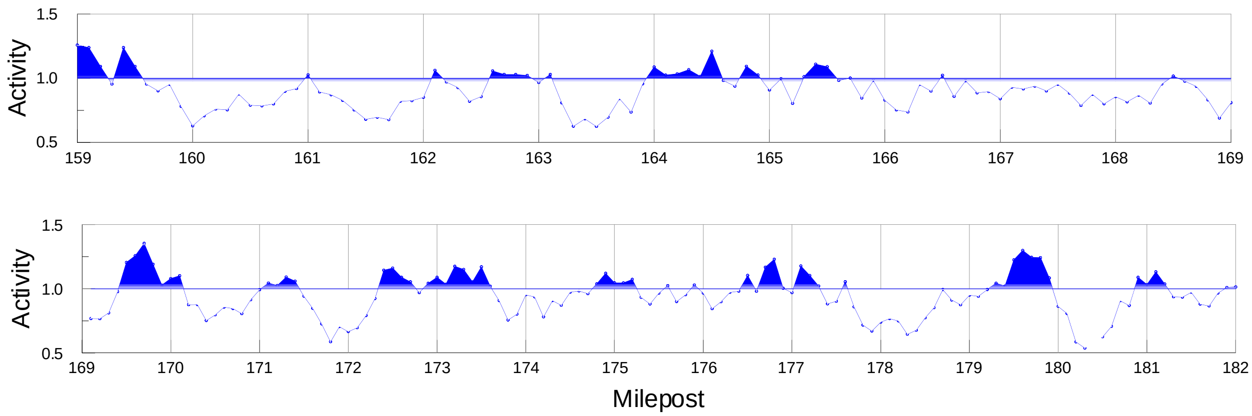



**Figure A.13, Line plot showing delamination indicators vs. milepost (blue fill equals delamination)**

4. Tabular summary of delamination indicators
   At the network level, a tabular summary of delamination conditions (or delamination potential) 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 A.2.

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

**Table A.2. Example Tabular Output at the Network Level**

# Appendix B

# Use of Spectral Analysis of Surface Waves and Impact Echo for Identifying Asphalt Pavement Delamination



This document provides guidelines for using non-destructive 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(s) 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.

**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 B.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 B.2(a) and B.2(b) show the dispersion curves for an intact pavement and a pavement with a known delaminated interface at a depth of 5 inches (in.). Figure B.3 is a SASW data analysis screen display. The material modulus determined from the SASW measurements represent low-magnitude (less than 1 micro-strain), high-frequency (greater than 3000 Hz) values. These material modulus values are higher than modulus values computed from current dynamic modulus tests.

