Air-Coupled and Ground-Coupled Ground Penetrating Radar Techniques

A Thesis Presented

By

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Abstract

Deterioration, and specifically corrosion, of transportation infrastructure in the United States is leading to substantial problems, which must be addressed. Ground Penetrating Radar (GPR) has been show effective by many researchers and is gaining in popularity as a method of assessing the conditions of reinforced concrete. Ground penetrating radar offers a high-speed and accurate form of assessment for transportation infrastructure. The speed and accuracy of GPR can save significant sums of money through early identification and mitigation of damaged infrastructure and improve safety for inspection crews and commuters by limiting hazardous road closers and providing greater inspection coverage of bridges.

One problem with the current state of GPR is that sophisticated data processing algorithms, which are implemented with a ground-coupled GPR data mindset. They cannot be applied to the higher speed air-coupled GPR systems. Recent advances in GPR technology have improved the quality of air-coupled GPR data. This thesis demonstrates the use of these algorithms on the higher speed air-coupled data, and further shows that this can be done without much loss of accuracy when compared to the corrosion identification done using ground-coupled GPR data. This thesis also addresses the selection of a proper antenna for air-coupled GPR data collection. Without the selection of a proper antenna, it is not possible to collect air-coupled GPR data that can be processed using the sophisticated ground-coupled GPR data processing algorithms. Multiple antennas were fabricated and tested in this thesis, and a final selection was made to compliment the high-speed air-coupled GPR system.
This thesis reaches the conclusion that advances in GPR technologies have made possible the processing of air-coupled GPR data in a manor similar to ground-coupled GPR data. This is a significant improvement for the accuracy and speed of GPR as a transportation infrastructure assessment tool.
I would like to graciously acknowledge all of the funding sources which made the completion of this thesis possible. These funding sources include the Integrative Graduate Education and Research Traineeship (IGERT) fellowship through the Intelligent Diagnostics for Aging Civil Infrastructure Systems program supported by NSF grant number DGE 0654176. Additional funding was provided through The National Institute of Standards and Technology (NIST) under the Technology Implementation Program (TIP) Cooperative Agreement No. 70NANB9H9012 with Northeastern University in connection with the Versatile Onboard Traffic Embedded Roaming Sensors (VOTERS) project. The IGERT fellowship gave me to opportunity to explore and understand that with any civil engineering project there are important political and community aspects which need to be considered while designing engineering solutions. The VOTERS project allowed me to leverage resources, providing me with a vast amount of expertise and experience.

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Chapter 1

Introduction

Corrosion in bridge decks is a major problem. According to the American Society of Civil Engineers (ASCE, 2013), in 2013 approximately one in nine of the nation’s bridges are rated as structurally deficient. ASCE estimates that to eliminate the backlog of deficient bridges, $20.5 billion must be invested annually over the next 15 years (ASCE, 2013). Corrosion is the major contributor to deterioration of bridges and therefore represents a significant problem to the safety and sustainability of the nation’s transportation infrastructure. Roadways and bridge decks only visually show deterioration when a problem has advanced to a significant and costly situation. Early detection of deterioration can lead to early mitigation, resulting in cost savings (Mohammadi et al., 1995).

The current highway system in the United States was built starting with the Eisenhower administration in the late 1950’s and major construction continued through 90’s, but the majority of the construction was completed by 1970. The country is now confronted with vast extents of aged infrastructure, representing a significant financial burden. The average age of all the bridges in the United States is currently 42 years. These older bridges require more attention, more repairs and more money. While financial constraints remain omnipresent, efficiency becomes imperative. This imperative for efficient assessment of infrastructure is the motivation for this research.
1.1 Evaluation of Civil Infrastructure

There are many methods in use today to evaluate civil infrastructure. Evaluation methods are typically separated into two main categories, Non-destructive evaluation (NDE) techniques, and destructive evaluations. Destructive evaluations include coring, saw cutting, and deconstruction. These methods have obvious disadvantages due to the damage they cause to the infrastructure, but they can allow for close inspections of the actual condition of the infrastructure. NDE techniques on the other hand do not provide the same level of certainty, but what they lack in certainty they make up for by leaving the infrastructure undamaged. Some NDE techniques include visual inspections, Impact-echo, Ground Penetrating Radar (GPR), hammer sounding or chain drag, Infrared Thermography, Half-Cell Potential (HCP), and ultrasonic testing (Vaghefi et al. 2012). Today, the most common way to evaluate civil infrastructure is visual inspection assisted by hammer sounding. Evaluating bridge decks visually with hammer sounding is popular because it is a simple and straightforward approach, furthermore, inspection has been done this way for years and it is what the inspection agencies are accustomed to. There are multiple problems with this method of evaluation. First, any damage that can be seen visually has progressed to a point that remediation cost may already be quite high. Second, this is a very time and labor intensive approach. Finally, since this method of evaluation requires inspectors to be out in traffic, it can be dangerous for the inspectors and requires lane closures that cost commuters time and money. There is value in the ability to identify damage earlier and faster to allow for lower cost maintenance, which sustains the life of the infrastructure (Mohammadi et al., 1995).

Two important NDE techniques are GPR and HCP, because they offer valuable insights into the condition of transportation infrastructure and because many researchers have found
evidence of their efficacy (Al-Qadi et al., 2011; ASTM, 2009; Chen and Wimsatt, 2009; Gucunski et al., 2010; Hugenschmidt, 2004; Martino et al., 2013; Maser, 1995; Maser et al., 2012). GPR utilizes electromagnetic waves to propagate through the pavement and reflect back at the interface of materials with different dielectric properties. GPR provides an image of the interior structure of the civil infrastructure which can then be used to come to conclusions on the health of the infrastructure. HCP measures the voltage potential differences between reinforcing steel and the surface of the civil infrastructure. The voltage difference provides information on the health of the infrastructure because corrosion is an electro-chemical process that causes increased voltage differences at the location of corrosion activity. HCP testing is covered by the ASTM standard C876-09 (ASTM, 2009), where guidelines are given for the testing and the processing of data obtained.

