Air-Launched GPR Evaluation for Rapid Assessment of MoDOT Bridge Decks

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FINAL REPORT

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Prepared for
Missouri Department of Transportation

by

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16. Abstract

This study demonstrated the utility of the air-launched ground penetrating radar (GPR) tool in terms of evaluating the condition of MoDOT bridge decks. The objective was to confirm that the air-launched GPR tool can be implemented as a part of a long-term program that enables faster, better, and more cost-effective assessments of MoDOT bridge decks.

Ten bridge decks were investigated using an air-launched GPR system. Four of the bridge decks investigated were previously investigated using a ground-coupled GPR system, and results from those four bridge decks served as ground truth for the air-launched GPR interpretations. Findings show reasonably good spatial correlation between the ground-coupled GPR and air-launched GPR data sets in terms of deteriorated regions and overall percentages of deteriorated regions in terms of bridge deck surface area. Apparent discrepancies between the air-launched and ground-coupled GPR interpretations can be attributed to several factors, including interpolation between adjacent GPR traverses, differences in signal attenuation due to different antenna frequencies, and differences in signal resolution due to different distance from the antenna to the embedded reinforcing steel.

Recommendations for optimum acquisition, processing, and interpretation parameters for air-launched GPR reconnaissance-style assessment were provided as part of this study.

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EXECUTIVE SUMMARY

This study demonstrated the utility of the air-launched ground penetrating radar (GPR) tool in terms of evaluating the condition of MoDOT bridge decks. The objective was to confirm that the air-launched GPR tool can be implemented as a part of a long-term program that enables faster, better, and more cost-effective assessments of MoDOT bridge decks.

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Recommendations for optimum acquisition, processing, and interpretation parameters for air-launched GPR reconnaissance-style assessment were provided as part of this study.

This research was performed by the Missouri University of Science and Technology. The report fully documents the research.

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1 INTRODUCTION

1.1 Project Goal

The overarching goal of this study was to demonstrate that advanced nondestructive testing/evaluation (NDT/NDE) techniques can be rapidly, effectively, and economically implemented as part of routine MoDOT bridge deck surveys to determine the general condition of bridge decks. This study extends the work of a separate study (*Nondestructive Evaluation of MoDOT Bridge Decks - Pilot Study,* MoDOT Award TRyy1308; Sneed et al. 2014) focused on NDT/NDE techniques for comprehensive bridge deck assessment. It is envisioned that the condition assessment conducted in this study would be utilized as reconnaissance to identify those bridges requiring a more detailed investigation, which would help MoDOT optimize the use of resources and reduce the cost of bridge deck evaluation.

Results of this study will be used to evaluate the feasibility of a large scale, long-term program (multi-year, routine basis) that incorporates NDE techniques into MoDOT bridge deck surveys for the purpose of reducing cost on assessment and maintenance of bridge decks.

1.2 Project Objectives

The primary objectives of this project were to:

- Demonstrate the utility of the air-launched GPR tool in terms of evaluating the condition of MoDOT bridge decks.
- Confirm that the air-launched GPR tool can be implemented as a part of a long-term program that enables faster, better, and more cost-effective assessments of MoDOT bridge decks.
- Provide recommendations for optimum acquisition, processing, and interpretation parameters for the air-launched GPR tool for reconnaissance-style assessment of MoDOT bridge decks.

1.3 Scope of Work

Field investigations of 10 different bridge decks took place as a part of this study. The following work was performed:

- Each bridge deck was imaged along multiple traverses using two 2.0 GHz GSSI 42000S air-coupled horn antennas. The spacing and length of the GPR traverses varied from bridge to bridge.
- Four of the bridges had been previously imaged by the researchers with a ground-coupled GPR antenna (Sneed et al. 2014). The air-launched GPR interpretations were compared the ground-coupled GPR interpretations to demonstrate comparable quality.

The bridge decks that were investigated were selected by MoDOT and researchers from Missouri S&T. Bridges investigated and dates of investigation are summarized in Table 1-1; bridge locations are shown in Figure 1-1. The bridges are listed in numerical order throughout this report.

1.4 Organization of the Report

Chapter 1 presents the goal, objectives, and scope of this project. In Chapter 2 the results of the air-launched GPR investigations are presented and discussed. Section 2.5 includes recommended parameters for air-launched GPR data acquisition, processing and interpretation. Finally, in Chapter 3 results and recommendations based on the findings of this project are summarized.

Table 1-1 Summary of Bridges Investigated

Bridge	Date of Air-Launched GPR Investigation	Weather Conditions	Date of Ground-Coupled GPR Investigation (Sneed et al. 2014)
A0523	1/26/2015	30-54° F, absence of rain	-
A0569	7/30/2014	57-82° F, absence of rain	11/26/2012
A1880	1/26/2015	30-54° F, absence of rain	-
A2110	12/16/2014	29-38° F, absence of rain	-
A3034	1/26/2015	30-54° F, absence of rain	-
A3405	10/16/2013, 6/5/2014	40-56° F, absence of rain 64-72° F, light rain	11/14/2012
A3406	10/16/2013, 2/2/2014, 4/27/2014	40-56° F, absence of rain 10-25° F, absence of rain 62-75° F, light rain	11/15/2012
A4780	7/31/2014	59-86° F, absence of rain	-
A4781	7/31/2014, 12/16/2014	59-86° F, absence of rain 29-38° F, absence of rain	-
K0197	10/16/2013 6/5/2014	40-56° F, absence of rain 64-72° F, light rain	11/28/2012

Figure 1-1 Map of Bridge Locations (Source: Google Earth)

2 BRIDGE DECK INVESTIGATIONS

2.1 Overview

Ground penetrating radar (GPR) is a non-destructive geophysical tool that uses pulsed electromagnetic radiation (GPR source signal) to image the top, base, and interior of bridge decks. With respect to this study, the GPR system records the amplitudes and arrival times of emitted GPR signals that are partially reflected by the top of the bridge deck, the base of the deck, and from features within the bridge deck such as embedded reinforcing steel bar (rebar) and delaminations. Analysis of the reflected signal (magnitude and arrival time) enables the operator to estimate the apparent depth to each reflector and to assess the overall condition of the bridge deck. The most significant output of the GPR investigation is a map depicting variations in the amplitude of the reflections from the top of the uppermost transverse layer of rebar. Based on the interpretation of the amplitude map, the interpreter is able to identify regions of the bridge deck where there is no evidence of deterioration, and evidence of deterioration.

It should be noted that interpretation of GPR amplitude maps is based on *variations* in the reflection amplitudes, where values of amplitudes lower than the maximum reflection amplitude are usually attributed to the presence of degradation, or to conditions favorable for the development of degradation. ASTM D6087 states that “the spatial location of scans containing reflection amplitudes less than 6 to 8 dB below the maximum reflection amplitudes typically correspond to deterioration detected using other information” (ASTM D6087 2008). The interpretation of the GPR amplitude maps can be challenging for cases where the condition of the bridge deck is uniform (i.e. entirely sound, or entirely degraded) because of lack of contrast in the data. Therefore, for these cases visual assessment or other methods of ground truth are required. However, it is noted that these cases are relatively simple to diagnose visually. Barnes and Trottier found that air-launched GPR evaluation is most effective (i.e., most consistent with ground truth data) for bridges with deterioration between 10 and 50% of the bridge deck surface area (2004).

GPR can be used to evaluate the condition of a concrete bridge deck with or without an asphalt or concrete overlay. GPR is currently the only non-destructive method that can be used to evaluate a concrete bridge deck with an asphalt overlay (ASTM D6087 2008).

The primary objective of the GPR investigations conducted in this study was to evaluate the capability of the air-launched GPR tool to rapidly and reliably assess the relative condition of bridge decks (reconnaissance-style assessment). In Section 2.2 a discussion of the methodology is presented. Section 2.3 is a presentation of the GPR results for each of the 10 bridge decks investigated. Section 2.4 compares the air-launched and ground-coupled GPR data for four bridge decks, and Section 2.5 presents recommendations based on the results of this study.

2.2 Methodology

GPR data were acquired using an air-launched GSSI SIR-30 system, equipped with two high-frequency 2.0 GHz GSSI 42000S air-coupled horn antennas, mounted parallel to each other on the front of a survey truck, with 2/4 ft center-to-center spacing as shown in Figure 2-1. The primary goal was to map the amplitude and apparent embedment depth of the uppermost layer of transverse rebar.

The truck was coupled to a survey wheel and driven in a constant position with respect to the lane being surveyed. Survey parameters were selected to enable the relatively rapid (reconnaissance-style) acquisition of good quality data. Chalk marks or visible joints were used to identify the start and end positions for each traverse.

For those bridges with the top-most layer of reinforcing bars oriented in the bridge longitudinal direction, the spacing of the reinforcing bars was determined using the bridge deck drawings provided by MoDOT, and the locations of the bars were marked in an attempt to position the GPR antenna between them.

In general, air-launched GPR data can be acquired at vehicle speeds of up to 50 miles per hour. However, when the vehicle is operated at high speed, it is difficult to accurately acquire GPR data along multiple pre-specified parallel traverses spaced at uniform distances (on the order of 1 to 2 ft). It is also difficult to visually assess the quality (QC purposes) of incoming GPR data in real time at high acquisition rates. For the purposes of this study, the air-launched GPR data were acquired at vehicle speeds of about 10 miles per hour to allow for the real time monitoring of the incoming data (QC purposes) and to ensure data were acquired along pre-specified, closely spaced parallel traverses. At those bridge sites where GPR data had been previously acquired using a ground-coupled antenna, the intent was to ensure that comparable density air-launched antenna data were acquired across similarly placed traverses to allow for the direct spatial comparison of both GPR data sets.

As previously mentioned, reconnaissance-style GPR data acquired using an air-launched antenna would normally be acquired at speeds significantly greater than 10 miles per hour along a minimum number of traverses (typically 2 or 4) in each lane of a bridge deck. Lane closures would not be required. During this study, lanes were closed because the air-launched GPR data were acquired at low speeds (for real time QC purposes) and along multiple pre-specified parallel traverses in each lane.

For analyses purposes, the material within the bridge deck, and therefore the dielectric constant of that material, was estimated to be uniform. This introduces some level of error into estimates of the estimated depth to the uppermost layer of reinforcing steel, but it does not adversely affect the quality or utility of the output normalized amplitude data or the reflection arrival time data.

The GPR data were processed using GSSI RADAN 6.6 and RADAN 7 processing software. Initial processing steps included time-zero correction and filtering to eliminate noise. The arrival times and amplitudes of the reflections from each imaged segment of transverse reinforcement were recorded (“picked”). The output of processing was a Microsoft Excel spreadsheet that included reflection amplitudes (in units of normalized decibels, NdB) and two-way travel times (in units of nanoseconds, ns) for each imaged segment of transverse rebar. Post-processing included converting travel times to apparent depths and combining the Microsoft Excel spreadsheet information from individual GPR profiles into one Microsoft Excel file with assigned coordinates for each GPR profile. Finally, a contour map depicting the reflection amplitude from the top of each imaged segment of transverse layer of rebar was generated using the software program Surfer (by Golden Software) for each bridge deck.

Figure 2-1 GSSI SIR-30 GPR System with two GSSI 2.0 GHz air-coupled horn antennas

For four bridges, namely Bridges A0569, A3405, A3406, and K0197, GPR data were acquired as part of a previous study using a GSSI SIR-3000 system and a GSSI 1.5 GHz ground-coupled antenna mounted to a push-cart (Figure 2-2). The ground-coupled GPR data were acquired on the top surface of the bridge deck along parallel traverses variably spaced at 0.75 to 2 ft. intervals (depending on the nature of the bridge deck and time constraints). GPR traverses were marked with chalk on the deck surface prior to the start the survey; the cart was pushed along each traverse to acquire data. The GPR traverses were oriented parallel to the direction of traffic flow (i.e., longitudinal direction of the bridge). The primary goal was to map the amplitude and apparent embedment depth of the uppermost layer of transverse rebar (Sneed et al. 2014).

During the present study, air-launched antenna GPR data were acquired across these same four bridge decks. The intent was to acquire a comparable density of air-launched antenna data to allow for a direct spatial comparison of the plotted output variable rebar amplitude maps in order to assess the utility of the air-launched antenna GPR tool.


Figure 2-2 GSSI SIR-3000 GPR System with a GSSI 1.5 GHz ground coupled-antenna

2.3 Results

2.3.1 Bridge A0523

Built in 1958, Bridge A0523 is located near Sherrill Creek (Phelps County), Missouri, and spans over a waterway. The bridge is two lane, 162 feet long, with a 21 ft. - 11 in. wide deck. The five-span bridge structure is a solid slab reinforced concrete structure. The bridge deck has an asphalt overlay with noticeable cracking throughout, especially along the center of the bridge deck. Photos of the bridge deck are shown in Figure 2-3 and Figure 2-4. Bridge details are summarized in Table 2-1.

