Ground-Penetrating Radar Applications for the Assessment of Airfield Pavements

Y. L. Edwards & D. R. Alexander
US Army Engineer Research and Development Center, Vicksburg, MS, USA

ABSTRACT: Growing volumes of aircraft traffic and the introduction of heavier aircraft are significantly impacting airports around the world. Pavement management systems are being relied upon heavily to monitor pavement condition, forecast performance, and plan for timely maintenance activities. The most widely used tools for maintenance and rehabilitation management for airfield pavements have been the falling weight deflectometer and dynamic cone penetrometer. However, these commonly used tests do not provide adequate information with respect to the thicknesses of individual layers within a pavement system. The layer thicknesses must be known in order to backcalculate the structural capacity using nondestructive test results. Supplementing these commonly used test procedures with core samples is disruptive, costly, and time consuming. Rapid, nondestructive techniques for assessing the pavement surface, base, and sub-base layer thicknesses are needed. Ground-penetrating radar (GPR) has shown some promise in this area. The US Army Engineer Research and Development Center (ERDC) has completed a Small Business Innovative Research (SBIR) project with Pulse Radar, Inc., to develop a GPR system for airfield/road pavements. The system currently under evaluation at ERDC consists of multiple antennas with frequencies ranging from 100 MHz to1 GHz. This paper will describe the Pulse Radar system in detail, show data acquired with the system, and discuss the accuracy of the system.

KEY WORDS: Radar, nondestructive tests, pavement thickness

1 INTRODUCTION

The ability to nondestructively evaluate airfield pavement structures is critical to the success of managing airfields. Increases in traffic volume and the introduction of heavier aircraft on an airfield necessitate the requirement for structural assessments to predict pavement performance and determine upgrade requirements. Unforeseen pavement failures can be costly and result in lengthy delays and severely limit operations at an airfield. Recently, the global war on terrorism has significantly impacted both the type and amount of traffic on military airfields.

The ERDC routinely performs airfield assessments to determine the load-carrying capacity and physical condition of pavements. These evaluations provide critical information for determining airfield operational capabilities and planning for pavement maintenance, repairs, and structural improvements. An evaluation typically consists of a combination of nondestructive testing, dynamic cone penetrometer (DCP) testing, and a visual condition survey. The falling weight deflectometer measures surface deflections that can be used to backcalculate layer moduli provided pavement layer thicknesses are known. Layer thicknesses can sometimes be obtained from construction records, but often are not available or updated with accurate information. Layer thicknesses can be approximated from changes in California Bearing Ratio (correlated from blows/unit penetration) with depth determined from the DCP results. DCP testing is time consuming and therefore only a minimal number of locations can be tested. Layer thicknesses can also be determined by coring through the pavement surface and auguring into the underlying materials. Coring is more invasive than the DCP, time-consuming, and requires patching, which causes additional down time for the airfield. Alternatively, pavement layer thicknesses can be nondestructively determined with ground-penetrating radar (GPR). GPR has proven to be a valuable tool for applications such as the evaluation of highways, railroad tracks, and bridge decks. GPR has been used to locate layer interfaces, buried utilities, voids, and concrete structures.

The most commonly used type of GPR system is the pulsed system. A short electromagnetic pulse is transmitted into the pavement, and when the electromagnetic wave encounters an interface with a dielectric discontinuity, the electromagnetic wave is partially reflected back to the receiving antenna. The relationships between the layer thicknesses, dielectrics, and the reflection amplitudes have been described by Scullion et al. (1994). The measured reflection time represents the two-way travel time of the electromagnetic wave, and by utilizing the dielectric of the material, the thickness of the pavement can be calculated, as described in the following equation:

$$h = \frac{c \times \Delta t}{2\sqrt{\varepsilon}} \qquad \text{(Equation 1)}$$

where h=layer thickness, c=speed of light, Δt=two way travel time, ε=dielectric.

If the reflection from a metal plate is also measured, the top layer dielectric can be calculated for each GPR signal, as shown in the following equation:

$$\varepsilon_a = \left[\frac{1+\frac{A_0}{A_m}}{1-\frac{A_0}{A_m}}\right]^2 \qquad \text{(Equation 2)}$$

where A_0 = surface reflection amplitude, A_m = metal reflection amplitude, and ε_a = dielectric of the first layer. The base dielectric values (ε_b) can also be calculated if the reflection amplitude from the base (A_1) is measured. This is described in the following equation:

$$\sqrt{\varepsilon_b} = \sqrt{\varepsilon_a}\left[\frac{1-\left[\frac{A_0}{A_m}\right]^2+\left[\frac{A_1}{A_m}\right]}{1-\left[\frac{A_0}{A_m}\right]^2-\left[\frac{A_1}{A_m}\right]}\right] \qquad \text{(Equation 3)}$$

Alternatively, the dielectric values can be obtained either by using known values reported in literature or by measuring the thickness in situ and using Equation 1 to calculate the dielectric value.