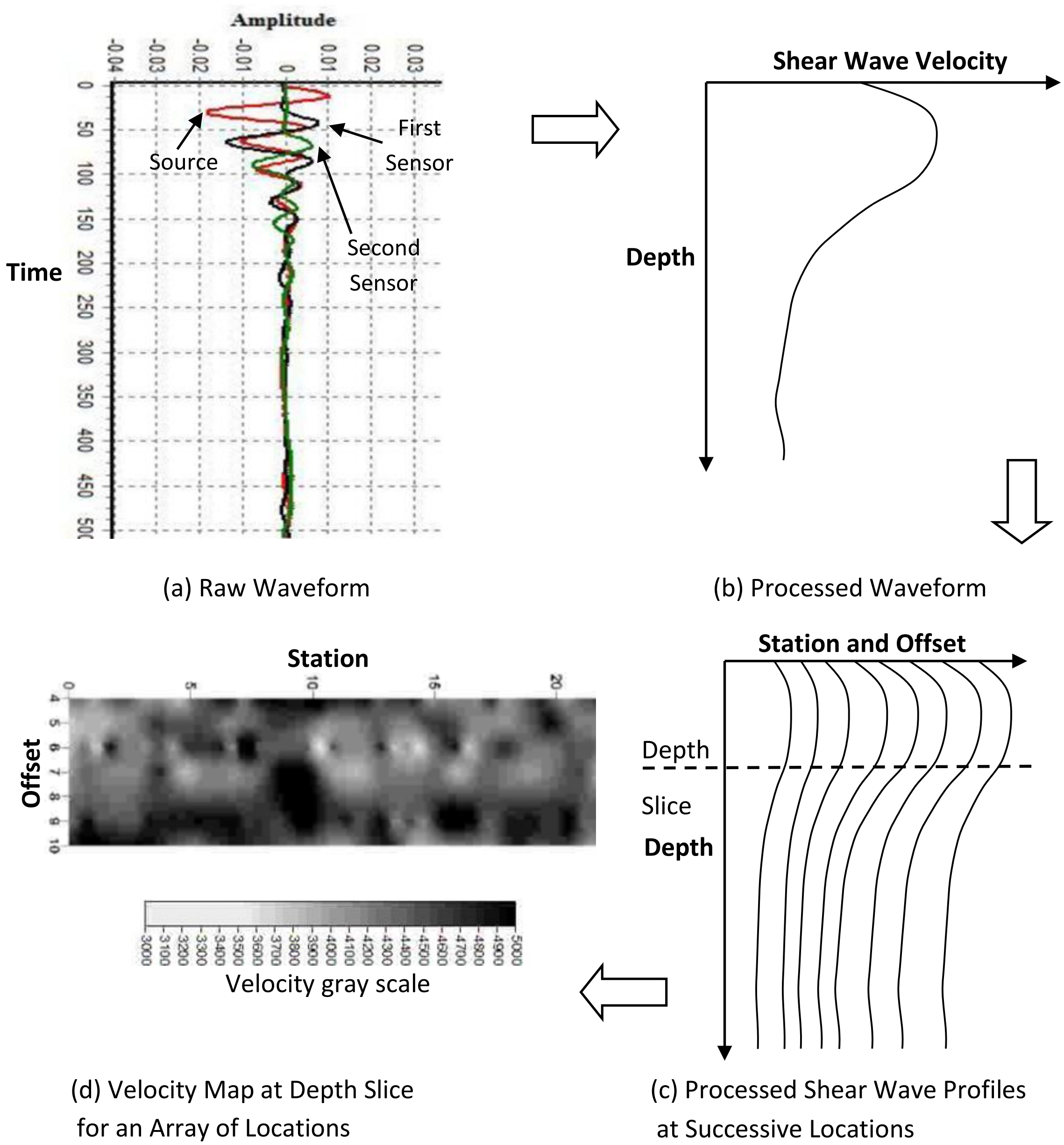



**Figure B.1, SASW testing and data analysis process**

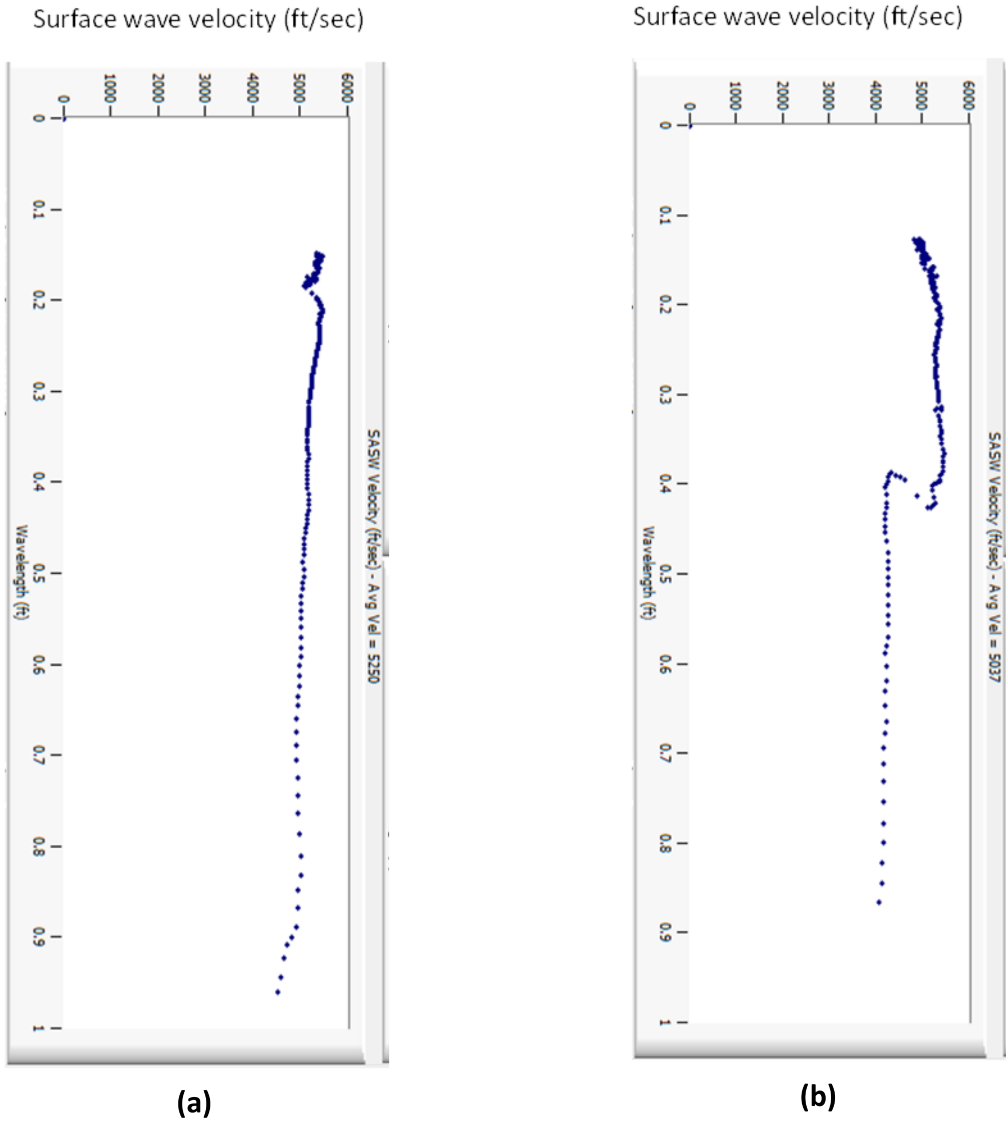



**Figure B.2, (a) Dispersion curve from an intact pavement and (b) dispersion curve from a pavement with delamination at a depth of 5 inches.**

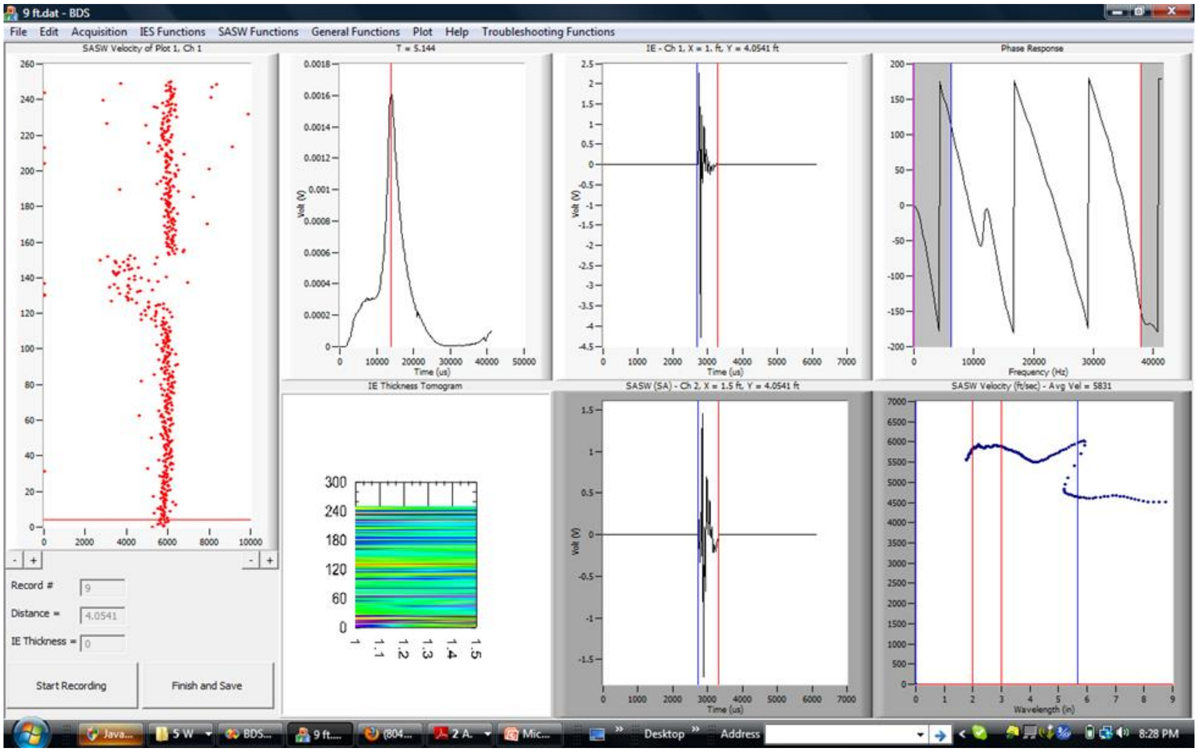


**Figure B.3, SASW data analysis screen**

## 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 (b) factor of 0.954 for a Poisson's ratio 0.2.

$$T = bV/2f$$

**Equation B1**

Where: T = the thickness

b = a beta factor

V = the P-wave velocity in the pavement

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 B.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 B.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.