1.2 Ground Penetrating Radar Evaluation of Reinforced Concrete

Ground Penetrating Radar systems take many forms, but all systems have the core components that include, transmitting and receiving antennas, pulse generating electronics, receiver electronics, a control computer, and data storage. The pulse generating electronics produce an electro-magnetic pulse that is then broadcast, or radiated, by the transmitting antenna as an electro-magnetic wave. The electro-magnetic wave then interacts with the surrounding environment, some of the wave gets reflected back and some of the wave disperses. The receiver antenna then picks up the wave that has been reflected back. The waveform received by the antenna is saved by the GPR system for later processing and visualization. In GPR surveys over reinforced concrete the electro-magnetic wave is first strongly reflected by the interface between air and the concrete, and then by the interface between the concrete and the reinforcement. A schematic of the wave propagation through reinforced concrete can be seen in Figure 1.1.
Figure 1.1 Basic schematic of ground-coupled GPR

Ground Penetrating Radar can take two general forms. The antennas can be in contact with the ground in what is referred to as ground-coupled GPR \((h=0)\), or they can be above the ground which is air-coupled GPR \((h>0)\). Ground-coupled GPR can get more energy in to the ground and more energy out of it, which results in clearer data. Air-coupled GPR on the other hand produces more difficult data to work with, but since the antennas are not in contact with the ground data can be collected at a much higher speed without damaging the antennas. Figure 1.2 shows a basic schematic of air-coupled GPR. On the right hand side of the figure is an idealization of a trace, which illustrates the separation of the direct coupling and the ground reflection. The direct coupling and ground reflection occur together in ground-coupled data. If
the height $h$ of the antenna above the ground is small the direct coupling and ground reflection can interfere with each other.

Figure 1.2 Basic schematic of air-coupled GPR

1.3 Objective

One of the major advantages of GPR is the speed and ease at which the GPR surveys can be conducted, but if damage assessment algorithms require high quality ground-coupled GPR data then much of the speed advantage of the GPR systems must be sacrificed. Roads would still need to be closed and traffic diverted, which greatly reduces the value added of a GPR inspection
system. Since significant work has been done on producing effective GPR damage detection algorithms based on the high quality ground-coupled GPR data (Maser et al., 2012; Martino et al., 2012), research is needed to identify the feasibility of applying these detection algorithms to high-speed air-coupled GPR data. Advances have been made in GPR hardware and software allowing for high density, roadway speed data collection (Oden and Birken, 2011, 2012, 2013). Customized antennas to suit the specific needs of the radar system have also been developed (Li et al., 2013). In this thesis, the selection of an antenna is made to meet the goals of the high-speed novel GPR system. These advances in technology have opened the door to the possibility of using the more commercially desirable air-coupled GPR data collection methods while still maintaining the option of using data processing techniques developed for the high quality ground-coupled data. The work presented here in this thesis explores novel air-coupled GPR systems and illustrates the possible advantages of using these advanced GPR systems. The data collected using the advanced system is presented and it is shown that with this data it is possible to use ground-coupled damage detection algorithms for air-coupled GPR data processing. This is significant for the advancement of GPR as a non-destructive testing method for bridge deck damage assessment, which could prove to be a very useful tool to address the growing problems associated with aging transportation infrastructure.
Chapter 2

Ground Penetrating Radar for Civil Infrastructure

Inspection of the ageing infrastructure is typically carried out by state departments of transportation (DOTs). While practices vary between states, the typical method of bridge deck inspection is limited to a visual inspection. Visual inspection of bridges is often done in conjunction with a technique known as sounding. When the inspector identifies an area of possible delamination or damage, a hammer is used to hit the section and the inspector listens for a hollow sound that is indicative of damaged concrete. When this method of evaluation is used, it is not uncommon for the inspector to underestimate the deterioration by 40% (Revie et al., 2011). Visual inspection and sounding is a slow, labor-intensive method, which often requires shutting down lanes of traffic. Ground Penetrating Radar has the potential to provide inspection of roadways without the added expense of shutting down or diverting traffic. While this paper focuses on the use of GPR specifically for roadway and bridge deck solutions, the inspection method has been shown effective for various other applications (Spagnolini and Rampa, 1999; Maser et al., 2006; Al-Qadi et al., 2011).

2.1 Layer Detection

One of the many applications of ground-penetrating radar is layer detection. Layer detection is a common use of GPR and covers many disciplines. In geophysics layer detection is used to detect different layers of the earth’s surface or layers of mineral deposits (Daniels, 2004). In civil
engineering, layer detection is often used on roadways to find the thickness of pavements and sub-grades. Saarenketo and Scullion (2000) illustrate the wide variety of research done in the field of civil engineering pertaining to layer detection. Single channel GPR pavement thickness mapping was one of the first civil engineering applications. Early work was done by Maser and Scullion (1992) showing a single horn antenna could accurately map multiple layers of pavement. Hugenschmidt et al. (2004) is an example of GPR being used to detect the thickness of a bridge deck using layer detection. He also detects a layer of reinforcement. Loizos and Plati (2007) show layer detection of multiple pavements with GPR systems at different frequencies and delve into the accuracy of the systems by checking them against the ground truth with good results. The need for skilled personnel for data interpretation is commonly a drawback for new technologies, which can be addressed by automation of the data interpretation. Spagnolini and Rampa (1999) automated the process of tracking multiple layers, including layers diverging and converging, by using probability functions. A variation of layer detection is void detection. Void detection is essentially detecting a layer of air or water below the surface. Chen and Wimsatt (2009) use GPR to successfully detect voids under pavement, some of which posed serious potential problems for the roadway structure. Chen and Wimsatt (2009) show that an informed use of GPR can be exceptionally valuable.

