

**ADVANCED GROUND PENETRATING RADAR DATA
COLLECTION AND IMAGING OF BRIDGE DECKS USING 3-D
RADAR**

Report submitted to

The University of Vermont

as a part of

**Federal Highway Administration's (FHWA's)
"Advanced Ground Penetrating Radar (GPR) Research Project"**

Report prepared by

Nenad Gucunski, Director

and

Carl Rascoe, Research Engineer

**Infrastructure Condition Monitoring Program (ICMP)
Center for Advanced Infrastructure and Transportation (CAIT)
Rutgers University**

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16. Abstract The main objective of the conducted research was to evaluate 3D-Radar GPR in bridge deck condition assessment and imaging, with an emphasis on detection and characterization of corrosion induced bridge deck delamination. A broader objective of the study was to provide data for comparative evaluation of the performance of 3-D Radar, PERES (Precision Electromagnetic Roadway Evaluation System) GPR and other nondestructive (NDT) technologies in NDE bridge deck evaluation. The main task of this project was to provide comparative field evaluation of the 3D-GPR and impact echo (IE) technique in delamination detection and characterization			
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INTRODUCTION

Ground penetrating radar (GPR) is a very valuable technology for nondestructive evaluation of transportation infrastructure. It was successfully applied in pavement layer thickness evaluation, condition assessment of bridge decks, detection of cavities and other anomalies under pavements, etc. The existing ground penetrating radar (GPR) technology is limited in several aspects. The first limitation stems from the use of a single antenna. This limitation restricts testing during one pass to a single test line. The second limitation comes from the use of a fixed frequency antenna. The frequency defines the depth of penetration and resolution of the obtained image. Therefore, if of interest is to get a high-resolution image of a medium from the surface to depths of a few meters, it is necessary to use multiple antennas of different frequencies. The third major limitation represents the antenna orientation. A single oriented antenna can detect only objects in the test line direction. For example, to detect rebars in a bridge deck in both directions, it is necessary to use two mutually perpendicular antennas.

There is a new generation of GPRs, three-dimensional (3D) GPRs that provide significant improvements in the solution of the above problems. The new GPR generates high-resolution three-dimensional images of buried objects and natural interfacelayers down to a 3-meter depth, by using different antenna arrays. Of special interest for this investigation was 3-D GPR manufactured by 3D-Radar Company from Norway and powered by software made by RoadScanners Company from Finland. This 3D-GPR system is suitable for many applications: from fast road surveys at 90 km/h (55 Mph), or detailed utility mapping, to concrete bridge deck inspection. It operates in the step frequency mode in a frequency range from 100 MHz to 2GHz and current arrays are produced from a single pair of transmitting and receiving antennas to up to 63 pairs. An example of a 3D-GPR is shown in Figure 1. A clear advantage of the presented antenna over the existing ones is that it covers and can provide an image of an almost entire lane width from a single test run.

As a result of simultaneous surveying by multiple antennas, a three-dimensional image of the surveyed medium can be made. (In contrast to a vertical cross section plane image along the test line obtained from the current GPR testing.) Therefore, results of GPR surveys can be presented in terms of both horizontal planes at different elevations, and multiple vertical cross section planes along a number of survey lines. This is illustrated in Figure 2 for the GPR survey of a pavement. Of special interest for this project was the application of the 3D-Radar GPR in bridge deck condition assessment, with an emphasis on bridge deck delamination detection. To evaluate 3D-GPR's ability to image and assess condition of bridge decks, decks of two bridges in Virginia were evaluated by 3D-GPR. For the comparison, and to a certain extent validation of 3D-GPR, sections of both bridge decks were tested and evaluated by impact echo (IE). The following sections of the report provide a brief description of 3D-GPR and IE technologies in bridge deck evaluation, results of evaluation of the two bridge decks by the methods, and conclusions of the evaluation and recommendations for improvements.

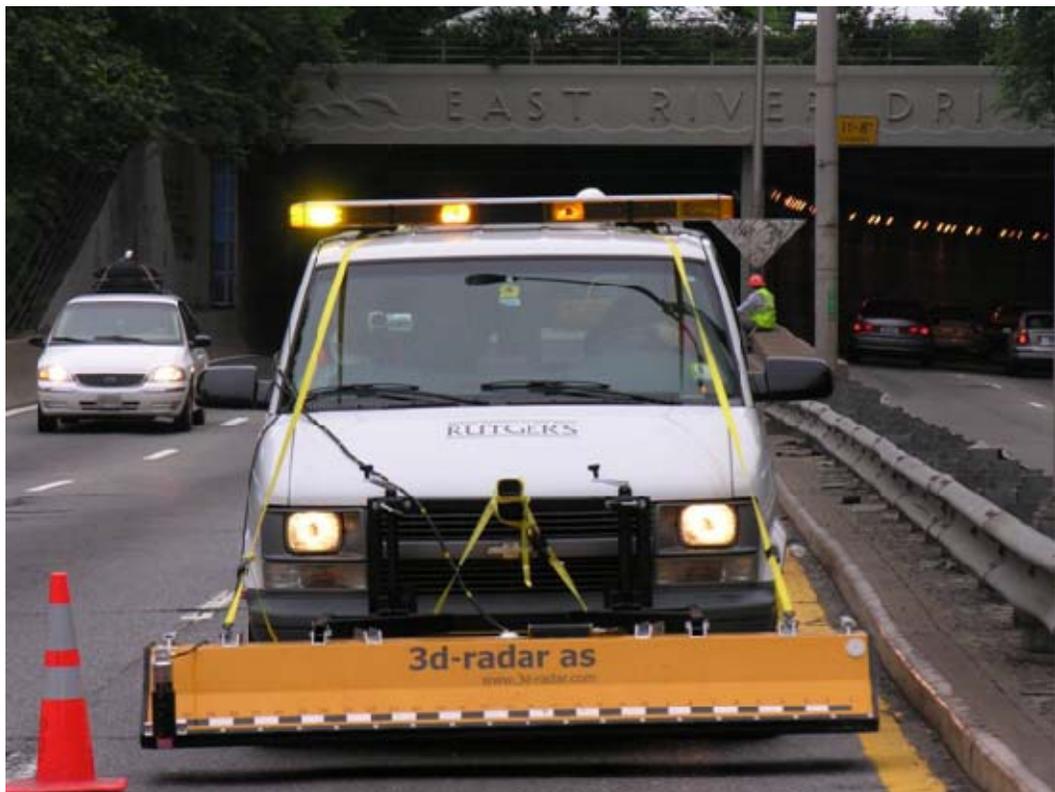


Figure 1. 3-D GPR for pavement surveys.

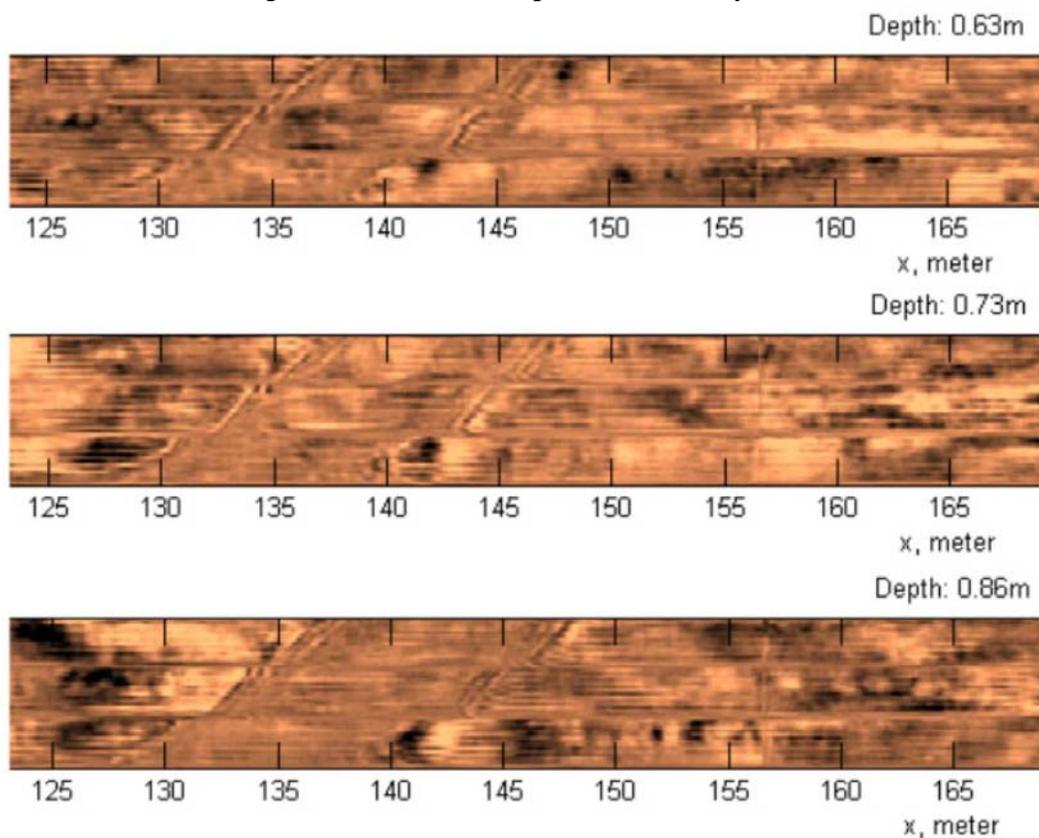


Figure 2. 3-D GPR horizontal plane images at three elevations of a pavement.

PROJECT OBJECTIVES

The main objective of the conducted research was to evaluate 3D-Radar GPR in bridge deck condition assessment and imaging, with an emphasis on detection and characterization of corrosion induced bridge deck delamination. A broader objective of the study was to provide data for comparative evaluation of the performance of 3-D Radar, PERES (Precision Electromagnetic Roadway Evaluation System) GPR and other nondestructive (NDT) technologies in NDE bridge deck evaluation. The main task of this project was to provide comparative field evaluation of the 3D-GPR and impact echo (IE) technique in delamination detection and characterization.

3D-GPR DESCRIPTION

3D-GPR utilizes different type of antenna arrays. The system described herein utilizes an array of 31 transmitting and receiving antenna pairs, as shown in Figure 2. The number of antennas active during the survey and the frequency range used control the maximum speed of the survey. Therefore, network level surveys of pavements, typically conducted at highway speeds, are done utilizing only three antennas. On the other hand, when of interest is a detailed image of the substructure, for example in imaging and condition assessment of bridge decks, all the antennas are deployed and the survey is conducted at speeds not faster than about 3 km/h (2mph). A clear advantage of the presented antenna array over the traditional single antenna GPR systems is that it covers, and can provide an image of, more than half of the lane width from a single test run with a resolution of 75 mm (3 inches). This will minimize the error due to misalignment of multiple passes of a traditional antenna.

