Chapter 2 – Experimental Study

2.1 Introduction

The PERES ground penetrating radar (GPR) system has demonstrated exceptional capabilities for detecting distress and construction details in concrete bridge decks. Examples of these detection capabilities have been reviewed in section 1.3 of this dissertation and more examples will be presented here in Chapter 2. The unique qualities PERES data exhibits for distress detection in concrete bridge decks make it an excellent candidate for automated data processing to locate problem areas. Three major experimental tasks must be completed to develop an automated processing method for bridge deck distress detection based on PERES data. First, data must be taken from representative bridge decks with the PERES system, keeping noise and bias in the data to a minimum. Second, automation algorithms must be developed or “trained” based on the representative data that have been taken. Third, test data must be processed using the automated algorithms developed for flaw and distress detection, allowing the accuracy of the method to be determined.

This chapter will describe the collection of PERES data from representative bridge deck specimens in the FHWA’s inventory. It will also describe additional test data that was taken to determine the field capabilities of flaw and distress recognition algorithms. The data collection described in this chapter is followed by discussions in chapters 3 and 4 about effective data processing. The analysis described in these chapters covers data processing algorithms and testing results respectively.

2.1.1 FHWA Bridge deck sections

Bridge decks are subjected to a variety of different loading and environmental
conditions depending on the location, weather, traffic and maintenance procedures they are exposed to. In order to reflect the damage modes that bridge decks exhibit when they experience these varying conditions, the FHWA has acquired several bridge deck specimens from three locations across the country. Thus far, 10 sample bridge decks have been extracted from selected sites in North Carolina, Utah and Washington DC. There are plans to acquire more deck sections, from other locations, to make the collection more extensive. The selected bridge deck sections were transported to the NDE Validation Center to make them available at a single location. The deck sections are pictured in Appendix A, Figures A3 through A12. Two other bridge deck sections were fabricated at the NDE Validation Center for testing (Appendix A, Figures A1 and A2). In addition, two small test slabs were fabricated and used to characterize PERES performance for carefully controlled applications.

2.1.2 Data collection using PERES

For the purposes of this study, 12 bridge deck sections were scanned using the PERES system and field data were collected from the Van Buren Street Bridge. Two experimental slabs with different thickness asphalt overlays placed on them were also scanned with PERES. The results of the analysis of PERES data will be compared with available tests and measurements to confirm both the effectiveness of PERES and the accuracy of the data analysis methods. An initial study using the chain drag test method has been conducted on the decks that do not have asphalt overlays. A plan is currently in place for cores to be taken from the decks in the future (after this dissertation has been completed) to confirm the presence of distress areas. The cores will also be used for petrographic analysis and chloride content testing that will directly characterize the bridge deck concrete.

PERES collects data over an entire deck in the configuration pictured in Figure 2.1. During testing, the antenna in the foreground is rastered back and forth along the rail and pauses at each end of the rail when the cart moves forward a small increment, (minimum 1 cm). Averaged data is sampled at regular intervals (minimum 1 cm) as the antenna moves along the rail. Collected data are three dimensional. The resolution of the
data in the two spatial dimensions are determined by data sampling as the antenna is moved in two orthogonal directions to create a real aperture, (later converted to a synthetic aperture using wavefield backpropagation calculations). The third dimension is created by sampling return signals from the radar at regular time intervals, over a prescribed window determined by the “span” setting on PERES.

Another setting on PERES, called the “offset” determines when data sampling will begin. Optimally, this setting is determined by the location, (in the collected data) of the surface reflection from the deck. All data collected during the course of this study included this surface reflection. The antenna should be placed as close as possible to the deck surface, without allowing the coupling pulse, the radar signal that travels directly from the transmitting antenna to the receiving antenna, to interfere significantly with the subsurface reflected signal. A consistent height of eight cm between the midpoint of the antenna housing and the deck surface was maintained during all data collection phases, which produced a reasonable compromise for all of the factors involved. The surface reflection from the deck was in the time window where thermal noise was the dominant
feature of a radar pulse traveling into air and the antenna was still very close to the deck surface. The “offset” was also maintained constant during all data collection phases.