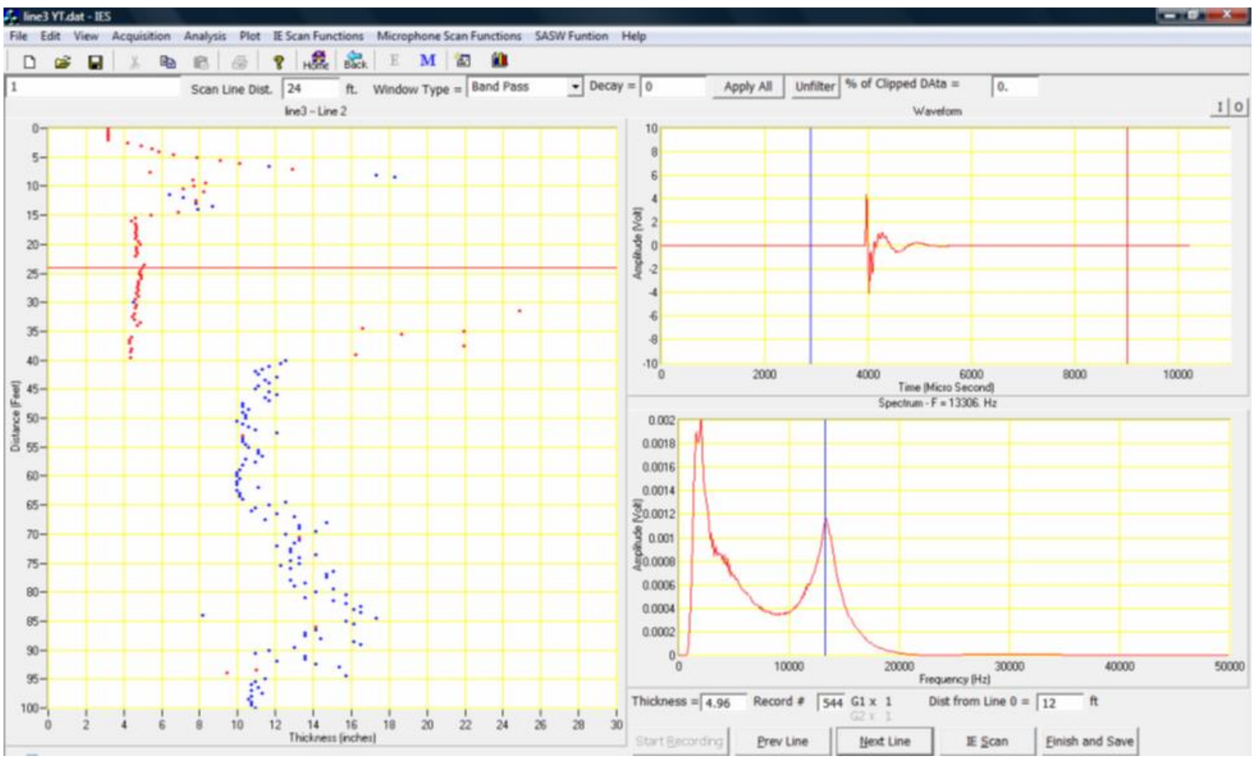



**Figure B.4, IE testing and data analysis**

## 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 B.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 miles per hour (mph) using three testing units in an array to cover a half lane-width, completing approximately 264 tests per minute over

528 square feet (sq ft) (1 test per 2 sq ft). The proto-type equipment also demonstrated a test frequency of 1 test per 1 sq ft. 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 sq ft 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 B.1 Equipment Specification for Continuous SASW and IE Testing for Detecting Pavement Delamination**

| System Component | SASW Specification | IE Specification |
|---|---|---|
| System type [1] | 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 [2] | Up to 50,000 hertz (Hz) | Up to 50,000 Hz |
| Impact source input frequency [2] | Up to 50,000 Hz | Up to 50,000 Hz |
| Lateral spacing between sensors [3] | 2 feet between center of sensor pairs (maximum) | 2 feet between sensors (maximum) |
| Lateral coverage per pass [4] | 6 ft (half lane width) | 12 ft (full lane width) |
| Longitudinal data collection rate [3] | 1 test per foot (minimum) | 1 test per foot (minimum) |
| Travel speed during data collection[5] | 1 to 2 mph | 1 to 2 mph |
| Travel speed during mobilization | Posted speed limit | Posted speed limit |
| Real time display [6] | 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 distance-measuring instrument (DMI), external distance wheel, or global positioning system (GPS) | Vehicle DMI, external distance wheel, or GPS |

