Phenomenology Study of HERMES Ground-Penetrating Radar Technology for Detection and Identification of Common Bridge Deck Features

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Foreward

This report documents the findings of a phenomenology study that analyzes the performance of HERMES ground-penetrating radar technology. HERMES technology was designed for the evaluation of concrete bridge deck deterioration, with a particular emphasis on the detection of corrosion-induced delaminations. HERMES technology was developed by Lawrence Livermore National Laboratory through a cooperative research agreement with the Federal Highway Administration (FHWA). Research funds for the project were provided by the FHWA and recently a State pooled fund has been established to continue funding system improvements. This report will be of interest to bridge engineers, designers, and inspectors who are involved with the evaluation of our Nation's highway bridges.

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Research and Development

Notice

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16. Abstract
Accurately evaluating the condition of a bridge deck over time and using this information to choose appropriate maintenance techniques has become critical for the efficient allocation of resources to bridge deck maintenance. Tomographic imaging of subsurface bridge deck features using ground penetrating radar (GPR) is one method of addressing this problem that has been pursued through a research program at the Federal Highway Administration (FHWA) Nondestructive Evaluation Validation Center. Prototype GPR systems, developed by Lawrence Livermore National Laboratory (LLNL), have been used in a phenomenology study of several controlled specimens. These specimens were designed with subsurface features that simulate cracks, voids and other common problem phenomena for bridge decks. The specimens have some unique features that make the data collected from them compelling. Results from these phenomenology tests are the primary focus of this paper. Field tests have also been conducted that produced inconsistent results, clarifying the need for system improvements. These improvements are planned for incorporation into a new prototype GPR system currently beineloped by LLNL that will be tested by FHWA in the coming year.

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1. Introduction

This report provides important information on the performance characteristics of a prototype bridge inspection technology called HERMES (High Speed Electromagnetic Roadway Mapping and Evaluation System. HERMES is a prototype ground-penetrating radar (GPR) system designed to perform accurate and swift evaluations of concrete bridge decks. The motivation for the report comes from the need to accurately define the limitations of the current prototypes from the HERMES project and to consider the possibilities for system refinement and changes for an improved system based on design requirements. The performance characteristics outlined here provide information for two audiences. First, this information clarifies relevant performance issues for project sponsors (State pooled-fund participants in the HERMES II project) and other interested parties. Second, this information defines a useful performance baseline that can be used by system designers to aid in the improvement and refinement of the new system prototype, HERMES II. This new HERMES II is currently being designed by the original HERMES designers and builders, Lawrence Livermore National Laboratory (LLNL).

The testing results from field studies and limited controlled testing of the original HERMES conducted by Federal Highway Administration (FHWA) Nondestructive Evaluation Validation Center (NDEVC) staff indicated that collected data from the system had distinct advantages over commercially available technology. Specifically, synthetic aperture radar (SAR) data collected using HERMES allowed three-dimensional reconstructions of interior bridge deck features to be generated for display as images. Commercially available systems do not currently have this capability. However, results also showed that HERMES did not consistently detect important subsurface bridge deck delaminations. The ability to detect delaminations was defined at project inception as one of the most important system capabilities due to the high proportion of bridge deck problems associated with this type of distress. The challenge of consistently detecting delaminations using GPR was not met by the original HERMES due to radar design issues and an incomplete understanding of the characteristics of delamination cracks in the field. The experience gained through the HERMES project and more recent testing to pinpoint system problems has provided important information to improve the understanding of these issues.

Example data from testing by NDEVC staff on the Van Buren Road bridge are provided in figure 1. Here, data collected using the HERMES system are graphically overlaid on data

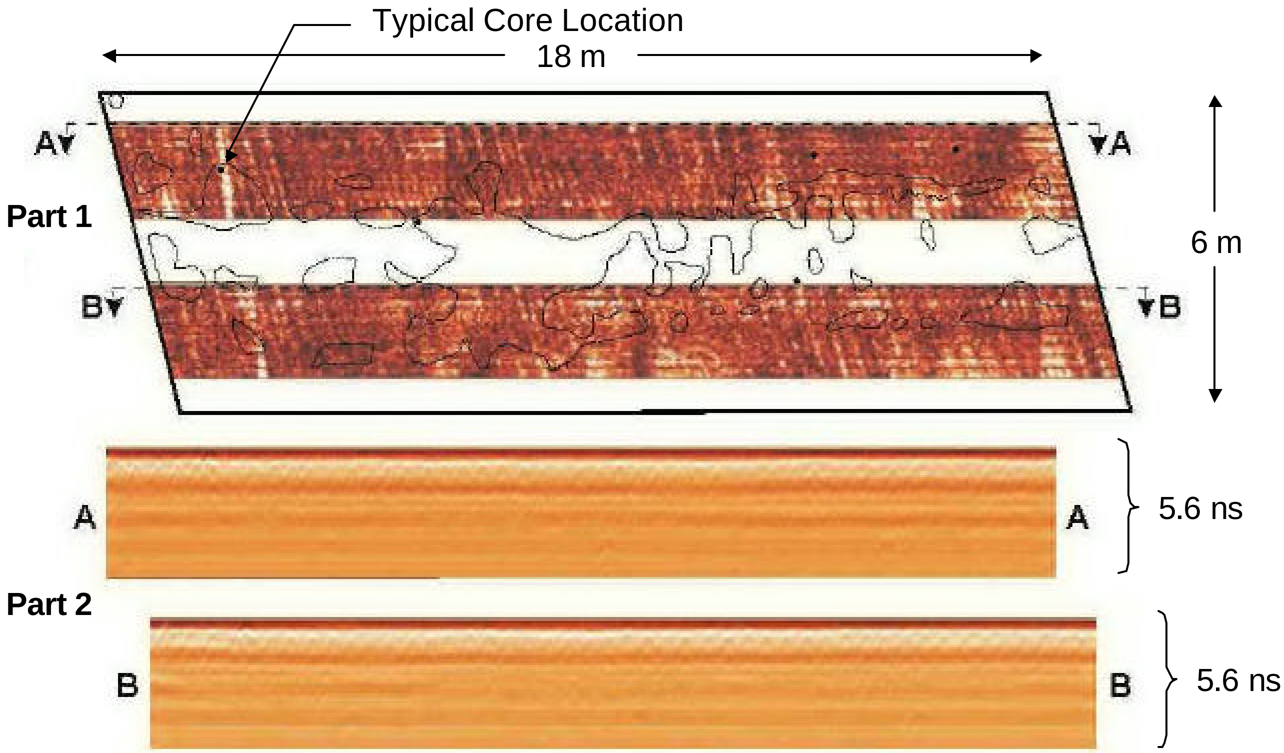


Figure 1. HERMES data and chain drag test data collected from the center span of the Van Buren Road Bridge.

from a chain drag survey of the bridge deck. The chain drag survey detects delaminated areas in bare concrete bridge decks using a technician's interpretation of the bridge deck's acoustic response to a chain dragged over the surface. This test method is outlined in American Society for Testing and Materials (ASTM) D4580-86. Part 1 of figure 1 indicates delaminated areas as determined by chain drag testing with black outlined enclosed areas. Black dots in the image indicate locations where concrete cores were removed from the bridge to confirm delamination detection results. Two horizontal strips of HERMES data (plan view tomographic layers extracted at the reinforcing steel depth of the three-dimensional reconstructed data) overlaying the chain drag data are shown in Part 2 of figure 1. This data presentation allows the reader to examine the HERMES response to confirm delaminated regions. Response magnitudes in the HERMES data are color coded to a scale that spans from black for low magnitudes to white for high magnitudes. The GPR response to reinforcing steel bars in plan view can be observed in the reconstructed data as high-magnitude responses along lines angled with the skew of the bridge deck. Bridge plans show that the orientation in the HERMES image is correct. Some other high-magnitude areas are found in the image, but there is not a strong correlation between these areas and the delamination locations. This result indicates that the delamination features are not reflecting the incident radar pulse. Raw data from HERMES are presented for two antenna paths along the length of the bridge deck at the locations indicated by Sections A and B. The raw data from each of the two sections are shown in Part 2 of figure 1. Like the reconstructed data, the raw data also lack strong or consistent responses to the delaminations in the bridge deck, even though features like the reinforcing steel are detected as prominent responses. The reasons for the HERMES results and the implications of these results will be clarified in subsequent sections of this report.

As a result of findings consistent with the example presented here, the phenomenology study was undertaken with the goal of identifying system performance characteristics. The phenomenology results and data analysis from the HERMES project prototypes that are presented here provide timely information for the current HERMES II project. Project management and HERMES II designers can both benefit from the findings in this report, which prepare the way for a significantly improved HERMES II system.

2. Experimental Plan

While the HERMES project has achieved many goals, some specific goals for the original project were not achieved. The principle objective that the project did not accomplish was to develop a system capable of consistently and reliably detecting delaminations in bridge decks. Determining the reasons why the system does not perform this critical function as originally expected is a key part of the ongoing HERMES II project. The phenomenology study that has been conducted by the FHWA NDEVC makes these determinations and clarifies the response characteristics of the current system, allowing the HERMES II project to move forward with a clear knowledge of the design challenges it faces. To carry out this phenomenology study, an experimental plan was developed to identify and isolate specific problems with the system and to test its performance in realistic, controlled test scenarios. This phenomenology study involved testing custom-designed concrete specimens with a specific geometry by evaluating the prototype radar system response. The prototype used for the study was PERES (Precision Electromagnetic Roadway Evaluation System). PERES was developed as part of the HERMES project and was chosen for the phenomenology study due to its simple configuration and its consistent single-antenna response characteristics. HERMES was designed as an array of radar antennas for large-scale data collection and was not suitable for small-scale testing in a laboratory setting.

