SHRP 2 Renewal Project R06G

# Tunnel Nondestructive Testing Equipment User's Manual



TRANSPORTATION RESEARCH BOARD OF THE NATIONAL ACADEMIES

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TRANSPORTATION RESEARCH BOARD

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## TUNNEL NONDESTRUCTIVE TESTING EQUIPMENT USER'S MANUAL

by

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SHRP 2 R06G Project Title: Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings

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## Introduction

This user's manual includes information for three in-depth nondestructive testing devices: the ultrasonic tomography device, the Portable Seismic Property Analyzer, and the ultrasonic echo device. This manual can also be used as a guide for developing training courses relating to the use of these devices in tunnels. These devices may be useful for investigating small areas where there is reason to suspect further inspection is warranted. The manual contains additional information about these devices that many not be available in their respective operating manuals or their manufacturers' websites; i.e., this manual should be considered a supplement to the manufacturers' information. However, links to websites and other information available through the Internet are provided in this manual. Users of these devices should review the manufacturers' equipment manuals and instructions before reading this manual.

The contents of the manual are mainly based on the experience of the research team members when they used these devices for SHRP 2 R06(G). All three devices were used in actual tunnels during the course of this SHRP 2 study.

## **CHAPTER 1: Ultrasonic Tomography User's Manual**

#### Introduction

This user's manual was compiled based on the working experience of a commercially available ultrasonic tomograph (the A1040 MIRA, produced by Acoustic Control Systems [ACS]) and provided for the second Strategic Highway Research Program (SHRP 2) Project R06(G), High-Speed Nondestructive Testing Methods for Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings. The objectives of this project were:

- To identify nondestructive testing (NDT) technologies for evaluating the condition of various types of tunnel linings and tunnel-lining finishes such as tile. The techniques had to be capable of analyzing conditions within the tunnel lining and the surrounding substrate.
- To evaluate the applicability, accuracy, precision, repeatability, ease of use, capacity to minimize disruption to vehicular traffic, and implementation and production costs of the identified technologies.
- To conduct the required development in hardware or software for those techniques that showed potential for technological improvement within the time limitations of the project.
- To prove the validity of the selected technologies and techniques to detect flaws within or verify conditions of the targeted tunnel components.
- To recommend test procedures and protocols to successfully implement these techniques.

#### **Manufacturer's User Manual**

This field manual is not intended to replace the manufacturer's user manual but rather to accompany it by providing guidance for practical field use.

Two manufacturer user manuals exist: an early version produced by ACS in 2010, and a later version produced by Germann Instruments in 2012. The 2010 version is available for download (http://downloads.acsys.ru/eng/Documents/) or can be requested from ACS. The 2012 version is available when purchasing the system from Germann Instruments. This field manual references the user manual produced by ACS, hereinafter referred to as the user manual.

The following information was compiled from testing both laboratory specimens with simulated defects as well as over 170 field testing sites, including tunnel linings, continuously reinforced concrete pavements, bonded concrete overlay airport runways, and bridge decks.

#### **Ultrasonic Tomography Description**

The ultrasonic tomography (UST) system used in SHRP 2 Project R06(G) is a device that utilizes an array of ultrasonic transducers to transmit and receive acoustic stress waves for the inspection of concrete structures. The system used, the A1040 MIRA, is produced by ACS (http://acsys.ru/eng/production). The tomograph, shown in Figure 1.1 (left), uses a 4 by 12 grid of mechanically isolated and dampened transducers that can fit the profile of a rough concrete testing surface with a variance of approximately 10 mm (0.4 inch). Each row of four transducers transmits stress waves sequentially while the remaining rows act as receivers. In this manner, there is a wide coverage of shear wave pulses that reflect at internal interfaces where the material impedance changes. With the help of a digitally focused algorithm (an alteration of the synthetic aperture focusing technique [SAFT]), a three-dimensional volume is presented with each point of

possible reflection in half-space represented by a color scheme, scaled according to reflecting power. This three-dimensional image can also be dissected into each of the three planes representing its volume: the B-scan, C-scan, and D-scan (Figure 1.1, right). The B-scan is an image slice showing the depth of the specimen on the vertical (z) axis versus the width of the scan on the horizontal (x) axis. This slice is a plane perpendicular to the scanning surface and parallel to the length of the device. The C-scan is an image slice showing the plan view of the tested area, with the vertical (y) axis of the scan depicting the width parallel to the scanning direction and the horizontal (x) axis of the scan representing the length perpendicular to the scanning direction. Note that the scanning direction is always defined as the y-axis, as seen in Figure 1.1, right. The D-scan is like the B-scan in that it images a plane perpendicular to the testing surface, but it is oriented parallel to the scanning direction. On each of the scans, the various intensities reported by the returned waves are color coded from light blue to deep red, representing low reflectivity (typically sound concrete) and high reflectivity (any type of impedance), respectively (Figure 1.2). With this intensity scaling, it is easy to see any discontinuities with distinctly different wave speeds, such as voids, delaminations, cracks, and other abnormalities.



Figure 1.1. The A1040 MIRA system (left) and B-scan, C-scan, and D-scan relative to

the tomograph.



Figure 1.2. Scale of reflectivity (or acoustic impedance).

## **Equipment and System Integration Requirements**

The A1040 MIRA system is a stand-alone system that only integrates with specialized reconstruction software, IDealViewer. When the A1040 MIRA system is purchased, a laptop is provided with IDealViewer software ready for use. Data sets collected with the MIRA system are transferred to and analyzed using the IDealViewer software (see User Manual Appendix *IDealViewer*).

#### **Test Procedures**

The following procedures have been developed and modified based on actual field evaluations with the A1040 MIRA system. As all case studies will be different, it is necessary to adapt testing procedures to fit the needs of the evaluation specific to the location, type of surface, type of construction, and primary defects under consideration. The following remarks are to be used in conjunction with the user manual.