The PERES system must be calibrated whenever a span or offset setting is changed on the radar control box. It is also advisable to calibrate PERES if a large temperature change occurs because significant parts of the radar electronics are analog. Calibration is accomplished by placing two metal rods at different, (greater than 20 cm through air), distances from the antenna in adjacent locations along a linear real aperture. The distances to the two poles should be measured manually and provided to the PERES software. Raw data is taken along the synthetic aperture and wavefield backpropagation calculations are performed based on manually provided locations of the poles in the raw data. If the distances to the poles that the radar calculates based on wavefield backpropagation are close to the manually measured values, (less than 2 cm), then the system is calibrated successfully. If the calibration is unsuccessful, the manual locations of the poles in the raw data should be checked for accuracy. If these locations are correct, the process should be repeated to ensure that measurements to the poles were made accurately.

2.1.3 Chain drag survey

For concrete bridge decks without an asphalt overlay, the standard test for detecting delaminations in concrete bridge decks is ASTM D 4580-86. This test covers a variety of techniques for detecting delaminations using sounding, but the dominant method in use in the field is the chain drag test. This method for detecting delaminations is simple and generally effective. The method involves a technician dragging a chain across the surface of a bridge deck and listening for significant changes in the tone, which corresponds to the frequency content of the response. “Hollow” sounding responses that depend on the geometry of the bridge deck and the distress are indicative of delaminated areas, while sound concrete produces consistent sounding responses with different frequency content. Due to the variety of frequency responses that can be produced by different distress and bridge deck geometries, (Sensalone, 1997) the test is carried out using the qualitative judgment of the technician conducting the test. This can lead to inconsistencies in
assessment but other than impact-echo there are no alternatives for detecting delaminations currently in use. Impact-echo is a very time consuming and painstaking test where plots of the acoustic frequency responses to surface impacts at many locations over an entire deck are assessed.

Both chain drag and impact-echo testing require lane or bridge closures, which is costly for bridge users. Neither method is applicable to decks with asphalt overlays. The accuracy of the chain drag and impact-echo tests depends on the bridge, distress and technician, so it has only been determined for specific cases, (Sensalone, 1997). Bridge engineers have found that the chain-drag test is the most reliable, practical method currently available for detecting delaminations, but the drawbacks of bridge closures, qualitative accuracy, and a lack of applicability to asphalt covered decks make it a less than ideal method.

Appendix B presents data collected during a chain drag survey of the 7 bridge deck sections in the FHWA inventory that do not have asphalt overlays. These results are intended for use in comparing PERES with the current state of the art.

2.2 PERES data collection from FHWA bridge deck sections

Peres data were collected from each of the 12 available FHWA bridge deck sections in anticipation of using the data for developing and specifically training a pattern recognition algorithm tailored to analysis of PERES data. Much of the data was useful for this purpose, but some had a lower signal to noise ratio than anticipated. Specifically, radar signals from deck sections with asphalt overlays were severely attenuated in addition to the presence of clutter introduced by the asphalt layer, (Section 4.2) which masked features of interest in the concrete. Data that were still usable for pattern recognition analysis came from the bare concrete decks and were generally indicative of expected deck section features, (Section 4.3). All PERES data were collected at 1 cm resolution in the two cross-range dimensions, (length and width). A summary of the collection and visualization of data from these bare concrete decks is detailed in the following sections.
2.2.1 **Deck section R13**

Bridge deck R13 was fabricated by FHWA for the NDE Validation Center and included four synthetic inserts that simulated distress. A picture of this deck is presented in Figure A1, Appendix A. Data collected from bridge deck R13 has already been presented in Figures 8 and 9 in Chapter 1. These data showed that the PERES system was capable of detecting two synthetic defects in the deck based on magnitude responses from PERES, while two other synthetic defects were not detected. The synthetic defects that were not detected were extremely thin relative to detected synthetic defects and were made from polyethylene sheets, (see Figure 1.10). Figure 1.11 displays a plan view of the three dimensional reconstructed data volume obtained using PERES and Figure 1.12 displays a two dimensional slice from this data volume, as described in section 1.3.2. Figures 1.11 and 1.12 both provide strong indications of the locations of reinforcing steel in the deck which also correspond closely to construction plans. Figure 1.10 provides a diagram of the locations and dimensions of the four synthetic inserts that simulate distress in the deck. Figure B1 in Appendix B shows results from a chain drag survey of bridge deck R13, which located all four of the synthetic defects in the deck.