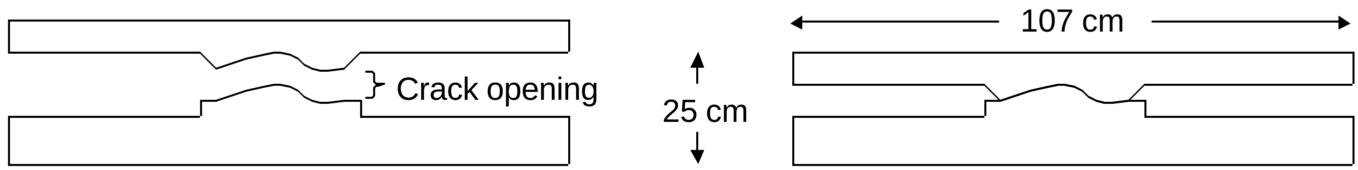
A variety of test configurations were evaluated using PERES so that analyzed responses to simulated features revealed information about a representative range of situations. Simulated field conditions that were evaluated during the study using PERES included subsurface delaminations, voids, reinforcing steel, and asphalt overlays. Some unique approaches to simulating subsurface features were used in the test specimen design that allowed data interpretations to relate directly to system performance. The experimental designs that allowed these interpretations to be made included geometric configurations that could be modified to simulate different feature sizes and designs that included a range of feature sizes. Most specimens were designed with target features that could be measured directly using a ruler or caliper. When adjustable features were incorporated into a specimen design, at least two data sets were always obtained for comparison. The experimental plan for the study was to scan the test specimens using PERES and to analyze the results such that meaningful conclusions could be drawn about system performance.

3. Specimen Design

Several concrete test specimens were designed and fabricated by the FHWA NDEVC for the phenomenology study. Many of these test specimens accurately simulated internal bridge deck features, while others were duplicates of field deck configurations. Specimens included in this study contained real or simulated features that were indicative of delamination cracks, reinforcing steel, voids, and asphalt overlays. The following descriptions provide details about each of the specimens.

Fabricated Crack Specimen

This specimen was designed to closely mimic the subsurface corrosion-induced delamination cracks observed in bridge decks. A unique slab design and fabrication method, along with a procedure for cracking the slab into two separate parts, creates crack surfaces that have a similar geometry and surface roughness to a real delamination crack (figure 2). The formwork used to cast the specimen, including a steel frame and blade for cracking the specimen, is shown in figure 3(a). The specimen has been used to examine the scattering effect of incident radar pulses from the crack surface [Figure 3(b)], and the gap between the crack faces has been varied to determine the resolution characteristics of the system. The ability to control



(a) *(b)*

Figure 2. Fabricated crack specimen schematic with: (a) crack open and (b) crack closed.

(a) *(b)*

Figure 3. (a) A custom made concrete form with a steel concrete cracking mechanism and (b) one of the two crack surfaces created after the specimen had been cracked into two pieces.

the air gap spacing between two crack faces makes this specimen an extremely valuable tool for evaluating system performance. The concrete mix used for the cast specimen was a typical Virginia bridge deck concrete mix (Appendix A).

Parallel Plate Air Gap Specimen

A set of parallel plate specimens was designed to investigate the resolution and attenuation characteristics of the PERES system. The specimen set was designed to test the sensitivity of PERES to subsurface air gaps in the absence of the radar scattering effects caused by typical crack surface morphology. The specimen design incorporates separate concrete elements that can be stacked with spacers, as shown and illustrated in figures 4 and 5, respectively. Three cover plates, each with a different thickness, were made to illustrate the effects of varying the subsurface depth of the air gap. Spacers for making the air gap between the cover slab and base slab were made from polyvinyl chloride pipe in a range of sizes to allow a variety of air gap sizes to be tested. Concrete for casting the specimen was a typical bridge deck concrete mix (Appendix A).

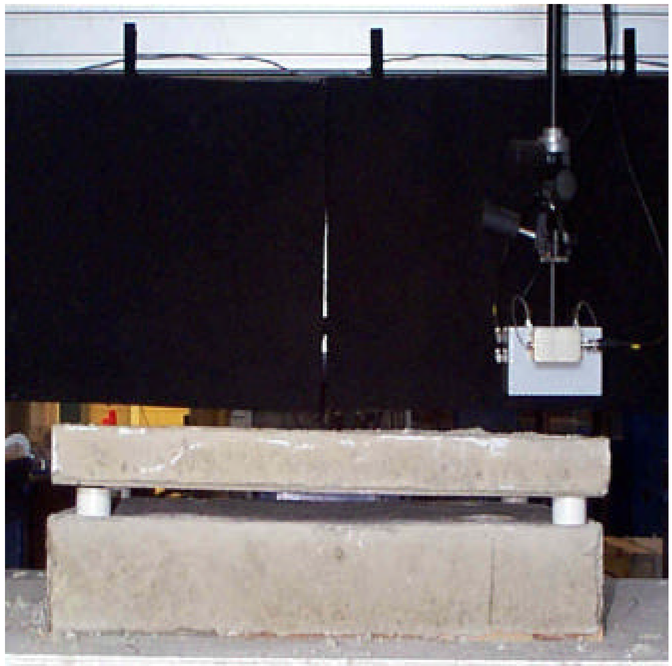


Figure 4. Cover plate and base plate from the set of parallel plate air gap specimens (photographed edge on).

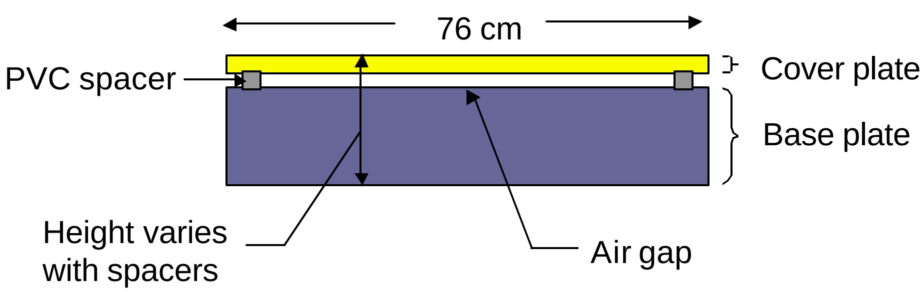


Figure 5. Parallel plate air gap specimen configuration (the base plate is 10 cm thick, while the three cover plates range from 2.5 cm thick to 7.5 cm thick).

Variable-Diameter PVC Pipe Specimen

A specimen was needed to realistically simulate void features while the ability to directly measure the feature size with a ruler or caliper was maintained. The variable-diameter PVC pipe specimen was developed to meet these needs. The specimen (shown in figure 6) contains three PVC pipe sections, each with a different diameter. The voids where the PVC pipes are located in the concrete simulate real voids observed in field bridge decks. Ideally, there would only be air or water inside the simulated void to mimic the dielectric properties of the void most accurately; however, PVC dielectric properties are relatively close to air. The cylindrical shape of the simulated voids is also an approximation. However, the requirement of knowing the void size, shape, and location definitively for controlled testing makes the use of a pipe an excellent option for simulation purposes. All of the reinforcement used in the specimen was fiber-reinforced plastic, in order to minimize the effects of undesirable background reflections.

(a) *(b)*

Figure 6. Variable-diameter PVC pipe specimen: (a) before casting and (b) after casting.

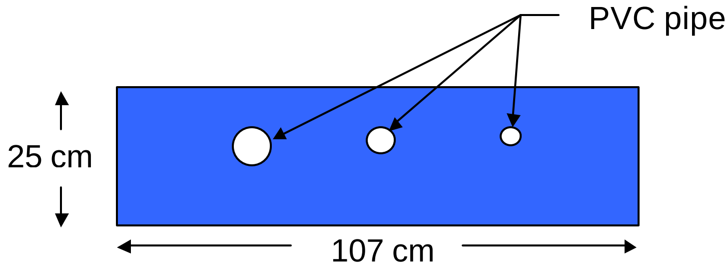
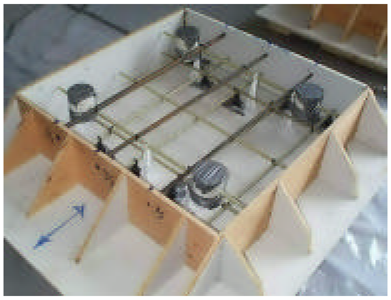


Figure 7. Variable-diameter PVC pipe specimen concept viewed edge on.