#### **Data Collection Modes (see User Manual Section 1.4)**

There are two modes of data collection for the MIRA system: review mode and map mode. In the review mode, data are collected as discrete point locations and can be analyzed by viewing the B-scan on the display. This B-scan is the only information collected in this mode. In the map mode, the user will create a grid on the test specimen and collect a series of discrete point tests on that grid. This series of testing points is called a map. During the building of the map, the user can observe the B-scan on the display. After the map is collected, the data set is then downloaded onto the laptop with IDealViewer software for three-dimensional data reconstruction. Using this software, each point of data collection is fused, or stitched, together to form a three-dimensional image of the mapped specimen for analysis.

#### **Review Mode Testing Procedures (See User Manual Section 1.4.2)**

#### Step 1: Determine Wave Speed

In review mode, there are two options for wave speed determination. The first option is to use the automatic wave speed generated per scan without inputting a constant wave speed. The benefit of this approach is that the user can see the variation of wave speed over the object of inspection. A change in wave speed signifies a change in modulus, density, and/or Poisson's ratio within the first few inches of the surface. In areas of deterioration or significant defects, the automatic wave speed decreases due to path lengthening of the acoustic pulse. The second option is to take a sample of wave speeds and use the average as a manual input. This approach allows discontinuity details to be measured accurately (provided the modulus, density, and Poisson's ratio are constant), since the wave speed is fixed for the concrete medium. An average is taken by first setting the wave speed control to automatically generate per individual scan (see user manual Section 1.4.1). It is then necessary to collect eight to 10 randomly oriented scans in areas free of surface deterioration or severe unevenness and attempt to collect the wave speed in locations where potential shallow reinforcement and other shallow discontinuities will not affect the measurements. This can be done by viewing the B-scans and attempting to measure in between shallow reinforcement layouts if any are present. After collecting the scans, the next step is to use the numeric average of the wave speeds and manually set the wave speed control to this velocity.

#### Step 2: Set Z-Scanning Depth

Z-scanning depths in the review mode can be changed according to the user manual Section 1.4.2. Choosing an appropriate scanning depth (*z*-scanning direction) is an important decision when using review mode. If the chosen depth is too shallow, it might be that critical information

regarding the depth of details is omitted. If the z-scanning depth is set too deep, the resolution of shallow details is diminished. An appropriate *z*-scanning depth should be chosen after multiple inspections via the review mode. When the operator has obtained a feel for structural characteristics that should be included in the map, a depth should be chosen that slightly exceeds the lowest element that needs to be captured. An example would be an analysis on concrete pavements, where the operator is building a map for analyzing possible delamination at any depth within the concrete section. In this case, it would be recommended that the depth be set to only capture the depth of the overlay. This minimizes unnecessary data and improves resolution for delamination detection. On the other hand, if the operator is to generate a map for an analysis of bonding assessment between a top layer and a sublayer, it would be advisable to choose a minimum z-scanning depth that at a minimum exceeds twice the depth of the top layer. This is due to the fact that bonds that have fully separated will produce backwall multiples, or echoes, which are repeated backwall reflections at multiples of the initial layer depth. This feature is caused by the nearly elastic reflection of the acoustic waves as they encounter the concrete-air original interface. The presence and intensity of such backwall echoes can depict the severity of debonding. If few or no echoes are present, but instead a weak signal at the top layer or sublayer interface is present, then this feature may indicate a partially bonded interface. If no interface is detected at all, then a fully bonded pavement at that location can be expected.

#### Step 3: Begin Scanning

To collect the data, fully press the system to the surface very firmly, and then press the collect trigger. Wait until the red status bar has gone to green before moving the device to another location. It is suggested to use welder's soapstone when scanning to mark on the concrete surface when an interesting feature is observed. Note that the variety of parameters included in the main

control can be altered (see user manual Section 1.4.1), including color and analog gain, number of periods, pause between emission pulses, operating frequency, wave speed (velocity), and time delay. It is suggested to keep these values at their default settings unless there is a way to calibrate the device for the object of inspection. If a known discontinuity is available for calibration, the appropriate settings can be altered to fine-tune the measurements. Note that shear wave frequency can be varied from 25–85 kHz so that smaller and shallower defects can be seen at the expense of greater wave attenuation.

#### Map Mode Testing Procedures (See User Manual Section 1.4.3)

#### Step 1: Determine Grid Increments

When using map mode to construct an array of data, it is necessary to determine an appropriate grid increment. An appropriate choice will consider the object of inspection's lateral size and depth. If measurements are not overlapped, the constructed images will be spotted or will be without full coverage. If a continuous image is desired for comprehensive defect dimensioning, scanning overlap is necessary. The transducer array has a limited aperture, due to the combination of Snell's Law of refraction and superposition of acoustic waves. Snell's Law states that the angle of incidence is equal to the angle of reflection for a given wave. By this law, an undisturbed ultrasonic pulse will always reflect from discontinuities located half the distance from a transducer pair. However, the modified synthetic focusing technique used in the software image reconstruction utilizes repeated signals to develop the colored output. This means that the signal strength (as observed by the color output of the MIRA scans) representing a given discontinuity's width (in the *x*-scanning direction) will vary in signal strength depending on how close it is to the center of the focused aperture. The goal in continuous mapping then becomes to

overlap in such a manner that critical planes of inspection are fully covered by a large number of transducer beams. Therefore, closely spaced scanning increments will better suit defects such as small voids, clay lumps, and early propagation of small cracks, whereas general slab thickness can be estimated from very widely spaced scanning increments. Table 1.1 suggests scanning increments for generating a three-dimensional map for defect analysis. These suggestions are experimentally determined, based on defects within 305 mm (12 inches) of the surface.