2 PULSE RADAR SYSTEM

The GPR system discussed in this paper (Figure 1) was developed by Pulse Radar, Inc., under an SBIR project with the ERDC. This system has multiple antennas that integrate two technologies, ground-coupled GPR and air-coupled GPR, to perform shallow and deep ground penetration. The Pulse Radar system is designed to be rugged, can collect data in the temperature range of -10 to 50 degrees Celsius, and can tolerate relatively high humidity, rain, dust, shock, and vibrations that are frequently encountered during field testing (Pulse Radar, 1995).

Figure 1: Pulse Radar GPR system developed under a small business innovative research program with the ERDC.

2.1 Data acquisition

The Pulse Radar system consists of three air-coupled antennas: a 1 GHz antenna that penetrates up to 1 meter, a 500 MHz antenna that penetrates up to 2 meters, and a 250 MHz antenna that penetrates up to 3 meters. There is one ground-coupled antenna of 100 MHz that can penetrate from 5 to 10 meters. As the frequency decreases, the depth of penetration increases, but the resolution of the data acquired decreases. The penetration depths are approximate and represent expected ranges for ideal materials and conditions.

The 250 MHz, 500 MHz, and 1 GHz antennas are air-coupled pulsed radar systems that can operate at speeds up to 50 miles per hour. Each system is bistatic in that they have two antennas, one for transmitting, and one for receiving. For the 1 GHz system, each signal, or trace, consists of a 1 nanosecond transmitting pulse, followed by 18 nanoseconds of receiving the reflected signals. Each trace for the 500 MHz system consists of a 2 nanosecond transmitting pulse followed by a 36 nanosecond period of receiving reflected signals. Both of these systems have the capability of acquiring data at a rate of 50 traces per second, but data acquisition is distance driven so the operator can specify the frequency of data collection.

A sample trace can be seen in Figure 2. Each peak in the trace represents a layer interface where there is a dielectric change between the two layers. The amplitudes of the peaks can be used to calculate the dielectric values of each layer by using Equations 2 and 3 discussed in the previous section. By using the time measured between the peaks, the calculated or measured dielectric value, and Equation 1, the thickness of each layer can be calculated.

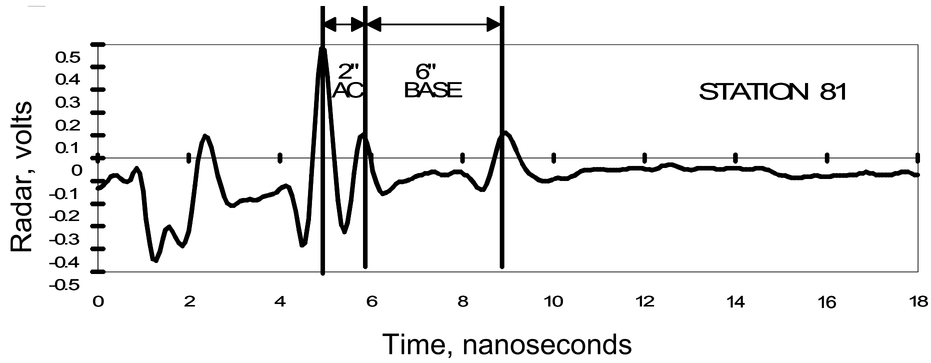

Figure 2: Sample trace of radar signal with each peak indicating a layer interface.

The Pulse Radar data acquisition program includes a metal plate calibration, which is a self-calibrating process where the metal plate reflection is measured. This process is performed prior to collecting data, and the metal plate reflection amplitude is used in post-processing to calculate the dielectric values. To decrease constant background noise, the data acquisition has an internal noise reduction option. To utilize this option, the signal is measured when the antennas are directed upwards towards the sky. This signal is then subtracted from pavement data collected to remove internal background noise.