Variable-Diameter Reinforcing Steel Specimen

A specimen was needed to demonstrate the effects of varying reinforcing steel diameter on the PERES GPR response. There were a variety of reasons for testing the response to reinforcing steel in a range of sizes. These included the need to observe the masking effect of different bar sizes, testing the capability of the system to distinguish between bar diameters, and to observe typical responses to reinforcing steel bars for general analysis purposes. The implemented specimen design contains reinforcing steel with three different bar sizes: #3, #4, and #6. The bars are positioned at approximately the same depth in the specimen and are spaced to prevent the radar response to adjacent bars from interfering with the response to any particular



(a)

(b)

Figure 8. Variable-diameter reinforcing steel specimen: (a) before casting and (b) after casting

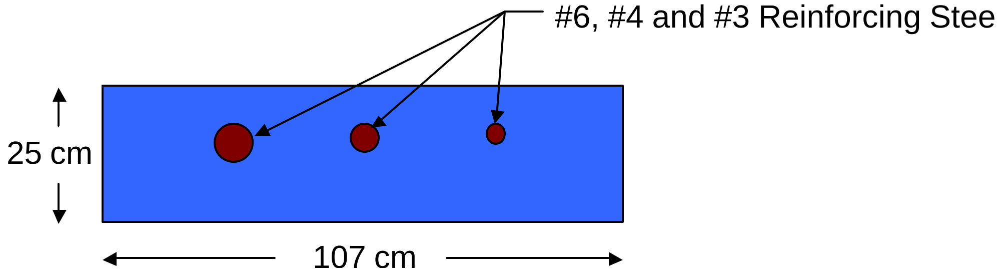


Figure 9. Variable-diameter reinforcing steel specimen viewed edge on.

bar. The specimen design that was used is pictured before and after concrete casting in figures 8(a) and (b) respectively. Other than the three pieces of reinforcing steel placed in the specimen for testing, all other reinforcement was fiber-reinforced plastic, in order to reduce background reflections from sources other than particular reinforcing steel bars.

Variable-Depth Reinforcing Steel Specimen

The variable-depth reinforcing steel specimen was designed to provide test information about the penetration depth that can be achieved by the PERES system. Due to signal attenuation and scattering in the inhomogeneous concrete material, responses to features deeper below the surface become much less pronounced and lower in magnitude. Understanding the penetration capabilities of PERES is important for estimating the practical limitations of the system under typical circumstances. Reinforcing steel was selected as the target feature placed at variable depths below the concrete surface due to the high-magnitude radar response to this conductive material. The range of depths at which the steel was located vary from 3 cm on the shallow side down to 18 cm on the deep side, as shown in Figures 10a and b. Figure 11 shows the specimen concept schematically. The reinforcing steel used in the specimen were #5 bars.

(a)

(b)

Figure 10. Variable-depth reinforcing steel specimen shown: (a) before casting and (b) after casting.

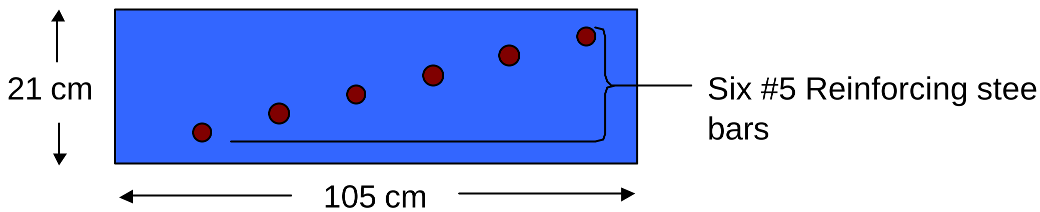


Figure 11. Variable-depth reinforcing steel specimen viewed edge on.

Asphalt Overlay Simulation

Asphalt tiles and a concrete specimen, with no reinforcement, were used to create a simulation of an asphalt overlay on a concrete bridge deck. The purpose of the test was to compare the PERES response to a plain concrete specimen with the response to an otherwise identical specimen with an asphalt overlay. Four asphalt tiles, each 3 cm thick, were placed adjacent to one another on a concrete specimen as shown in figure 12. A schematic view of the specimen is presented in figure 13.

The collection of specimens fabricated for PERES phenomenology testing represents the primary configurations where any GPR system will have to function effectively to obtain meaningful engineering data from bridge decks. Although the added variability inherent in field testing is not present in these controlled tests, the most important and challenging distress detection scenarios are addressed. Field testing with the PERES and HERMES systems has led to the conclusion that these types of controlled tests are necessary to allow current systems to be tested and new systems to be tested in comparison to current baseline results. This will allow performance improvements to be measured and to be more fully understood.

Figure 12. Simulated asphalt overlay configuration.

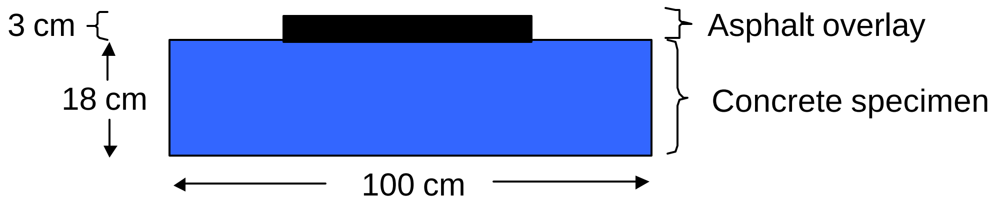


Figure 13. Simulated asphalt overlay specimen viewed edge on.

4. Testing and Analysis

Data were collected from a range of configurations of the PERES phenomenology specimens in order to assess PERES performance characteristics. The most important data are presented in this section to show how these response characteristics relate to design issues for a new HERMES II system. The most critical testing conducted in the course of the phenomenology study involved the fabricated crack specimen and the parallel plate air gap specimen. These two bridge deck simulations specifically address the issue of delamination detection.

Delamination Simulation

The fabricated crack specimen simulates the delamination crack using the approach described in Section 3. The results from the testing of this specimen are very interesting because the effects of the limits of range resolution can be observed directly. Figures 14 and 15 illustrate this resolution limit with raw data from the system, while data that have been reconstructed using wavefield-backpropagation calculations are presented in figures 16 and 17, with the same resulting conclusion. The locations of interest in the data are circled in red in each of these four figures. The response to the significantly larger air gap, shown in figure 14, causes a downward opening parabola-shaped, high-magnitude response. The air gap size is about 1.3 cm. These raw data are presented as a through-the-thickness radar response to the specimen, where a series of radar waveforms sampled at regularly spaced intervals across the specimen are stacked together. This presentation provides magnitude reflection information at locations across the specimen width and in time (as the wave propagates through the specimen). Many of these raw two-dimensional images could be stacked together to represent an entire three-dimensional volume of collected data from PERES. The high-magnitude, parabolic-shaped response observed in figure 14 is indicative of a response to a crack opening that the PERES system can resolve. Figure 15 shows data from the same specimen, where the air gap was minimized and the resulting response, circled in red, shows no parabolic response. The air gap size is about 1 mm.

Reconstructed data that illustrate the PERES response to these same features show the same result. Here, the crack surface pictured in figure 3(b), produces a reflection when a significant air gap is present, (circled in red in figure 16) while no response is observed when the air gap is closed down (red circled area in figure 17). The images in figures 16 and 17 display plan view data slices, which are sampled at a constant depth of approximately 8 cm. The results presented here clarify the reasons why thin profile cracks, typical of corrosion-induced delaminations in bridge decks, are not currently detected by the HERMES system. After obtaining these initial results, some additional questions about the PERES response to a delamination crack are raised. It is possible that the scattering of the radar response caused by the texture of the crack prevents the crack from being observed when the crack faces are very close together. The parallel plate air gap specimens were developed to address this specific question.

Flat concrete plates were cast in three thicknesses (2.5 cm, 5.0 cm, and 7.6 cm) to determine whether a crack between two flat parallel plates with almost no texture could be detected. The results were very similar to those obtained from the fabricated crack specimen. Where the air gap was simulated realistically, by creating a thin profile air gap through stacking a cover plate directly on top of a base slab, there was not a significant radar response attributable to the air gap (figure 18). A thin metal plate was placed in the air gap between the concrete plates to indicate the expected location of any potential radar response to the air gap (figure 19).

The strong reflection observed at 2 ns, approximately midway across the width of the collected data, indicates the response to the metal plate. Ringing effects from the plate reflection are also observed in figure 19 as high-magnitude responses that follow the initial reflection in time. With the information from figure 18, figure 19 can be reviewed at the specific location where the radar response to the air gap would be expected; however, there was no response. Figure 20 illustrates the response when a significant air gap is introduced between the concrete plates. The initial response can be observed immediately before the 2 ns mark and subsequent ringing responses are also present. Figures 21 and 22 illustrate PERES responses to another air gap between parallel concrete plates at a deeper cover depth of 7.6 cm. Figure 21 presents the response where the gap is minimized, while figure 22 presents the response where a significant gap is introduced. Results are very similar to the response to the thinner plate, but the reflection shown in figure 22 is attenuated relative to the reflection shown in figure 20. Data obtained from a range of other configurations of these parallel plate air gap specimens illustrate the same phenomenon.

Two basic conclusions can be drawn from these experiments thus far. First, the resolution of PERES is not currently high enough to detect the thin profile crack features that delaminations typically exhibit. Second, the detection problem for these thin profile cracks still exists, even when the scattering effect of a rough crack surface morphology is removed by using flat plates to test detection capability.