Type of Discontinuity	y-Scanning Direction	Recommended Grid Spacing (Y
		Versus X)
Voids with diameter < 50 mm (2.0	Any orientation	Maximum of 50 mm x 150 mm (2.0
inches) (air and water filled)		inches x 5.9 inches)
Voids with diameter > 50 mm (2.0	An entropy of the	Minimum of 50 mm x 150 mm (2.0
inches) (air and water filled)	Any orientation	inches x 5.9 inches)
Horizontal delaminations	Any orientation	Optimal: 50 mm x 150 mm (2.0
		inches x 5.9 inches) to 100 mm x
		200 mm (3.9 inches x 7.9 inches)
Vertical cracks	Parallel to surface crack direction	No greater than 50 mm x 100 mm
		(2.0 inches x 3.9 inches)
Clay lumps < 150 mm (5.9 inches)	Any orientation	Maximum of 50 mm x 150 mm (2.0
		inches x 5.9 inches)
Clay lumps > 150 mm (5.9 inches)	Any direction	Minimum of 50 mm x 150 mm (2.0
		inches x 5.9 inches)
Deinforcement detail in and	Demos l'a la demo à Conserve d	Optimal: 50 mm x 150 mm (2.0
Reinforcement detail in one	Perpendicular to reinforcement	inches x 5.9 inches) to 100 mm x
direction	layout	250 mm (3.9 inches x 9.8 inches)
Reinforcement detail in two	45° from reinforcement direction	Optimal: 50 mm x 150 mm (2.0
directions		inches x 5.9 inches)
Slab thickness	Any direction	Maximum of 100 mm x 200 mm
		(2.0 inches x 5.9 inches)

## Table 1.1. Recommended Scanning Directions and Grid Spacing

#### Step 2: Determine Scanning Direction (y-Scanning Direction)

The *y*-scanning direction is defined to be the direction perpendicular to the B-scan. When building a map, it is necessary to choose a *y*-scanning direction. Since the shear wave transducers send and receive pulses in the *x*-direction, the tomograph has greater resolution for objects that pass through the *x*-axis, or parallel to the *y*-scanning direction. Therefore, the operator will have to decide which direction is more desirable to have the greatest resolution of detail, and the *y*scanning direction is perpendicular to that direction. For objects under inspection that have no defined direction (thickness calculation, delamination, some voids and lumps), the *y*-scanning direction is largely irrelevant.

For example, consider that the operator desires to check longitudinal reinforcement spacing on a concrete slab with both longitudinal and transverse reinforcement (in this scenario, consider that the longitudinal reinforcement lies along a *v*-axis and the transverse reinforcement lies along a *u*-axis). The desired direction for greatest resolution would be the direction perpendicular to the longitudinal reinforcement, as it would provide the greatest detail for center-to-center measurements. Therefore, the user should choose a *y*-scanning direction along the *v*-axis.

Operators are encouraged to scan, if time permits, two orthogonal directions so that details in both directions are collected at optimal resolution.

#### Step 3: Establish a Grid

For the UST system to operate in map mode, it is necessary to construct an accurate grid or marking system to fully characterize the specimen under evaluation. The creation of a grid can be one of the most critical jobs when building a map with the tomograph. Every grid must be square and accurate in order to utilize the map for noting precise areas of interest.

There are two methods of grid construction that are recommended here. The first method is constructing chalk lines that outline the area to be tested, including the interior grid spacing. It is recommended to use white or blue chalk lines when it is desirable to have a water-removable grid, while permanent grids can be established using red or black chalk. (Note: red and black chalk contains dyes that cannot be completely removed from concrete.) The creation of the grid starts with generating a right angle that extends a minimum of half the length of the tomograph past the outer boundary of the desired testing surface in the x-scanning direction and half the width of the tomograph past the outer boundary of the desired testing surface in the y-scanning direction. The first side of this right angle can be made by popping a chalk line that is visually approximated to be in line with the desired x- or y-scanning direction. The second side of the right angle can be projected by using a standard framing square or by using a measuring tape to establish a point corresponding to a 3-4-5 triangle. Once the second side of the right angle is popped, it is necessary to mark the x- and y-scanning increments (from Step 1) on the appropriate sides of both right angle projections. Welder's soapstone is an excellent marking tool, as it is highly durable on concrete surfaces, yet removal is possible with water. Once the length and width of the grid have been marked off, it is necessary to use a measuring tape to finish marking the perimeter of the inspection area by projecting the ends of the right angle's sides by the appropriate distance to establish the corner opposite the origin. Increments can then be marked along these sides, and the interior x- and y-scanning direction gridlines can be popped via chalk lines. When the scanning begins, it will only be necessary to place the light-emitting diode (LED) beam from the upper left corner of the device (when viewing the control panel) on the crosshairs of the incremented grid, using the remaining LEDs to visually square the device with the map.

The second, albeit more permanent, method for grid placement involves constructing a grid template from a thin sheet of plywood or particle board and using landscaping paint to spray grid increments on the test specimen. The preferred material used in the SHRP 2 research was 3.2 mm (0.125 inch) medium-density fiberboard (MDF). A section of sheet can be as long and wide as is appropriate for the size of the area under investigation. After cutting the sheet (which is typically purchased in 1.2- x 2.4-m [4- x 8-ft] stock) down to the desired size, incremental rips should be made using a table saw. The slots cut by the table saw should begin within 100 mm (4 inches) of the sheet's edge and proceed to 100 mm from the sheet's opposite edge. It is recommended that the slots be made at a 50 mm increment in order for the user to apply the landscaping paint on whichever increment is chosen. The grid established by this method is shown in Figure 1.3.

To use this sheet as a template for the grid spacing, place it on the testing surface in the direction of the desired x- or y-scanning direction. Use landscaping paint to mark the slotted areas. This process can be repeated for the remaining x- or y-scanning direction by rotating the grid template until it is square with the previously marked grid.



Figure 1.3. Gridlines using grid template.

#### Step 4: Determine Wave Speed

In map mode, it is recommended to take an average of the calculated wave speeds over the testing area to be used as a fixed input. This approach allows discontinuity details to be measured accurately (provided the modulus, density, and Poisson's ratio are constant) since the wave speed is fixed for the concrete medium. An average is taken by first setting the wave speed control to automatically generate per individual scan (see user manual Section 1.4.1). It is then necessary to collect eight to10 randomly oriented scans in areas free of surface deterioration or severe unevenness and attempt to collect the wave speed in locations where potential shallow reinforcement and other shallow discontinuities will not affect the measurements. This can be done by viewing the B-scans and attempting to measure in between shallow reinforcement layouts if any are present. After collecting the scans, the next step is to use the numeric average of the wave speeds and manually set the wave speed control to this velocity.