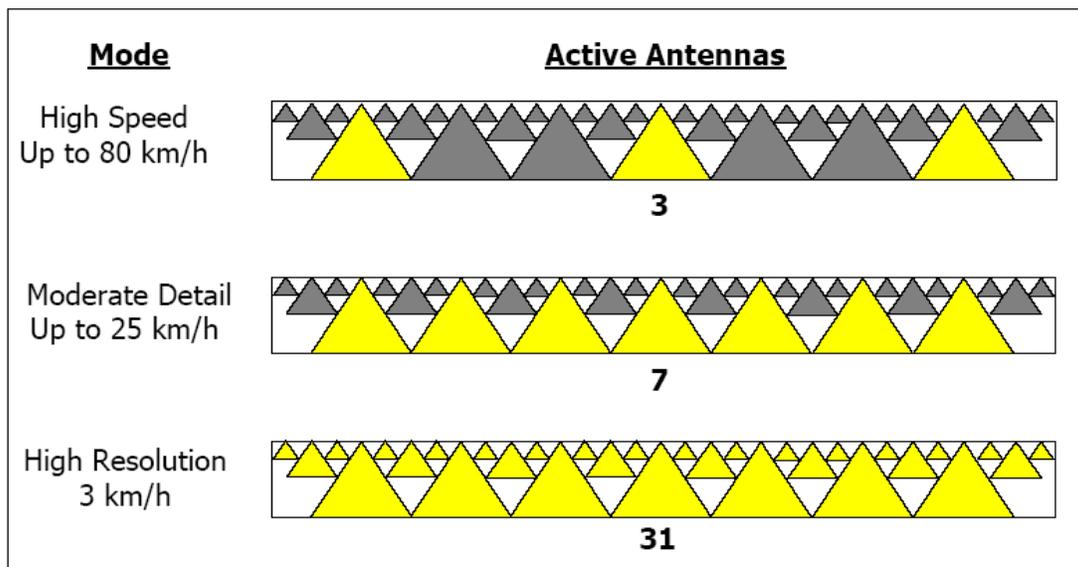


Figure 2: 3D-GPR antenna array.

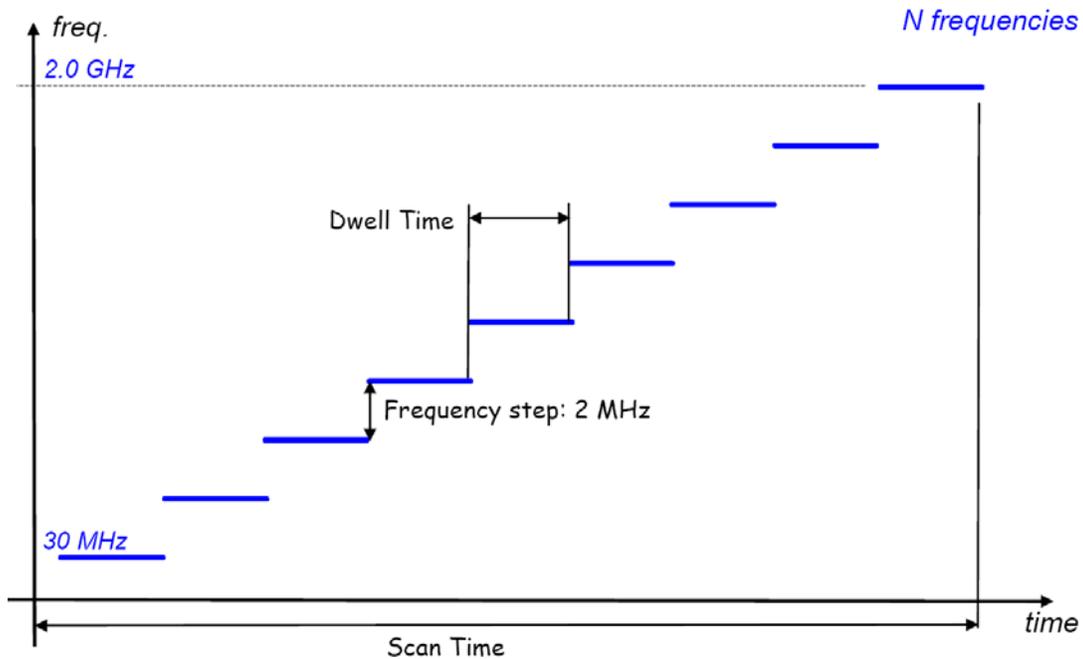


Figure 3: Step-frequency waveform.

3D-GPR operates in the step frequency mode, with a frequency step of 2 MHz (Figure 3). Pulse antennas, even those of ultra wide bands, provide a dominant part of energy around the antenna's center frequency. On the other hand, step frequency systems can cover broad frequency ranges at about same power levels. The 3D-GPR system covers (about uniformly) a frequency range from 140MHz to 2GHz, as illustrated in Figure 4.

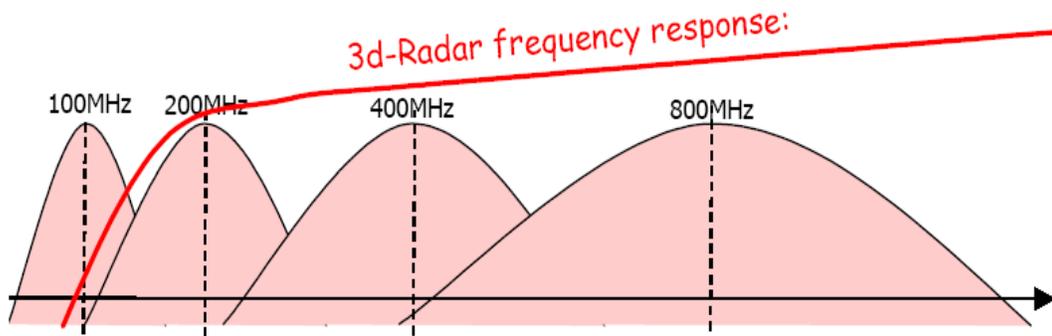


Figure 4: Frequency range of 3D-GPR and typical pulse systems.

The operator has the ability to select the start and stop frequencies and therefore optimize the processor speed while collecting data yet covering the selected target range. Other than selecting antenna pairs, frequencies and sampling interval there are minimal operator settings. Traditional radars rely on the operator to set up the survey by selecting a number of variables including gain, position and other scan settings. The minimal set up allows for data collection by a less skilled technician than that of other radars. With

traditional radars it is necessary to plan the survey in advance and select appropriate antennas for depth of penetration and required resolution. The 3D-GPR offers the advantage of multiple frequencies (varied depth of penetration) and the resolution associated with each wavelength all in a single scan.

Equipment typically used in 3D-GPR surveys consists of (a) Geoscope® data acquisition unit; (b) 3D-GPR antenna model B2431; (c) a portable antenna deployment frame, (d) an attached survey wheel; and (e) a laptop to control data acquisition unit. A GPS unit can be added for additional location information. The GPS and video (if used) are synchronized with the radar data using the Camlink software from RoadScanners.

As a result of simultaneous surveying by multiple antennas, results of 3D-GPR surveys can be presented in terms of both horizontal planes at different elevations, and vertical cross section planes in the longitudinal and transverse direction to the pavement survey direction. This is illustrated in Figure 5 by a screen with the longitudinal vertical cross section (top left), horizontal cross section or “time slice” (bottom), and transverse vertical cross section (right). By applying various data migration techniques, it is possible to create images of objects in the surveyed areas. This was illustrated in Figure 2 by time slices of a pavement with identified utilities and a pavement cut.

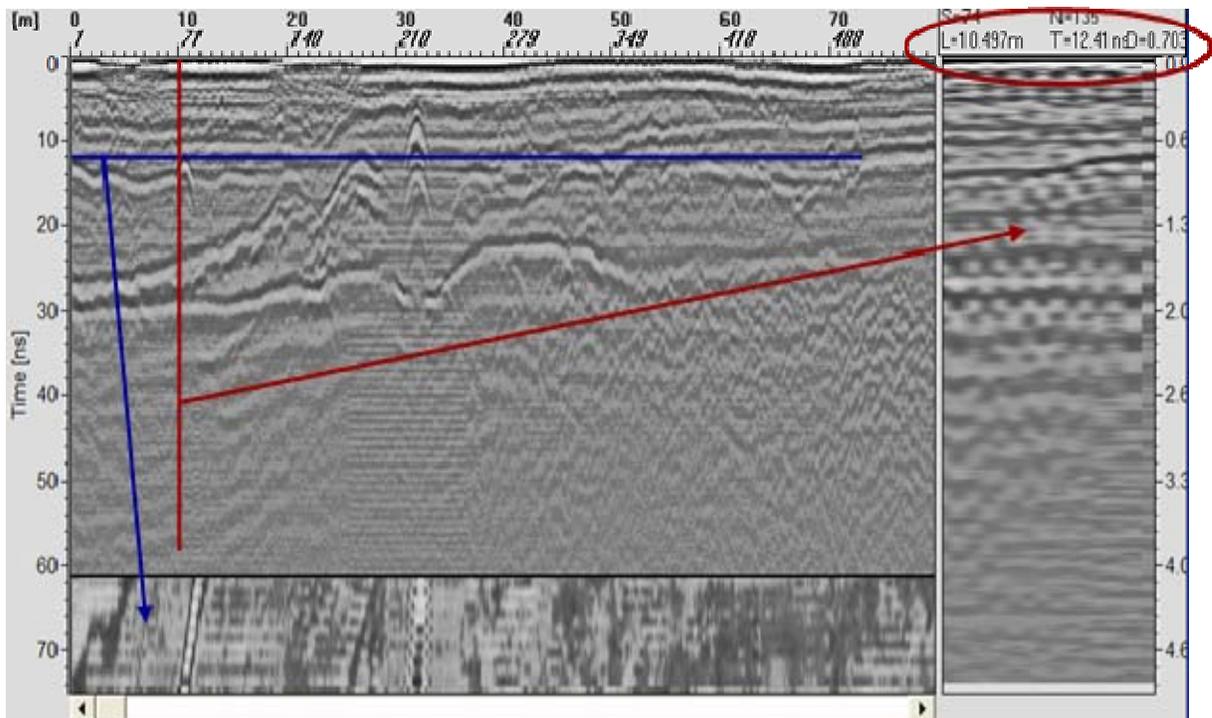


Figure 5. 3D-GPR image of a pavement section: vertical longitudinal (top left), vertical transverse (right) and horizontal/time slice (bottom).

BRIDGE DECK CONDITION ASSESSMENT BY IMPACT ECHO

IE method is an ultrasonic seismic method that is in the case of bridge deck evaluation, often used in conjunction with other ultrasonic seismic methods. Seismic methods enable evaluation of material properties and detection of structural defects by measuring the velocity of propagation of elastic waves and by observing various wave propagation phenomena, such as reflections, refractions and dispersions. Of particular interest for bridge deck evaluation are three ultrasonic techniques: UBW, USW and IE. UBW and USW techniques are used to measure velocities of propagation of compression (P) and surface (R) waves. Since velocities can be well correlated to elastic moduli, UBW and USW can be described as material evaluation techniques. The IE technique is used to identify position of wave reflectors in a bridge deck. Thus, it is used to detect defects in the structure and can be thought of as a diagnostic tool in defect identification.