As data is collected, it can be displayed real time in one of two methods. In the A scan method, each time-voltage trace is displayed individually as it is acquired. The other method is the B scan, which is a color-coded vertical stacking of the traces showing multiple traces on the same screen. This method of display requires the operator to set upper and lower bounds at which the peaks indicating layer interfaces occur. The layer interfaces are thus differentiated, and with the color coding, the operator can infer variations in thickness as data is collected. The A scan and B scan methods also can be displayed simultaneously, as shown in Figure 3.

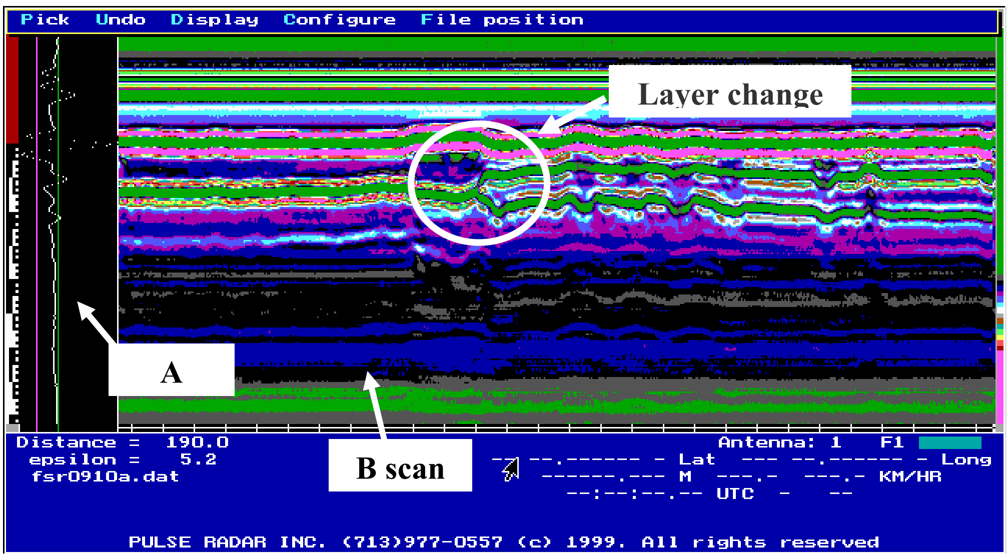

Figure 3: A-scan (individual time-voltage trace) and B-scan (color coded for visual layer identification) displayed simultaneously for data viewing.

2.2 Post-processing

The Pulse Radar system has post-processing software to calculate layer thicknesses and dielectric values. The operator can view data in the same display methods discussed in the previous section. Layer thicknesses and dielectric values are calculated using Equations 1-3 discussed in Section 1. Layer detection is performed by using a cross-correlation technique that compares the acquired GPR signal with an expected signal response waveform. At each position where the actual GPR signal shape correlates well with the expected signal, a peak is produced, indicating a high probability of a layer interface at that location.

As the GPR signal penetrates into the pavement, it is scattered and absorbed, thus causing the signal intensity to decrease as the signal travels through each layer. The signal response at the first layer is usually high, thus causing the GPR receiver to saturate. The result is that the remaining deeper layers become more difficult to detect. To correct for this, Pulse Radar has implemented a variable gain correction that will increase the signals from the deeper layers. This gain correction is a linear gain applied to the cross-correlation signal and is controlled by three parameters, the start, max, and slope. The start value is the constant at which the gain will start, the max value is the upper limit of the linear gain, and the slope is the rate that the gain will increase from the start to max value. The gain is not applied until ten samples after the first surface interface detection so that the signal will not be saturated.

3 USE OF GROUND-PENETRATING RADAR

GPR data presented in this paper was collected with the Pulse Radar system on test pavements at ERDC and actual airfield pavements. Structures beneath the surface of the pavement can be easily detected and pavement layer thicknesses can be determined with the Pulse Radar post-processing software.

3.1 Visualizing structures in pavement

When using the B scan display method, structures such as pipes, culverts, and utilities can be quickly and easily visualized in real time. Changes in the pavement layers can also be easily detected, as seen in Figure 3. Figure 4 shows the presence of a pipe and utility located beneath an airfield pavement as captured with the 100 MHz ground-coupled antenna.