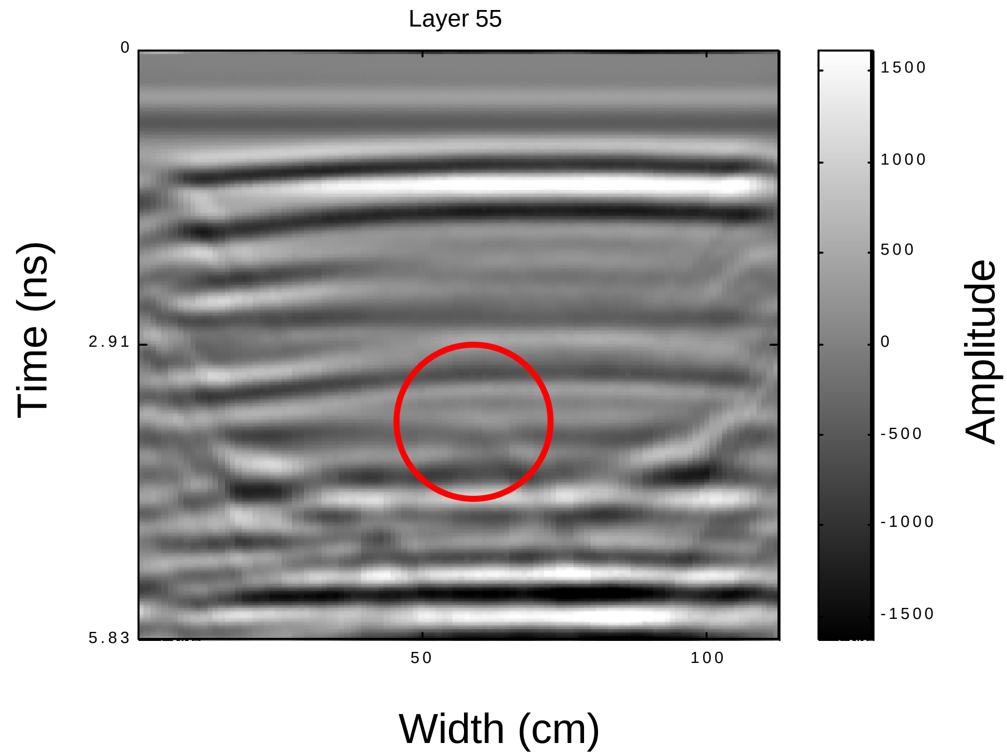


Figure 14. Response to a 1.3-cm air gap in the fabricated crack specimen.

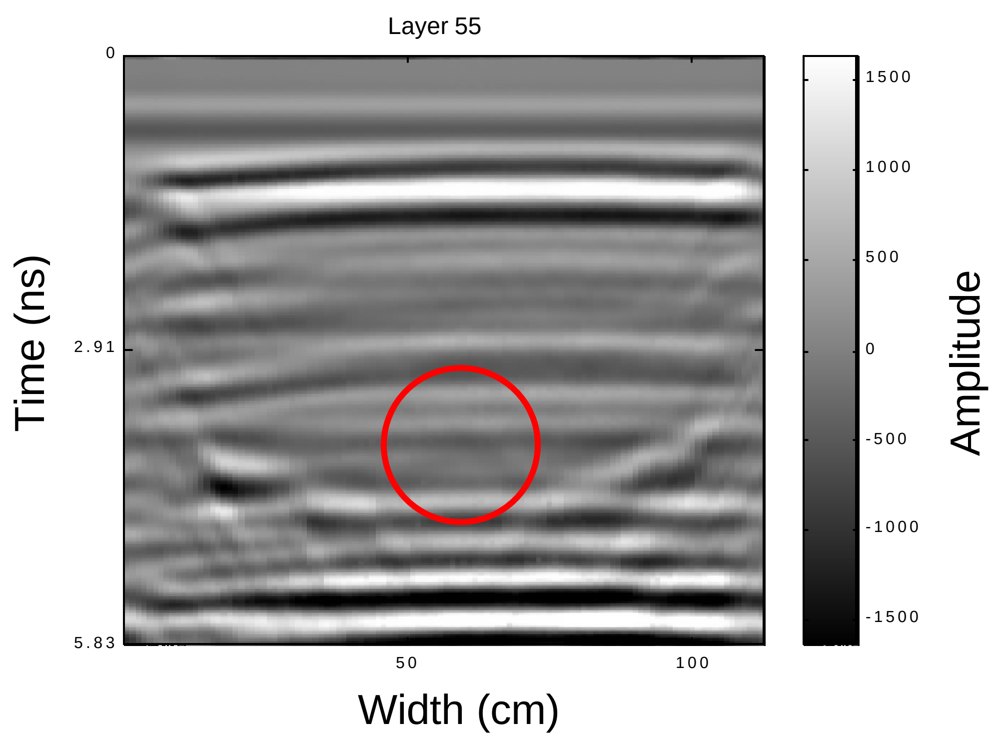


Figure 15. Response to an ~1-mm air gap in the fabricated crack specimen.

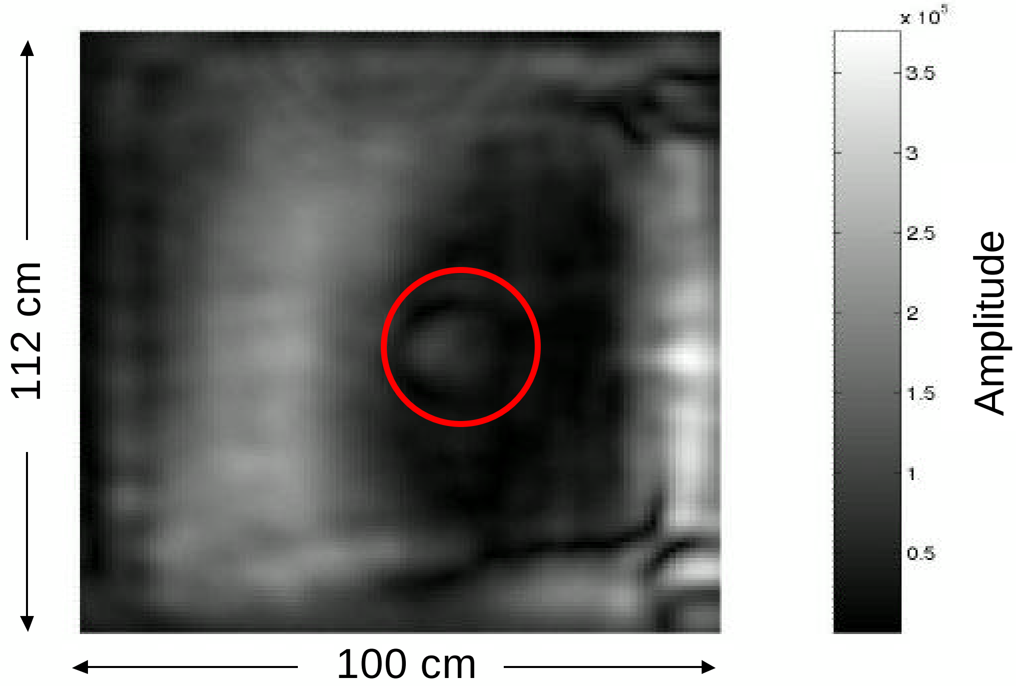


Figure 16. Reconstructed response to a 1.3-cm air gap in the fabricated crack specimen.

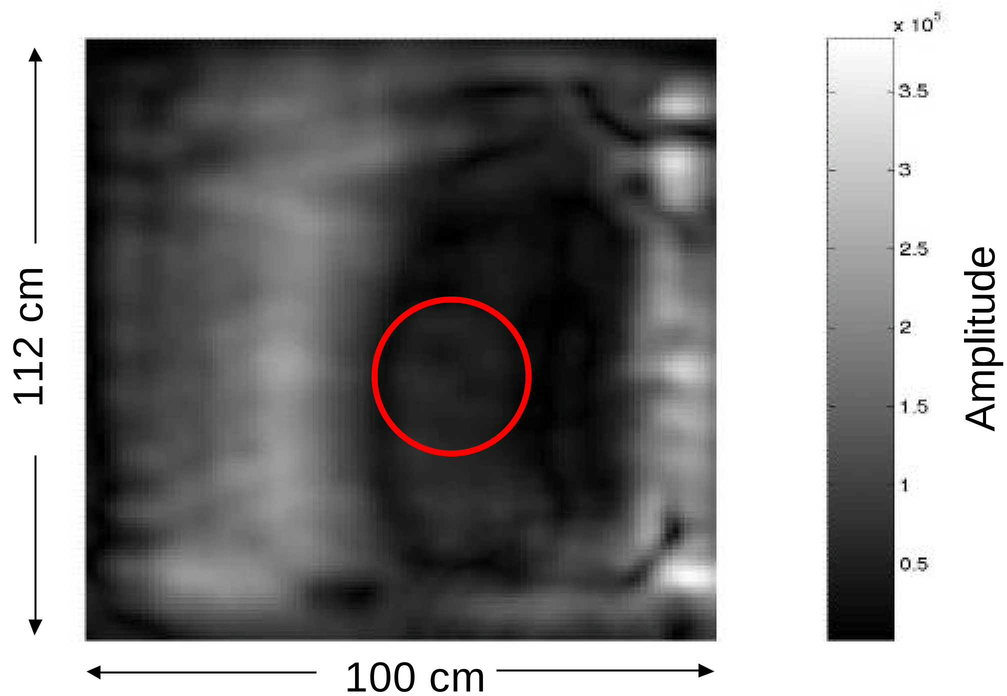
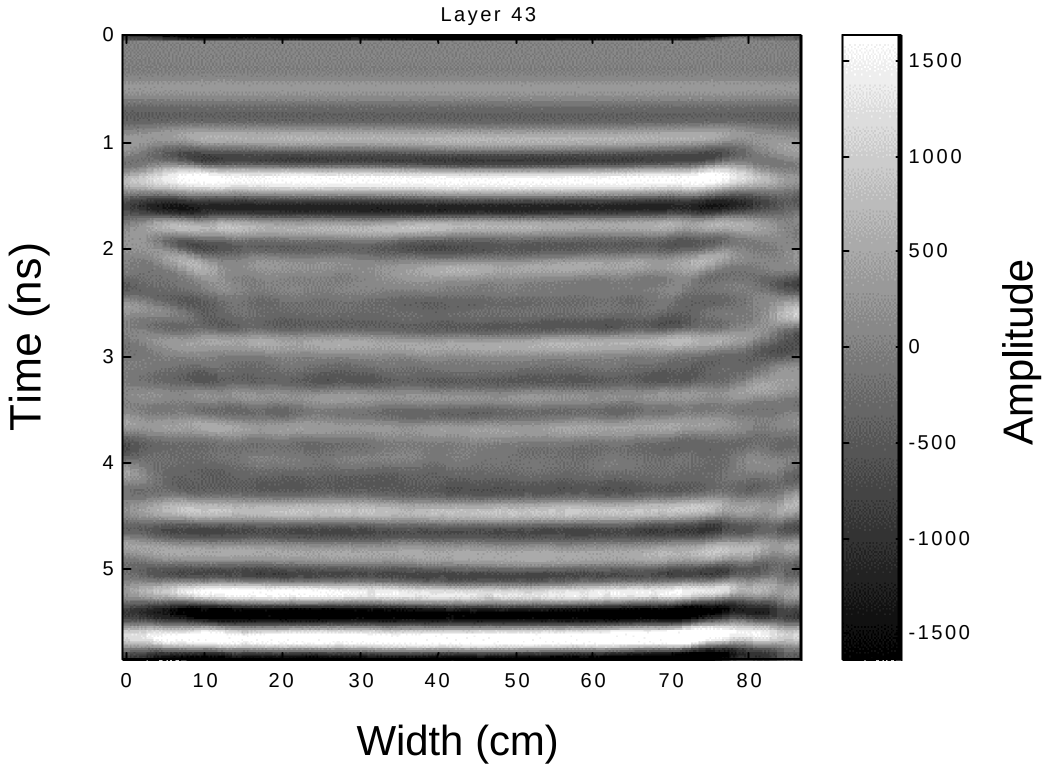