2.2 Quality Control and Quality Assurance

When vast expanses of roadway are constructed impressive amounts of construction materials are required for construction. Contractors have significant motivation to skip on material and save on cost. For a contractor to construct a roadway fractions of an inch thinner than what was specified could represent a large sum of money. Constructing a thinner roadway, or one with less sub-grade, could reduce the durability of the road and thereby the life span of the roadway. To
assure proper construction, cores are typically taken in selected locations but this requires
destroying a location of the roadway, and only offers information about a discrete location. GPR
has been shown effective in scanning spans of roadway to check layer thickness, ensuring
construction practices (Maser et al., 2006). GPR has also been used to scan Asphalt pavements to
identify the density of the pavement and to ensure that the contractor achieved the specified
strength of the pavement (Al-Qadi et al., 2011). A large-scale test site was constructed to prove
the use of GPR for asphalt density assessment (Al-Qadi et al., 2011).

In buildings and bridges, GPR can be brought in to reveal reinforcement placement. This
assures that the structure was built according to the plans. Both the contractor and the owner
assure proper construction commonly through the use of GPR (Al-Qadi and Lahouar, 2005).

2.3 Corrosion Identification

Corrosion identification is another key GPR application. Current research in the use of GPR for
health monitoring of bridge decks focuses on three main categories; corrosion of reinforcement,
electro-magnetic properties of the pavement, and voids or delaminations (Sbartai et al., 2005;
Martino et al., 2012; Chen and Wimsatt, 2009; Belli et al., 2013). These three categories are all
attempting to identify the level of damage in a bridge deck, and typically any one of these
problems will lead to the others. While GPR can be used to assess buildings, dams or retaining
walls, for this thesis roadways and bridge decks will be the focus.

This work is done as part of the VOTERS project. The project provides a framework and
prototype system to complement periodical localized inspections of roadways and bridge decks
with continuous network-wide health monitoring (Birken et al., 2012). One innovative idea of
the project is to use traffic-embedded Vehicles of Opportunity (VOOs). The VOOs deployed by
the project would travel through daily traffic collecting data and eliminating would have been
hazardous work zones. The VOTERS project also utilizes multiple sensor systems to identify roadway quality. The data from these sensors can be used in concert to better identify damaged areas. GPR is one of these sensors, and the ability of GPR to identify corrosion is one of the keys to the VOTERS system identifying damaged areas. High quality GPR data that can locate individual reinforcements in roadways and bridge decks is ideal for identifying corrosion, and in order to achieve this goal a significantly faster air-coupled GPR system is necessary.

2.3.1 Ground-Coupled GPR Corrosion Identification

Martino and Maser (Martino et al., 2013; Maser et al., 2012) have been investigating an algorithm to identify deterioration, specifically corrosion, in bridge decks. This is a difficult task due to the number of variables that confuse the data and make it hard to identify damage. According to Martino and Maser, to identify that damage, the data must go through a string of processes. The researchers chose to use the highest quality data available to prove the concept. Their work was done with a high frequency 2.6 GHz commercial ground-coupled GPR system. The conclusion of Martino and Maser was that a decrease in the amplitude of the reflection from the reinforcement was related to the level of corrosion at that location. Figure 2.1 illustrates what the drop in amplitude looks like. The reinforcements in the center of the figure have much stronger reflections than the reinforcements on either side of the figure. According to Martino and Maser, the reinforcements in the center are less likely to be corroded than the reinforcements with lower amplitude reflections on the sides.
Once the data was collected, the first step for the processing of the data is to remove all the gain typically used when collecting GPR data in the field. This allows for the amplitude of a target to be compared directly with other amplitudes and not have the comparison skewed by the gain. Then the data is time corrected so that the zero time for each trace is at the ground-antenna interface. The next step is to migrate the hyperbolas. Migration is a processing technique that uses back propagation to refocus the hyperbola to its original image (Robindon, 1983). Using the migrated data, the peak amplitude of each rebar is manually picked. This value is then used to represent the state of the reinforcement at that location. When the amplitude is picked it remains associated with the reflection travel time and location. The amplitude values of the migrated data are then converted into a decibel scale based on the maximum voltage of the GPR system. This is done because the decibel scale is the most common way of analyzing electromagnetic data. The next step for processing the data is known as depth correction. The goal of this process is to reduce the effects of the depth of the target on the data. This is done to more accurately compare the values of each data point. The depth correction process is outlined in Barnes et al. (2008).
Figure 2.2 shows healthy reinforcement at different levels. The amplitude of the reflection of each of the reinforcements should be approximately the same value since there is no corrosion, but since there is more material for the electro-magnetic waves to pass through, there is more attenuation of the signal for targets deeper in the material. This problem is what the depth correction algorithm addresses (Barnes et al., 2008).

![Figure 2.2 Non-corroded reinforcement at various depths](image)

After depth correction the data is ready to be plotted. A threshold is identified for the data set and the resulting plot is a GPR deterioration map. This entire process is explained and carried out in Martino et al. (2013). This thesis uses this data processing algorithm to create deterioration maps of the air-coupled GPR data collected using the novel high-speed GPR
system. This algorithm was selected due to the high correlation the researchers obtained. The results of this data processing method are presented in Chapter 6.

### 2.3.2 Air-Coupled GPR Corrosion Identification

Air-coupled GPR data is processed differently than ground-coupled GPR data because the data takes a different form. Where ground-coupled data has characteristic hyperbolas, which are the reflections from the reinforcement, air-coupled data has a layer or more descriptively a blurry line where the rebar are located. Figure 2.3 below shows a comparison between typical ground-coupled GPR and air-coupled GPR data.