#### Step 5: Program x, y, z-Scanning Lengths, Wave Speed, and Other Parameters

Refer to the user manual Section 1.4.1.5 to input the selected *x*-, *y*-, and *z*-scanning lengths (these are referred to in the user manual as the horizontal, vertical, and depth lengths, respectively), wave speed, and other parameters.

#### Step 6: Begin Scanning

To scan with the system, place the LED light in the upper left corner (as viewed when facing the display screen) on the crosshairs of the grid's origin, using the light beams from the remaining LEDs to visually square the device relative to the grid. Begin collecting data in either the x- or y-scanning direction according to user manual Section 1.4.3. Either direction can be used for data collection. To collect the data, fully press the system to the surface very firmly, and then press the trigger on either handle. Wait until the red status bar has gone to green before moving the device to the next location.

#### Step 7: Transfer Data Set and Process

Using the appropriate cables, transfer the data set from the system to the computer with the proprietary software according to user manual Appendix *IDealViewer*. Analysis can take place immediately after the dataset has been downloaded, often allowing an analysis to be started in the field.

#### **Inspector's Training Requirements**

Field operation training for the specific ultrasonic tomograph discussed in this manual typically requires no more than 2 days of hands-on training. This should include a hands-on overview of the operation of the device, an information session on the science behind shear wave ultrasonic imaging, and hands-on training on practice specimens. General and specific certification requirements may be required according to the agency performing testing. For example,

certification requirements, required by paragraphs 8.3 and 8.4, respectively, of the *Recommended Practice No. SNT-TC-1A*, are provided by the American Society for Nondestructive Testing (ASNT) nondestructive testing (NDT) Level I, Level I Limited, Level II, and Level III certification programs for NDT employers.

- ASNT Level I Limited technicians are only qualified to perform a specific procedure for a specific inspection on a certain component with direct supervision and guidance of higher-level technicians.
- ASNT Level I technicians are only qualified to perform specific calibrations and tests under the guidance of a higher-level technician.
- ASNT Level II technicians are qualified to set up and calibrate systems; inspect according to procedures; and evaluate and report the testing results for the specific certificate issued.
- ASNT Level III technicians are qualified to establish testing procedures and techniques by interpreting governing codes, standards, and specifications, and they can train lower-level technicians.

## **Data Management Procedures**

Data files for typical grid spacing (50–200 mm by 50–200 mm) for comprehensive maps range from  $12 \text{ kb/ft}^2$  to  $35 \text{ kb/ft}^2$ .

## **Data Analysis Procedures**

Data reconstruction and imaging is performed automatically by the system for the twodimensional review mode, and data reconstruction and imaging is performed automatically by the accompanied IDealViewer software for the three-dimensional map mode. Raw data files are generated as .lbv, .bin, .bmp, and .cfg files.

## **Interpretation Guidelines**

Data interpretation should be performed by an experienced operator who is familiar with ultrasonic testing and has the appropriate NDT certifications. General interpretation guidelines involve identifying and recording all typical features of interest, including backwall reflection, depth to center of reinforcement, width of apparent discontinuities, etc. This can be done in either mode, but a thorough analysis requires building a map in the map mode.

Interpretation guidelines are given below for typical features under inspection:

Backwall (element thickness). The backwall, or element thickness, can only be successfully identified if there is a mismatch in impedance between the concrete and the material beneath it. Unless the concrete is fully bonded to a material with similar impedance, the backwall is usually readily identified by a constant high-amplitude (red) region on the B-scan. If the backwall thickness is relatively constant, then this region should remain unchanged when scanned at any location. A typical B-scan viewed from the display showing the backwall location is given in Figure 1.4 (left).



Figure 1.4. B-scans showing reinforcement, backwall, delamination, and multiples.

- *Reinforcement, conduit, tendons, etc.* Reinforcement, conduit, tendons, and other cablelike objects are identified by scanning perpendicular to the direction of their layout. The operator should search for circular high-amplitude (red) regions. These are distinguished from other possible anomalies by taking numerous scans along the direction of their layout. The system is not capable of identifying the material of a particular anomaly, so the operator must use good judgment to identify the anomaly. Both B-scans in Figure 1.4 show typical cross-sections of reinforcement. It is easily identified as reinforcement because the spacing is typical for longitudinal reinforcement and is consistent along this direction.
- *Delamination*. Delamination can only be identified after the operator has established a benchmark for the expected backwall location. Delamination is seen as a high-amplitude region (much like the backwall), but it should not be expected to maintain a constant depth. Delamination often occurs close to cracking (prior to spalling) and can be seen in the B-scan to curve toward surface cracks. Figure 1.4 (right) shows a typical delamination. Note the typical backwall depth (Figure 1.4, left) is not seen under the area

of delamination, but rather an echo of the delamination is seen. This is because shear waves cannot be supported in air and do not penetrate the material beyond an air gap. The shear waves are instead traveling back and forth between the test surface and the initial air gap (the delamination), thus causing these multiples to occur.

- *Cracks*. Cracks are the most difficult feature to ascertain due to their multiple orientations and the pitch-catch mode of operation for the tomograph. To identify cracks as high-amplitude (red) regions, the cracks must begin to form non-perpendicular to the testing surface in order for the tomograph's pitch-catch mode of operation to work. If they remain perpendicular to the testing surface, they can only be distinguished by their shadow, or complete lack of reflectivity. This is seen in the B-scans as a light blue region with no reflections.
- *Air- and water-filled voids*. Voids cannot always be discerned from delaminations until they take an irregular shape, but they will appear as a high-amplitude region similar to other types of air interfaces. The tomograph cannot determine the difference between air-and water-filled voids.
- *Tile debonding*. For tiled linings, tile debonding is usually observed by tapping the tiles and listening for the hollow drum sound, which signifies a debonded tile. Since tile thicknesses are usually very thin, the debonded area is seen on the tomograph but typically appears as a high-amplitude (red) region deeper than the actual location of debonding.