Air-launched GPR data were acquired along parallel traverses spaced at 1-2 ft intervals. The air-launched GPR data were acquired on January 26, 2015 (Table 1-1). The acquisition parameters employed were 512 samples/scan, 473 scans/second, and 24 scans/ft. The dielectric constant was estimated to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-5.

The map shown in Figure 2-5 indicates regions of deterioration within each of the five spans, especially along the center (mid width) of the bridge. This is consistent with the locations of cracks observed in the asphalt overlay (see Figure 2-4). Based on the air-launched GPR data with traverses spaced at 1 ft intervals and a threshold value of -68 dB (-7 dB from the maximum value selected in accordance with ASTM D6087), 6% (172 ft^2) of the bridge deck exhibited no evidence of deterioration, and 94% (2690 ft^2) exhibited evidence of deterioration. (Note that the surface area of the deck given corresponds to the area surveyed.) Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-5, with lower values corresponding to a higher degree of deterioration.

Figure 2-3 Photo of Bridge A0523 bridge deck

Figure 2-4 Photo of Bridge A0523 bridge deck

Table 2-1 Bridge A0523 Details

Nearest City	Rolla
County	Phelps
Roadway Carried	RT K E
Feature Intersected	Sherrill Creek
Year Constructed	1958
Reconstructed Year	Never Reconstructed
Number of Driving Lanes	2
Direction of Traffic	Two-Way
AADT	508 (2012)
AADT Truck Percent	11%
Structure Length	162 ft. – 0 in.
Total Deck Width	25 ft. – 10 in.
Curb to Curb Br. Width	21 ft. – 11 in.
Main Structure Material Type	Concrete Continuous
Main Structure Construction Type	Slab
Number of Main Spans	5
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	Varies (12 1/8 in. sides, 19 in. centerline)
Wearing Surface	Bituminous
Orientation of Top Reinforcement Layer	Longitudinal
Designed Depth to Top Transverse Reinforcement	3 in. (without asphalt overlay)
Slab Reinforcement, Transverse Direction	#4 @ 18 in. o.c. top #5 @ bottom, spacing varies
Slab Reinforcement, Longitudinal Direction	#4, #6, or #9 bottom, spacing varies #6 or #9 bottom, spacing varies
Other Information	Asphalt overlay had noticeable cracking throughout

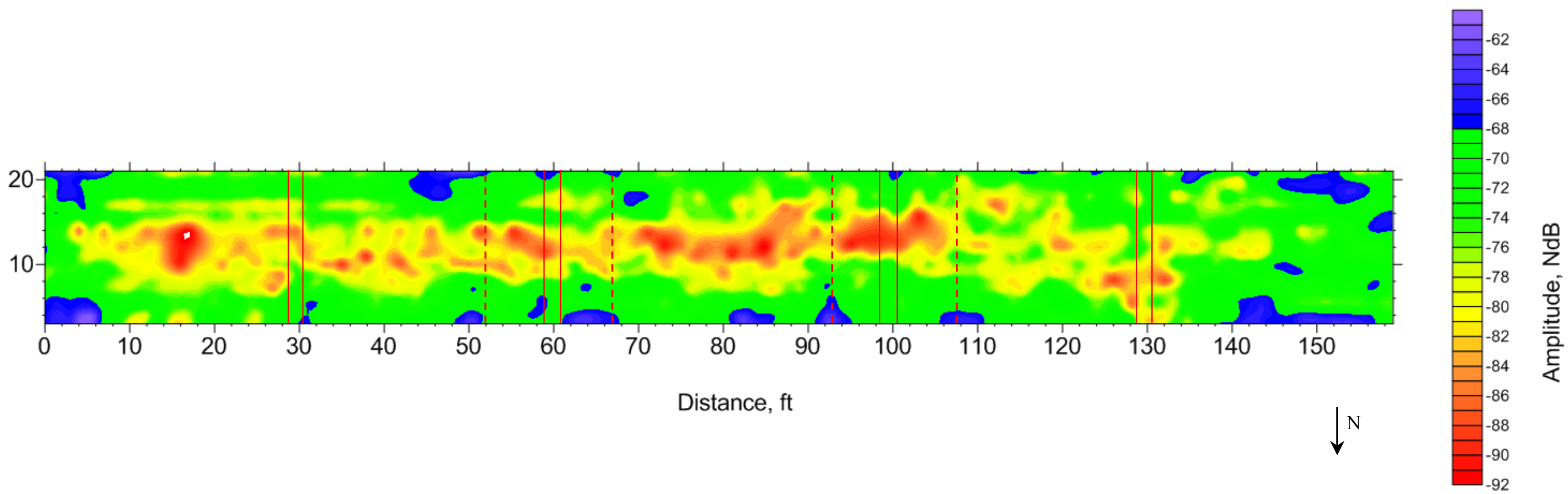

Figure 2-5 Air-launched GPR amplitude map (Bridge A0523). Dashed red line indicates keyed construction joint; solid red line indicates bent location.

2.3.2 Bridge A0569

Built in 1959, Bridge A0569 is located in Jefferson City, Missouri. The bridge carries three lanes of two-way traffic on a 57 ft – 8 in. wide deck. The 139 ft long structure is a reinforced concrete frame with one main span and a cast-in-place concrete deck with an asphalt wearing surface. The asphalt wearing surface was noted to be extensively deteriorated at the time of the investigation. Many locations of asphalt rutting and shoving were observed, along with many cracks and potholes. A photo of the bridge deck is shown in Figure 2-6. Bridge details are summarized in Table 2-2.

Air-launched GPR data were acquired along parallel traverses spaced at 2 ft intervals. The air-launched GPR data were acquired on July 30, 2014 (Table 1-1). The acquisition parameters employed were 1024 samples/scan, 261 scans/second, and 24 scans/ft. The dielectric constant was estimated to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-7. Regions of deterioration are associated with regions of lower reflection amplitudes.

Ground-coupled GPR data were acquired for this same bridge deck along parallel traverses spaced at intervals of approximately 2 ft. The ground-coupled GPR data were acquired on November 11, 2012 (Table 1-1; Sneed et al 2014). The acquisition parameters employed were 512 samples/scan, 120 scans/second, and 60 scans/ft. The dielectric constant was estimated to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-8.

The two reflection amplitude maps (Figures 2-7 and 2-8) are very similar, indicating that the air-launched GPR tool and the ground-coupled GPR tool produce comparable results. Both maps (Figures 2-7 and 2-8) indicate variable deterioration, especially at the interior edges of the north and south abutments. Differences can be attributed to several factors: 1) the air-launched and ground-coupled data were not acquired along precisely the same traverses; 2) the air-launched and ground-coupled GPR data were acquired at different times of the year and under different weather conditions; and 3) the ground-coupled antenna and the air-launched antenna are different frequency, and different frequencies are attenuated at slightly different rates. Additionally, it is generally accepted that ground-coupled GPR data are slightly higher resolution than air-launched antenna data. Further discussion of the correlation of the two maps is provided in Section 2.4.1.

Based on the air-launched GPR data with traverses spaced at 2 ft intervals and a threshold value of -71 dB (-7 dB from the maximum value based on the ground-coupled GPR data and in accordance with ASTM D6087), 28% (1558 ft^2) of the bridge deck exhibited no evidence of deterioration, and 72% (4042 ft^2) exhibited evidence of deterioration. Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-7, with lower values corresponding to a higher degree of deterioration. For comparison, results from the ground-coupled GPR survey indicated that 21% (1291 ft^2) of the bridge deck exhibited no evidence of deterioration, 47% (2897 ft^2) of the bridge deck exhibited evidence of moderate deterioration, and 32% (1944 ft^2) exhibited evidence of severe deterioration (Sneed et al 2014). (Note that the surface areas of the deck given corresponds to the areas surveyed.)

Figure 2-6 Photo of Bridge A0569 bridge deck

Table 2-2 Bridge A0569 Details

Nearest City	Jefferson City
County	Cole
Roadway Carried	Clark Avenue
Feature Intersected	U.S. 50
Year Constructed	1959
Reconstructed Year	Never Reconstructed
Number of Driving Lanes	3
Direction of Traffic	Two-Way
AADT	8,763 (2011)
AADT Truck Percent	10%
Structure Length	139 ft. – 0 in.
Total Deck Width	57 ft. – 8 in.
Curb to Curb Br. Width	48 ft. – 10 in.
Main Structure Material Type	Concrete
Main Structure Construction Type	Frame
Number of Main Spans	1
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	6.5 in.
Wearing Surface	Bituminous
Orientation of Top Reinforcement Layer	Transverse
Designed Depth to Top Transverse Reinforcement	1.75 in. (without asphalt overlay)
Slab Reinforcement, Transverse Direction	#5 @ 6 in. o.c. top and bottom main span, #5 @ 5 in. o.c. top and bottom abutments
Slab Reinforcement, Longitudinal Direction	#5 top and bottom main span and abutments, spacing varies
Other Information	Asphalt wearing surface was extensively deteriorated at the time of both NDE investigations. Many locations of asphalt rutting and shoving were observed, along with many cracks and potholes.

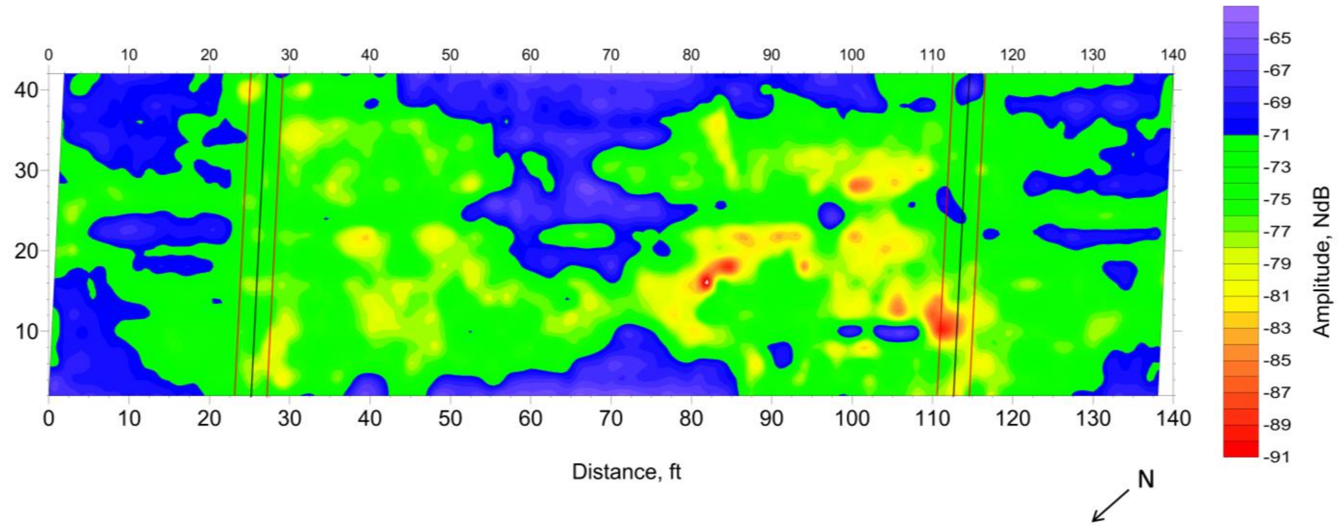

Figure 2-7 Air-launched GPR amplitude map (Bridge A0569). Solid black and red line indicates deck joint and bent locations, respectively.

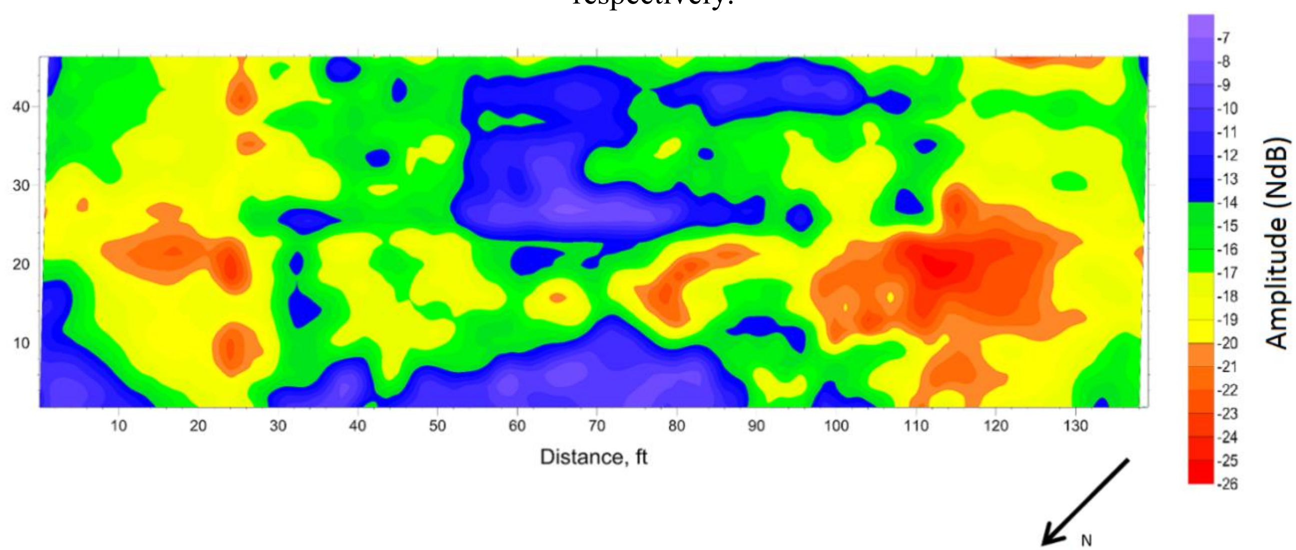

Figure 2-8 Ground-coupled GPR amplitude map (Bridge A0569)

2.3.3 Bridge A1880

Built in 1967, Bridge A3034 is located near Newburg, Missouri, and crosses a waterway. The bridge carries two lanes of two-way traffic and is 241 ft long. The bridge structure is a three-span steel continuous structure with a cast-in-place concrete deck and an asphalt overlay. The bridge is super elevated (sloped down from west to east). A photo of the bridge deck is shown in Figure 2-9. Bridge details are summarized in Table 2-3.