A three dimensional view of the reconstructed data from PERES, as observed from an off diagonal perspective, is presented in Figure 2.2. This view allows the thickest synthetic defect to be distinguished in yellow, with both the initial reflection and a ghost reflection visible beneath it. The ghost reflection is an artifact of radar data that is not removed by the wavefield backpropagation reconstruction algorithm. Ghost reflections are observed when a radar pulse is reflected multiple times between material interfaces. In this case the multiple reflections occur between the synthetic defect and the radar antenna. The reinforcing steel mat and the second defect, observed in other images of this data, are occluded (data between the viewer and features of interest in the data reduces the visibility of features of interest) significantly in this view due to the off diagonal perspective.
2.2.2 Deck section R12

Deck section R12 was fabricated by the FHWA NDE Validation Center in an effort to produce a corrosion induced delamination experimentally. The deck is pictured in Figure A2, Appendix A. Experimental production of a corrosion-induced delamination was attempted by ponding water with a high chloride content over a 43 X 27cm area, (Figure 14). Current was applied to the reinforcing steel in the deck beneath this location for several months, while the ponded water was present. At the end of the experiment, a corrosion product from the top mat of reinforcing steel had diffused to the surface and was visible as a dull orange-brown colored rust, (Fe₂O₃), deposit.

PERES data from deck R12 is presented in Figures 15 through 17. Figure 15 provides a plan view of the three dimensional magnitude responses obtained from reconstructed PERES data, allowing the viewer to look down through the data volume.
In this image, indications of the reinforcing steel mat are prominent and fall in a magnitude range generally corresponding to blue, (for this view). Strong indications of a delamination or other distress are also observed in the area where the corrosion experiment was conducted, (see Figure 2.3). The responses for this area are in the blue range, (for this view). Responses from a chain drag test (Figure B2, Appendix B) also suggested delaminated areas in this location. Figure 2.5 provides a side view of the same data set presented in Figure 2.4. Observing data features from this direction allows reinforcing steel to be visualized in cross section. These reinforcing steel indications are generally lozenge shaped, (ideally they would have a circular shape) and fall in a magnitude range that corresponds to blue and yellow. Between 150 cm and 210 cm along the length dimension in this image, indications of distress are observed that correspond to noted distress in the plan view. Finally, an individual layer of data with significant responses corresponding to the reinforcing steel mat and an area of distress is presented in the plan view in Figure 2.6. It should be noted that the chloride content of the concrete in the area of the corrosion experiment is likely to be significantly higher than the remainder of the deck. This chloride content has not been quantified, but the difference could influence the dielectric properties and conductivity of the concrete in this area.

2.2.3 Deck section R11

During the spring of 1998, bridge deck section R11 was extracted from a State Route 4 South bridge that spans a viaduct in Utah. The deck had been in service for twenty years when it was removed and had been overlaid using concrete in 1987. The surface of this deck was tined, which can be observed in the photograph of the deck presented in Figure A3, Appendix A. The concrete cover depth for the top mat of rebar in this deck, (and a second deck taken from the same bridge, R10), was deeper than the other sample decks in this study, at 11 cm. This condition is near the limits of PERES performance because the radar signal becomes significantly attenuated and scattered when it is required to travel through thicker concrete sections.
Figure 2.3 Location of high chloride content pooled water for artificial production of a delamination.
Figure 2.4 Three-dimensional plan view of PERES data for bridge deck R12 (7.5 cm deep).
Figure 2.5 Three-dimensional side view of PERES data for bridge deck R12 (203 cm width).
Figure 2.6 Two-dimensional plan view of PERES data for bridge deck R12 (depth=8 cm).
Visualizations of reconstructed magnitude response data taken from deck R11 using PERES are presented in Figures 2.7 through 2.9. Figure 2.7, displaying a plan view of the data from deck section R11 in three dimensions, allows two prominent features to be observed. The first is the imaging of four areas, (one near each corner of the deck), where cores were taken. These core locations left holes in the deck that can be seen in the photograph of deck R13, (Figure A3, Appendix A). The second prominent feature is a large magnitude response across the width of the data at length=220 cm. This response corresponds to a prominent piece of reinforcing steel that produced a much larger reflection than neighboring reinforcing steel in the deck.