For analysis in the map mode, it is recommended to start with a volume-scan in order to get a glimpse of the entire element under inspection and then comb through each B-, C-, and D-scan for any irregularities as outlined above. The color gain dial allows the relative intensities to

be decreased in order to visualize slighter changes in impedance. Note that depths to discontinuities are usually taken as the distance to the center of the reflectivity region.

To relocate areas of interest from the map in IDealViewer to the physical grid, the operator can use the review mode to scan until directly on top of the area of interest or can reference the section "Origin/Boundary Establishment; Relation to Computer Model" in Section 9 of the user manual to mark the areas accurately on the physical specimen.

#### Limitations

The technical, operational, and environmental limitations of the system are described below.

#### **Technical and Operational**

- Low speed of data acquisition. If the system is used for detailed mapping in the map mode, the user should expect the scanning process to take between 9 to 25 min/m<sup>2</sup> (0.8–2.3 min/ft<sup>2</sup>). The review mode can be used for single-point evaluations at much faster rates of inspection (3–5 s per scan), but only limited-width B-scans are available for evaluation in this mode.
- *No indication of phase change.* The color palette response represents quantity of reflectivity regions and is a measurement relative to the medium (in which there should ideally exist zero reflectivity, the blue spectrum). As such, the type of defect is largely guesswork on the part of the user and requires greater skill and knowledge of ultrasonics to interpret these signals.
- *Detection of layered defects.* If defects are stacked, particularly in such a manner that air gaps are located above other types of defects, then the device can rarely determine anything below the initial air-filled gaps. This is due to ultrasonic pulse attenuation at air boundaries. If pulses are capable of being transmitted past air interfaces, then the

received signal is extremely weak and should be examined to be certain it is not a multiple or echo of the initial flaw.

- *No reliable reinforcement detail beyond two layers of reinforcement.* At the nominal operation frequency of 50 kHz, the system has difficulty reliably detecting reinforcement below two layers of existing reinforcement mesh.
- *Shallow defects.* Due to the low frequency, spacing of the transducer array, and beam spread of the individual transducers, defects that exist approximately 25 mm (1 inch) from the surface cannot be expected to be received by other transducers and carry any accurate information regarding the depth and lateral dimensions of the shallow defects. However, near-surface anomalies with an air interface can leave a shadow on the data collected below the near-surface defects, indicating the anomaly's presence. This is due to the air gaps inhibiting ultrasonic pulses to be transmitted (or received) beyond the anomaly.
- *Small diameter objects*. Small diameter objects (approximately less than 13 mm [0.5 inches]) are not reliably detected at the nominal operational frequency of 50 kHz due to the limitation in wavelength at wave speeds in concrete. This can be partially mitigated by increasing the frequency to the maximum allowed central frequency of 85 kHz, but the energy loss with higher frequencies still makes it difficult to discern smaller diameter bars.

#### Environmental

The system should not be used in wet environments (no standing water on testing surface). Additionally, the operating temperature of the system is from -10°C to 50°C.

#### **Additional Information**

#### **Origin/Boundary Establishment—Relation to Computer Model**

Due to the aperture of the transducer array, actual discontinuities discovered by the threedimensional analysis cannot be referenced from the established origin. The width of the ultrasonic tomograms are dependent on the size of the grid spacing and *z*-scanning depth and must be superimposed on the physical grid to determine with certainty the location of a particular defect. The process for establishing the relationship between the computer model's origin and the grid's origin is described here.

After the data from each successive increment have been gathered and downloaded to the remote computer, the three-dimensional model analysis program will allow measurements to be made relative to the device's aperture. Unfortunately, this aperture can be less than or greater than the created grid, depending on the scanning depth. To be able to relate the origin of the physical specimen (denoted as  $\{0, 0\}_0$ ) to the origin on the analysis software (denoted as  $\{0, 0\}_1$ ), the relationship between origins must be developed. To establish this relationship, several terms must be defined as follows:

- *X*<sub>0</sub>, the total *x*-offset between {0,0}<sub>0</sub> and {0,0}<sub>1</sub>, taken as positive in the *x*-scanning direction.
- Y<sub>0</sub>, the total *y*-offset between {0,0}<sub>0</sub> and {0,0}<sub>1</sub>, taken as positive in the *y*-scanning direction.
- *X*<sub>1</sub>, the chosen *x*-scanning increment.
- $Y_1$ , the chosen *y*-scanning increment.
- $W_0$ , the width of the tomograph array in the *x*-scanning direction, measured from outside transducer to outside transducer (330 mm [13 inches] for the A1040 MIRA).

- $L_0$ , the length of the tomograph array in the *y*-scanning direction, measured from outside transducer to outside transducer (90 mm [3.5 inches] for the A1040 MIRA).
- $W_1$ , the distance in the *x*-scanning direction from the lead LED guide to the nearest transducer (10 mm [0.4 inch] for the A1040 MIRA).
- $L_1$ , the distance in the *y*-scanning direction from the lead LED guide to the nearest transducer (10 mm [0.4 inch] for the A1040 MIRA).
- *W*<sub>3</sub>, the total width of a single B-scan as can be seen from the review or map modes. Using the definitions defined above, the physical location of the three-dimensional

image's origin  $(\{0, 0\}_1)$  relative to the origin of the grid on the specimen  $(\{0, 0\}_0)$  is defined by:

$$X_0 = (W_1 + W_0/2) - W_3/2$$

and

$$Y_0 = L_1 + L_0/2$$

Or for the MIRA system (in mm):

$$X_{0-\text{MIRA}} = (175) - W_3/2$$

and

$$Y_{0-\text{MIRA}} = 55$$

Again, positive values are taken to be in the *x*- and *y*-scanning directions. After establishing this origin  $(\{0, 0\}_1)$  on the specimen, all *x*- and *y*-dimensions taken directly from the three-dimensional software can be measured from this point of reference.