![Comparison of GPR data](image)

**Figure 2.3** Qualitative comparison of ground-coupled and air-coupled GPR data over rebar

Part of this difference is due to the additional interface (Figure 1.2) air-coupled GPR signals must travel through (Maser and Roddis, 1990). The air-ground interface scatters much of the air-coupled GPR signal while the ground-coupled system has less difficulty getting energy into the concrete and again on the way out. Without the characteristic hyperbolas of ground-
coupled data, it is necessary to process the reinforcement layer as a whole to make assertions on the data. The reason the entire layer must be used is because it is not possible to distinguish the exact location of a single target. The layer contains some information about the condition of the reinforcement, but it also contains information about the concrete between the reinforcements. To process the band of data from air-coupled GPR systems, some fairly sophisticated processing techniques have been developed. For current air-coupled processing techniques the picked band is sufficient. GPR systems with air-coupled antennas are often used for identifying layer thicknesses (Maser et al., 2006).

Although many practitioners have made do with the reinforcement band from air-coupled GPR data, it would be ideal to be able to pick individual reinforcement and duplicate the analysis of similar ground-coupled GPR data (Maser et al., 2012; Martino et al., 2013). Individual values for the reinforcement provide a better representation of the actual state of the reinforcement.
Chapter 3

Novel Ground Penetrating Radar Technologies

In this chapter the various components of the GPR system used for testing in this thesis are outlined and discussed. There are two major components addressed here, the radar electronics and the antennas. Earth Science Systems (ESS) designed the novel radar electronics with the VOTERS project at Northeastern University. To achieve high-speed performance, ESS completely redesigned the method of data acquisition within the electronics. The second major component, the antennas, was designed at Northeastern University with the VOTERS project. The testing of these antennas with the new high-speed GPR system is covered in this thesis.

3.1 Radar Electronics

An experimental prototype of a GPR system developed by Earth Science Systems (Oden and Birken, 2011, 2012, 2013) with shielded RF cables was used for the experiments. The GPR system was selected because the system has the capability of collecting dense data at very high speeds, approximately 1 scan every inch at 60 mph. Most current GPR surveys must be done at speeds around 5-10 mph, or if the survey is done at high speeds data is only collected every 3 inches, which is not close enough to identify individual reinforcement in concrete. The Earth Science System radar electronics can achieve a high data density of 1000 traces/s through a novel data collection method. The recorded time triggered traces are tagged with location information provided by a distance measurement instrument. The ESS system’s method achieves
full waveform digitization, while current commercially available systems require up to 512 pulses to be sent for every waveform collected. The reduced number of pulses needed for digitization of a single scan also can allow for lower radiation, which is important to meet the FCC regulation 02-48 for electro-magnetic radiation emissions (Federal Communications Commission, 2002).

The GPR electronics generate a pulse with a center frequency around 2.5 GHz and a bandwidth of approximately 3 GHz, as shown in Figure 3.1. The figure was created using actual data by attenuating a pulse in a loop back experiment. The attenuators were used because the amplitude of direct measurement in a loop back test would over power the receiver electronics.

![Figure 3.1 Pulse from a loop back test with a 20dB attenuator. (a) Pulse in time domain; (b) Pulse in frequency domain](image)

From Figure 3.1, it is evident that the time-domain source pulse is about 1.2 ns wide. The frequency content of the system was selected as an optimum frequency content for imaging reinforcement in a concrete bridge deck, while the small pulse width is important when attempting to image shallow reinforcement.
These GPR electronics were also chosen because they have the capability to be set-up in an array and because of their small size. The Earth Science Systems radar electronics are approximately 6 inches by 1.5 inches (Figure 3.2). This will allow for future work with an array system spanning the full width of a roadway, and will create the possibility of 3D imaging.

Figure 3.2 Earth Science Systems Radar Electronics

3.2 Antennas

For the purposes of finding an optimal antenna for high speed Ground Penetrating Radar, a number of ultra-wideband (UWB) antenna families have been explored in the past few years. These antenna families include monopole, resistively loaded dipole, planar bulbous elliptical dipole and conical antenna (Li et al., 2013). UWB antennas are commonly used for pulse GPR systems, like the system recently developed and being tested for this thesis. The UWB antenna is used because the broadcast pulse from the radar electronics and the received electromagnetic wave are broadband signals (Figure 3.1(b)). To find the best suited antenna design, a few
possible antennas were designed, fabricated and packaged so that they could then be experimentally tested. Two UWB antenna types were decided on, the bowtie and Vivaldi shapes, and multiple iterations of each were created. The bowtie shaped antennas required a back cavity because it was important to have radiation only in one direction. All of the antennas were packaged for the experiments. Figure 5.1 shows one of the antennas packaged for testing. The different antenna designs can be seen in Figure 3.3. Each antenna is presented with the plots of the characteristics of the antennas. The first plot is the S11 vs. frequency. S11 is a measure of the power the antenna is able to reflect back to the receiver. Values below -10db are considered very acceptable. The S11 is dependent on the frequency the antenna is operating at. The target frequency for this set of antennas is approximately 2.6 GHz. The second plot is the gain vs. frequency. This provides information on the strength of the signal the antenna can broadcast at different frequencies. Higher values for gain at the proper frequencies are preferable.
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<td><img src="graph6" alt="Graph" /></td>
</tr>
<tr>
<td>15 cm x 14 cm (length)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Vivaldi-2 antenna</td>
<td><img src="image4" alt="Photo" /></td>
<td><img src="graph7" alt="Graph" /></td>
<td><img src="graph8" alt="Graph" /></td>
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<tr>
<td>10 cm x 18 cm (length)</td>
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<tr>
<td>Inrego Vivaldi antenna</td>
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<td><img src="graph9" alt="Graph" /></td>
<td><img src="graph10" alt="Graph" /></td>
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<tr>
<td>13.2 cm x 15 cm (length)</td>
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<tr>
<td>Rounded bowtie antenna</td>
<td><img src="image6" alt="Photo" /></td>
<td><img src="graph11" alt="Graph" /></td>
<td><img src="graph12" alt="Graph" /></td>
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<tr>
<td>9.8 cm x 7 cm x 5 cm</td>
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</tbody>
</table>