Figure 2.8 provides a side view of the reconstructed PERES data from deck section R11. The strong response from the prominent reinforcing steel observed in the plan view is visualized as a blue area with an oval shape in this image. Aberrations at shallow depths (above the surface reflection) do not correspond to features of interest in the data. The two-dimensional view of the data (Figure 2.9) taken from a layer in which apparent reinforcing steel responses (based on comparison to Figure C3, Appendix C) are prominent, is not particularly clear. Responses from reinforcing steel oriented in the length direction are distinguishable, but they are weak indications relative to results from decks R13 and R12. Responses from reinforcing steel oriented in the width direction are very poor and do not correspond to the number or locations of reinforcing steel known to exist in the deck based on observations of the deck cross section. This poor imaging of reinforcing steel in the deck is mainly attributable to the large cover depth. The surface tining and the thick concrete overlay are also detrimental to PERES signal quality and imaging.

A notable feature in the upper left corner of Figure 2.9 is a high magnitude response, which corresponds to the expected location of a delamination. The edge of this delamination can be observed on the exposed edge of deck section R11, as shown in Figure 2.10 and detected in chain drag results, (Figure B3, Appendix B).
Figure 2.7 Three-dimensional plan view of PERES data from bridge deck R11, (10 cm deep).
Figure 2.8 Three-dimensional side view of PERES data from bridge deck R11 (145 cm width).
Figure 2.9 Two-dimensional plan view of PERES data for bridge deck R11 (depth=13 cm).
Figure 2.10 Delamination observed in bridge deck R11.
Figure 2.11 Three-dimensional plan view of PERES data from bridge deck R10 (10 cm deep).
Figure 2.12  Two-dimensional plan view of PERES data from bridge deck R10, (depth=16 cm).
Figure 2.13 Two-dimensional plan view of PERES data from bridge deck R10, (depth=18 cm).
Bridge decks R10 and R11 came from the same Utah bridge that was described in Section 2.2.3. Deck R10 is pictured in Figure A4, Appendix A which shows the tining marks on the top surface and the locations of four cores that were taken from it, (the deck layout is diagramed in Figure C4, Appendix C). Figures 2.11 through 2.12 present PERES data taken from this deck section. Figure 2.7 shows a three-dimensional plan view of the deck data in which three features are notable. First, the four core hole locations are distinguishable, although one of them is less prominent than the other three in this rendering. Second, vague indications of the reinforcing steel mat in the deck are visible, but these indications are occluded by artifacts and features between the viewer and the data. These artifacts, which are the third notable feature, take on nebulous blue shapes in this visualization that are not consistently observed in the data sets taken with PERES. As a result, it has been difficult to determine what causes these artifacts. Clutter, thermal noise, edge effects other physical distortions that occur in radar could each be contributing.