Figure 17. Reconstructed response to an ~1-mm air gap in the fabricated crack specimen.



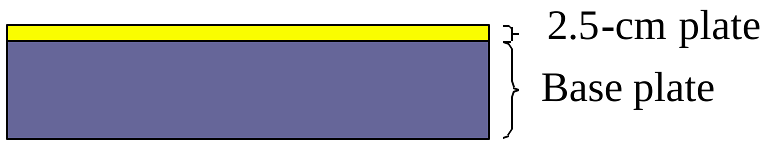
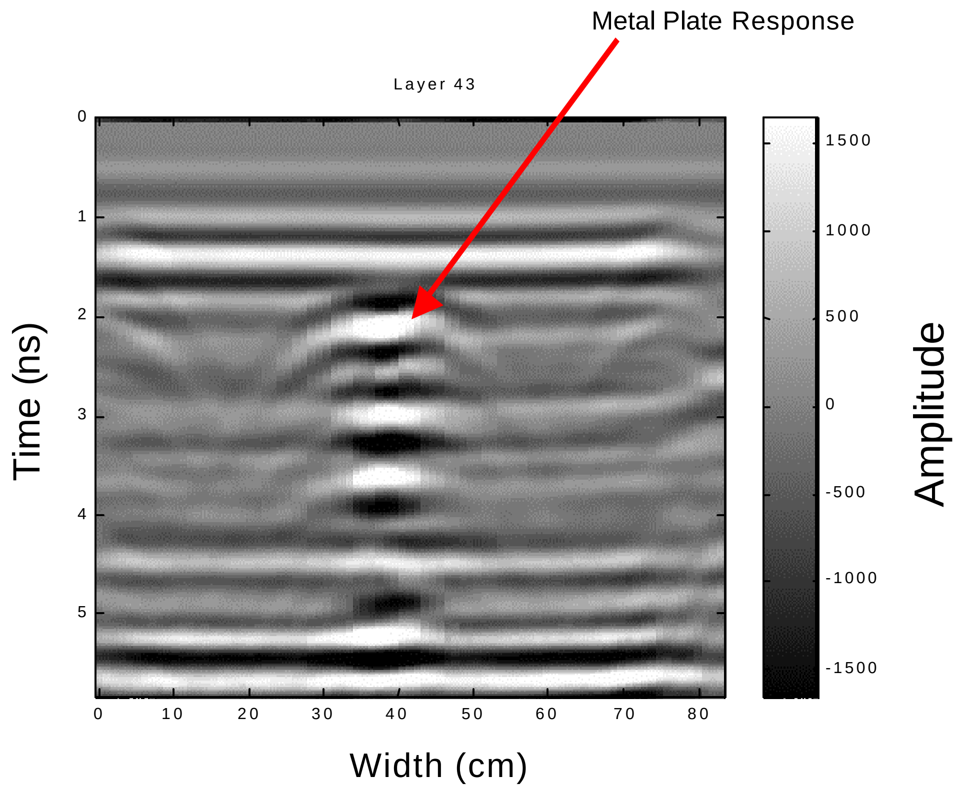


Figure 18. Parallel plate air gap specimen with a 2.5-cm cover plate and an ~1-mm air gap.



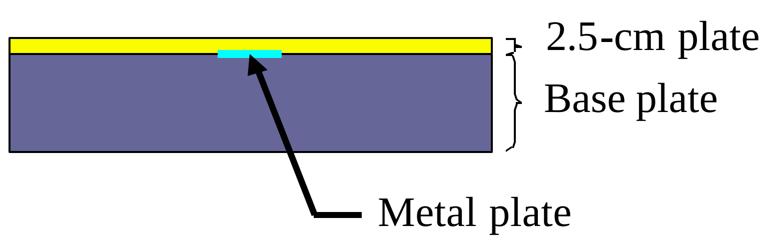


Figure 19. Parallel plate air gap specimen with a 2.5-cm cover plate, an ~1-mm air gap, and a metal plate inserted in the air gap.

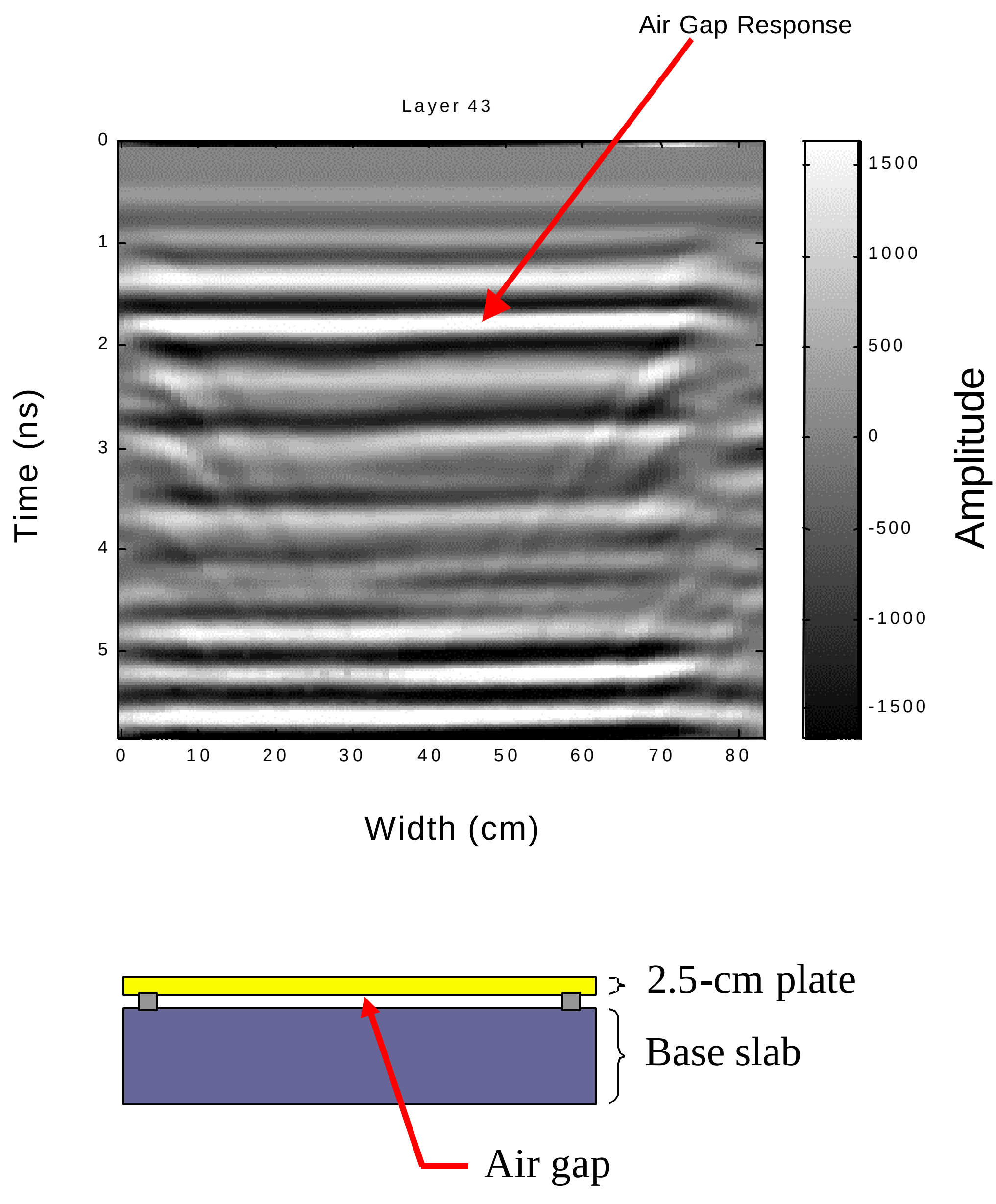
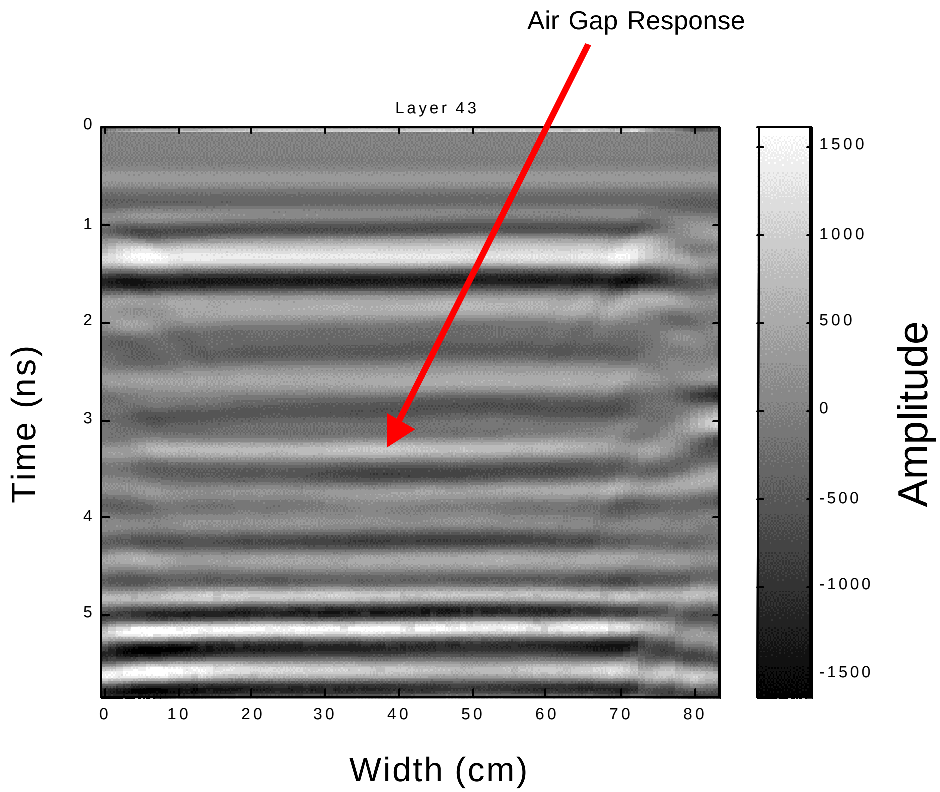