The air-launched GPR data were acquired along parallel traverses spaced at 2-4 ft intervals. The air-launched GPR data were acquired on January 26, 2015 (Table 1-1). The acquisition parameters employed were 512 samples/scan, 473 scans/second, and 24 scans/ft. The dielectric constant was assumed to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-10. It should be noted that the bridge curve is not depicted in the map.

The map shown in Figure 2-10 indicates regions of deterioration especially along the east side of the bridge, which is likely the result of saline moisture from deicing agents running off to the low side of the super elevation of the deck. Based on the air-launched GPR data with traverses spaced at 2 ft intervals and a threshold value of -70 dB (-7 dB from the maximum value selected in accordance with ASTM D6087), 12% (629 ft^2) of the bridge deck exhibited no evidence of deterioration, and 88% (4628 ft^2) exhibited evidence of deterioration. (Note that the surface area of the deck given corresponds to the area surveyed.) Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-10, with lower values corresponding to a higher degree of deterioration.

No ground-coupled GPR data were acquired on Bridge A1880.

Figure 2-9 Photo of Bridge A1880 bridge deck

Table 2-3 Bridge A1880 Details

Nearest City	Newburg
County	Phelps
Roadway Carried	RT P E
Feature Intersected	Mill Creek
Year Constructed	1967
Reconstructed Year	Never Reconstructed
Number of Driving Lanes	2
Direction of Traffic	Two-Way
AADT	346 (2001)
AADT Truck Percent	10%
Structure Length	241 ft. – 0 in.
Total Deck Width	28 ft. – 6 in.
Curb to Curb Br. Width	25 ft. – 10 in.
Main Structure Material Type	Steel Continuous
Main Structure Construction Type	Stringer/Multibeam - GRD
Number of Main Spans	3
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	6.75 in.
Wearing Surface	Bituminous
Orientation of Top Reinforcement Layer	Longitudinal
Designed Depth to Top Transverse Reinforcement	2.375 in.
Slab Reinforcement, Transverse Direction	#5 @ 6 in. o.c. top and bottom
Slab Reinforcement, Longitudinal Direction	#4 @ 12 in. o.c. top #5 @ 9 in. o.c. bottom
Other Information	-

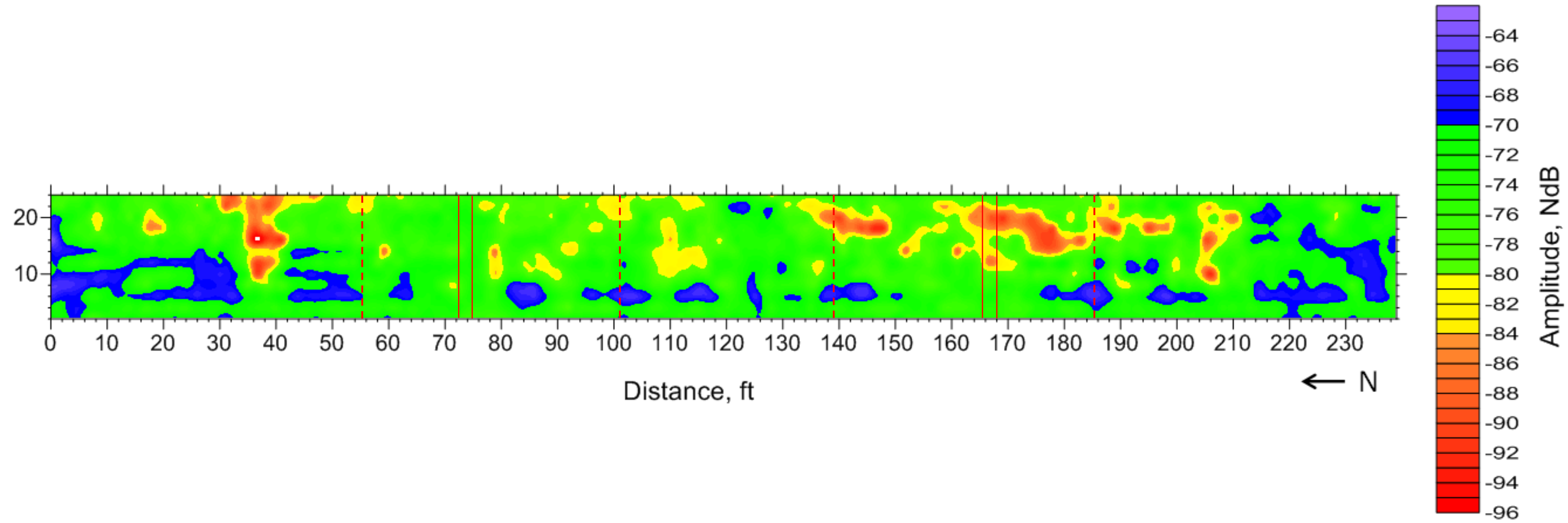

Figure 2-10 Air-launched GPR amplitude map (Bridge A1880). Bridge is curved (not depicted). Dashed red line indicates keyed construction joint; solid red line indicates bent location.

2.3.4 Bridge A2110

Built in 1968, Bridge A2110 is located near Fulton, Missouri. The bridge carries two lanes of one-way traffic on 40 ft – 8 in. wide deck. The four-span structure is a continuous steel system with a cast-in-place concrete deck and a monolithic concrete wearing surface. The total structure length is 205 feet. The bridge is super elevated (sloped down from east to west). The surface of the deck exhibited many cracks and patches at the time of the investigation. A photo of the bridge deck is shown in Figure 2-11. Bridge details are summarized in Table 2-4.

Air-launched GPR data were acquired along parallel traverses spaced at 2-4 ft intervals. The air-launched GPR data were acquired on December 16, 2014 (Table 1-1). The acquisition parameters employed were 512 samples/scan, 473 scans/second, and 24 scans/ft. The dielectric constant was assumed to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-12. It should be noted that the bridge curve is not depicted in the map.

The map shown in Figure 2-12 indicates regions of deterioration, on the south side of the deck and the north-most span. Based on the air-launched GPR data with traverses spaced at 2 ft intervals and a threshold value of -74 dB (-7 dB from the maximum value selected in accordance with ASTM D6087), 72% (4635 ft^2) of the bridge deck exhibited no evidence of deterioration, and 28% (1790 ft^2) exhibited evidence of deterioration. (Note that the surface area of the deck given corresponds to the area surveyed.) Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-12, with lower values corresponding to a higher degree of deterioration.

No ground-coupled GPR data were acquired on Bridge A2110.

Figure 2-11 Photo of Bridge A2110 bridge deck

Table 2-4 Bridge A2110 Details

Nearest City	Fulton
County	Callaway
Roadway Carried	U.S. 54
Feature Intersected	BU 54
Year Constructed	1968
Reconstructed Year	Never Reconstructed
Number of Driving Lanes	2
Direction of Traffic	One-Way
AADT	4,806
AADT Truck Percent	20%
Structure Length	205 ft. – 0 in.
Total Deck Width	40 ft. – 8 in.
Curb to Curb Br. Width	38 ft. – 0 in.
Main Structure Material Type	Steel Continuous
Main Structure Construction Type	Stringer/Multibeam Grd
Number of Main Spans	4
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	7.5 in.
Wearing Surface	Monolithic Concrete
Orientation of Top Reinforcement Layer	Transverse
Designed Depth to Top Transverse Reinforcement	2 in.
Slab Reinforcement, Transverse Direction	#6 @ 6.5 in. o.c. top and bottom
Slab Reinforcement, Longitudinal Direction	#4 @ 12 in. o.c. top and bottom, #6 @ 9.5 in. o.c. bottom
Other Information	-

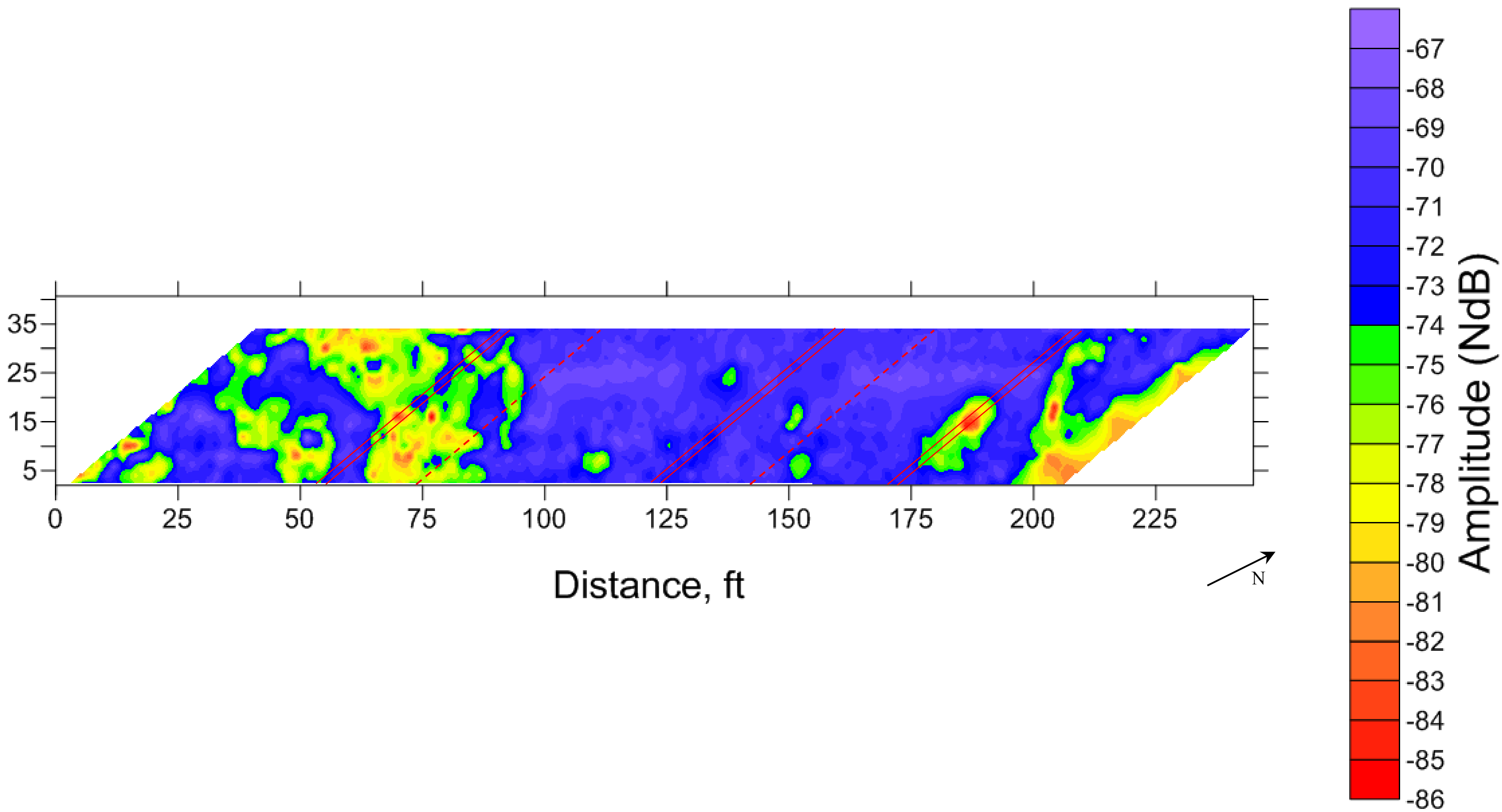

Figure 2-12 Air-launched GPR amplitude map (Bridge A2110). Bridge is curved (not depicted). Dashed red line indicates keyed construction joint; solid red line indicates bent location.

2.3.5 Bridge A3034

Built in 1976, Bridge A3034 is located near Doolittle, Missouri. The 235 ft long bridge carries two lanes of two-way traffic on a 46 ft – 10 in. wide deck. The two-span structure is a steel girder system with a cast-in-place concrete deck with an asphalt wearing surface. The top surface of the deck exhibited cracks and deterioration along the edges at the time of investigation. A photo of the bridge deck is shown in Figure 2-13. Bridge details are summarized in Table 2-5.