Application of seismic techniques in bridge deck evaluation is illustrated in Figure 6. In the first part of the evaluation, UBW and USW tests are conducted using an impact source and two receivers to find P-wave velocity. Because it is often difficult to identify P-wave arrivals in the UBW test data in an automated way, a more reliable procedure to estimate the P-wave velocity is through a measurement of the surface (Rayleigh or R) wave velocity using the USW test. The USW test is identical to the spectral analysis of surface waves (SASW) test, except that the frequency range of interest is limited to a narrow high frequency range where the velocity of the surface wave does not vary significantly with frequency. In the second part of the evaluation, the IE test is conducted using an impact source and a single nearby receiver. Because of a significant contrast in rigidity of concrete and air, the elastic wave is reflected off the bottom of the deck back to the deck surface. The frequency of the reflection, called return frequency, can be identified in the response spectrum of the recorded signal. Finally, the depth of the reflector, in this case the deck thickness, can be obtained from the return frequency and the previously determined P-wave velocity, as illustrated in Figure 6.

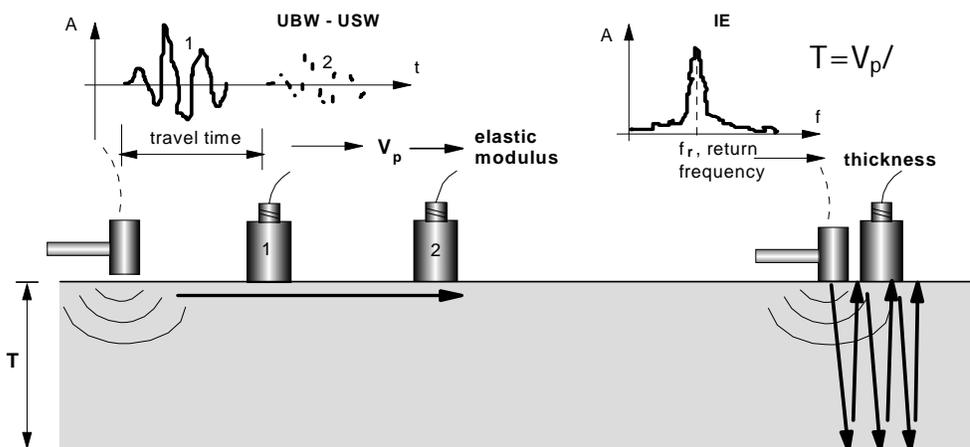


FIGURE 6 Measurement of bridge deck elastic modulus and thickness by UBW and IE methods.

While the primary objective of IE testing is to determine dominant reflectors, according to the relationship described in Figure 6, a unique thickness or depth of the reflector can be correlated to every component of the frequency spectrum. This is illustrated in Figure 7 by a frequency spectrum, and the corresponding thickness spectrum. The thickness spectrum enables simple data interpretation, because positions of the dominant and secondary peaks describe clearly the pattern of energy partitioning, and thus the degree of delamination. Spectra for a set of points along a single test line can be combined to form spectral surfaces. As shown in the same figure, frequency spectra for one test line on a bridge deck are combined to form a frequency spectral surface and are converted into a corresponding thickness spectral surface.

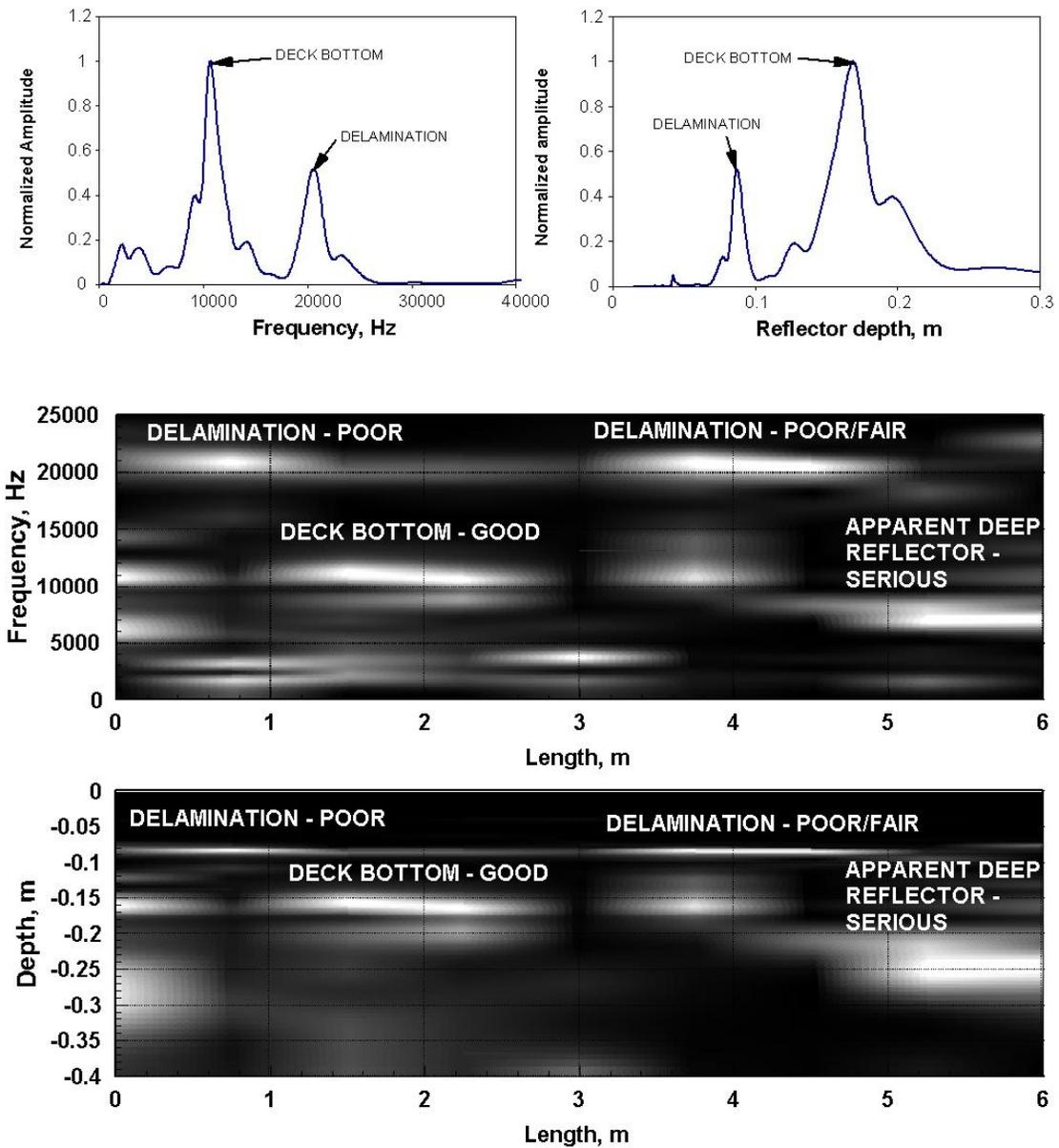


FIGURE 7 Frequency and thickness spectra and spectral surfaces.

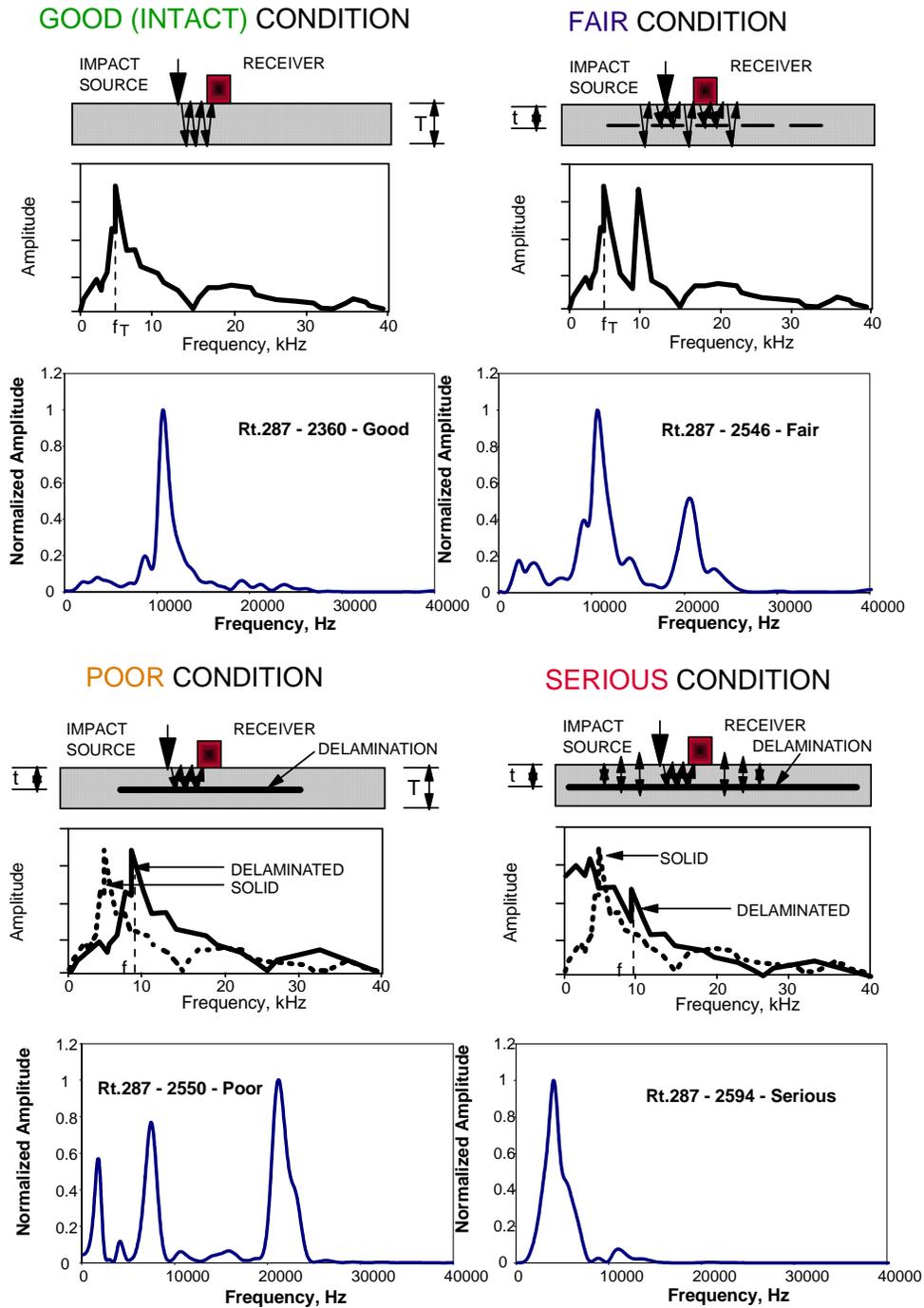


FIGURE 8 Grades for various degrees of deck delamination.