Figure 3.3 Antennas fabricated by Northeastern University, with the corresponding S11 and gain for each antenna
The goal for each of these antennas was to find the one with the highest gain in the frequency range of interest, while maintaining high quality performance with respect to the data collected. One of the performance measures of an antenna is called ringing. Ringing occurs when the electro-magnetic pulse does not completely leave the antenna during the initial transmission. This then causes multiple emissions of radiation from the transmitting antenna. The receiving antenna can also have ringing effects. In the receiving antenna, the entire received pulse does not get transmitted to the GPR electronics. The pulse remaining in the antenna then reflects within the antenna and returns a second time to the GPR electronics. Either way ringing occurs, the effects are the same. Ringing can be seen in the GPR data as extra bands. Beyond the performance requirements there additional objectives the antennas must meet. The antennas must be rugged and able to stand up to the high-speed data collecting process. The final qualification for this list of antennas is that they are of a small enough size to fit easily on the underside of a vehicle for data collection. In order to design these antennas, an iterative process was adopted (Li et al., 2013). This process is outlined in Figure 3.4 below.
By following the iterative approach outlined in the antenna design flow chart (Figure 3.4) high quality antennas were fabricated. Some of the design features that were decided against during this process included many shapes, such as, equi-angular spiral, conical spiral, log periodic antenna and other self-complementary structures. These were all chosen against because of their poor time domain responses and insufficient bandwidth. Both the bandwidth and time domain responses are important for pulse radar systems. Horn antennas were selected against because of their large dimensions. The large dimensions of the horn prevent the antenna from being mounted on a high-speed vehicle for data collection and used in high-channel count arrays. Resistively Loaded antennas also were not chosen because they resulted in a significant reduction of gain for the antennas (Li et al., 2013).
After reducing the number of possible designs and simulating those designs, the designs selected for fabrication were then characterized and tested in the lab. The methodology and results of the antenna field tests are shown in Chapter 4 and Chapter 5.
Chapter 4

Sand Box Tests

This chapter covers the initial sand box tests. These tests were intentionally kept as simple as possible with the hope of being able to identify clear differences between each of the antennas and the capabilities of the radar electronics as well. A second goal of this experiment was to further refine the test set-up and testing methods to be used in future more advanced tests. This chapter explains the test set-up first and then presents the results of the tests along with some discussion of those results.

4.1 Test Set-up

The sand box tests were designed with the intent to compare the antenna designs in a practical setting and at the GPR frequencies of interest. To achieve the goals of this test, realistic testing dimensions were established. The test bed was approximately 1.2 m (4 ft) by 0.6 m (2 ft) with nearly 20 cm (8 in) of sand. The antennas were placed approximately 30 cm (12 in) above the sand surface, and the height was maintained throughout the experiment. This test set-up attempted to approximate the operation of an air-coupled GPR system attached under a vehicle. Buried about 2-2.5 inches beneath the surface of the sand was a metal ¾ inch metal pipe. This pipe served as the target for the radar systems in this experiment. This test set-up can be seen in Figure 4.1 below.
The initial sand box tests were done with the hopes of quickly identifying antennas that would be more suitable for operation with the novel GPR electronics. The antennas were connected directly to the GPR board using coaxial cables that matched the impedance of the antennas. Since early prototype versions of the GPR system did not have a distance measuring mechanism or encoder wheel, data was collected in a more manual fashion. In order to approximate distance triggered data, a data file was saved at each location and then the antennas were manually moved to the next location. Marks were placed on the two rails, which the antennas would be slid along, to maintain constant increments. After all of the data files were collected, the files were compiled into one single file which allowed for the visualization of a B-scan.
The sand box test was conducted with 6 antennas, five that were designed as described above in Chapter 3 and one, which was a high quality commercial antenna. This commercial antenna was tested along with the 5 novel ones to provide a benchmark for comparison. The antennas tested with the sand box were as follows; Rounded Bowtie, Slotted Bowtie, Vivaldi 1, Vivaldi 2, Pacman Bowtie, and the Commercial Vivaldi.

4.2 Results

Figure 4.2 below shows the results from the sand box tests. The six antennas tested are shown above the corresponding B-scan. On the far left of the figure is a schematic to aid in the interpretation of the B-scans. There are many similarities between each of the B-scans. The most important similarity between the B-scans is the hyperbola shape in the middle of each scan. That shape is the reflection from the target. As a note, the vertical axis for all the B-scans collected with the ESS system is the number of data points. The time between each data point is 0.3334 ns. For the B-scans in Figure 4.2, the spacing between each trace is approximately 1 inch.
One of the characteristics, which could assist in the selection of the antenna, is the bands or the reflections below the surface of the sand. These bands are the effects of ringing. Those extra bands can get in the way of the true reflection of the target making it difficult to obtain the actuate reflection required for data processing. A second characteristic, which could be important for antenna selection, is the difference between the intensity of the target reflection and the background data. The manual means of data collection resulted in some inconsistencies in the data, likely do to the high level of interaction. While measures were taken to limit these inconsistencies, it is especially clear in the Vivaldi 2 test that some problems were unavoidable. After the encoder wheel was installed on the radar system, the sand box test was repeated with a reduced number of antennas. The results from that test are shown below in Figure 4.3. The trace spacing is approximately 0.5 inches.