Air-launched GPR data were acquired along parallel traverses spaced at 4 ft intervals. The air-launched GPR data were acquired on January 26, 2015 (Table 1-1). The acquisition parameters employed were 512 samples/scan, 473 scans/second, and 24 scans/ft. The dielectric constant was estimated to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-14.

The map shown in Figure 2-14 indicates regions of deterioration, especially along the edges of the deck. Based on the air-launched GPR data with traverses spaced at 4 ft intervals and a threshold value of -70 dB (-7 dB from the maximum value selected in accordance with ASTM D6087), 80% (6571 ft^2) of the bridge deck exhibited no evidence of deterioration, and 20% (1629 ft^2) exhibited evidence of deterioration. (Note that the surface area of the deck given corresponds to the area surveyed.) Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-14, with lower values corresponding to a higher degree of deterioration.

No ground-coupled GPR data were acquired on Bridge A3034.

Figure 2-13 Photo of Bridge A3034 bridge deck

Table 2-5 Bridge A3034 Details

Nearest City	Doolittle
County	Phelps
Roadway Carried	RT C S
Feature Intersected	I-44
Year Constructed	1976
Reconstructed Year	Never Reconstructed
Number of Driving Lanes	2
Direction of Traffic	Two-Way
AADT	810 (2012)
AADT Truck Percent	11%
Structure Length	235 ft. – 0 in.
Total Deck Width	46 ft. – 10 in.
Curb to Curb Br. Width	43 ft. – 11 in.
Main Structure Material Type	Steel Continuous
Main Structure Construction Type	Stringer/Multibeam Grd
Number of Main Spans	2
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	7.5 in.
Wearing Surface	Bituminous
Orientation of Top Reinforcement Layer	Transverse
Designed Depth to Top Transverse Reinforcement	1.875 in. (without asphalt overlay)
Slab Reinforcement, Transverse Direction	#5 @ 5 in. o.c. top and bottom main span
Slab Reinforcement, Longitudinal Direction	#4 @ 12 in. o.c. top #5 @ 7.5 in. o.c. bottom
Other Information	-

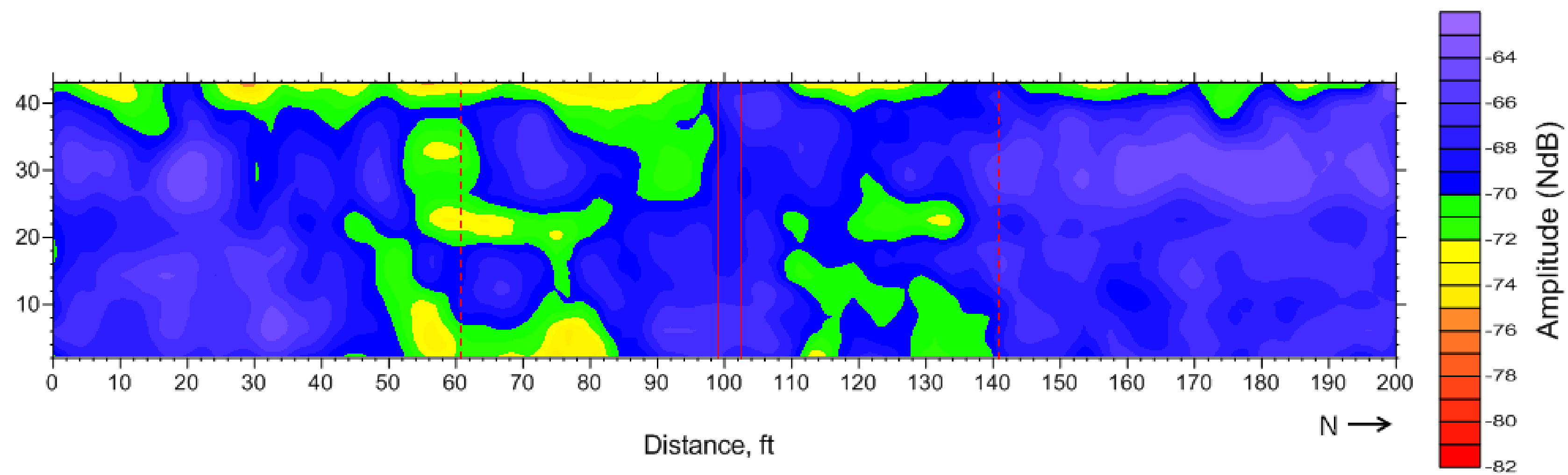

Figure 2-14 Air-launched GPR amplitude map (Bridge A3034). Dashed red line indicates keyed construction joint; solid red line indicates bent location.

2.3.6 Bridge A3405

Built in 1975, Bridge A3405 is located near St. James, Missouri, and spans a waterway. The bridge carries two lanes of two-way traffic on a 46 ft – 10 in. wide deck. The four-span structure is a continuous cast-in-place concrete slab. The total structure length is 144 ft. A photo of the bridge deck is shown in Figure 2-15. Bridge details are summarized in Table 2-6.

Bridge A3405 was one of the first bridges investigated in this project and was investigated multiple times (Table 1-1) in order to ensure that the acquisition process and parameters used were appropriate. This was done in part to try to overcome some of the challenges related to the longitudinally-oriented top layer of reinforcing bars. The appropriateness was determined by comparing the interpretations from the air-launched GPR data set with those from the ground-coupled GPR data set acquired in the previous study (Sneed et al. 2014), which served as ground truth. The results from only the last air-launched GPR investigation are presented in this section.

The air-launched GPR data were acquired on Jun 14, 2014 (Table 1-1). Air-launched GPR data were acquired along parallel traverses spaced at 4 ft intervals. The acquisition parameters employed were 512 samples/scan, 473 scans/second, and 24 scans/ft. The dielectric constant was estimated to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-16. Regions of deterioration are associated with regions of lower reflection amplitudes.

Ground-coupled GPR data were acquired along parallel traverses spaced at 0.75 ft and 1 ft intervals where possible. The ground-coupled GPR data were acquired on November 14, 2012 (Table 1-1; Sneed et al. 2014). The acquisition parameters employed were 512 samples/scan, 120 scans/second, and 48 scans/ft. The dielectric constant was estimated to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-17.

The two reflection amplitude maps are very similar, indicating that the air-launched GPR tool and the ground-coupled GPR tool generate comparable results. Further discussion of the correlation of the two maps is provided in Section 2.4.1.

Based on the air-launched GPR data with traverses spaced at 4 ft intervals and a threshold value of -78 dB (-5 dB from the maximum value based on the ground-coupled GPR data), 81% (4674 ft^2) of the bridge deck exhibited no evidence of deterioration, and 19% (1113 ft^2) exhibited evidence of deterioration. Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-16, with lower values corresponding to a higher degree of deterioration. For comparison, results from the ground-coupled GPR survey indicated that 73% (4147 ft^2) of the bridge deck exhibited no evidence of deterioration, 26% (1474 ft^2) of the bridge deck exhibited evidence of moderate deterioration, and 1% (23 ft^2) exhibited evidence of severe deterioration (Sneed et al 2014). (Note that the surface areas of the deck given corresponds to the areas surveyed.)


Figure 2-15 Photo of Bridge A3405 bridge deck

Table 2-6 Bridge A3405 Details

Nearest City	St. James
County	Maries
Roadway Carried	MO 68
Feature Intersected	Coppedge Creek
Year Constructed	1975
Reconstructed Year	Never Reconstructed
Number of Driving Lanes	2
Direction of Traffic	Two-Way
AADT	2,524 (2011)
AADT Truck Percent	18%
Structure Length	144 ft. – 0 in.
Total Deck Width	46 ft. – 10 in.
Curb to Curb Br. Width	43 ft. – 11 in.
Main Structure Material Type	Concrete Continuous
Main Structure Construction Type	Slab
Number of Main Spans	4
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	14.5 in.
Wearing Surface	Monolithic Concrete
Orientation of Top Reinforcement Layer	Longitudinal
Designed Depth to Top Transverse Reinforcement	3.375 in.
Slab Reinforcement, Transverse Direction	#5 @ 9 in. o.c. top and bottom
Slab Reinforcement, Longitudinal Direction	#10 @ 6 in. o.c. top over bents, #5 @ 9 in. o.c. top otherwise; #9 @ 18 in. o.c. bottom over bents, #9 & #10 @ 6 in. o.c. bottom otherwise
Other Information	-

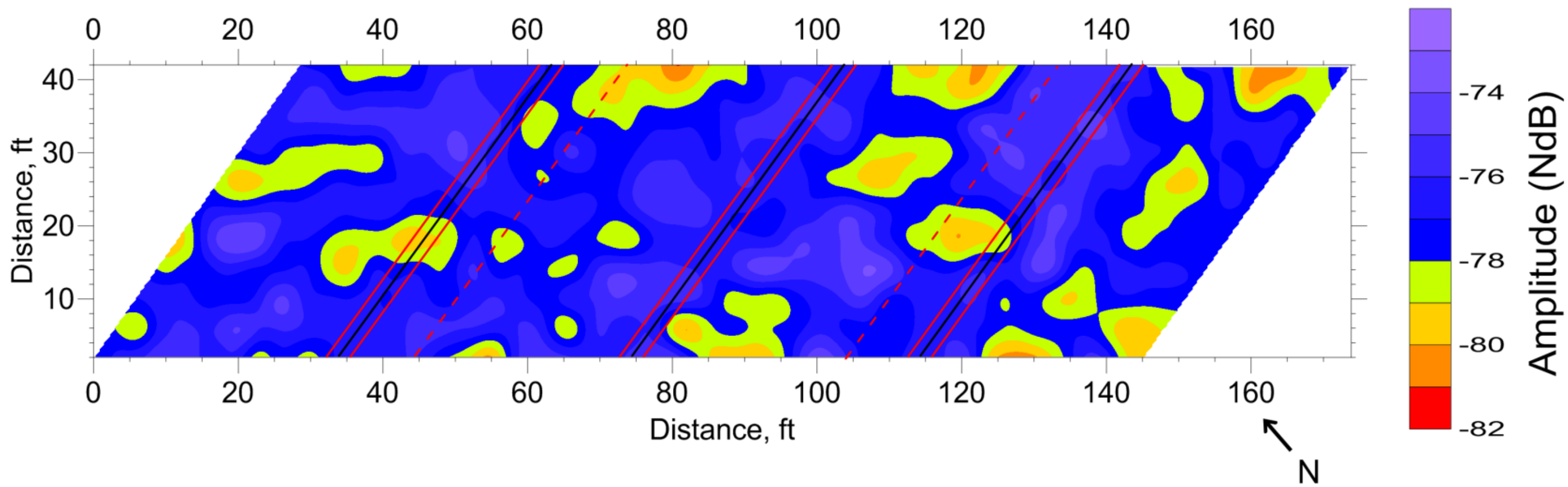

Figure 2-16 Air-launched GPR amplitude map (Bridge A3405). Dashed red line indicates keyed construction joint; solid black and red line indicates deck joint and bent locations, respectively.

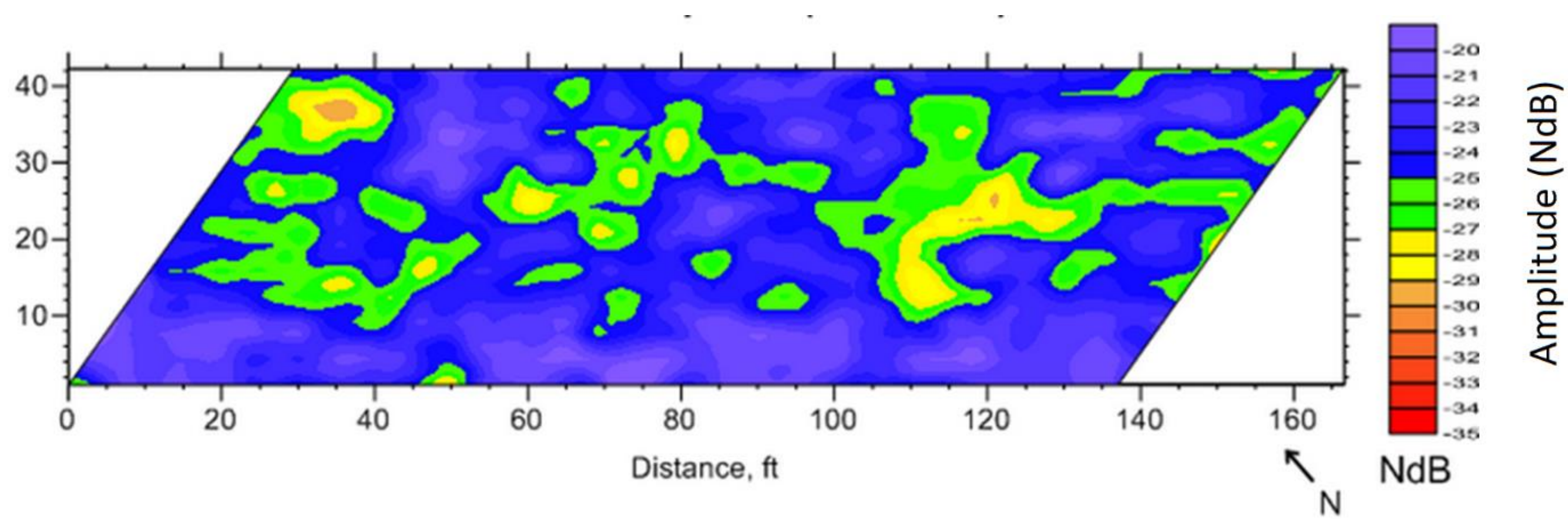

Figure 2-17 Ground-coupled GPR amplitude map (Bridge A3405)

2.3.7 Bridge A3406

Built in 1976, Bridge A3406 is located near St. James, Missouri, and spans a waterway. The bridge carries two lanes of two-way traffic on a 46 ft – 10 in. wide deck. The three-span structure is a continuous prestressed concrete with a cast-in-place concrete deck. The total structure length is 163 ft. A photo of the bridge deck is shown in Figure 2-18, which shows severe cracking, spalling, and patches on the deck surface observed at time of investigation. Bridge details are summarized in Table 2-7.