Figure 20. Parallel plate air gap specimen with a 2.5-cm cover plate and a 1.3-cm air gap.



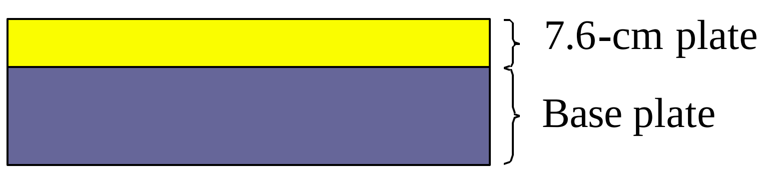
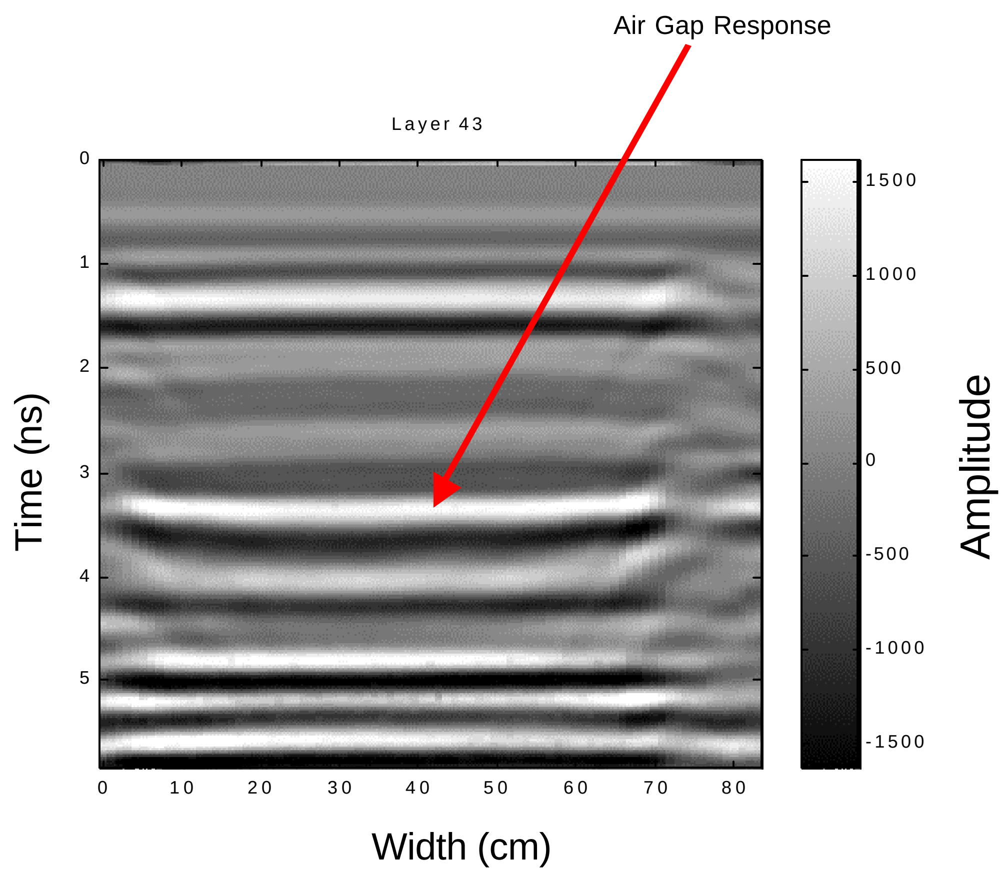


Figure 21. Parallel plate air gap specimen with a 7.6-cm cover plate and an ~1-mm air gap.



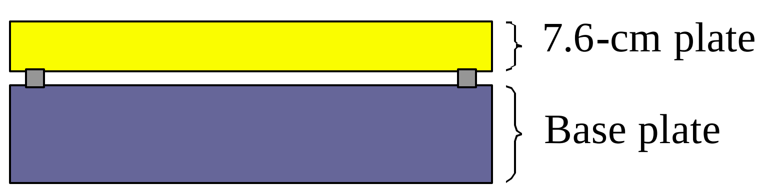


Figure 22. Parallel plate air gap specimen with a 7.6-cm cover plate and a 1.3-cm air gap.

Penetration Depth Testing

Another critical issue for the PERES is the depth below the surface at which the system can detect features of interest. The test configuration used to make this determination for a typical case was called the variable-depth reinforcing steel specimen (described in Section 3). Results from the specimen are presented in figure 23, where responses to the reinforcing steel

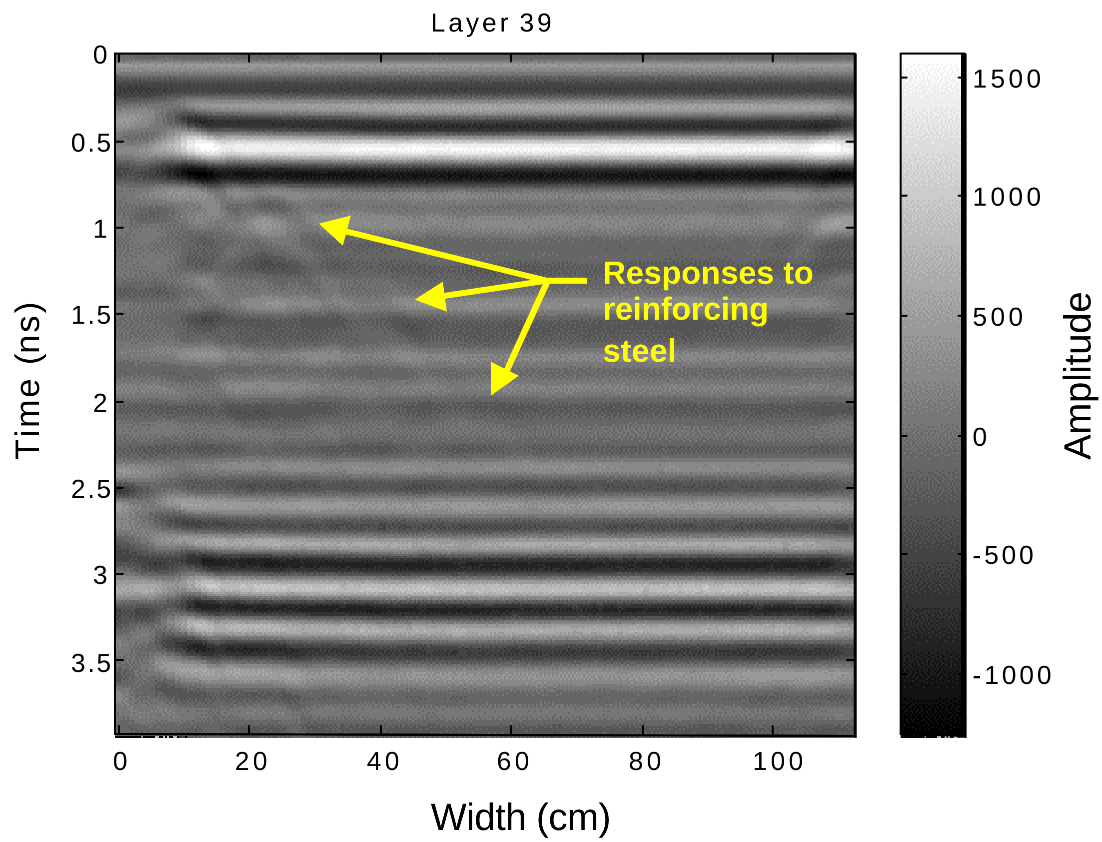


Figure 23. PERES data obtained from the variable-depth reinforcing steel specimen.