In the case of a delaminated deck, reflections of the P-wave occur at shallower depths, causing a shift in the response spectrum towards higher frequencies. Depending on the extent and continuity of the delamination, the partitioning of energy of elastic waves may vary and different grades can be assigned to that particular section of a deck as a part of the condition assessment process. This is illustrated in Figure 3. In the case of a sound

deck (good condition), a distinctive peak in the response spectrum corresponding to the full depth of the deck, can be observed. This is illustrated by two spectra under the cross section of the bridge deck. The upper spectrum in the figure represents a schematic of the expected spectrum, while the lower spectrum is taken from actual field testing. Initial delamination (fair condition) is described as occasional separations between the two deck zones. It can be identified through the presence of two distinct peaks, indicating energy partitioning from two dominant wave propagation patterns. The first peak corresponds to reflections from the bottom of the deck, while the second corresponds to reflections from the delamination. Progressed delamination (poor condition) is characterized by a single peak at a frequency corresponding to a reflector depth that is shallower than the deck thickness, indicating that little or no energy is being propagated towards the bottom of the deck. Finally, in a very severe case of a wide delamination (serious condition), the dominant response of the deck to an impact is characterized by a low frequency response of flexural mode oscillations of the upper delaminated portion of the deck. This response is almost always in the audible frequency range, unlike response of the deck in the fair and poor condition that may be in the ultrasonic range. Because it is significantly lower than the return frequency for the deck bottom, it produces an apparent reflector depth that is larger than the deck thickness.

IE is commonly implemented in deck evaluations by conducting point testing on a grid of selected spacing. The testing is conducted using impact echo devices, which in some cases integrate other ultrasonic seismic methods. One of such devices is PSPA which has a sole purpose of evaluation of surface pavement layers and bridge decks. The device integrates all three previously described ultrasonic techniques (UBW, USW, IE). The core of the PSPA system is a sensor box (Figure 9a) containing a solenoid type impact hammer and two high frequency accelerometers, 7.5 and 21.5 cm away from the hammer. All controls and data acquisition are in a computer that is connected by a serial cable to the sensor box. A new design of the PSPA (Figure 9c) has all data acquisition and control elements as a part of the unit. Field evaluation of decks is typically done on grids of 0.6x0.6 m to 0.9x0.9 m (Figure 9d).

Testing using the PSPA is simple and for a single point takes less than 30 seconds. On an average, about 50 m² of a deck can be tested per hour using 0.9 m spacing, or about 20 m² using 0.6 m spacing. The sensor box is placed at the test point (Figure 4c), a series of impacts (6-10) of 50 μs duration are applied and acceleration histories are recorded. The testing is fairly insensitive to traffic induced vibrations, because those are in a much lower frequency range than the IE test range, which is typically 2 to 30 kHz. PSPA testing results are commonly described in terms of shear and Young's moduli (or P- and S-wave velocity) distributions, and condition assessment distributions (with respect to the degree of delamination). This will be illustrated by condition maps for sections of the two evaluated bridges in Virginia (Figure 18).

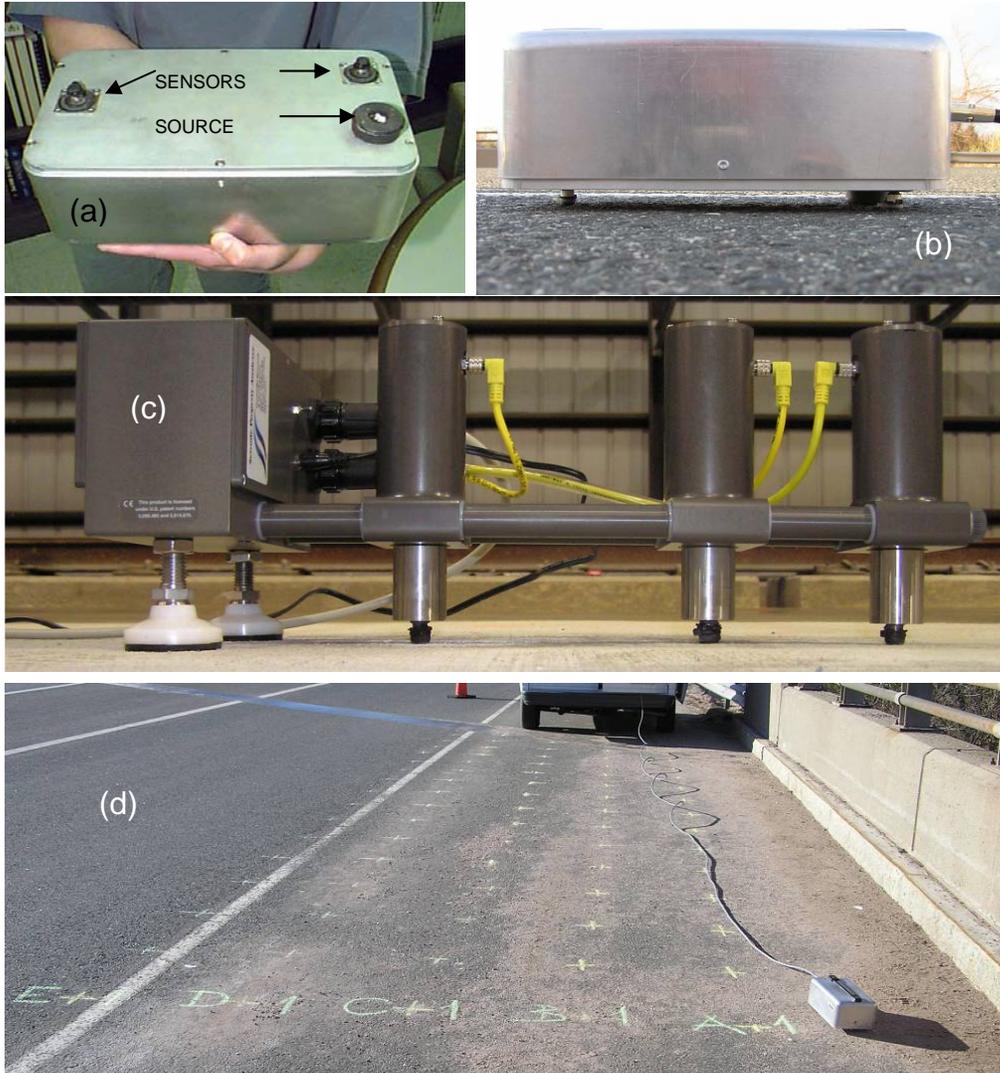


FIGURE 9 Older and newer versions of PSPA sensor box (a and c), and field implementation (b and d).

FIELD DATA COLLECTION

Two bridge decks: Van Buren Bridge over Quantico Creek in Prince Williams County, Virginia, and Carter Creek Bridge at Route 200, Lancaster County, Virginia, were evaluated using 3D-GPR and IE in October and November of 2006. The decks were previously evaluated by PERES GPR, impact echo (IE), chain drag and other methods.

3D-GPR equipment used in the surveys consisted of (a) Geoscope® data acquisition unit; (b) 3D-GPR antenna models B2431 (2.4 m wide with 31 antennas) and B1847 (1.8 m wide with 47 antennas); (c) a portable antenna deployment frame, (d) an attached survey wheel; and a (e) a laptop to control data acquisition unit. Prior to the start of the surveys, the survey wheel was calibrated over a distance of 50 ft and the system was setup to

record GPR scans at a distance-based rate of 12 scans per foot for all antennas. The frequency range of antennas used in particular runs, position of antennas, and data file names are given in Figures 10 and 11 for Carter and Van Buren Bridges, respectively. All the 3D-GPR surveys were conducted at a speed of about 1 mile per hour. Bridge deck evaluation by IE was done using Portable Seismic Property Analyzer (PSPA), a device manufactured by Geomedia Research and Development and shown in Figure 9. IE evaluation was done on areas marked in Figures 10 and 11 using a grid of 60x60 cm (2x2 ft).

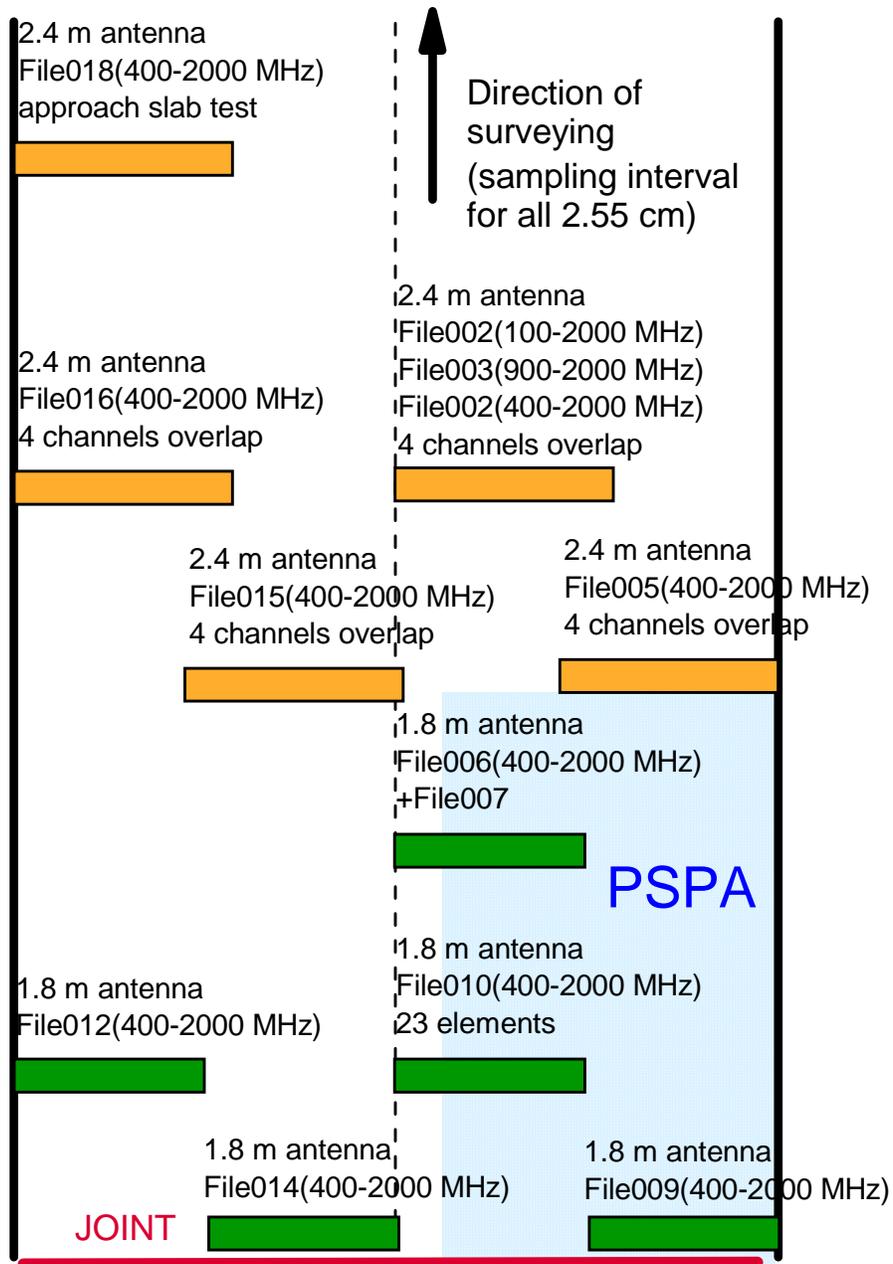


FIGURE 10 Schematic of 3D-GPR and IE (PSPA) surveys on Carter Creek Bridge.