**Table B.1 Equipment Specification for Continuous SASW and IE Testing for Detecting Pavement Delamination**

| System Component | SASW Specification | IE Specification |
|---|---|---|
| Note-1 | 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. | |
| Note-2 | The NDT system hardware should include variable frequency sources and sensors so the testing can be effectively performed under diverse climate and material conditions. | |
| Note-3 | 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 sq ft. Higher measurement densities of every 1 sq ft can be achieved with available prototype equipment. | |
| Note-4 | 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. | |
| Note-5 | 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. | |
| Note-6 | 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. 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
- Surface wave velocity–wavelength dispersion curve

Examples of this display are shown in Figure B.1, Figure B.2 and Figure B.3.

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

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

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

Output Format

- SASW output should be a volume of data with velocity as a function of x (longitudinal distance), y (transverse

## 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 DMI or 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 foot). For longer surveys, over 1.0 mile, user marks should be entered into the data at ground control points (mile markers, intersections, etc.) 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 degrees Fahrenheit (°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 weather proof.

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-foot increments. Six units spaced at 2-foot increments would provide full lane-width coverage with measurements at 1, 3, 5, 7, 9 and 11 feet transverse across the lane. If a higher test density is needed, the six units could be spaced every 1 foot 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 feet. The SASW test measures the surface waves traveling 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
- 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 (3D) 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 wave form 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 3D 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' software will combine these files into the 3D 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
- "Waterfall" plot of dispersion curves collected vs. 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
- 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 no problems with the data.
- 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 B.2). When the test encounters material delamination, there is a break and significant drop in the wave velocity (see Figure B.3).

Once the surface wave velocities versus depth are computed, the 3D 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 grey-scale or color-coded two-dimensional maps. Figure B.5 show 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 color areas in the slice at 0.4 foot (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 wave form 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 two-dimensional display is the computed thickness of the pavement based on the x-y locations of the measurements. Figure B.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 used 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 B.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.