In typical field applications, the offset varies from 100 mm (2 inches) inside the specimen grid to 406 mm (16 inches) outside the specimen grid. If this scale of accuracy is not required for the particular type of evaluation (say, the inspector is only interested in a nominal layer depth), the defect location can be estimated using the direct measurements from the analysis software

and then pinpointed by using the device in review mode. Whether or not great accuracy is necessary, using the review mode to fine-tune the final location can help to confidently establish the defect location.

## **CHAPTER 2: Portable Seismic Property Analyzer User's Manual**

#### Introduction

The Portable Seismic Property Analyzer (PSPA; Figure 2.1) was developed by Geomedia Research and Development (GRD). The PSPA is an instrument designed to determine the variation in modulus with the depth of exposed layer being concrete or asphalt. The operating principle of the PSPA is based on generating and detecting stress waves in a medium. The PSPA consists of two transducers and a source packaged into a handheld portable system that can perform the ultrasonic surface wave (USW) and impact echo (IE) tests simultaneously. This combination enhances the reliability of these methods in determining material properties and thickness, as well as detecting defects within the members with minimal additional field-testing time. The USW method can be used to determine the modulus of the material and relate it to material degradation and presence of internal defects. The IE method can be used as a tool to determine the thickness or the defects within concrete slabs or tunnel lining.



Figure 2.1. Portable Seismic Property Analyzer.

## **Equipment and System Integration Requirements**

The PSPA (Figure 2.1) is an integrated data collection and reduction unit. This device consists of four main elements. The core of the system is a solenoid-type high-frequency impact hammer and two high frequency accelerometers, which are deployed in the sensor unit. The receivers are connected to a data acquisition system in the electronics box. The system is operable from a laptop computer. This computer is tethered to the hand-carried transducer unit through the cable that carries power to the transducers and hammers and returns the measured signals to the data acquisition board in the computer. The data collection at one point takes about 15 seconds.

As mentioned earlier, two testing methods are used in the operation of the PSPA. The time records from the two receivers are used in the USW method to determine the properties of the top layer with Spa Manager Software in the computer. The modulus of each point can be obtained as soon as the data collection is completed. The PSPA also performs the IE method by measuring the frequency content of the first sensor's time record and estimating the layer thickness or depth of defect.

#### **Test Procedures**

At each site, the first step consisted of selecting a test section and marking the test points. The density of data collection depends on the smallest defect of interest to the agency (Azari et al., 2012). To obtain better quality time records, there should be a good contact between the sensors and the top surface; therefore, the surface of the test object should be smooth and clean of debris. Then, each point is tested with the PSPA. Test procedures are documented at http://www.geomedia.us/.

To collect data with the PSPA, the user initiates the testing sequence through the computer. The thickness (or the required penetration depth) and test material are input by the user as nominal values. By collecting data, the high-frequency source is activated four to six times. The outputs of the two transducers from the last three impacts are saved and averaged (stacked). The other (prerecording) impacts are used to adjust the gains of the preamplifiers. The gains are set in a manner that optimizes the dynamic range.

After data collection at one point, the acquired time records can be observed with the PSPA software. In case of weak contact between the sensors and the material surface, either the time records will be erratic or no signal will appear. In this case, the test is rejected and a new test is performed. When the sensors achieve intimate contact with the surface, the acquired time records typically look like Figure 2.2. The red record is the time history of the source. This record is useful to the advanced user for ensuring that the source is functioning properly. Additionally, the record is used in the IE analysis. The black record shows the time history from the Sensor 2 (the far receiver). These two records are used in the determination of the modulus with

the USW method. Both records indicate the typical arrival of the surface wave followed by reflection from the bottom of the testing object or the bottom of the internal defect.

After accepting the collected waveforms, the operator can view the analyzed data, as shown in Figure 2.3. The graph at the bottom is the phase spectrum, which is determined by conducting a spectral analysis on the time records from the two receivers. The phase spectrum indicates the variation in phase delay between two receivers with frequency. The green curve is the measured phase spectrum from the time records, and the red one is the best fit to the measure spectrum when the effect of the body waves is removed. The fitted spectrum is then used to compute the dispersion curve (Desai and Nazarian, 1993). In the upper graph, the green dots show the variation in modulus with thickness, which is called a dispersion curve. The dispersion curve is directly calculated from the phase spectrum. The red solid line in this graph corresponds to the average modulus, which is obtained by averaging the dispersion curve down to approximately the nominal thickness of the layer. The average modulus is also shown in the results section on the left side of the figure (i.e., 3830 ksi). Therefore, the operator can get a qualitative feel for the variation in modulus with depth and also average modulus.



Figure 2.2. Typical time records by PSPA software.



Figure 2.3. Typical interpreted results by PSPA software.

## **Inspector Training Requirements**

Data collection and documentation are carried out through the Spa Manager Software provided with the device. Two days of on-site training are typically required for inspectors who are collecting data and about a week of training is required for the data analyst. The training of the data collector and data analyst should provide the fundamentals of elastic waves, sonicseismic testing methods, and common defects in different testing media in order to set up test parameters and interpret acquired data correctly. During data collection, the inspector should make sure that the source is functioning properly and the receivers are in full contact with the surface. The data interpreter should have a basic knowledge of signal processing to analyze surface waves and body waves reliably.

General and specific certification requirements may be required, according to the agency performing the testing. For example, certification requirements required by paragraphs 8.3 and 8.4, respectively, of the *Recommended Practice No. SNT-TC-1A* are provided by the American Society for Nondestructive Testing (ASNT) nondestructive testing (NDT) Level I, Level I Limited, Level II, and Level III certification programs for NDT employers.

- ASNT Level I Limited technicians are only qualified to perform a specific procedure for a specific inspection on a certain component with direct supervision and guidance of higher-level technicians.
- ASNT Level I technicians are only qualified to perform specific calibrations and tests under the guidance of a higher-level technician.
- ASNT Level II technicians are qualified to set up and calibrate systems; inspect according to procedures; and evaluate and report the testing results for the specific certificate issued.