Bridge A3406 was one of the first bridges investigated in this project and was investigated multiple times (Table 1-1) in order to ensure that the acquisition process and parameters used were appropriate. The appropriateness was determined by comparing the interpretations from the air-launched GPR data set with those from the ground-coupled GPR data set acquired in the previous study (Sneed et al. 2014), which served as ground truth. The results from only the last air-launched GPR investigation are presented in this section.

Air-launched GPR data were acquired along parallel traverses spaced at 2 ft intervals. The air-launched GPR data were acquired on April 27, 2014 (Table 1-1). The acquisition parameters employed were 512 samples/scan, 261 scans/second, and 12 scans/ft. The dielectric constant was estimated to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-19. Regions of deterioration are associated with regions of lower reflection amplitudes. Due to time constraints and traffic conditions, there was no safe area in the mid-width of the bridge to allow for data collection. Thus, an 8 ft data interval in the middle of the deck (along the longitudinal direction) was mapped via data interpolation between the closest GPR profiles.

Ground-coupled GPR data were acquired along parallel traverses spaced at 1 ft intervals. The ground-coupled GPR data were acquired on November 15, 2012 (Table 1-1; Sneed et al. 2014). The acquisition parameters employed were 512 samples/scan, 120 scans/second, and 48 scans/ft. The dielectric constant was assumed to be 10.0. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-20.

The two reflection amplitude maps are very similar, indicating that the air-launched GPR tool and the ground-coupled GPR tool generate comparable results. Further discussion of the correlation of the two maps is provided in Section 2.4.1.

Based on the air-launched GPR data with traverses spaced at 2 ft intervals and a threshold value of -77 dB (-4 dB from the maximum value based on the ground-coupled GPR data), 29% (1742 ft^2) of the bridge deck exhibited no evidence of deterioration, and 71% (4326 ft^2) exhibited evidence of deterioration. Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-19, with lower values corresponding to a higher degree of deterioration. For comparison, results from the ground-coupled GPR survey indicated that 39% (2611 ft^2) of the bridge deck exhibited no evidence of deterioration, 48% (3220 ft^2) of the bridge deck exhibited evidence of moderate deterioration, and 13% (852 ft^2) exhibited evidence of severe deterioration (Sneed et al 2014). (Note that the surface areas of the deck given corresponds to the areas surveyed.)

Figure 2-18 Photo of Bridge A3406 bridge deck

Table 2-7 Bridge A3406 Details

Nearest City	Vichy
County	Maries
Roadway Carried	MO 68
Feature Intersected	Lanes Creek
Year Constructed	1976
Reconstructed Year	Never Reconstructed
Number of Driving Lanes	2
Direction of Traffic	Two-Way
AADT	1,840 (2011)
AADT Truck Percent	18%
Structure Length	163 ft. – 0 in.
Total Deck Width	46 ft. – 10 in.
Curb to Curb Br. Width	43 ft. – 11 in.
Main Structure Material Type	Prestressed Concrete Continuous
Main Structure Construction Type	Stringer/Multibeam - Grd
Number of Main Spans	3
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	7.5 in.
Wearing Surface	Monolithic Concrete
Orientation of Top Reinforcement Layer	Transverse
Designed Depth to Top Transverse Reinforcement	1.875 in.
Slab Reinforcement, Transverse Direction	#5 @ 5 in. o.c. top and bottom
Slab Reinforcement, Longitudinal Direction	#4 @ 6 in. o.c. top over bents, #4 @ 12 in. o.c. top otherwise; #5 bottom, spacing varies
Other Information	Severe cracking, spalling, and patches were observed at time of investigation

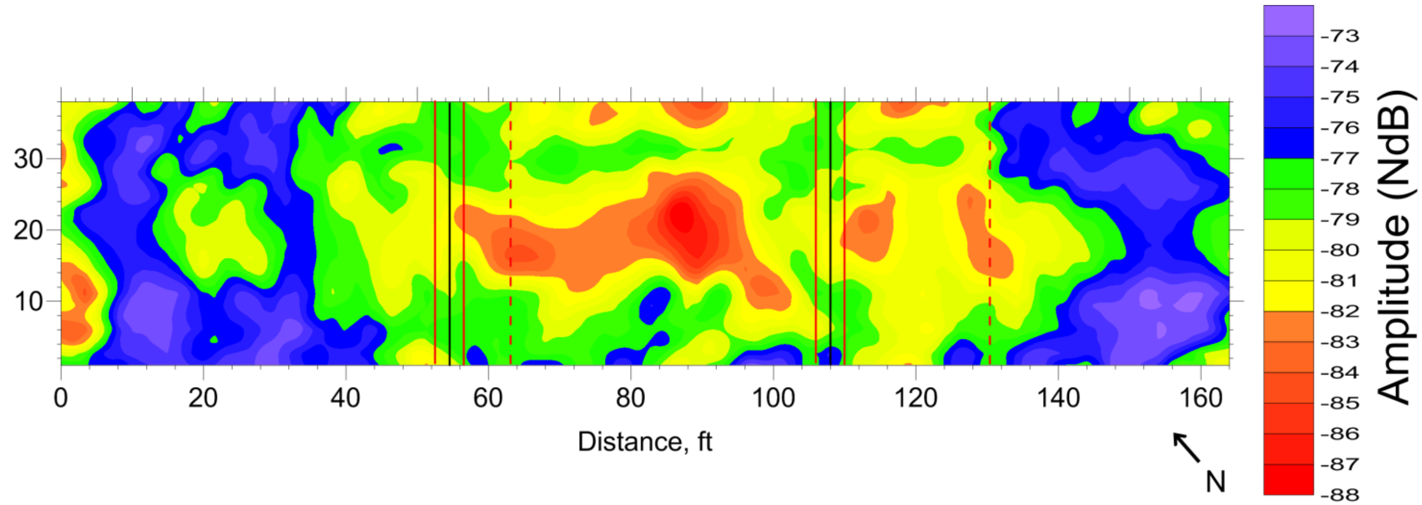

Figure 2-19 Air-launched GPR amplitude map (Bridge A3406). Dashed red line indicates keyed construction joint; solid black and red line indicates deck joint and bent locations, respectively.

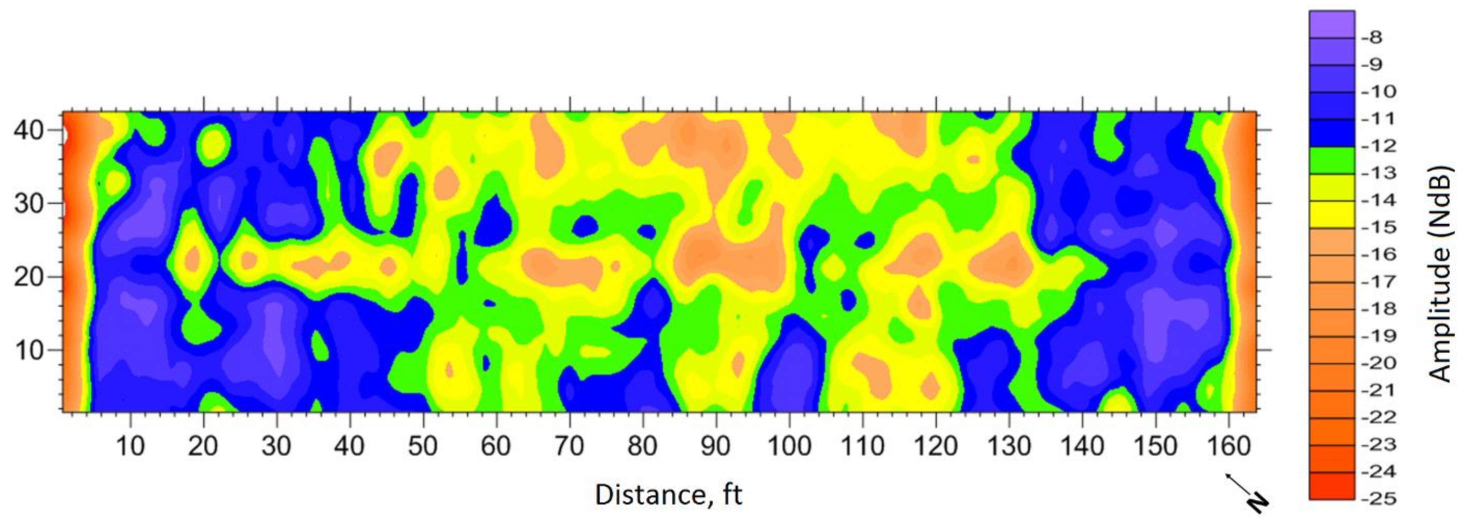

Figure 2-20 Ground-coupled GPR amplitude map (Bridge A3406)

2.3.8 Bridge A4780

Built in 1990, Bridge A4780 is located near Kingdom City (Callaway County), Missouri, and carries highway US 54 over Auxvasse Creek. The 304 ft long bridge carries two lanes of one-way traffic on a 41 ft - 3 in. wide deck. The five-span structure is a continuous prestressed concrete with a cast-in-place concrete deck with a monolithic concrete wearing surface. The bridge is super elevated (sloped down from east to west). A photo of the bridge deck is shown in Figure 2-21. Bridge details are summarized in Table 2-8.

Air-launched GPR data were acquired along parallel traverses spaced at 3 ft intervals. The air-launched GPR data were acquired on July 31, 2014 (Table 1-1). The acquisition parameters employed were 1024 samples/scan, 231 scans/second, and 24 scans/ft. The dielectric constant was estimated to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-22. It should be noted that the bridge curve is not depicted in the map.

The map shown in Figure 2-22 indicates regions of deterioration, especially within the south half of the deck. Based on the air-launched GPR data with traverses spaced at 3 ft intervals and a threshold value of -75 dB (-7 dB from the maximum value selected in accordance with ASTM D6087), 75% (6596 ft^2) of the bridge deck exhibited no evidence of deterioration, and 25% (2237 ft^2) exhibited evidence of deterioration. (Note that the surface area of the deck given corresponds to the area surveyed.) Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-22, with lower values corresponding to a higher degree of deterioration.

No ground-coupled GPR data were acquired on Bridge A4780.