are indicated by arrows. From top to bottom, where increasing time correlates with increasing depth, the reinforcing steel produced radar reflections at depths of 3, 6, and 9 cm. Reinforcing steel at depths below 9 cm was not detected by PERES in this specimen. This was due to the power of the transmitted PERES radar pulse, which is depleted by signal attenuation as it travels through the concrete medium. In many instances, PERES responses of interest are also masked by ringing and noise, but that is not the dominant issue here. Reinforcing steel bars at 12 cm and deeper were not observed in this data mainly due to signal attenuation effects on the initial radar pulse.

Asphalt Overlay Testing

Another scenario that is important to test for many applications of GPR for bridge decks involves asphalt overlays. Asphalt overlays and concrete overlays are typically used to protect the wearing surface of a bridge deck and thus extend its service life. These overlays are important to GPR surveys of bridge decks for two reasons. First, these overlays prevent standard acoustic methods from being used for bridge deck evaluation due to significant damping. Second, the overlays present a significant challenge for GPR surveys because their dielectric properties differ from those of concrete. The ringing effect that radar systems exhibit at a dielectric interface, such as the asphalt-to-concrete boundary of an asphalt overlay, can mask the radar response to interfaces beneath the asphalt surface. The current PERES and HERMES both exhibited significant ringing effects in collected data from field bridge decks. Isolating this effect from others to examine this performance issue demonstrates the significant effect it can have on data. For example, the individual waveform responses, presented in figures 24 and 25, show the contrast between a PERES response to a concrete specimen with and without an asphalt overlay. These data were obtained from the asphalt overlay specimen, described in Section 3, where the asphalt tiles were not bonded to the concrete specimen and they were only placed adjacent to one another on the concrete. Thus, the real field condition may not be modeled exactly. The results also show that the effects of the ringing are significant and can primarily be observed as equally spaced, high-amplitude peaks in the waveform data labeled with arrows in figure 25. As the figure shows, these ringing peaks dominate the response in this portion of the signal response. The data in figures 24 and 25 were collected using identical system settings, so the variation between the two responses are entirely attributable to the presence of the asphalt overlay tiles. The presence of the asphalt overlay also effects the signal later in time, but these effects are more difficult to analyze due to the combination of an attenuated signal and a far gain that can exaggerate effects at later times (corresponding to deeper features).

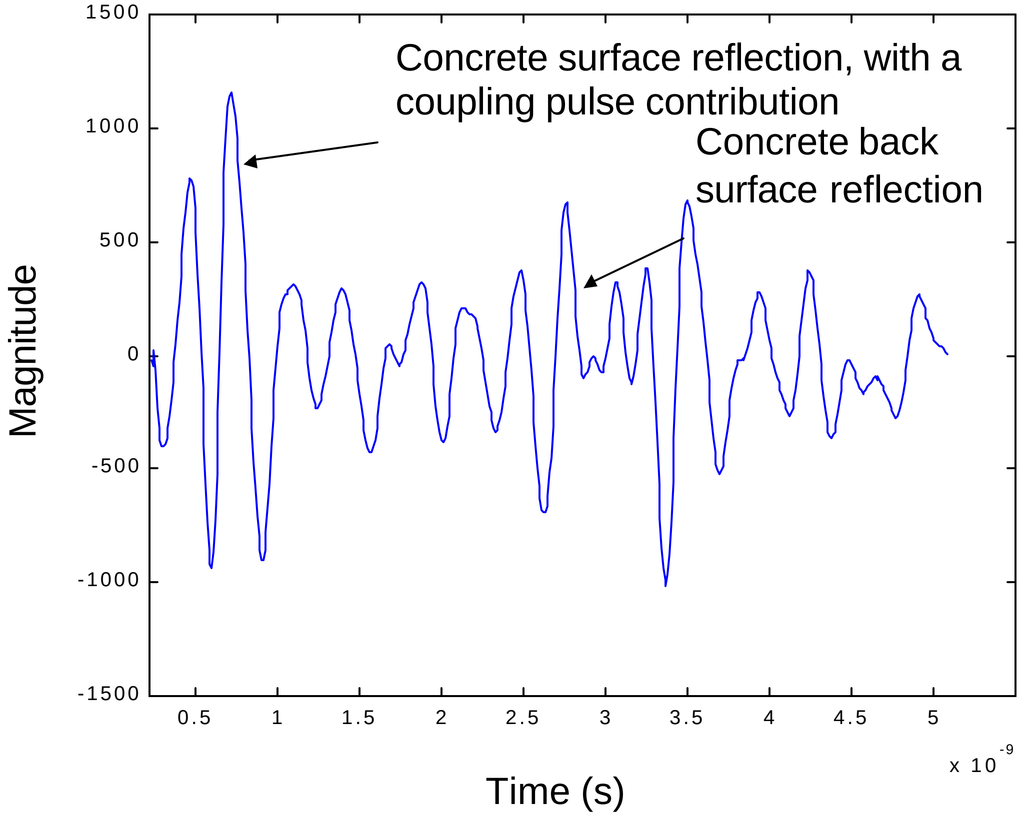


Figure 24. PERES data from test specimen e1, with no asphalt overlay.

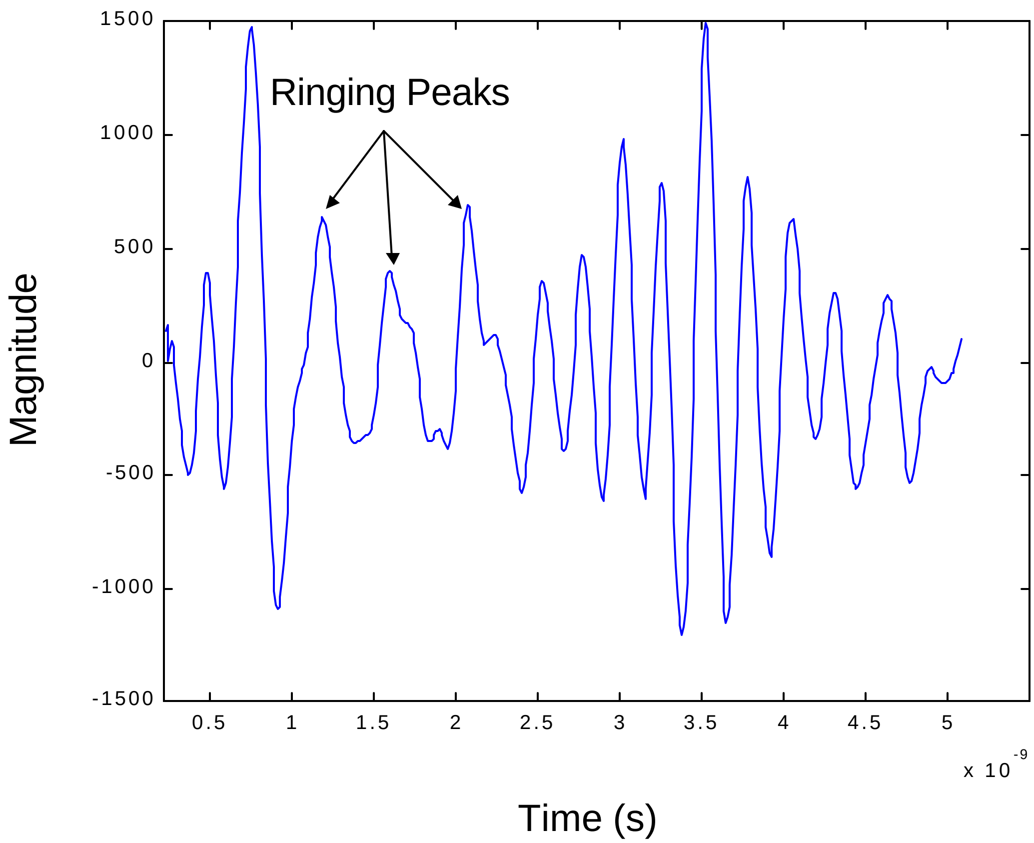


Figure 25. PERES data from test specimen e1, with a simulated 3-cm thick asphalt overlay.

Size Effect Testing

Finally, consideration should be given to the effect of size variation on PERES responses to features such as voids and reinforcing steel. Data from specimens with a range of feature sizes are presented in figures 26 and 27 to illustrate the types of responses that are observed in PERES data obtained from them. Descriptions of the variable-diameter void specimen and the variable-diameter reinforcing steel specimen that are depicted in these figures are presented in Section 3. The variations between responses were minimal, as the data shown indicate. Reflection magnitudes and the geometry of each response are very similar. However, further data analysis and signal processing need to be explored in order to extract additional details from the data. For now, it will be noted that minor variations in the diameter of point features in bridge decks are difficult to distinguish with PERES.