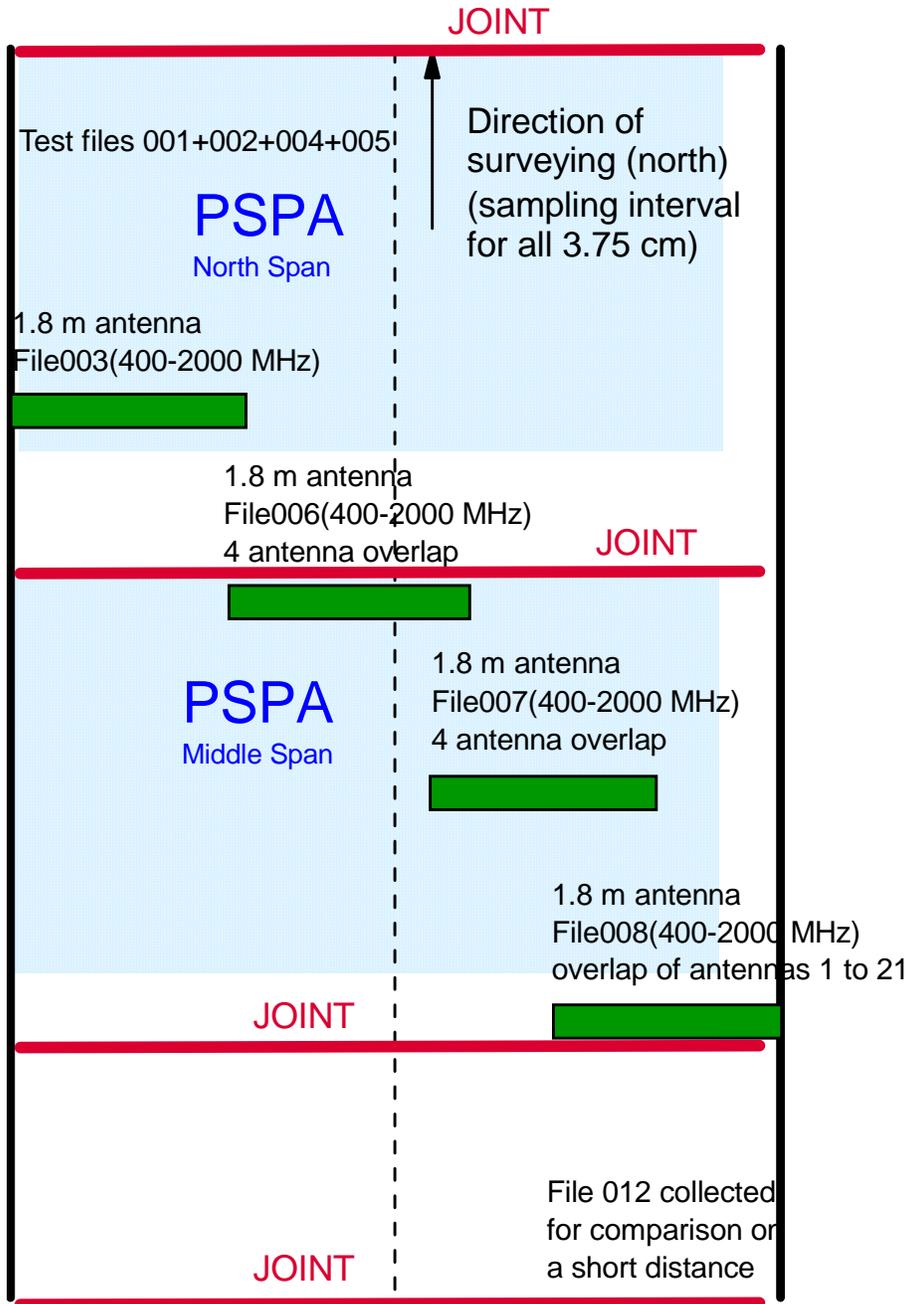


FIGURE 11 Schematic of 3D-GPR and IE (PSPA) surveys on Van Buren Bridge.

3D-GPR DATA PROCESSING AND SURVEY RESULTS

The following are the steps in the 3D-GPR data collection and processing side:

1. GPR setup – The 3D-GPR is attached to the vehicle mounting bracket and to the control unit, GeoScope (typically in the vehicle). The control unit is connected to the control computer, as shown in Figure 12. GeoScope is started, allowed to warm and stabilize and then configured for the survey type. A background and air shot were not

collected. During setup the operator can specify survey parameters such as the number and placement of antennas (system can use 1-31 antennas), frequency range (allowable selection of 30MHz – 2050MHz) and permittivity.

2. Data Collection – As the van drives along pre-defined and identified locations on the bridge (Figure 13), a file is collected by the GeoScope. A calibrated distance measuring device is used to trigger capture of a scan at the rate identified during setup. The bridge was surveyed with fixed radar parameters. Therefore each file contains data on all layers to the same depth. Multiple passes with different frequency ranges of antennas were not done during this study.
3. Data Pre-processing – Scans are saved to disk as raw data. Data pre-processing reformats the data to fit the .3dr format and to interpolate between lost scans. This step is performed by the GeoScope when the processor is not collecting data. It is usually complete within minutes of stopping the data collection. These .3dr files (frequency domain) are ready for analysis by software such as RoadDoctor.
4. Data Post-processing – To effectively use the .3dr files they need to be converted to time domain. RoadDoctor software performs an IFFT, filtering, gaining and editing as necessary to create the time domain files with the extension .3rd. During this process a background removal can also be performed. For this project, data migration was completed using the 3d-radar Company proprietary software.
5. Visualizing 3D data sets – Once the data has been identified by RoadDoctor, each channel of a .3rd file can be opened, viewed and interpreted on screen. RoadDoctor combines the individual longitudinal slices to form a 3D data set. The data can be viewed as a full 3D cube or as individual time slices at a specified depth.

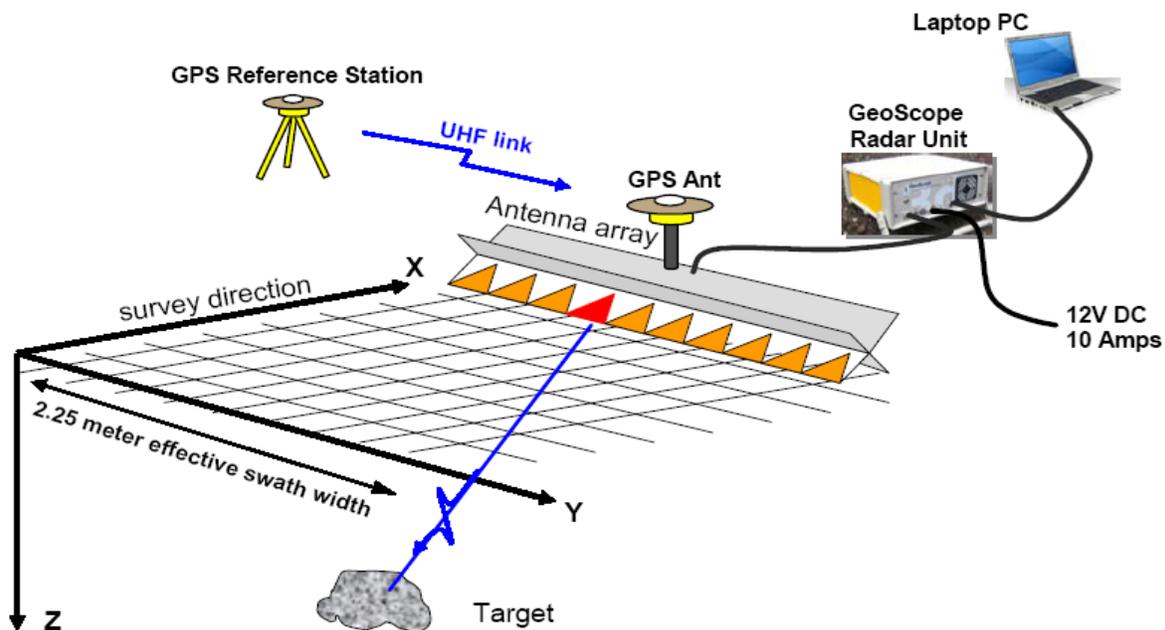


FIGURE 12 3D-GPR setup.

The first set of images from 3D-GPR data, shown in Figures 14 and 15, is for the Carter Creek Bridge deck. Time slices obtained from data collected using B1847 and B2431

antennas for about 11 cm depth, or approximately top rebar elevation, are shown in Figure 14. Time slices obtained from data collected by the same antenna pair, but for about 31 cm depth, or approximately girder and bracing elevation, are shown in Figure 15. From the comparison of the time slices, it is apparent that the B2431 antenna images are of higher resolution than B1847 images. The second set of 3D-GPR images in Figure 16 is for the Van Buren Bridge deck from the data collected using B1847 antenna. From a comparison with images for the same rebar and girder elevations for the Carter Creek Bridge deck, it is apparent that the Carter Creek Bridge images are sharper. As it will be demonstrated by impact echo results, this is a result of higher deterioration of the Van Buren Bridge deck that caused significantly higher attenuation of the GPR signal.

Very commonly, the objective of the use of 3D-GPR in bridge deck evaluation is condition assessment. It is done through evaluation of signal attenuation, or development of deck attenuation maps. Signal attenuation is obtained from evaluation of amplitudes of reflections from rebars, normalized by the amplitude of the signal at the surface of the deck and corrected for the depth of the rebar. A critical part in this process is accurate picking of rebars. An example of an attenuation map is given in Figure 17 for the Van Buren Bridge deck. While it was possible to generate attenuation maps for the tested bridges, the process was not repeatable due inconsistent picking of rebars. This problem should be corrected through improvements on the hardware side (for example increase of antenna frequency on the high frequency end side), improvements on the survey setup side (for example evaluation of the optimum antenna height), and improvements on the software side (most importantly in accurate and automated rebar picking algorithm side).



FIGURE 13 3D-GPR survey on Carter Creek Bridge.