Figure 4.2 B-scans from sand box tests
This second set of the sand box tests with the encoder wheel covered a larger distance than the original tests. Each of the scans start a few inches before the edge of the sand box and end a little after the sand box. This allows for a comparison of the entire length of the sand box along with a reference to the ground on either side of the sand box. Both the Vivaldi-2 and the commercially available Vivaldi antennas show a strong band or reflection passing through the middle of the sand box. This strong reflection through the middle affects the data, making it difficult to pick an accurate value at the target. It was decided not to use the Vivaldi antennas due
to that problem. The Pacman Bowtie antenna had the highest contrast between the target and the surrounding sand box. The Slotted Bowtie also showed good performance.
Chapter 5

Reinforced Concrete Tests

This chapter covers the reinforced concrete tests. These tests were significantly more complex than the sand box test because the reinforced concrete slabs have multiple targets at a dense periodic spacing, which is typical for bridge decks in the field. The concrete is also a more difficult medium than sand for GPR to image. This experiment was designed to show what the GPR system was capable of in a more realistic setting. Another goal of this experiment was to identify what antenna would perform best with the GPR system and make a selection to simplify all further testing. This experiment also allowed for investigation of the ability of air-coupled GPR to identify a single reinforcement target in concrete.

5.1 Test Set-up

The reinforced concrete tests were considered a second stage of the sand box tests. These tests kept many of the original parameters the same. The antennas were located the same height above the surface (12 inches). Again, the antennas for the reinforced concrete tests were placed on rails and incrementally moved in the same fashion as the sand box tests. The test set-up can be seen in Figure 5.1 below.
The sand box test only had one target, which made identifying that target very easy, the reinforced concrete being tested on had many targets, so efforts were made to clearly identify a single target. To do this, metal sheets were used to cover sections of the slab and simplify the data. Multiple tests were done each time including more targets in the test. These tests aided in the data processing, specifically the picking of individual targets. Figure 5.2 shows the placement of the metal sheets to allow for the data collection over a single target.
The initial data collection for these tests clearly showed that the method of manually collecting the data would not be sufficient. To collect more consistent data, an encoder wheel was integrated into the system. This encoder wheel collected distance data and associated the distance with individual scans allowing for the creation of more accurate and less time consuming B-scans. Data sets were then recollected using the higher accuracy encoder wheel readings.

5.2 Results

An initial data set was collected over the reinforced concrete slabs using the manual method of data collection that was originally used with the sand box. This data set was difficult to interpret,
so only the data set collected with the encoder wheel is presented in this section. Figure 5.3 shows the B-scans of the corresponding antennas. Due to the different dielectric of concrete and the slightly greater distance traveled the B-scans looks somewhat different from the B-scans of the sand box test presented above. The trace spacing in the B-scans in Figure 5.3 is the same as in Figure 4.3, 0.5 inches.

The picture to the left of the B-scans is an approximate scale image of the bridge deck to aid in the interpretation of the B-scans. Similar to the sand box tests, the Pacman Bowtie antenna showed the best performance when imaging targets in concrete. Since the Pacman Bowtie has a small rugged design, and was determined to have the best performance of all the antennas tested,
in both the sand box and the reinforced concrete, it therefor became the antenna of choice for the novel air-coupled GPR system and all subsequent tests.

Picking the exact location of the reinforcement target caused a large degree of difficulty. To clarify this process and ensure that the targets picked were the actual location of the reinforcements, metal sheets were placed to cover all but one of the reinforcement targets, as was discussed in Section 5.1. Figure 5.4 below shows the B-scan from that test. The trace spacing is consistent with Figure 4.3 and Figure 5.3, at 0.5 inches between traces.

![Figure 5.4 Single reinforcement target in concrete](image)

The identification of the exact location of the reinforcement target from this test was used to facilitate the picking process for the bridge deck slab tests in the next Chapter.
Chapter 6

Bridge Deck Slab Tests

This chapter covers the bridge deck slab tests, which most closely approximate actual operation of air-coupled GPR systems in the field. Every attempt was made to replicate the anticipated field conditions for the application of the high-speed air-coupled GPR system. Only one set of antennas were used for the bridge deck slab tests because the previous tests had shown that the Pacman Bowtie antenna had the best performance and it had been selected as the proper antenna for the novel GPR electronics. The bridge deck slab tests are compared with previous literature results from the same set of bridge deck slabs using a commercial ground-coupled GPR system.

6.1 Test Set-up

The bridge deck slabs are 4 sections of a deconstructed bridge deck, which were moved to the laboratory for testing. The slabs came from the Southbound Sabattus River Bridge on the Maine Turnpike. The bridge deck before being removed from service is shown in Figure 6.1, along with the saw cut section after being moved to the lab.
The bridge deck was in service for 28 year prior to its demolition in 2010. During the destruction the asphalt overlay was removed and then 4 saw cut sections of the bridge deck were shipped to the labs at Northeastern University for testing. The four sections were then placed side by side so that testing could be conducted as if the four slabs were one continuous bridge deck measuring 350 cm wide and 600 cm long (Figure 6.1). These slabs were used for the air-coupled data collection because ground-coupled GPR surveys were done on these same slabs by Maser et. al. (2012). The results obtained by Maser using the ground-coupled GPR system will be compared to the air coupled data collected for this thesis. The air-coupled data will also be processed using the same algorithm which was used in Maser et. al. (2012), to show that with a state of the art radar systems it is possible to use the sophisticated algorithms, developed for ground-coupled GPR data, to process air-coupled GPR data.

In order to collect the air-coupled GPR data the previous system of rails to run the antenna and encoder wheel along became impractical. The length, which needed to be span, exceeded the maximum possible length with the current rails and longer rails would need to be much stiffer to avoid sagging in the middle of the spans. To avoid these problems a push cart
was developed. The encoder wheel was connected to the wheel of the cart so that distance measurements could be accuracy recorded. The antenna was cantilevered over the edge of the cart to limit the interference the cart would have on the GPR data. The antennas were suspended at 12 inches above the concrete surface, similar to all previous tests. The cart set-up can be seen in Figure 6.2 below.