Figures 2.12 and 2.13 each present two dimensional plan views of the data from deck section R10. These image layers, taken from the three dimensional data, show indications of reinforcing steel much more clearly than the three-dimensional view in Figure 2.11. The Figure 2.12 image allows reinforcing steel oriented lengthwise from the top to the bottom of the image to be distinguished in several locations. However, many areas of the image do not present clear responses. Figure 2.13 allows reinforcing steel oriented lengthwise from left to right in the image to be distinguished, but there are also artifacts in this image that occlude the reinforcing steel. The image layer in Figure 2.13 corresponds to a deeper location in the deck, (and a longer radar travel time), than the image layer in Figure 2.12. This correlates with visual measurements because the left to right oriented reinforcing steel are deeper in the deck section than the top to bottom oriented reinforcing steel, based on cover depth measurements made at the specimen edges. Another interesting feature of the images in Figures 2.12 and 2.13 is that they have “texture”. This texture appears to correspond to the tining marks on the surface of
Figure 2.14 Three-dimensional end view of PERES data from bridge deck R9, (365 cm long).
Figure 2.15 Three-dimensional plan view of PERES data from bridge deck R9 (7.5 cm deep).
Figure 2.16 Two-dimensional plan view of PERES data from bridge deck R7, (depth=4.0 cm).
Figure 2.17 Two-dimensional plan view of PERES data from bridge deck R7, (depth=7.4 cm).
the deck, which could affect the PERES response through the depth of the deck section. These tining marks, (shown in Figure A4, Appendix 4) traverse the width of the deck section, and have a similar frequency to the image texture along its length. At the tining mark locations, the radar pulse travels through air for a longer time before encountering the concrete surface than ordinary surface locations, causing a small phase difference that could account for the texture. The reason that deck section R10 was imaged more clearly by PERES than deck section R11 is unclear, since they came from the same deck. One plausible reason is that the two deck sections may have different material properties due to uneven exposure to chlorides. Another possibility is that the geometry of R11, (which was cut much narrower than R10), caused problems for the radar.

2.2.5 Deck Sections R9, R8 and R7

Deck sections R9, R8 and R7 were each obtained from a bridge on a county border that was named North Carolina Bridge 9 (Northampton County) on one side and Bridge 141 (Halifax County) on the other side and carries southbound Interstate 95 traffic across the Roanoke River. This bridge was opened to traffic in 1960 and the deck was removed in the spring of 1998. All three of the deck sections extracted from this bridge are pictured in Figures A5 through A7, Appendix A. Each of these deck sections has a relatively thin cover depth of approximately 4 cm. Consequently, PERES is able to image the features in these decks with high accuracy. Figures 2.14 through 2.17 provide examples of the images that were obtained from the reconstructed data. Figure 2.14 is an end view of three-dimensional data from bridge deck R9, which provides a clear representation of the reinforcing steel in cross-section. These reinforcing steel produce a high magnitude radar response in the data. Ideally, the high magnitude spots, appearing as yellow, in this view would be more focused and circular in shape like the cross section of the reinforcing steel they represent. There are six pieces of reinforcing steel represented in this image, and a seventh response on the far right corresponds to the edge of the deck section, which often produces a reflection due to the sharp corner at the edge.

A plan view of three-dimensional data from bridge deck R9 in Figure 2.15 represents the reinforcing steel mat in the deck very accurately. The blue areas indicate high magnitude responses where the reinforcing steel are located. Images of layers taken from the three-dimensional data for deck section R7, Figures 2.16 and 2.17, show the
reinforcing steel oriented top to bottom and left to right respectively. The clear imaging
of the reinforcing steel in these images shows the potential of PERES for imaging
subsurface features. Delamination responses were not expected in these decks because
the shallow cover depth caused corrosion induced minor cracking that propagated
directly to the concrete surface, rather than the typical propagation between adjacent
reinforcing steel. This cracking was observed visually on the deck surface and by
observing the edges of the cut deck section. Because this cracking was parallel to the
direction of radar propagation, it was not imaged.

2.3 Asphalt covered deck sections

Five bridge decks, (R6 through R2), with asphalt overlays were scanned using the
PERES system. Data from these deck sections were very difficult to interpret due to
scattering, attenuation and ringing of the radar signal in the asphalt layer. The asphalt to
concrete interface that the radar signal had to penetrate to image features in the concrete
also reflected a portion of the radar energy when these deck sections were scanned.
Because the current PERES system is a prototype, the problems that have been
encountered with the data from asphalt covered bridge deck sections are important for
improving future PERES and HERMES prototypes. It is a high priority for PERES and
HERMES to image features in asphalt overlaid bridge decks since asphalt overlays
prevent current inspection techniques, in particular chain drag surveys, from properly
functioning. Therefore, a series of experiments were performed to define the
performance capabilities of PERES and provide needed information for improving future
prototypes. These tests, which are described in the following sections, addressed ringing
in the radar signal for a range of asphalt overlay thicknesses and also addressed feature
detection at different concrete cover depths. Improvements to these prototype systems
should offer data that is more amenable to pattern recognition analysis for a variety of
bridge deck configurations.
2.3.1 Data collection from experimental slabs