 ASNT Level III technicians are qualified to establish testing procedures and techniques by interpreting governing codes, standards, and specifications, and they can train lowerlevel technicians.

#### **Data Management Procedures**

The PSPA saves the raw data in binary format from each test point with appropriate metadata indicating the time and information about the test parameters. Upon initiation of a project, the user will identify the location where the data have to be stored. The analysis software (Spa Manager Software) is able to read the binary data format and also to transform the data into American Standard Code for Information Interchange (ASCII) format. The ASCII format data can be reanalyzed readily with new algorithms if necessary.

### **Data Analysis Procedures**

The data analysis is defined as the processing of the raw data collected by the PSPA and includes preprocessing, data analysis, and presentation of data. In the preprocessing phase of the IE method, utilizing a time window to remove the surface wave energy from the time records provides a more robust and accurate thickness measurement compared to when the entire waveform is utilized. On the other hand, in the USW method, the surface wave energy should be reinforced by implementing proper filters to minimize the reflection and body wave energy. The data analysis includes fast Fourier transform of time records to frequency domain, which can be used to determine amplitude spectrum and phase spectrum of the acquired time records.

The data presentation of the USW and IE results in the form of color contour maps, namely "traditional with unlimited color index," "traditional with two color index" and "checkerboard" (Azari et al. 2012). The traditional contouring utilizes a smoothing algorithm to ensure that the displayed contour lines change gradually and incrementally from a minimum value to a maximum value. A large number of shades of primary colors are used in the smoothing algorithm when the unlimited color index approach is selected. The two-color index contours contain only two colors delineated by a threshold value. However, a smoothing algorithm is still used to depict the results. The checkerboard algorithm plots a rectangular array of cells. The value for each cell is determined by smoothing the results using the values of that cell and the four adjacent cells to define a surface rectangle. Azari et al. (2012) showed that representing the data in a checkerboard format enhances the evaluative power of the results.

#### **Interpretation Guidelines**

To interpret the results, it is necessary to define the modulus and frequency threshold to delineate between the intact and delaminated areas. In USW results, the modulus threshold is set at 0.86 times the mean of the measured moduli of each slab to ensure that the delaminated areas are detected with a level of confidence of about 95% (Azari et al. 2012). The test points with a modulus less than the threshold are demonstrated in red, indicating that they are defective. The threshold frequency in IE contour maps is selected based on thickness of the slab as well as depth and extent of defect. The test points with dominant frequency less than thickness frequency are marked as red (defective).

#### Limitations (such as Technical, Operational, Environmental)

Although USW and IE methods are shown to be successful in detecting internal defects, there are some apparent disadvantages to consider. They are localized testing methods, and testing a long section may take a lot of resources and time. In addition, although the IE method does have the ability to show the existence of a defect, it is difficult to quantify the depth of defects that are shallow or extensive. Inadequate contact between the sensors and the material surface will result in inaccurate and false measurements, especially for very rough concrete surfaces and oily and curved surfaces, such as tunnel linings, that cause occasional slips of devices during testing. On the other hand, the USW method does not differentiate between an intact slab and a slab with deep defect, and, therefore, this method is not very effective in detecting deep defects.

## **Other Information**

More information can be found at <u>http://www.geomedia.us/</u>; in the SHRP 2 R06(A) final report (to be published shortly); and in Azari et al. (2012), Boone et al. (2009), Delatte et al. (2003), Fisk et al. (1994), Gucunski et al. (2006), Hisatake et al. (1994), Nazarian and Baker (1997), and Nazarian et al. (2006).

## **CHAPTER 3: Ultrasonic Echo User's Manual**

#### Introduction

The information contained in Chapter 1, Ultrasonic Tomography User's Manual, relating to test procedures and data interpretation, can also apply to this device. Therefore, please review the pertinent information in Chapter 1 as well.

An ultrasonic transducer is used to generate and/or receive ultrasonic waves in/from a test medium. The ultrasonic echo technique involves sending and receiving ultrasonic pulses from the same side of the test object by the same or two separate transducers. The ultrasonic pulse velocity (UPV) is correlated to material strength or quality. The measurement of propagation time is used to localize cracks, voids, and delaminations and/or to estimate the thickness of a structure. Large enough defects (with respect to the ultrasonic wavelength), as well as structural boundaries, induce a high contrast in acoustic impedance and result in the reflection of ultrasonic waves. The reflected waves are detected in ultrasonic scans, and the two-way travel time is used to estimate the reflector location (assuming or knowing the ultrasonic wave velocity in the test medium).

The hand-held ultrasonic transducer used for field testing and the corresponding data acquisition/analyzer unit are shown in Figure 3.1. In tunnel testing applications, the ultrasonic echo technique can be used to estimate the thickness of the tunnel lining as well as to detect delaminations and voids within the lining.



Figure 3.1. Ultrasonic echo equipment A1220 Monolith, by Acoustic Control Systems (ACSYS) (<u>http://acsys.ru/eng/</u>).

## **Equipment and System Integration Requirements**

The ultrasonic echo equipment used is the A1220 Monolith (Figure 3.1) developed by ACSYS in cooperation with BAM. It is a low-frequency ultrasonic flaw detector, suitable for thickness measurement and flaw detection in heterogeneous large-grained materials such as concrete. The array consists of 24 spring-mounted ultrasonic point transducers, out of which 12 serve as transmitters and 12 as receivers. Because of the structure of the array, a higher amount of ultrasonic energy is transmitted and the reflected signals are averaged, thereby minimizing the scattering noise. However, the array is still small enough to allow testing on rough surfaces. Since the transducers are of dry-contact type, the array is directly pressed against the test object, and therefore no coupling agent or special preparation of the test object's surface is required. Testing can be done either manually (point-by-point) or automatically (over a grid) using robatic scanner systems.