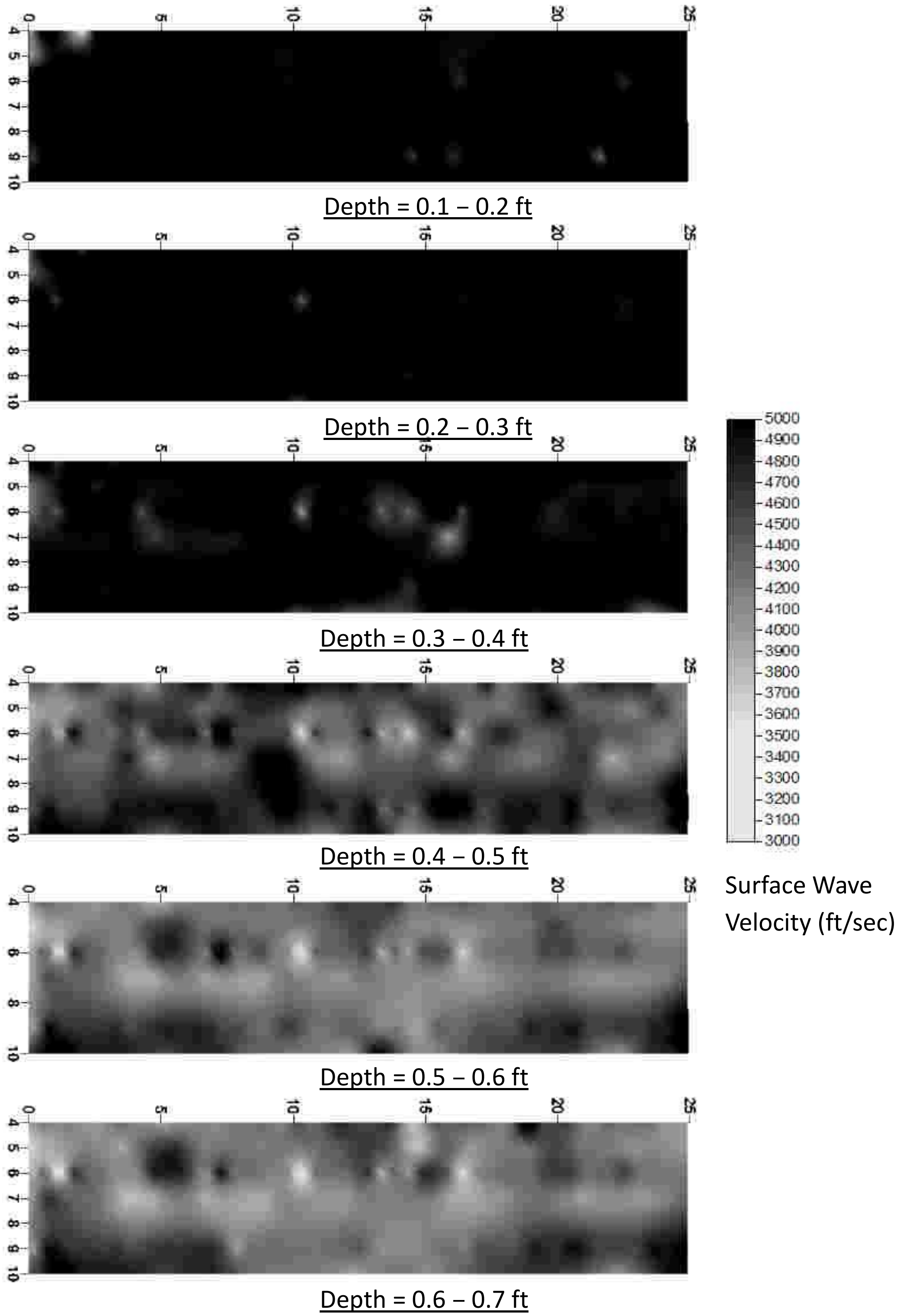
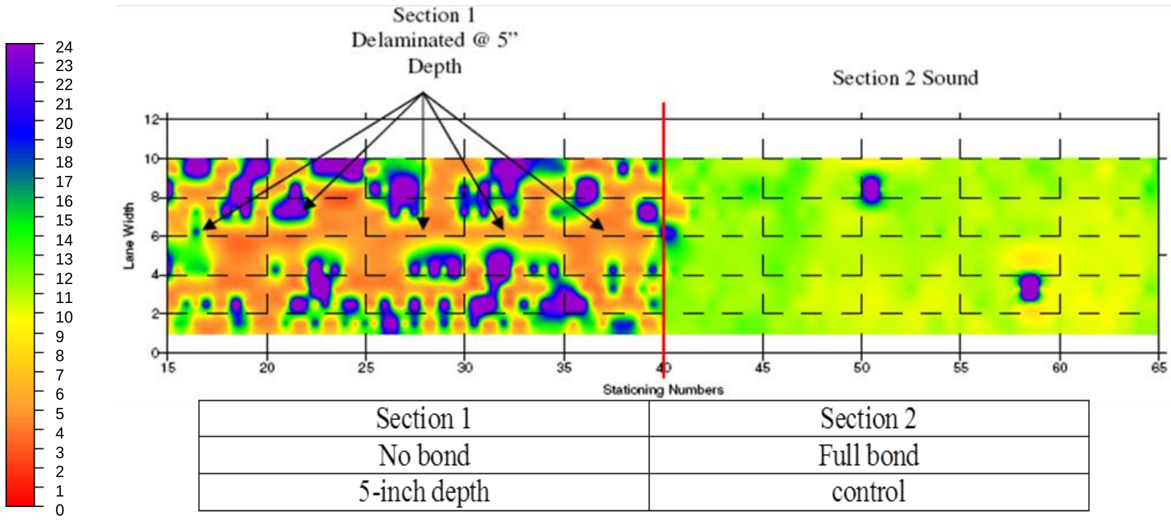



**Figure B.5, Depth slices of the SASW measured surface wave velocity at incremental pavement depths**




| Section 1 | Section 2 |
|---|---|
| No bond | Full bond |
| 5-inch depth | control |

Thickness Color Scale (in)

**Figure B.6, Example of Impact Echo pavement thickness plot**

**Table B.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 4500 fps | 4000 to 4500 | Less than 4000 | VELOCITY greater than 4500 fps | 4000 to 4500 | Less than 4000 | VELOCITY greater than 4500 fps | 4000 to 4500 | Less than 4000 |
| 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 |