Figure 2-21 Photo of Bridge A4780 bridge deck

Table 2-8 Bridge A4780 Details

Nearest City	Kingdom City
County	Callaway
Roadway Carried	U.S. 54
Feature Intersected	Auxvasse Cr
Year Constructed	1990
Reconstructed Year	Never Reconstructed
Number of Driving Lanes	2
Direction of Traffic	One-Way
AADT	4326 (2012)
AADT Truck Percent	23%
Structure Length	304 ft. – 0 in.
Total Deck Width	41 ft. – 3 in.
Curb to Curb Br. Width	38 ft. – 8 in.
Main Structure Material Type	Prestressed Concrete Continuous
Main Structure Construction Type	Stringer/Multibeam - GRD
Number of Main Spans	5
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	8.5 in.
Wearing Surface	Monolithic Concrete
Orientation of Top Reinforcement Layer	Longitudinal
Designed Depth to Top Transverse Reinforcement	3.625 in.
Slab Reinforcement, Transverse Direction	#5 @ 5 in. o.c. top, #5 @ 7.5 in. o.c. bottom
Slab Reinforcement, Longitudinal Direction	#5 or #7 top, spacing varies #5 @ 10 in. o.c. bottom
Other Information	-

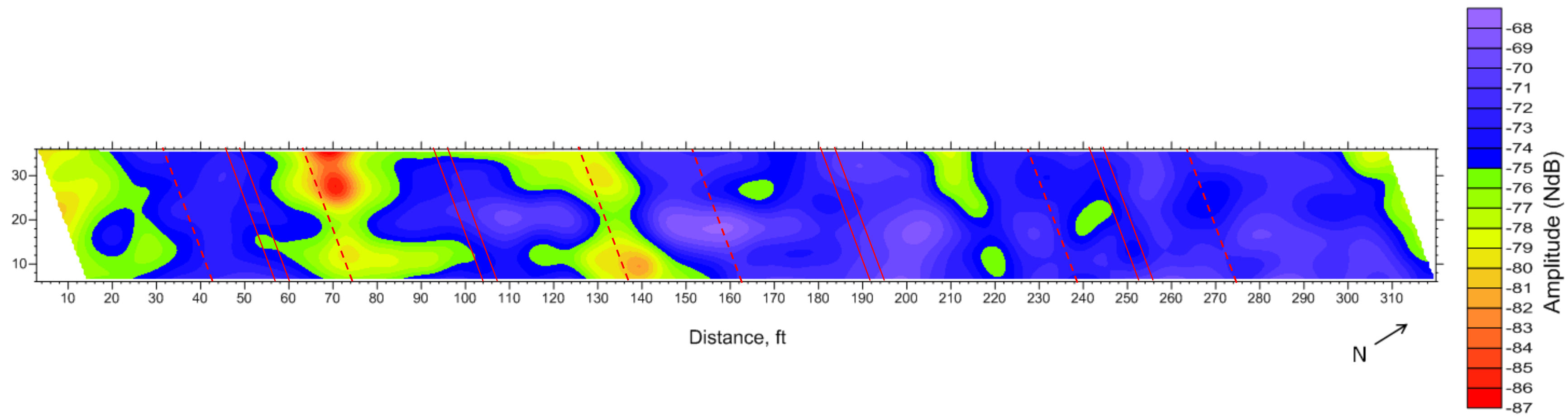

Figure 2-22 Air-launched GPR amplitude map (Bridge A4780). Bridge is slightly curved (not depicted). Dashed red line indicates keyed construction joint; solid red line indicates bent location.

2.3.9 Bridge A4781

Built in 1990, bridge A4781 is located near Kingdom City (Callaway County), Missouri, carries highway US 54 over Auxvasse Creek; parallel to Bridge A4780. The 304 ft long bridge carries two lanes of one-way traffic on a 41 ft – 3 in. feet wide deck. The five-span structure is a continuous prestressed concrete with a cast-in-place concrete deck with a monolithic concrete wearing surface. The bridge is super elevated (sloped down from east to west). A photo of the bridge deck is shown in Figure 2-23. Bridge details are summarized in Table 2-9.

Bridge A4781 was investigated twice (Table 1-1). The first investigation occurred the same day as Bridge A4780 (Section 2.3.8), however problems occurred with the survey wheel coupled to the truck which rendered the data unusable. Therefore, the data were reacquired at a different date. The results from only the last air-launched GPR investigation are presented in this section.

The air-launched GPR data were acquired along parallel traverses spaced at 2 ft intervals. The air-launched GPR data were acquired on December 16, 2014 (Table 1-1). The acquisition parameters employed were 256 samples/scan, 795 scans/second, and 12 scans/ft. The dielectric constant was assumed to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-24. It should be noted that the bridge curve is not depicted in the map.

The map shown in Figure 2-24 indicates regions of moderate deterioration towards the north side of the deck, especially over the bent locations. Based on the air-launched GPR data with traverses spaced at 2 ft intervals and a threshold value of -73 dB (-7 dB from the maximum value selected in accordance with ASTM D6087), 66% (6537 ft^2) of the bridge deck exhibited no evidence of deterioration, and 34% (3386 ft^2) exhibited evidence of deterioration. (Note that the surface area of the deck given corresponds to the area surveyed.) Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-24, with lower values corresponding to a higher degree of deterioration.

No ground-coupled GPR data were acquired on Bridge A4781.

Figure 2-23 Photo of Bridge A4781 bridge deck

Table 2-9 Bridge A4781 Details

Nearest City	Kingdom City
County	Callaway
Roadway Carried	U.S. 54
Feature Intersected	Auxvasse Cr
Year Constructed	1990
Reconstructed Year	Never Reconstructed
Number of Driving Lanes	2
Direction of Traffic	One-Way
AADT	4473 (2012)
AADT Truck Percent	13%
Structure Length	304 ft. – 0 in.
Total Deck Width	41 ft. – 3 in.
Curb to Curb Br. Width	38 ft. – 8 in.
Main Structure Material Type	Prestressed Concrete Continuous
Main Structure Construction Type	Stringer/Multibeam - GRD
Number of Main Spans	5
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	8.5 in.
Wearing Surface	Monolithic Concrete
Orientation of Top Reinforcement Layer	Longitudinal
Designed Depth to Top Transverse Reinforcement	3.625 in.
Slab Reinforcement, Transverse Direction	#5 @ 5 in. o.c. top, #5 @ 7.5 in. o.c. bottom
Slab Reinforcement, Longitudinal Direction	#5 or #7 top, spacing varies #5 @ 10 in. o.c. bottom
Other Information	-

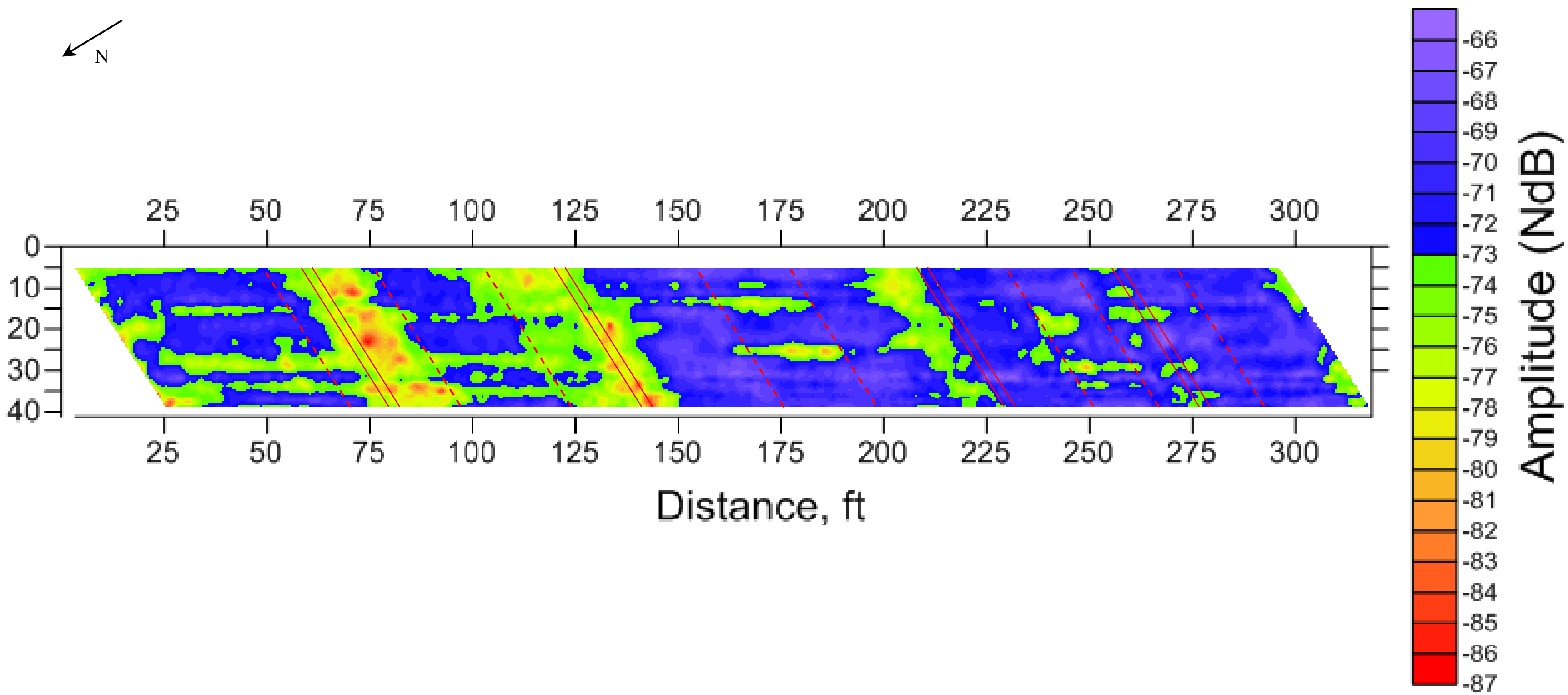

Figure 2-24 Air-launched GPR amplitude map (Bridge A4781). Bridge is slightly curved (not depicted). Dashed red line indicates keyed construction joint; solid red line indicates bent location.

2.3.10 Bridge K0197

Built in 1965, bridge K0197 is located near St. James, Missouri spanning over a waterway. The bridge carries two lanes of two-way traffic on a 32 ft – 5 in. wide deck. The three-span structure is a continuous steel system with a cast-in-place concrete deck and an asphalt wearing surface. The total structure length is 207 ft. Bridge details are summarized in Table 2-10. Unfortunately photos of Bridge K0197 did not record properly and are not available. However, detailed information on the previous investigation of Bridge K0197 is available in the report by Sneed et al. (2014).

Bridge K0197 was one of the first bridges investigated in this project and was investigated multiple times (Table 1-1) in order to ensure that the acquisition process and parameters used were appropriate. The appropriateness was determined by comparing the interpretations from the air-launched GPR data set with those from the ground-coupled GPR data set acquired in the previous study (Sneed et al. 2014), which served as ground truth. The results from only the last air-launched GPR investigation are presented in this section.

Air-launched GPR data were acquired along parallel traverses spaced at 4 ft intervals. The air-launched GPR data were acquired on June 5, 2014 (Table 1-1). The acquisition parameters employed were 512 samples/scan, 473 scans/second, and 24 scans/ft. The dielectric constant was assumed to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-25. Regions of deterioration are associated with regions of lower reflection amplitudes.

Ground-coupled GPR data were acquired along parallel traverses spaced at 1 ft intervals. The ground-coupled GPR data were acquired on November 28, 2012 (Table 1-1; Sneed et al. 2014). The acquisition parameters employed were 512 samples/scan, 120 scans/second, and 48 scans/ft. The dielectric constant was assumed to be 10. A map of reflection amplitudes from the top layer of transverse rebar is shown in Figure 2-26.

The two reflection amplitude maps are similar, but there are significant differences. These differences are attributed mostly to the fact that the air-launched and ground-coupled data were not acquired along precisely the same traverses. The similarities indicate that air-launched GPR would be a good tool for cost-effectively evaluating the relative condition of multiple bridge deck. The differences indicate that a protocol should be established such that (to the extent possible) air-launched GPR data are acquired along essentially the same traverses across all surveyed bridge decks (to facilitate relative comparative assessments). Further discussion of the correlation of the two maps is provided in Section 2.4.1.

Based on the air-launched GPR data with traverses spaced at 4 ft intervals and a threshold value of -66 dB (-5 dB from the maximum value based on the ground-coupled GPR data), 54% (2385 ft^2) of the bridge deck exhibited no evidence of deterioration, and 46% (2047 ft^2) exhibited evidence of deterioration. Regions of deterioration are associated with regions of lower reflection amplitudes in Figure 2-25, with lower values corresponding to a higher degree of deterioration. For comparison, results from the ground-coupled GPR survey indicated that 48% (2264 ft^2) of the bridge deck exhibited no evidence of deterioration, 46% (2554 ft^2) of the bridge deck exhibited evidence of moderate deterioration, and 6% (318 ft^2) exhibited evidence of severe deterioration (Sneed et al 2014). (Note that the surface areas of the deck given corresponds to the areas surveyed.)

Table 2-10 Bridge K0197 Details

Nearest City	St. James
County	Phelps
Roadway Carried	MO 68
Feature Intersected	Bourbeuse River
Year Constructed	1965
Reconstructed Year	1984
Number of Driving Lanes	2
Direction of Traffic	Two-Way
AADT	2,524 (2011)
AADT Truck Percent	18%
Structure Length	207 ft. – 0 in.
Total Deck Width	32 ft. – 5 in.
Curb to Curb Br. Width	29 ft. – 10 in.
Main Structure Material Type	Steel Continuous
Main Structure Construction Type	Stringer/Multibeam - Grd
Number of Main Spans	3
Number of Approach Spans	0
Deck Material	Concrete CIP
Designed Slab Thickness	7.5 in.
Wearing Surface	Bituminous
Orientation of Top Reinforcement Layer	Longitudinal
Designed Depth to Top Transverse Reinforcement	2.5 in. (without asphalt overlay)
Designed Slab Reinforcement, Transverse Direction	#6 @ 6.5 in. o.c. top and bottom
Designed Slab Reinforcement, Longitudinal Direction	#4 @ 6 in. o.c. top over bents, #4 @ 12 in. o.c. top otherwise; #4 bottom, spacing varies
Other Information	1984 reconstruction consisted of half soled and full depth repair, along with an asphalt overlay with a minimum thickness of 1.5 in.