Two experimental concrete slabs were fabricated for testing PERES performance capabilities. The first experimental slab, Figure 2.18, was composed of two stacked concrete pieces. Neither of these pieces contained any reinforcing steel. Asphalt pieces of two thicknesses were also fabricated and could be stacked in combinations to produce three different total thicknesses when placed on the deck surface, (a fourth configuration leaves the concrete surface bare with no asphalt). Figures 2.19 shows one of these thickness combinations. The air gap between the two concrete pieces provided a simulation of a delamination. Steel washers were used as spacers between the two slabs to create an air gap. These tests provided significant information on PERES imaging of delaminations with different asphalt overlay thicknesses.

![Experimental slab 1 with air gap simulating a delaminated area.](image)

Experimental slab 2, (slab form shown in Figure 2.20), was fabricated with reinforcing steel at six different cover depths, (3 cm to 18 cm in increments of 3 cm). This slab was scanned with PERES to examine the detection of reinforcing steel at a variety of cover depths to gain a better understanding of the effects of attenuation, noise and ringing in
Figure 2.19 Experimental slab 1 with 8 cm thick asphalt pieces placed on the top surface.

Figure 2.20 Form for experimental slab 2, which has a range of reinforcing steel cover depths.
PERES data. Interpretations of data from these tests are presented in Section 4.2, where PERES performance will be detailed.

2.4 Field data

Field data was collected at the Van Buren Street Bridge in Virginia using PERES to obtain field data for analysis using the pattern recognition algorithm and to determine the practical advantages and deficiencies of the current PERES prototype in field use. The Van Buren Street Bridge carries Van Buren traffic over Quantico Creek and is located in Prince William County near the town of Dumfries, approximately 45 meters west of the Interstate 95 bridge over Quantico Creek. Figure 2.21 shows the PERES system on the Van Buren Street Bridge collecting data. System power was provided by a gasoline electric generator and one lane of traffic was closed during the testing. A chain drag test was performed on the deck prior to the testing to locate potentially delaminated areas. Paint spots were used to mark the locations of these potentially delaminated areas and measurements of their locations were noted relative to prominent deck features. Unfortunately, the system had some mechanical and electrical problems during the field test and as a result a small area was covered by the only successful PERES scan. Results from this scan are presented in Figures 2.22 and 2.23, which show two dimensional plan view layers from the data. The top and bottom layer of the reinforcing steel in the top mat is apparent in Figures 2.22 and 2.23 respectively. Areas where potential delaminations were detected using the chain drag test are indicated in both figures with red circles. These results provide a reference to the current ASTM D 4580-86 standard. For this field data, a definitive interpretation of features in the data is currently unavailable due to the inability to extract and examine cores and other evidence directly from the deck. Therefore, evaluations of this data are subject to confirmation by evidence that could be provided by thorough sample extraction and testing from the deck. This testing, if it is conducted, will be done after this dissertation is completed. Responses in the red circled areas in Figures 2.22 and 2.23 generally have high magnitudes relative to surrounding responses. This appears to confirm the expected high magnitude response in locations where delamination cracking is potentially present;
Figure 2.21  Field data collection using PERES at the Van Buren Street Bridge.
Figure 2.22  Reconstructed data layer (1 mm thick) taken from a PERES scan of the Van Buren Street Bridge at depth=6.0 cm.

Figure 2.23  Reconstructed data layer (1 mm thick) taken from a PERES scan of the Van Buren Street Bridge at depth=9.0 cm.
however, there are several other areas in these images that also display high magnitude responses. This issue will be addressed in Section 4.4, where analysis of this data using the pattern recognition algorithm described in Chapter 3 will also be presented.