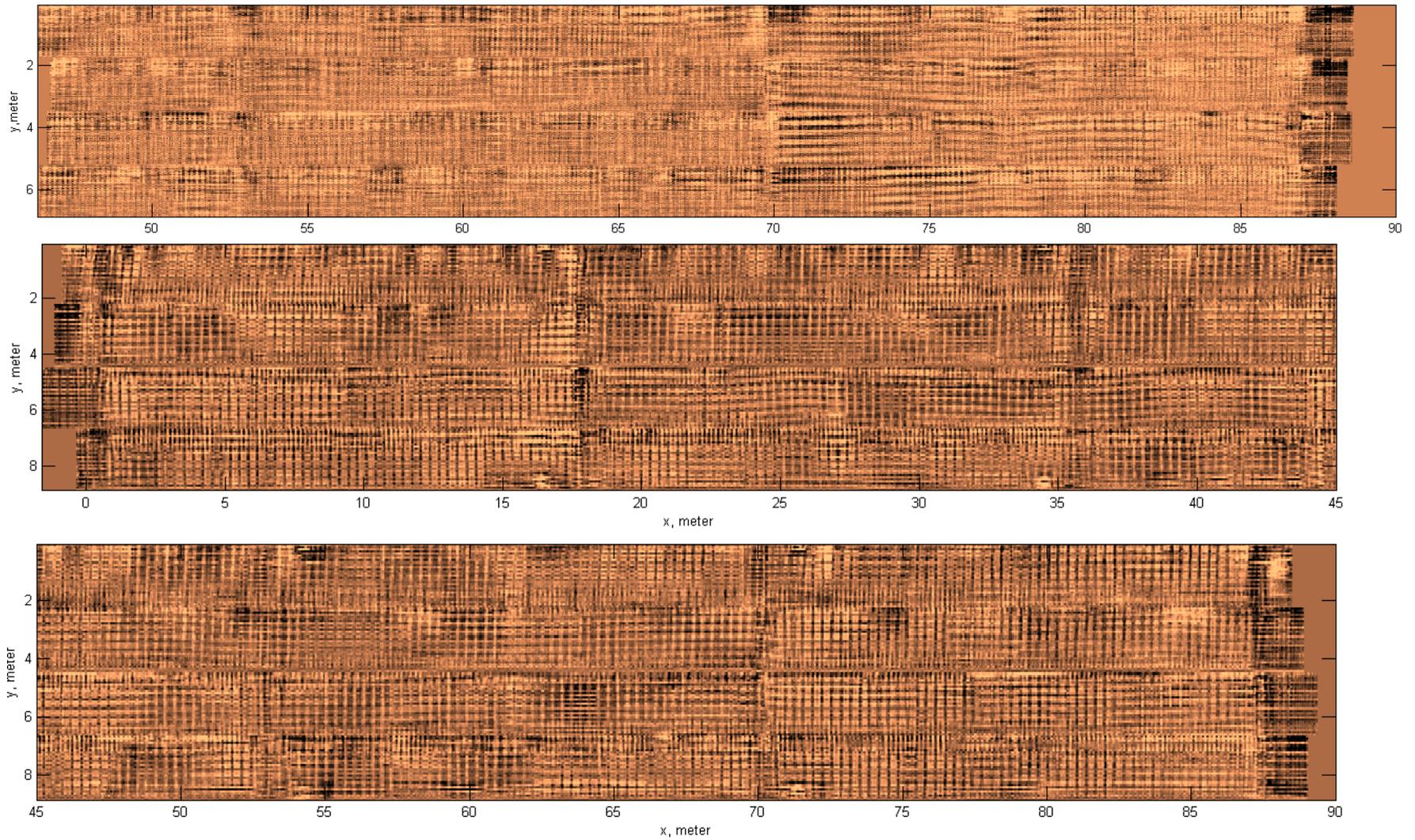


FIGURE 14 Time slices for 11 cm depth of Carter Creek Bridge deck from B1847 (top) and B2431 antenna scans (bottom two).

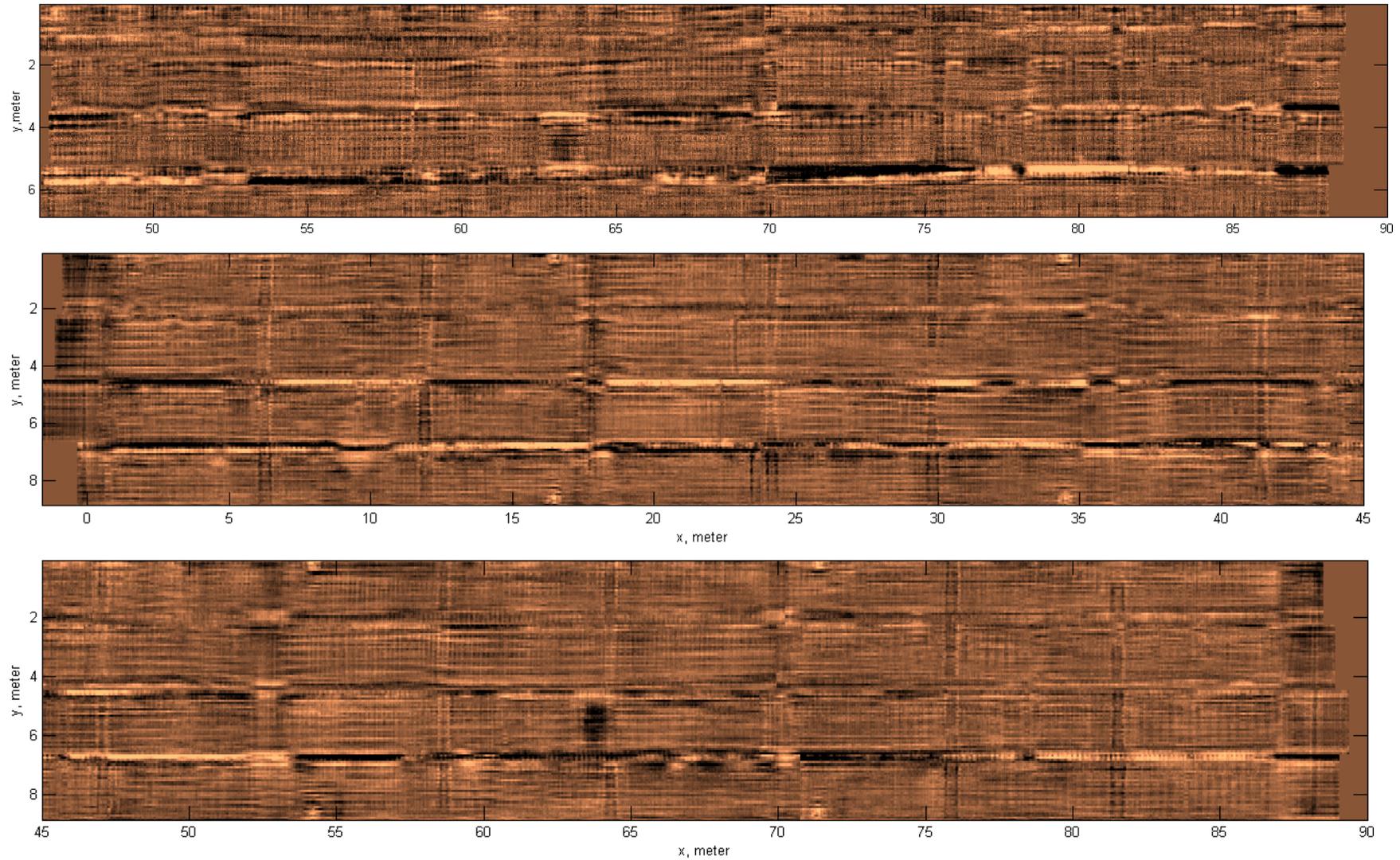
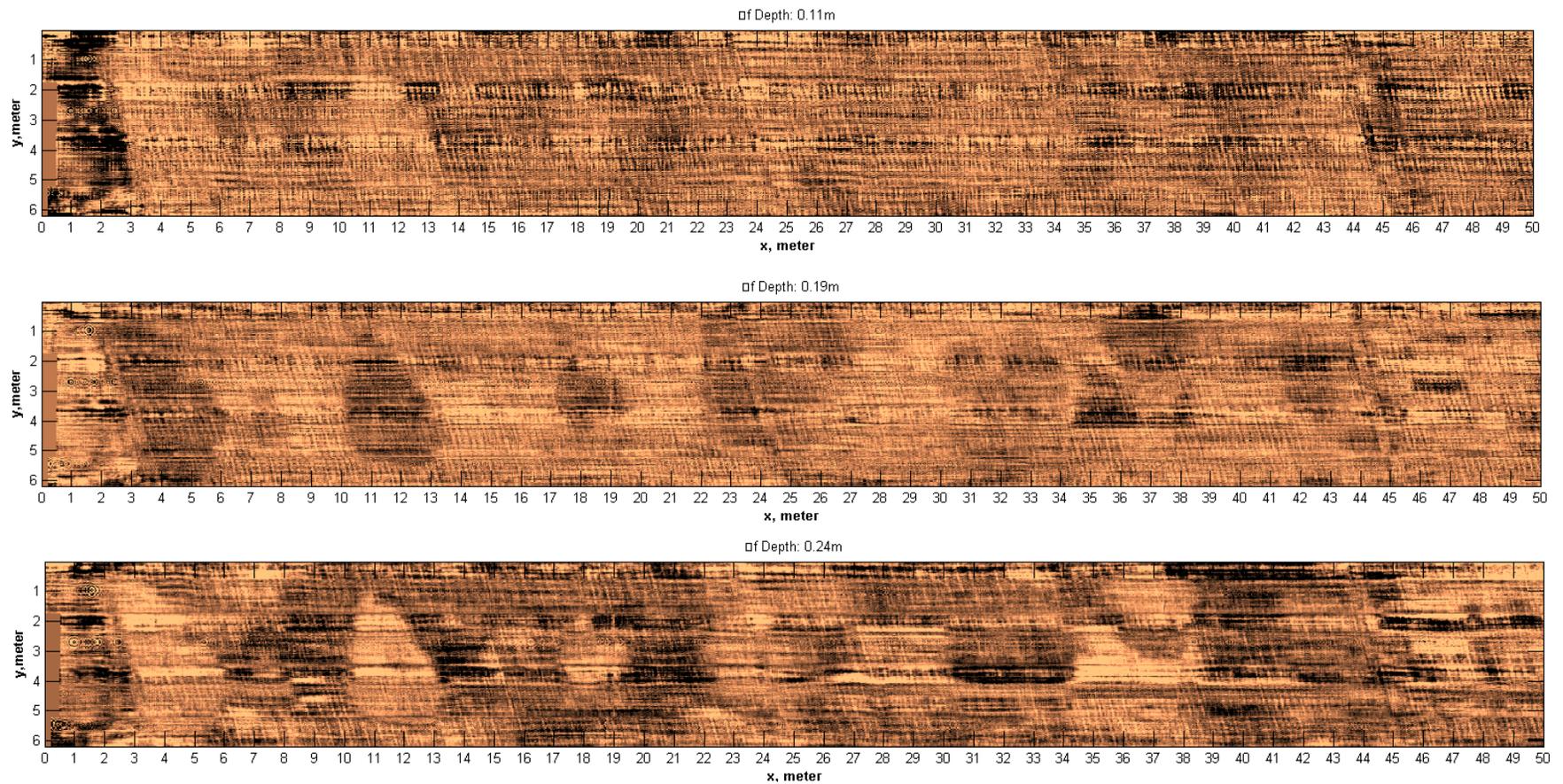


FIGURE 15 Time slices for 31 cm depth of Carter Creek Bridge deck from B1847 (top) and B2431 antenna scans (bottom two).