For testing larger test areas, the A1220 transducer can be mounted directly on an automated scanning device. One such scanning system developed by BAM, the ZfP-Scanner (shown in Figure 3.2), can be used for measurements on horizontal surfaces and vertical surfaces

as well as for overhead testing. Its adjustable size allows scanning in narrow areas. The scanner is fixed to the surface using vacuum feet or plates. The speed of the ultrasonic scanning on a 1-by 1-inch (2.5- x 2.5 cm) grid is about 11 ft<sup>2</sup>/h (1 m<sup>2</sup>/h). The ZfP-Scanner is not commercially available.



Figure 3.2. ZfP-Scanner on a test site in Chesapeake Bay Bridge Tunnel with the ultrasonic echo equipment mounted on it.

#### **Testing Procedures**

When using dry-point contact probes, no coupling liquids need to be applied on the surface. However, it is necessary to clean the surface from dust and sand and remove all the materials from the surface that could prevent the penetration of low-frequency ultrasonic energy in the material.

The location (with respect to a permanent reference) and size of the test site should be carefully noted. In case of the scanner testing, the location of the scanner feet and the dimension of the scanner aperture need to be carefully recorded. It is equally important to record the orientation of the probe (i.e., its polarization) with respect to the test area or scanner opening. The parameters to be set before starting with the measurements are the center frequency, the delay time, and the voltage level. The choice of parameters depends on the particular application, i.e., test material and required penetration depth. For testing of concrete tunnel linings up to 3 ft (1 m) thick, a center frequency of 55 KHz could be used.

The number of test points and grid spacing depends highly on the required resolution (i.e., the minimum size of sought defects) and the allocated time for field investigations. In the SHRP 2 R06(G) project, a spacing of 1 inch (2.5 cm) in each direction was chosen, allowing the scanning operation at about 11 ft<sup>2</sup>/h (or 1 m<sup>2</sup>/h), for acoustic testing requires contact. Investigations revealed that doubling the grid spacing to 2 inches (about 5 cm) would not compromise the accuracy of the test results. Reconstruction algorithms used for post-processing the data (e.g., synthetic aperture technique) are most effective for grid spacing of 2 inches (about 5 cm) or less. To achieve the maximum accuracy, it might be necessary to do the measurements with two polarizations.

#### **Inspector Training Requirements**

A 1-day training is necessary before setting out for manual testing. The training should provide the fundamentals of ultrasonic echo testing as well as operational principles of the specific transducer (e.g., A1220) including a hands-on training module. One or several mock-ups of typical tunnel lining sections with sought-after features and defects may be developed for training purposes. Handling and programming the scanning system requires 2 to 3 days of additional training.

Some general information about the tunnel lining structure and the types of defects sought is required for setting the test parameters. Data interpretation can be done by trained users only and usually demands engineering judgment.

General and specific certification requirements may be required, according to the agency performing testing. For example, certification requirements required by paragraphs 8.3 and 8.4, respectively, of the *Recommended Practice No. SNT-TC-1A* are provided by the American Society for Nondestructive Testing (ASNT) nondestructive testing (NDT) Level I, Level I Limited, Level II, and Level III certification programs for NDT employers.

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- ASNT Level II technicians are qualified to set up and calibrate systems; inspect according to procedures; and evaluate and report the testing results for the specific certificate issued.
- ASNT Level III technicians are qualified to establish testing procedures and techniques by interpreting governing codes, standards, and specifications, and they can train lower-level technicians.

#### **Data Management Procedures**

The collected data are downloaded from the ultrasonic hardware and saved on an external hard disk for safekeeping. Depending on the amount of data acquired, downloading might be necessary in between a measurement cycle, or an external hard disk can be hooked up to the instrument. Using the A1220 device on a 1- by 1-inch (2.5- by 2.5-cm) grid of size 48 by 24 inches (1225 data points, 1024 samples per signal, sampling frequency of 1 MHz) produces a 16-bit binary file of 2.39 MB. The analysis software delivered with the hardware is able to read the

binary data format in which the information is saved. When using other analysis software, data transformation into a different file format might be needed.

## **Data Analysis and Interpretation**

Basic data analysis software is provided by the manufacturer. Other standard data analysis software can be used to post-process the experimental data.

Interpretation depends on the mode of testing (one point [A-scan], linear [B-scan], or surface measurements [D- and C-scans]) and may be enhanced using advanced analysis and visualization tools. For example, applying SAFT to the data improves signal-to-noise ratio. Phase analysis, on the other hand, makes it possible to distinguish between features and anomalies of different constitutes, e.g., steel or void. Built-in plans or other information about the test area may greatly facilitate the interpretation of the results.

Data interpretation can be done by experienced trained users and usually demands engineering judgment.

#### Limitations

The main limitation of conventional ultrasonic techniques is that the sensors have to be in contact with the structure during the measurements. This leads to several issues, such as poor repeatability and/or inconsistency of measurements, as well as delays in displacing and reinstalling the transducers. Mounting the ultrasonic on a scanning system accelerates the measurements and greatly enhances the repeatability and consistency of the measurement results. However, in comparison to contact-free measurement systems, conventional ultrasonic testing (even with dry-contact transducers like A1220) is relatively slow. Therefore, it is suitable for the

assessment of areas deemed problematic during screening. Other limitations of this technique include:

- At (or near) block joints or other structural boundaries, the signals suffer great disturbances, due to the reflection of surface waves. This makes the reliable evaluation of measurements difficult.
- The acoustic waves reflect partially at the interface between the inner shell concrete and roof gap backfill material. If these two materials are well bonded, the reflection is very small or may not be identified. However, there is often a separation between these two materials. A gap of a few hundredths of a millimeter is sometimes enough to completely reflect the sound waves. In such cases, only the thickness of the inner shell is measured (excluding the backfill material).
- Generally speaking, even with the phase evaluation, it is not always possible to establish the difference between certain types of defects, e.g., a flaw and an excessively thin cross-section of lower acoustic impedance.
- In the case of air-entrained concrete or fiber reinforced concrete, the range of thickness measurements is reportedly reduced, or carrying out the measurements is more difficult.

## **Other Information**

Other information can be obtained via the Acoustic Control System (2004) and Zoega et al. (2012).

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