![Air-coupled GPR cart](image)

**Figure 6.2 Air-coupled GPR cart**
The cart was used to collect data passes at one-foot increments along the slab. This provided 11 passes with the cart, but heavy spalling near the top of the slab caused the antenna to bounce severely, and the data in the final pass could not be processed. Despite losing the final pass, the data set still provides good coverage of the entire set of slabs.

6.2 Results

The bridge deck slab tests covered the entire bridge deck in eleven passes. The GPR data for all of the bridge deck slabs were collected at a spacing of 0.25 inches between traces. All processing was done using the data with a trace spacing of 0.25 inches, but it was possible to have picked the data with a trace spacing of 1 inch. Figure 6.3 shows a representative B-scan down sampled to 1 trace per inch.

![Figure 6.3 Sample B-scan from bridge deck test](image)
The air-coupled data collected was processed using a similar method as presented in Chapter 2, Section 2.3.1. The first step to process the data was to pick the amplitudes that were representative of the reinforcement. This is the step that is not possible with traditional air-coupled GPR data. Figure 6.4 below shows a comparison between a ground-coupled GPR system, the new high-speed air-coupled GPR system and a commercial air-coupled GPR system. The red line in the figure shows the location of the reinforcement targets.

![Figure 6.4 Qualitative comparison between the data collected by various GPR systems over reinforced concrete](image)

Figure 6.4 clearly shows the advantage of the new high-speed air-coupled GPR system. As is evident, the individual reinforcements are clearly distinguishable and can therefore be picked and used for data processing. This ability to pick the individual reinforcements is a significant advancement for an air-coupled GPR system. The rest of the steps for data processing, with few noted exceptions, follow the same procedure as Maser et al. (2012). Again, this was the same bridge deck used by Maser et al. (2012). Although every attempt was made to
follow an identical procedure, there were two distinct differences necessary for the processing of the air-coupled GPR data. There were also differences in methodology used to plot and compare the data sets. These are discussed later. The two differences in data processing were that migration was not done with the air-coupled data and that a background removal was necessary for the air-coupled data. Migration was not done because although the characteristic hyperbola was present in the air coupled data, it was not as well defined and the resulting hyperbola could not be collapsed as easily as in the ground-coupled GPR data. Air-coupled GPR data also requires a two-layer migration. This is required because the velocity of the electromagnetic wave is different when traveling in air and concrete. It was not expected that eliminating the data migration would cause a significant change in the results. Migration is primarily performed to facilitate the picking of the reinforcement targets and has little effect on the amplitude value if the amplitude is picked from a trace directly above the target, which was the procedure followed in this thesis. The background removal was determined to be necessary for the air-coupled GPR system because with air-coupled data there is a larger reflection from the surface of the slabs. With ground-coupled GPR data, the antenna is in contact with the ground, which changes the antenna’s characteristics and reduces the reflection from that surface. The differences between air-coupled and ground-coupled GPR systems are illustrated in Figures 1.1 and 1.2, and field data from the two types of systems are compared in Figure 2.3. Since the reinforcement was located close enough to the surface, there was interference from the surface reflection and the background subtraction was necessary.

To pick the targets for each location, first the background removal was carried out. The background removal subtracted the average of 300 traces from each individual trace. The target locations were then identified with the background removed data. For each target, the x and y
coordinates were recorded along with the time and amplitude of the target reflection. Finally the time of the surface reflection above each target was recorded. This was used to identify the apparent depth of each reinforcement target, and then was used during the depth correction process. Figure 6.5 below shows the location of the picked targets from the air-coupled GPR data.

![Figure 6.5 Example pick locations of air-coupled GPR data](image)

After the targets were picked for each B-scan of the air-coupled data set, a depth correction was carried out according to Barnes et al. (2008), which was the same used by Maser et al. (2012). To perform this depth correction, the amplitude and time were plotted for each of the data points. These data points were then placed into time bins and the 90th percentile point was then plotted for each time bin. Next, a regression line was fit to the 90th percentile points. The final step was to correct the original data using the line of best fit. Correcting the data for this line of best fit centered the 90th percentile of each bin at zero db. For further discussion on
this topic refer to Barnes et al., 2008. Figure 6.6 below illustrates the data at the three major steps of the depth correction process. The plot on the far left shows the original picked amplitudes in db plotted against their corresponding times beneath the surface in nanoseconds. The middle plot is the 90th percentile points for each of the time bins along with the line of best fit used to correct the entire data set. The final plot on the far right in Figure 6.6 shows the resulting depth corrected data.

The resulting air-coupled GPR data set is presented as a deterioration map in Figure 6.7. The figure shows a contour plot fitting the data along with a post map to show the individual locations of each data point. The contour plot was created using a commercial software package. The red areas represent areas of high attenuation, which has been linked to locations with a high potential for active corrosion.
Figure 6.7 Bridge deck slab deterioration map with air-coupled GPR data. The black dots indicate the actual data locations, and the gray areas indicate delaminations.

For comparison, the deterioration map adapted from the data used in Maser et al. (2012) is presented in Figure 6.6 below. The original picked data files from Maser et al. (2012) were available for this thesis, so the available ground-coupled GPR data were processed in exactly the same way as the newly collect air-coupled data on the same slabs. Slightly different results are expected from the original publication due to differences in the way the data is compared. The two major differences are the method of data gridding, and the selection of the data points used for comparison. This thesis uses a Gaussian process that estimates an appropriate HCP value at the location of each of the GPR data points (shown as black dots in Figures 6.7 and 6.8), whereas, the previous literature “gridded” the HCP and the GPR using commercial software package which provided periodic co-located values of both HCP and GPR. Both methods are valid means of creating co-located data points for comparison, but since they are different, the
two methods will result in slightly different correlations. The second major difference is the selection of the data points. This thesis used all the data points that had been picked during the picking process. In Maser et al. (2012), any data point that had been picked in areas with spalled off sections of concrete was removed from the analysis. The spalled areas can be seen in Figure 6.1 above. Both approaches are valid methods for data processing, and arguments can be made for choosing one or the other. Figure 6.8 is plotted using the same contour parameters as the air-coupled data in Figure 6.7. The post map of all the data points is again plotted on the contour map to show the individual location of each data point.