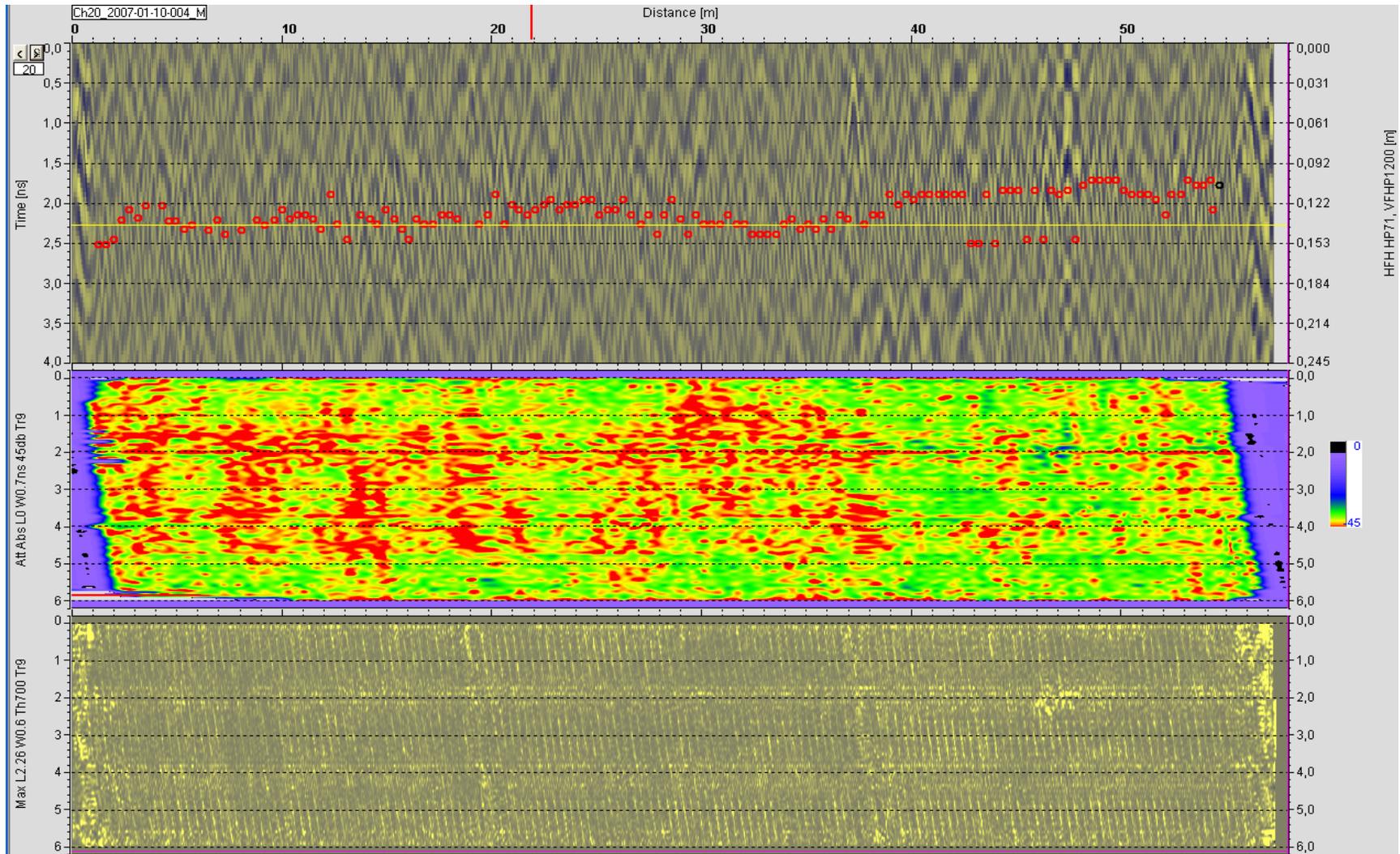


FIGURE 17 B-scan with picked rebars (top), attenuation map (middle) and time slice at 2.2 ns (bottom) for Van buren Bridge deck.

IE SURVEY RESULTS

Conditions maps for a section of the Carter Creek Bridge deck shown in Figure 10 are plotted in Figure 18. The condition is defined in terms of the actual grades assigned to each test point (top) and four condition grades (middle). As can be observed in the upper condition assessment plot for the Carter Creek Bridge, the deck is in a good condition and only smaller zones of initial and progressed delamination, and minor zones of a deck in a serious condition, can be identified. On the other hand, the bottom condition assessment plot in Figure 18 for Van Buren bridge deck illustrates a deck in a significantly deteriorated condition. Zones of all previously described conditions (grades) can be identified in the condition assessment plot.

The Van Buren Bridge deck was also evaluated by chain dragging. Results of IE testing were compared to those of the chain drag in the same figure. The comparison points to similarity of the two approaches in detection of areas with progressed delamination (poor to serious condition). The ability of the chain drag to identify zones in a serious condition can be explained by the fact that the frequency response in such cases is in the audible range. On the other hand, the most of the zones identified by IE as zones of initial delamination (fair to poor grades) were not detected by the chain drag. This ability to detect signs of initial delamination represents a significant advantage of IE (seismic ultrasonic testing) over the chain drag approach. It allows more accurate definition of boundaries of delaminated zones, better prediction of delamination progression, and leads to better assessment and timing for implementation of rehabilitation measures

3D visualization images of IE data for the two bridge decks were developed. Similar to the observations in the previous section, in the visualizations provided in Figure 19 it can be noticed that the Carter Creek Bridge deck, visualized in 19a and 19c is in a reasonably good condition. Primary reflections for that bridge are coming from the bottom of the deck. In contrast, the Van Buren Bridge, visualized in Figures 19b and 19d, has a large number of reflections throughout the volume, indicating a highly deteriorated condition.

From the practical point, of highest interest and benefit is identification of zones on the deck that are in serious condition (progressed delamination) or fair to poor condition (initial delamination). The process of identification of such zones is illustrated in Figure 20. Initial delamination (fair to poor conditions) is primarily identified by medium to strong reflections at the depth corresponding to the position of the top rebars. This is illustrated in Figures 18a and 18e for Carter Creek and Van Buren bridges, respectively, with strong reflection maps for slices between 7 and 13 cm. Similarly, sound zones of the deck are identified by strong reflections from the bottom of the deck, or in this case described by slices between 16 and 24 cm depth in Figures 20b and 20f. Finally, progressed delamination (serious condition) can be described by strong reflection maps for the slice for the depth deeper than the depth of the bottom of the deck. This is illustrated by the strong reflection maps for slices between 30 cm and 1 m in Figures 20c and 20g. To obtain the map of zones candidates for repair, the map for serious condition is superimposed on the map of initial delamination, as e.g. repair map in Figure 20d is obtained from the map in Figure 20c superimposed on the map in Figure 20a.

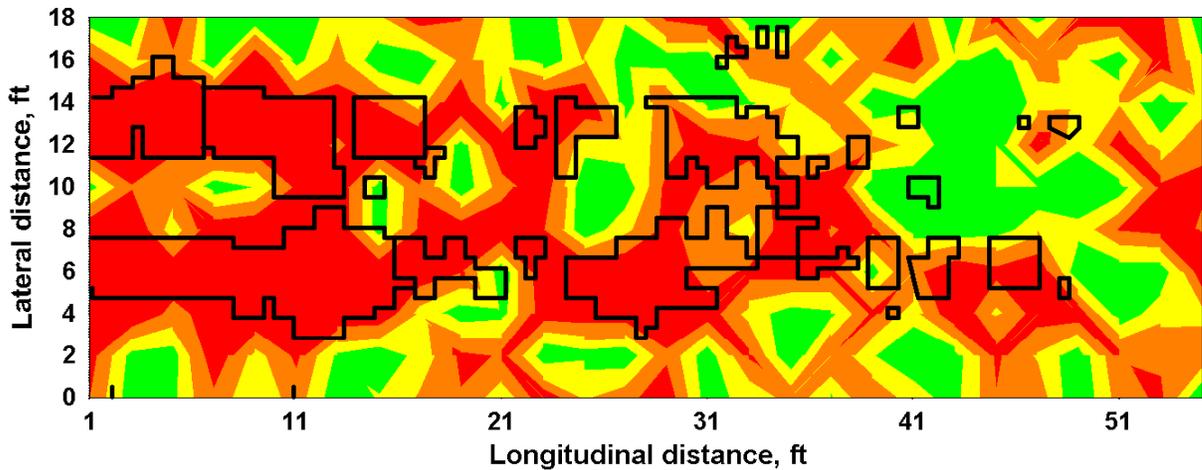
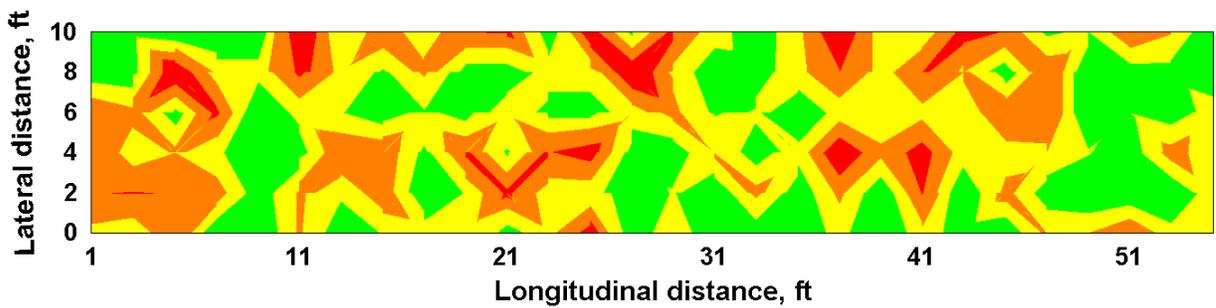
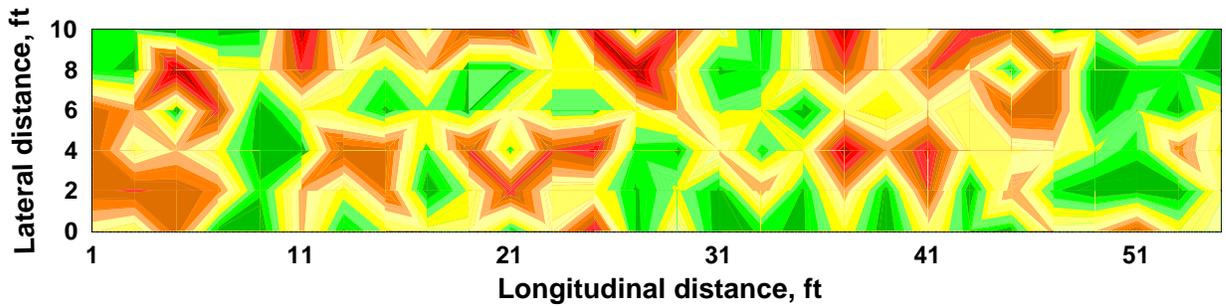
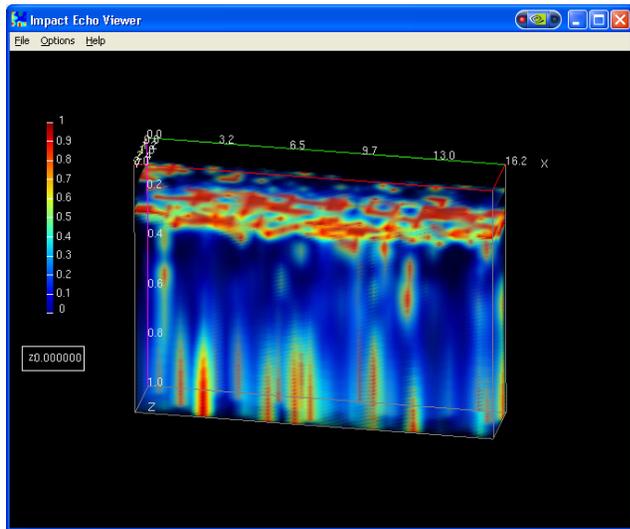
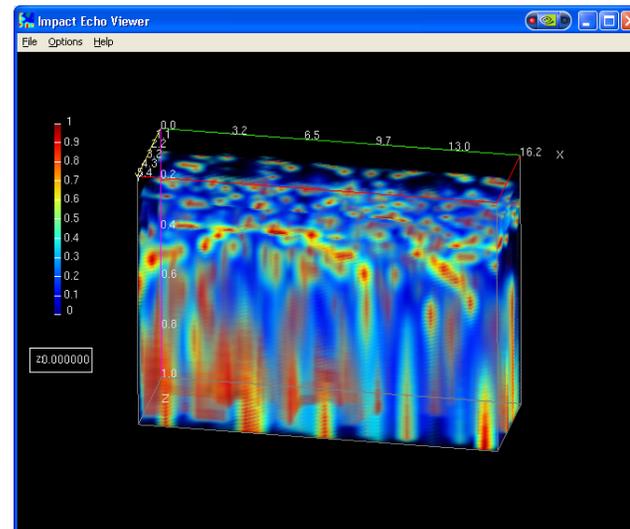