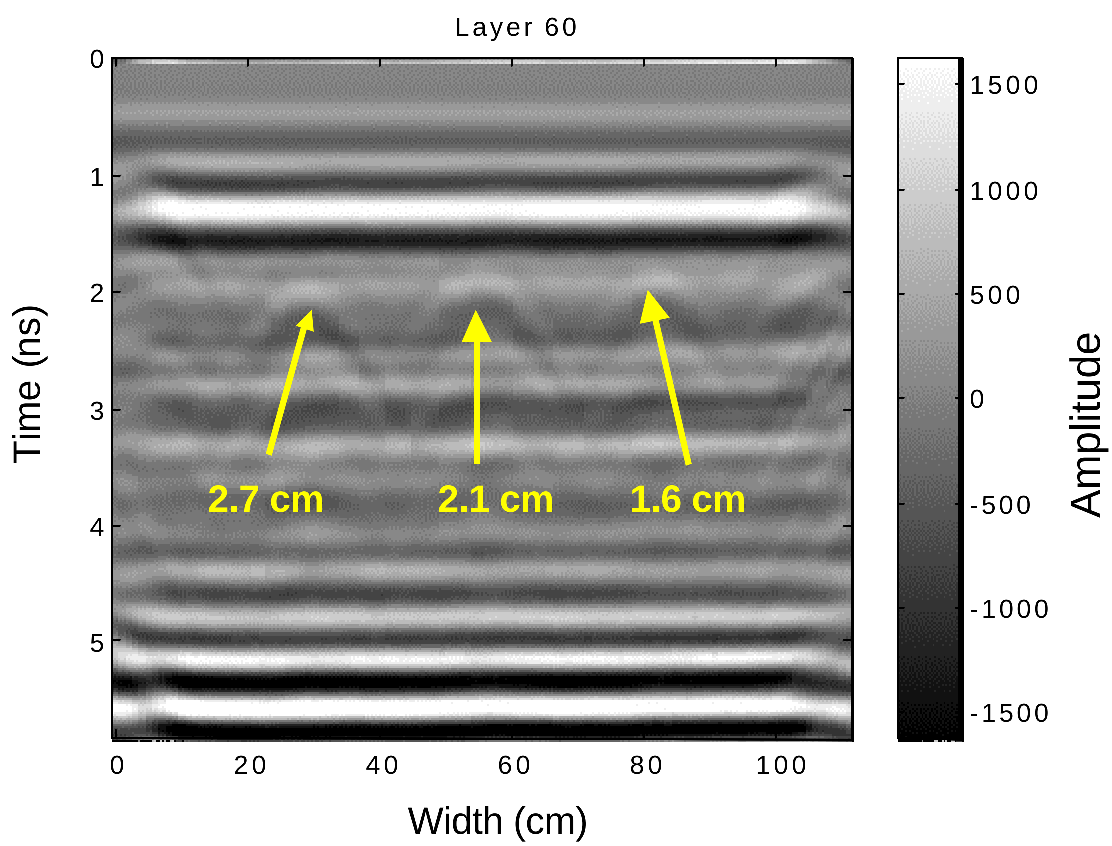


Figure 26. PERES response to the variable-diameter void specimen.

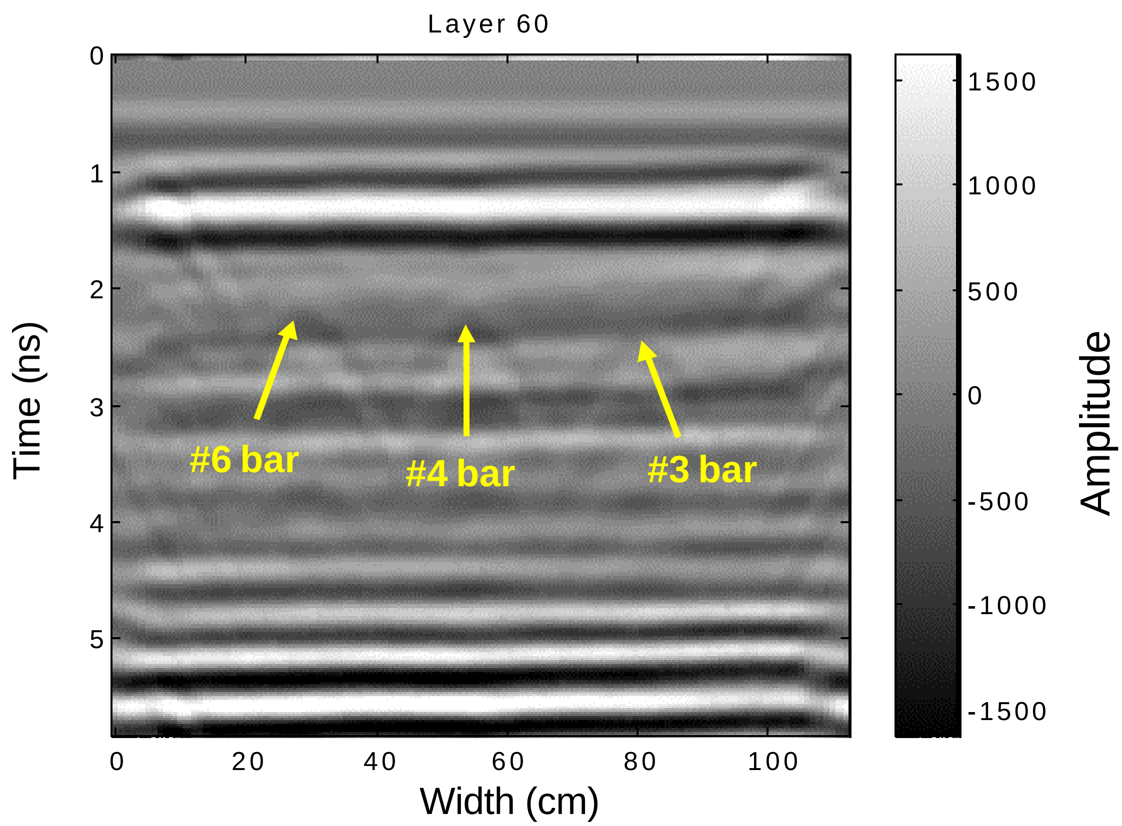


Figure 27. PERES response to the variable-diameter reinforcing steel specimen.

5. Testing Implications for HERMES II

The test findings presented in Section 4 raise several important issues that must be considered in the design of a new prototype HERMES II. The most critical of these issues involves the resolution of the new HERMES II antenna and the associated ringing and noise characteristics. Field test results collected previously and the controlled tests conducted for this phenomenology study show that features with the characteristics of a typical delamination crack are not detected by the current PERES and HERMES radar designs.

Controlled tests specifically showed that many simulated cracks and air gaps evaluated by PERES were not detected due to inadequate system resolution. Large crack openings were clearly detected in the study, while small crack openings were not detected. Simulated crack features that were not detected were in a size range that was comparable to the crack widths associated with real corrosion-induced delamination cracks. These results indicate that improvements in the system resolution will be an important feature of the new HERMES II design. In addition, the ringing phenomena observed in the PERES data, particularly from specimens with asphalt overlays, are severe enough to mask the detection of important subsurface features, such as delaminations and reinforcing steel. The severity of this ringing can be reduced by radar design changes and signal processing, but it can never be entirely eliminated. Reducing the ringing as much as possible will be a tremendous benefit to the HERMES II system response characteristics. Finally, the penetration depth that PERES can effectively achieve to detect features was tested. For the test specimen used, PERES did not detect reinforcing steel features at or deeper than 12 cm below the concrete surface. It will be important for the new prototype system to have improved penetration-depth capabilities to detect features through the depth of a typical bridge deck, which is significantly deeper than 12 cm.

Although other issues were addressed by this study, the three emphasized here (resolution, ringing, and penetration depth) are the key ones related to future system development. The new HERMES II will need to address these three issues to be a successful prototype. The testing of a new system prototype will be facilitated by the phenomenology specimens designed for this study, since they will allow HERMES II performance to be compared and contrasted with the original HERMES project prototypes. These specimens will also allow the capabilities of the system to be determined before field testing, identifying any system shortcomings before additional testing is recommended. Initial work on the HERMES II system by the Lawrence Livermore National Laboratory shows significantly improved results due to preliminary design changes, so better results are anticipated with the new prototype when it is delivered.

6. Conclusion

A phenomenology study was conducted using the PERES prototype GPR system to collect data from a range of controlled test specimens. These data revealed important information about the performance of PERES that will be useful for improving the system design. Specifically, the testing revealed that performance improvements are needed in the range resolution, penetration depth, and clutter produced by the new HERMES II radar relative to the original HERMES and PERES prototypes. The data presented here in this study, along with an extensive archive of additional data that was collected, will provide a great resource for comparison when data are collected from the same specimens using the HERMES II system. The controlled test specimens from this study will also provide an excellent preliminary test for the new systems before they are used in field trials.

7. References

ASTM D4580-86 (Reapproved 1992), Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding, ASTM Committee D-4 on road and paving materials, subcommittee D-04.36 on bridge deck protective systems, 1992, pp. 491-493.

8. Appendix A

Component	Composition (kg/m^3)
Cement	189
Pozzolan	189
Sand	673
VDOT No. 10 Stone	126
Water	158
Hycol Admixture	44.3 g/m^3
Daravair 1000 Admixture	7.3 g/m^3