![Figure 6.8 Bridge deck deterioration map with ground-coupled data adapted from Maser et al. (2012). The black dots indicate the actual data locations, and the gray areas indicate delaminations](image)

Once the data was in its processed form, a statistical correlation between HCP and GPR was found using receiver operator characteristics (ROC) curves to identify the optimum threshold. A ROC curve cycles through possible thresholds for data and at each threshold plots a
point corresponding to the rate of true positives and the rate of false positives. The top left corner corresponds to perfect classification (Fawcett, 2006). Figure 6.9 shows the ROC curve for the air-coupled data set.

![ROC Curve](image)

Figure 6.9 ROC curve for the air-coupled GPR data set

Half-cell potential was used as a surrogate for ground truth. This was possible because any location with a half-cell potential reading of less than -350mv has a 90% likelihood of being in a state of active corrosion. The HCP data is spatially plotted in Figure 6.10. As with the previous two plots, Figure 6.10 is plotted with the same contour parameters and the post map is overlaid on the contour plot to indicate the location of individual data points.
Figure 6.10 Bridge deck Half-Cell data map. The black dots indicate the actual data locations, and the gray areas indicate delaminations.

In order to compare both the air-coupled and the ground-coupled GPR data with the HCP data spatially, a Gaussian process was performed on the HCP data (Rasmussen and Williams, 2006). By only doing a Gaussian process on the HCP data set, it allowed the GPR data to not go through further processing, such as averaging or interpolation to a new location. The Gaussian process is a stochastic process that allowed for an estimation of an appropriate HCP value at the location of each of the GPR data points. Since after the Gaussian process, each GPR data point had a collocated HCP data point, a spatial correlation is straightforward. Using the optimum threshold for GPR, the accuracy of the air-coupled and ground-coupled GPR data sets are displayed in Table 6.1. Accuracy was calculated using the binary classification definition of accuracy, which states that accuracy is the percentage of the entire population which was correctly identified. A correct identification is when both HCP and GPR agree on the state of the reinforcement at an individual location.
<table>
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<th>Data Set</th>
<th>Accuracy Identifying Active Corrosion</th>
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<tr>
<td>Air-Coupled Data Set</td>
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</table>

Table 6.1 Accuracy of air and ground-coupled GPR data

The air-coupled and ground-coupled GPR data sets, when mapped as deterioration maps, visually show strong similarities. Furthermore, both data sets demonstrate high accuracy when identifying areas of active corrosion. This indicates that the air-coupled GPR data, processed using the ground-coupled GPR algorithm outlined in Maser et al. (2012), is capable of producing similar results with the advantage of a much higher speed of data acquisition.
Chapter 7

Summary and Conclusions

The ability to quickly and accurately assess the state of the nation’s bridges is extremely important for the safety of our nation’s citizens. With many of the bridges approaching the end of their intended service life, solutions must be identified to address what bridges must be replaced and what bridges can stay in service. A non-destructive technology that can quickly and accurately identify deterioration would be a valuable tool. Many researchers have hoped that GPR could be that tool. The adoption of high speed GPR as an inspection method can save significant sums of money, and reduce the need for the labor intensive and time-consuming visual inspection done by most departments of transportation today. The high speed of the GPR inspection also eliminates the need for lane closures. This saves time for commuters, saves gas from idling cars and can save lives by keeping inspectors off busy roads.

The objective of this thesis was to identify if it is possible to use newly developed GPR technology to collect high speed, high quality GPR data, which could then be processed with the most advanced GPR data processing algorithms. The results of the experiments with various antennas and test set-ups indicated that high-speed data collection could be used with the most advanced algorithms. The most significant of the experiments done was the bridge deck slab experiment. The results show that with a well-designed GPR system the air-coupled GPR data has a similar accuracy to ground-coupled data. This conclusion further supports the use of GPR as a means of roadway and bridge deck inspection.
Antenna selection is an important aspect in the design of an effective air-coupled GPR system. The experiments in this thesis illustrate the importance of a proper antenna, and offer some insight into criteria for choosing that antenna. A non-optimal antenna for an air-coupled GPR system can distort essential data needed for the identification of corrosion in bridge decks. The Pacman Bowtie antenna chosen provided clear data, but just as importantly it has a rugged design and a small size making it suitable for application under a vehicle in an array set-up.

In conclusion, this thesis shows that it is possible to use the sophisticated ground-coupled GPR processing techniques with high-speed air-coupled GPR data. It is only possible to use these techniques because of the advancements made in the field of GPR technologies. These advances in technology will help meet the need for high speed, high quality assessment of damage in our nation’s transportation infrastructure.

7.1 Future Work

Future work includes the implementation of the novel GPR technology as an array under a high-speed vehicle. This will provide data that will span the entire roadway surface making data collection possible in a single pass. This advancement will meet one of the goals of the VOTERS project, bringing the project on step closer to periodic system wide assessment of transportation infrastructure.

After the GPR system is implemented in an array, it will become necessary to automate the picking and processing of the air-coupled GPR data. This is necessary due to the anticipated large volumes of data, which will be collected by the VOTERS project. Automation will increase the speed of the assessment process, which will allow for more roads to be scanned and eventually a time-lapse of the deterioration process for a single bridge. This time-lapse
deterioration data would be of great importance to departments of transportation to make decisions on the replacement of damaged infrastructure.