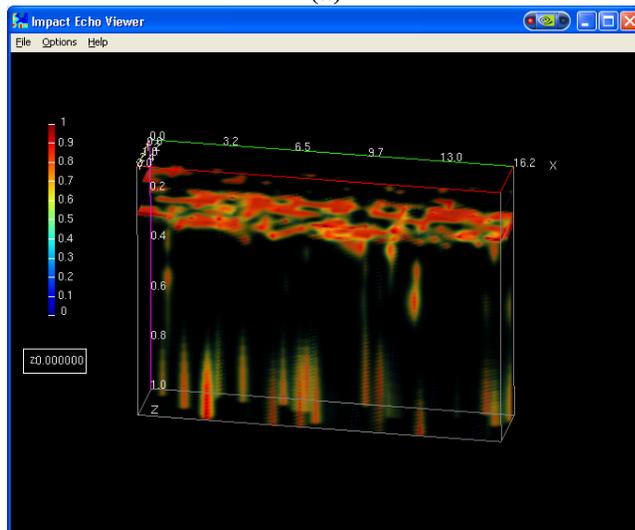
FIGURE 18 Condition assessment maps for Carter Creek Bridge (based on actual test point grades – top, and four condition grades - middle) and Van Buren Bridge (bottom).



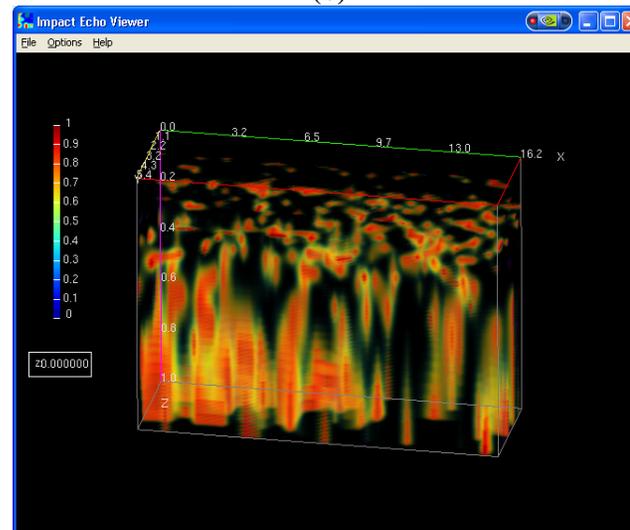
(a)



(b)



(c)



(d)

FIGURE 19 Interactive visualization of IE data. Carter Creek Bridge (a) (c), Van Buren Bridge (b) and (d).

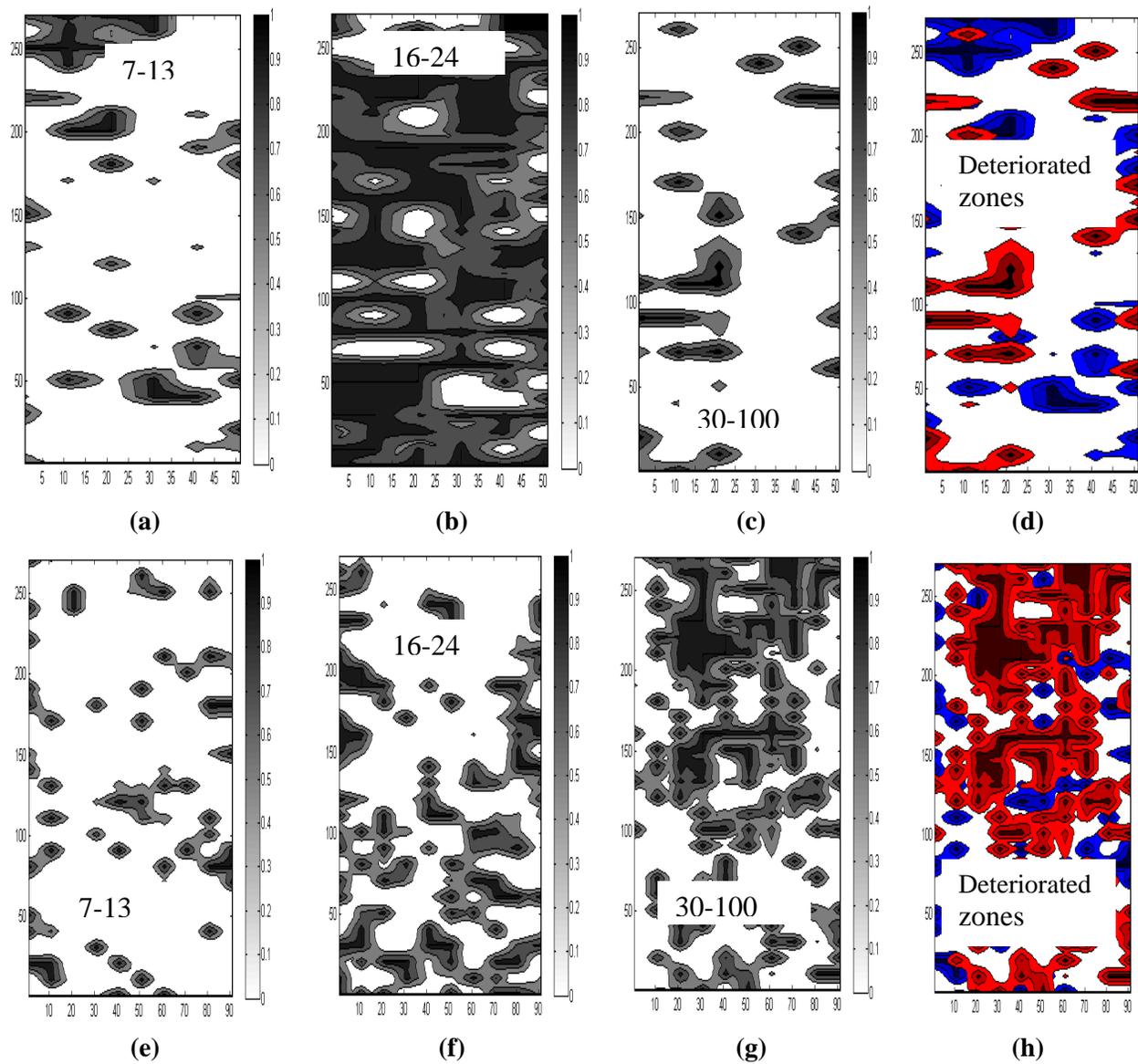


FIGURE 20. Plan view contour plots for deck repair. Top: Carter Creek Bridge, Bottom: Van Buren Bridge. Left to right: maximum reflectance in the “delamination zone” slice (7-13 cm) (a)(e), “bottom of the deck” slice (16-24 cm)(b)(f), and in the “apparent deep reflector” zone (30-100 cm)(c)(g). Identified deteriorated zones (d) and (h) (red - serious condition, blue – fair to poor condition).

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The new generation of GPRs, three-dimensional (3D) GPRs provide significant potential improvements in imaging and condition assessment of transportation infrastructure, utility detection, etc. Of special interest for this investigation was 3-D GPR manufactured by 3D-Radar Company from Norway and powered by software made by RoadScanners Company from Finland. This 3D-GPR system is suitable for many applications: from fast road surveys at 90 km/h (55 Mph), or utility mapping, to concrete bridge inspection. It operates in the step frequency mode in a frequency range from 100 MHz to 2GHz and current arrays are produced from a single pair of transmitting and receiving antennas to up to 63 pairs. The main advantage of the 3D-GPR antennas is that they can cover and can provide an image of an almost entire lane width of a pavement or a bridge deck from a single test run. As a result of simultaneous surveying by multiple antennas, a three-dimensional image of the surveyed medium can be made, but typically described in terms of horizontal planes at different elevations, and multiple vertical cross section planes along and perpendicular to the survey lines.

The main objective of the conducted research was to evaluate 3D-Radar GPR in bridge deck condition assessment and imaging, with an emphasis on detection and characterization of corrosion induced bridge deck delamination. A broader objective of the study was to provide data for comparative evaluation of the performance of 3-D Radar, PERES GPR and other nondestructive (NDT) technologies in NDE bridge deck evaluation. The main task of this project was to provide data that would allow comparative field evaluation of the 3D-GPR and impact echo (IE) technique in delamination detection and characterization. While the 3D-GPR produced good images of rebars and the main structural elements, girders and bracing, the condition assessment of tested bridge decks did not produce repeatable attenuation maps. The primary cause of this inconsistency is the difficulty in accurate and automated picking of rebars, which further prevents accurate reflection amplitude and rebar depth evaluation. Since both the 3D-GPR hardware and software are still in the development stage, and there has been no or limited experiences in bridge deck evaluation, the following are the recommendations for the improvement of the bridge deck application of the 3D-GPR:

1. Hardware should be improved to allow increase of the antenna frequency range on the high frequency side,
2. The survey setup should be examined for optimum bridge deck applications. For example, some preliminary results of the tests conducted in Finland suggest that the optimum antenna height should be higher than for the pavement applications and recommended by the manufacturer.
3. Software should be improved with algorithms that allow accurate and automated rebar picking.

Those improvements are expected to lead to more accurate and repeatable attenuation mapping of bridge decks and thus very beneficial usage of 3D-GPR in bridge deck condition assessment studies.