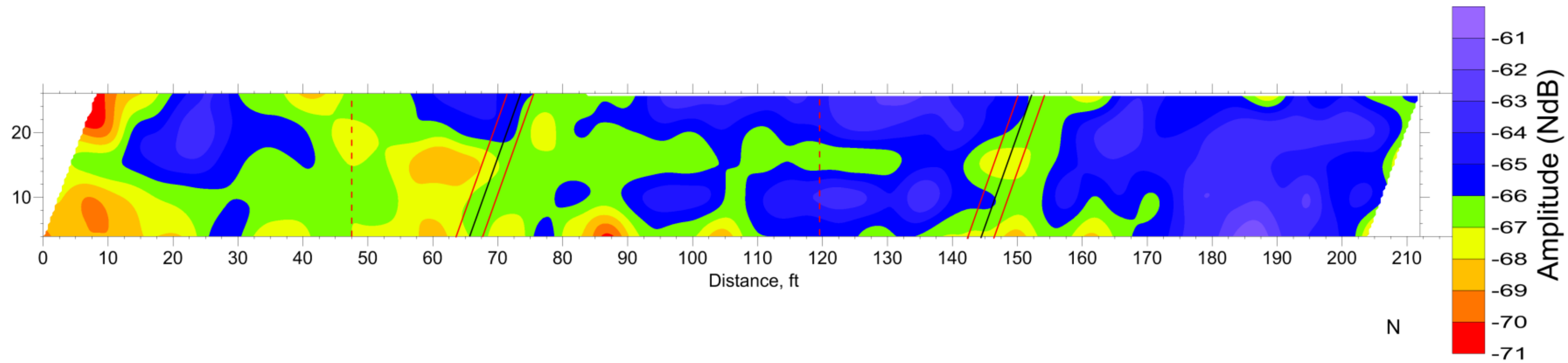

Figure 2-25 Air-launched GPR amplitude map (Bridge K0197). Dashed red line indicates keyed construction joint; solid black and red line includes deck joint and bent locations, respectively.

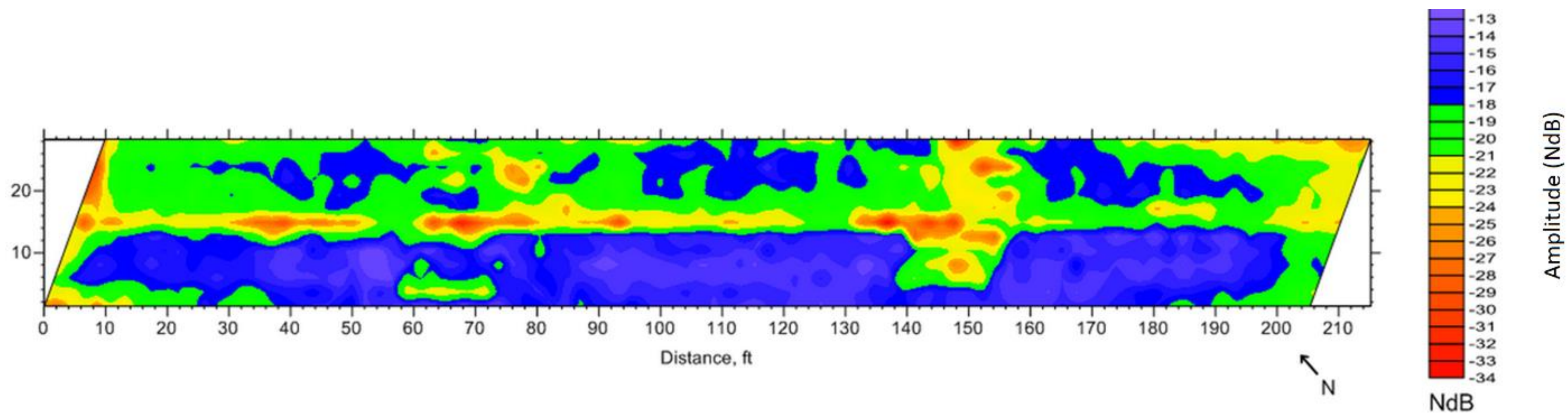

Figure 2-26 Ground-coupled GPR amplitude map (Bridge K0197)

2.4 Discussion

2.4.1 Correlation of Air-launched GPR data with ground-coupled GPR data

Based on the visual comparison of the air-launched and ground-coupled GPR data sets for Bridges A0569, A3405, A3406, and K0197 presented in Section 2.3 of this report, it is concluded that the two data sets generally compare well, especially in terms of overall deck condition. The spatial correlation of the air-launched and ground-coupled GPR data was stronger for bridges with transverse top bars (A0569 and A3406) than for bridges with longitudinal top bars (A3405 and K0197). Areas where poorer correlations are observed could be attributed to various factors including the following:

1. The plotting software interpolated between adjacent GPR traverses.
2. Air-launched and ground-coupled data were not acquired along precisely the same traverses.
3. The air-launched and ground-coupled GPR data were acquired at different times of the year and under different weather conditions.
4. The ground-coupled antenna and the air-launched antenna are different frequency, and different frequencies are attenuated at slightly different rates.
5. The air-launched antenna are at least 18 in. above the bridge deck surface. The ground-coupled GPR antenna, in contrast, is placed on the bridge deck surface and is therefore closer to the reinforcing steel being imaged. As a result, the ground-coupled GPR tool provides higher resolution of the embedded reinforcing steel.
6. Reflections from the longitudinal bars can mask the reflections from the transverse bars in bridge decks with longitudinally-oriented top bars, especially with the air-launched GPR antenna since the antenna is farther from the bars being imaged.
7. The air-launched GPR data were acquired at a later date than the ground-coupled GPR data were acquired from the same bridge (Table 1-1).

Differences associated with different traverses and different traverse spacings (Items 1 and 2 above) indicate that a protocol should be established such that (to the extent possible) air-launched GPR data are acquired along essentially the same traverses across all surveyed bridge decks (to facilitate comparative assessments). Aspects such as reinforcing bar orientation and spacing should be considered in order to establish the traverse locations for each bridge deck, which requires review of the bridge deck drawings before the GPR survey is conducted.

Results from this study indicate that air-launched GPR would be an effective tool for rapidly assessing the relative condition of multiple bridge decks, which could be used by MoDOT for programming purposes. If fuller and more definitive assessments are required, air-launched GPR data or ground-coupled GPR data should be acquired along a larger number of more closely spaced traverses.

2.5 Recommended Parameters for Air-Launched GPR Data Acquisition, Processing, and Interpretation

Based on the ten bridges investigated, parameters for GPR data acquisition, processing, and interpretation are recommended and summarized in Table 2-11. It should be noted that, in general, the volume and quality of the data acquired on each bridge depends on a bridge design (reinforcing bar spacing, deck width), availability of traffic control and lane closures, survey grid (GPR profiles spacing), equipment settings, and weather conditions.

For reconnaissance-style investigations, air-launched GPR data should be acquired along 2-4 traverses per lane. If fuller and more definitive assessments are required, air-launched GPR data or ground-coupled GPR data should be acquired along a larger number of more closely spaced traverses. However, increasing the number of traverses increases processing time and requires either more field time (i.e., more passes) or more GPR antennas. As discussed in Section 2.4, a protocol should be established to ensure traverses are placed essentially on the same optimal locations in all lanes to facilitate comparisons and to ensure data can be reacquired along essentially the same traverses (to facilitate comparative interpretation of data acquired across the same deck over periods of time).

High-quality air-launched GPR data can be acquired across bridge decks at speeds of up to 20 miles per hour. It is recommended that a video camera be coupled to the front of the vehicle to facilitate a comparison of the GPR data and the condition of the deck surface if/as necessary. This would help support interpretations for the cases where there is lack of contrast in the data (i.e., if the deck is either uniformly sound or uniformly deteriorated).

If air-launched GPR data are acquired along a limited number (2-4) of traverses per lane (compared to data density acquired in this study, discussed in Section 2.2), the assessment of the overall condition of the bridge deck will be based on a statistically smaller volume of data and hence be slightly less reliable. In an effort to reduce costs and to avoid errors introduced by extrapolation between data points acquired along more widely-spaced traverses, the overall bridge deck quality (percentages of surface area designated as "no evidence of deterioration", and "evidence of deterioration") should probably not be based on the assessment of contour maps (Figure 2-25, for example). Rather, percentage estimates should be based on the assessment of the linear GPR profiles. For example, if analyses indicate that 71% of the lineal footage of acquired GPR data imaged areas of the bridge deck are designated as "no evidence of deterioration", then the conclusion would be that 71% of the bridge deck shows "no evidence of deterioration." An advantage to this procedure is that processing time could be reduced since generation of a contour map would not be required. Note that generating a contour map for curved bridges takes significantly more time than for a rectangular bridge. As an example, Figure 2-27 shows the air-launched GPR amplitude map for Bridge A0569 (Section 2.3.2) with four GPR traverses identified in the figure. The amplitude data along the four traverses are plotted versus distance in Figure 2-28. If a threshold value is selected (using the procedure in ASTM D 6087, for example), the lineal footage along each traverse above and below the threshold value can be computed and used to estimate the areas of the deck with "no evidence of deterioration" or "with evidence of deterioration" (Figure 2-29). Values of the percent areas of the deck with "no evidence of deterioration" or with "evidence of deterioration" computed based on the four traverses acquired with the air-launched GPR, based on the contour map of data acquired with the air-launched GPR, and based on the ground-coupled GPR are compared in Figure 2-30.

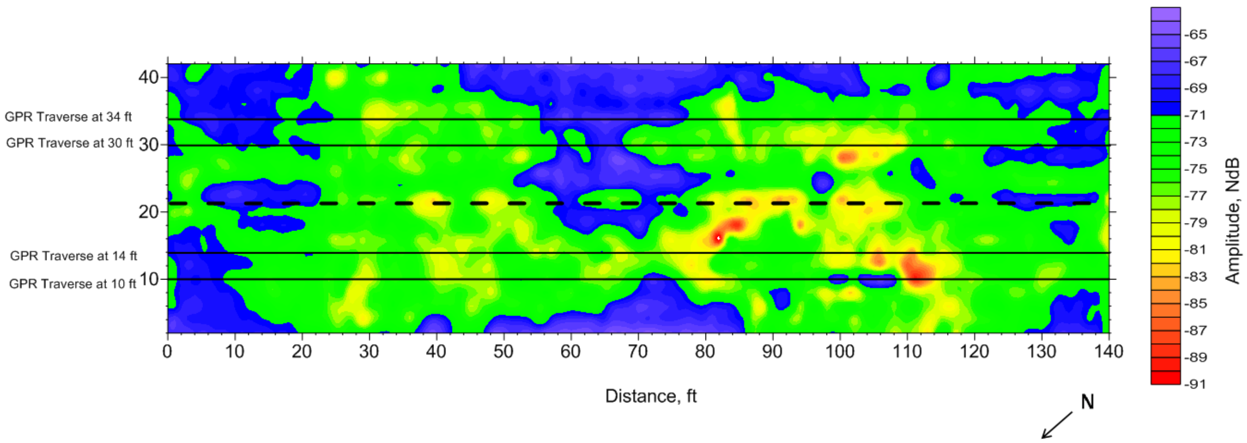

Figure 2-27 Air-launched GPR amplitude map (Bridge A0569) with four superposed GPR traverses used for estimating areas of deterioration based on reflections from top transverse rebar on individual GPR profiles. Total two passes with two channels (total four GPR profiles) are used to estimate areas of deterioration. Dashed line represents center of the bridge deck.

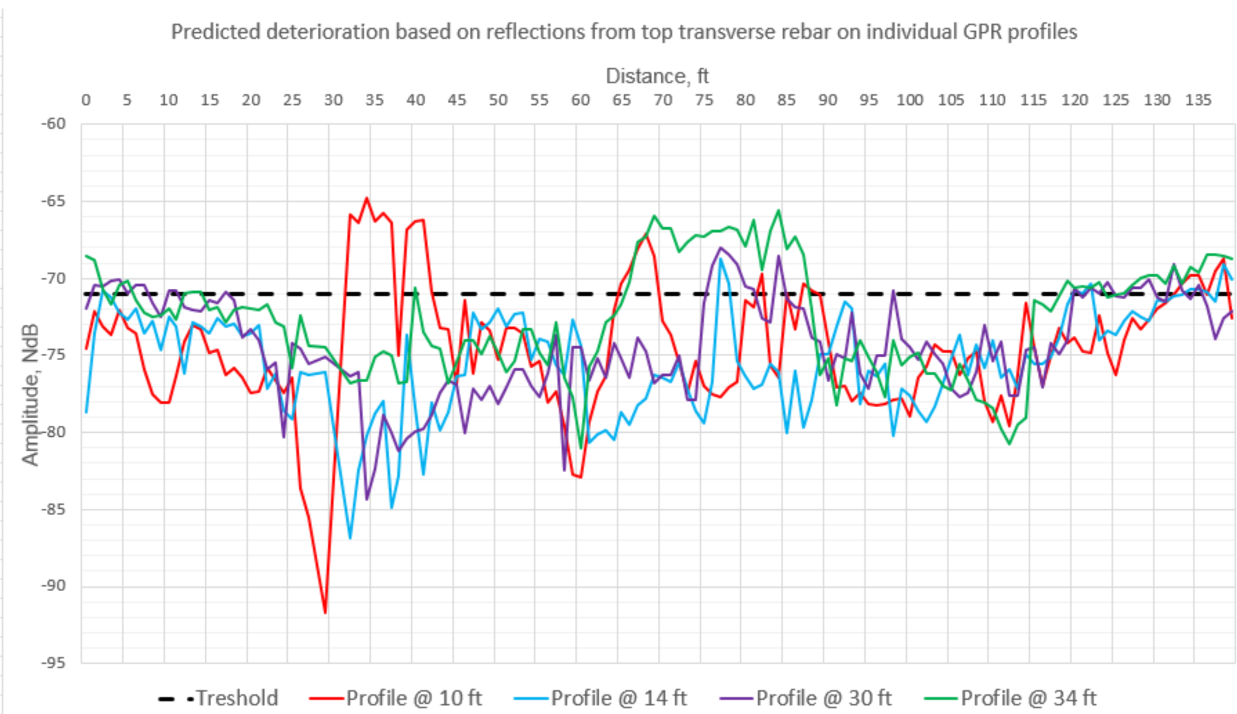

Figure 2-28 Air-launched GPR reflection amplitudes from top transverse rebar on profiles (traverses) located at 10 ft, 14 ft, 30 ft and 34 ft marks (Bridge A0569) (see Figure 2-27). Threshold value of -71 dB selected based on the results from ground-coupled GPR survey (see Figure 2-8).

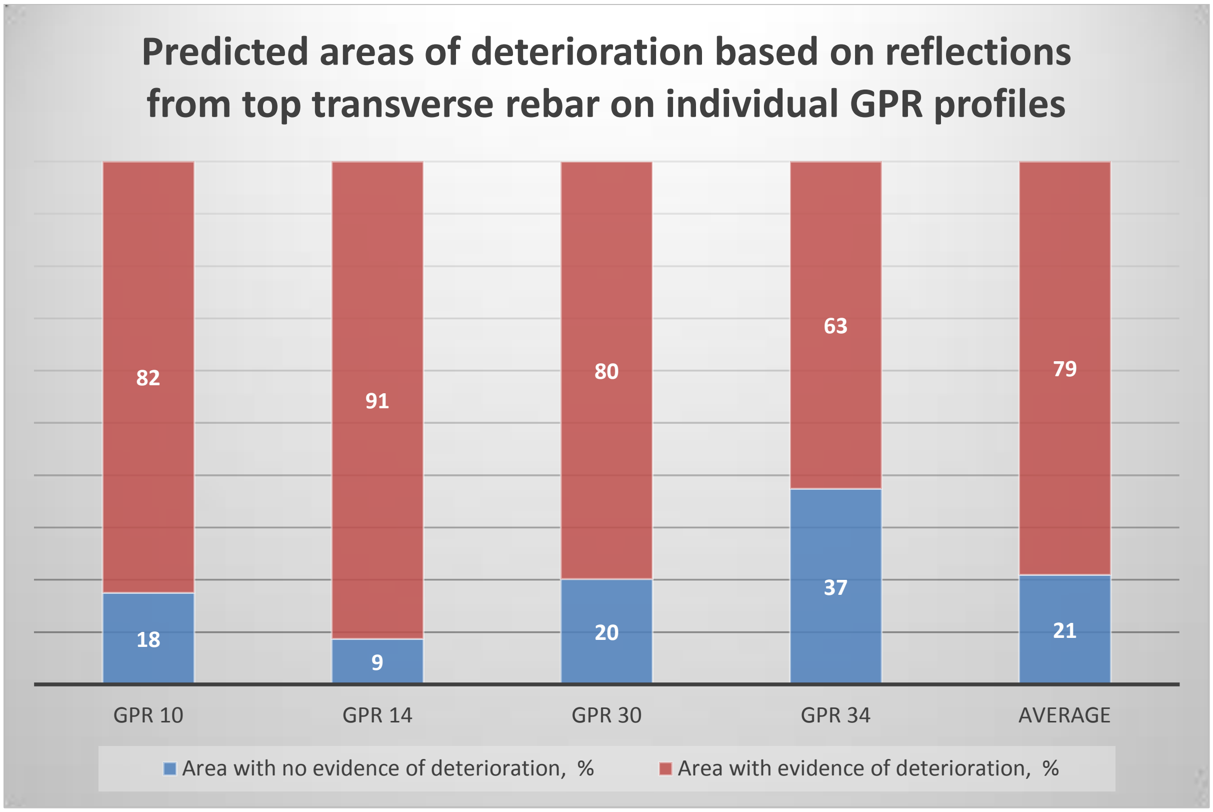

Figure 2-29 Chart showing distribution (percentage) of areas with no evidence and evidence of deterioration based on air-launched GPR profiles (traverses) located at 10 ft, 14 ft, 30 ft and 34 ft marks (Bridge A0569) (Figure 2-27). Also, the average value of distribution (percentage) is calculated.

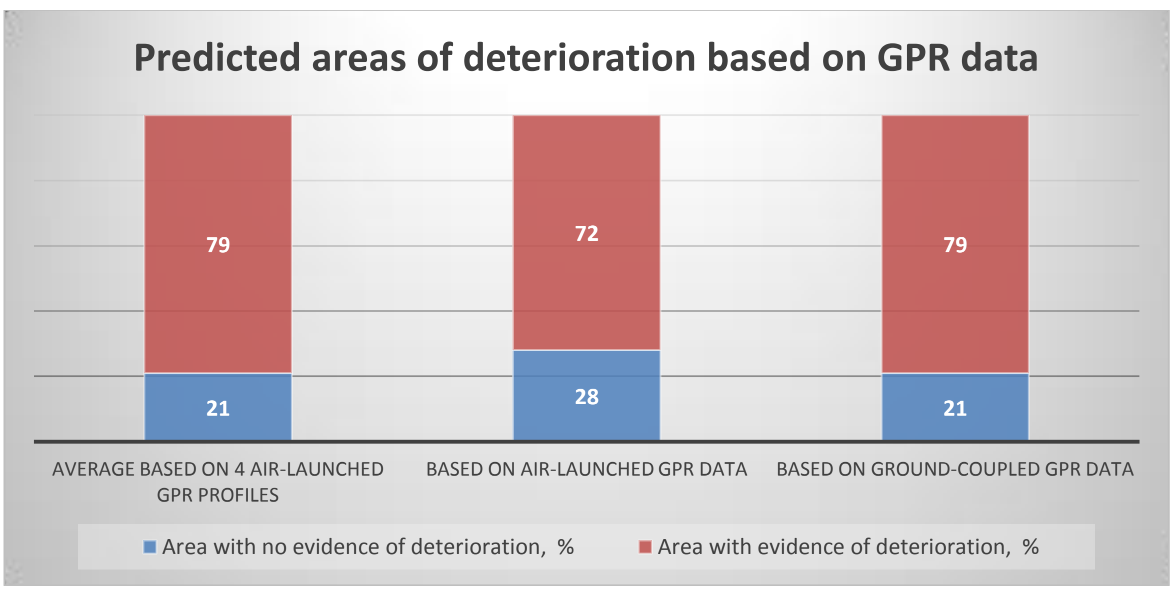

Figure 2-30 Chart showing comparison of three methods of predicted areas of deterioration (average, based on 4 air-launched GPR profiles, based on air-launched GPR data, and based on ground-coupled GPR data, accordingly).

Table 2-11 Recommended Parameters for Acquisition, Processing, and Interpretation of Air-launched GPR Data Acquired for Reconnaissance Purposes

Ground-coupled GPR antenna employed	SIR-30 GSSI GPR system Two high-frequency 2.0 GHz GSSI 42000S air-coupled horn antennas
Parameters measured	Two-way travel time of GPR-pulses, reflection amplitude from/to transverse reinforcement bars
How these parameters relate to concrete bridge deck	Variations in the amplitude of the reflections from uniformly embedded reinforcing steel is mostly a function of the variations in the conductivity (saline moisture content) of the overlying concrete. The GPR pulse signal is attenuated more rapidly as it passes through more conductive asphalt and/or concrete and reflected from corroded rebar, hence reflection GPR amplitudes are generally lowest where concrete/rebar is physically deteriorated. The velocity with which the GPR pulse propagates through asphalt and/or concrete is also a function of the moisture content with velocities being lower where more moisture is present. Hence, reinforcing steel embedded in physically deteriorated (moist) asphalt and/or concrete appears on a 2-D GPR profile to be embedded at greater depth.
Acquisition parameters recommended	Sampling interval: 2 scans/in. (24 scans/foot) Trace length: 512 samples per scan Bits/sample: 16 Dielectric constant: 10 Gain setting: 1-point automatic (bridge, type/condition dependent); display gain +6 dB used for visualization during data acquisition Spacing between GPR traverses: 2 ft or 4 ft
Weather conditions recommended	Not raining and no water or excessive moisture on deck surface. Above freezing temperatures. Watering of the bridge decks the evening before the GPR investigation during the hot dry season is recommended to ensure there is moisture in the bridge deck.
Crew size	Typically 2 persons; a driver and an operator.
Volume of data acquired; time required	Four to six closely-spaced typical MoDOT bridge decks can be investigated in a day (assuming an average bridge length of 250 ft and close proximity of the bridges), depending on length of deck, traffic volume, access to turnaround, number of lanes, and number of traverses per lane.
Acquisition problems (incl. potential)	• Sub-freezing temperatures (moisture in bridge deck may be frozen and non-conductive) • Hot dry conditions (there may be little moisture in bridge deck) • Standing water/dirt/trash/debris on bridge deck can create GPR anomalies that could be misinterpreted as "evidence of severe deterioration"
Ease of acquisition	• Procedure is straightforward, however requires a remote (e.g., laser-guided) system to ensure accurate GPR data acquisition along planned traverses
Processing parameters	• Mapping variations in reflection amplitude and variations in apparent embedment depth of reinforcing steel. Normalization of reflection amplitudes based on apparent embedment depth of reinforcing steel (if drawings/ground truth data are provided).
Time required to process data	Data acquired across four to six typical MoDOT bridge decks can be processed (profiles only) in a single day by a single technician, depending on length of deck, number of lanes, and number of traverses per lane.
Ease of processing	Procedure can be performed by a trained person (requires experience with Radan and Golden Software Surfer software packages; may require Matlab computational software skills; GIS software skills)

Potential processing problems	Presence of the longitudinal reinforcing bars as the top layer of reinforcement
Interpretation parameters	• Reflection amplitudes and apparent depth from top layer of rebar are exported to Microsoft Excel • Lineal plots of rebar amplitude reflections for individual GPR profiles are generated and percentages of bridge deck as designated as "no evidence of deterioration", "evidence of moderate deterioration" and "evidence of severe deterioration" are determined
Time required to interpret data	Data acquired across four to six typical MoDOT bridge decks can be interpreted (profiles only) in a single day, depending on length of deck, number of lanes, and number of traverses per lane. Video data will be viewed by interpreter.
Ease of interpretation	Procedure can be performed by a trained person (requires experience with Radan and Golden Software Surfer software packages if maps are generated; may require Matlab computational software skills; GIS software skills)
Deliverables	Quantitative estimates of the percentage of the bridge deck designated as "no evidence of deterioration" and "evidence of deterioration". Qualitative assessment of video data.
Reliability of interpretations	Interpretations will be reliable if acquired GPR data image areas of the bridge deck that are good quality as the overall quantitative assessment of GPR data is based on the premise that some areas of the bridge deck are in good condition. Larger volumes of data and core control would increase reliability but at significantly increased cost and are not considered necessary for reconnaissance-type assessment by the authors.
Potential interpretation problems	• Where the most top layer of reinforcement is oriented in the bridge longitudinal direction, a high-amplitude continuous reflector appears across the profile and affects the reflection amplitude and apparent depth to rebar • The proposed technique is not suitable for the assessment of bridge decks where the uppermost layer of rebar is oriented parallel to the axis of the bridge, unless additional effort is made to ensure traverses are centered between adjacent strands of longitudinal rebar so that the shallowest reflector is the transverse rebar. This can be done but will slow down data acquisition time considerably.

3 CONCLUSIONS

The following conclusions are made based on the results of this project:

The authors recommend that reconnaissance-style air-launched GPR data be acquired across MoDOT bridge decks with the goal of rapidly and effectively assessing the relative condition of the bridge decks. Based on the assessment of the acquired GPR control percentage estimates of the condition of the bridge deck (percentages of surface area designated as “no evidence of deterioration” and “evidence of deterioration”) can be generated, and this information can be used by MoDOT for programming purposes.

The authors recommend that reconnaissance-style air-launched GPR data be acquired along 2 to 4 optimally-placed traverses per lane. Increasing the number of traverses and acquiring core control would increase the reliability of the data, but at significantly increased cost, and is not recommended (or necessary) for a reconnaissance-style assessment and programming purposes.

Recommended parameters for reconnaissance-style air-launched GPR data acquisition, processing, and interpretation are summarized in Section 2.5 and in Table 2-11.

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