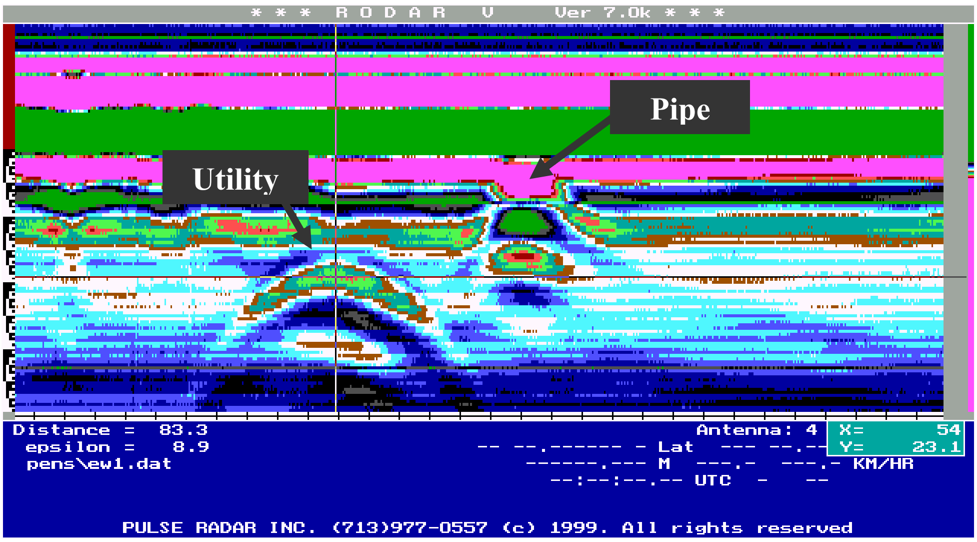

Figure 4: Detection of large pipe and utility located beneath the surface of a Portland cement concrete airfield pavement.

3.2 Verification

Thickness determination using GPR was verified for both asphalt and Portland Cement Concrete (PCC) pavement structures. The asphalt pavement structures were located within a test site at the ERDC. The test pavement consisted of three sections, each constructed with different layer thicknesses, as described in the following:

Table 1: Construction data for the asphalt test pavement

Section Number	Section 1	Section 2	Section 3
Layer 1 – Asphalt (inches)	4	4	4
Layer 2 – Aggregate Base (inches)	4	6	8

GPR data was collected with the 1 GHz antenna and verified with thickness measurements from cores taken at each section. Figure 5 shows the data for layer 1 processed with Pulse Radar's software and the same data corrected using one of the cores for "ground truth." In this case, the core at station 50 was used to calculate an accurate dielectric value, which was then used to recalculate thicknesses for all stations. In addition, the actual core thicknesses are plotted for comparison. The differences, or errors, between the GPR derived thicknesses and measured core thicknesses are shown in Figures 6 and 7. For the Pulse Radar software and internal plate calibration, the average difference between measured and calculated asphalt was 0.53 inches (range of 0.15 to 1.15 inches). When a core was used to calibrate the GPR data, the average difference was reduced to 0.20 inches (range of 0 to 0.45 inches). For the base layer, the average difference was reduced from 1.55 inches to 0.36 inches by utilizing a measured thickness. The accuracy of the GPR thicknesses for both the asphalt and base layers were significantly improved by the inclusion of a single core for "ground truth."

The rigid pavement tested for thickness verification was located on an in-service airfield. Tests were conducted along the 5300 foot length of the pavement facility with both the 1 GHz and 500 MHz antennas. An as constructed thickness of 14.5 inches of PCC was determined from construction records. Cores were extracted at various locations (200, 800, 2000, 3200, and 5100 ft) along the pavement facility to provide measured thicknesses for evaluating the accuracy of the GPR results. As with the flexible pavement, the measured thickness from one core location (station 2000) was used to adjust the GPR results. The measured thicknesses, computed thicknesses from Pulse Radar's software with internal plate calibration, and Pulse Radar's results adjusted using the core information from station 2000 are shown graphically in Figure 8. The differences between the measured thickness values and the GPR results are presented in Figures 9 and 10 for the 1 GHz and 500 MHz antennas respectively. The PCC-soil interface was clearly detected by both antennas, however, the higher resolution of the 1 GHz antenna produced more accurate results. The errors in the uncorrected 1 GHz GPR results ranged from 0.21 to 1.79 inches (average = 1.07 inches) and the core-corrected values ranged from 0.0 to 0.08 inches (average = 0.05 inches). The uncorrected 500 MHz GPR results were in error by an average of 2.10 inches, however, the average error in the corrected values was reduced to only 0.26 inches.

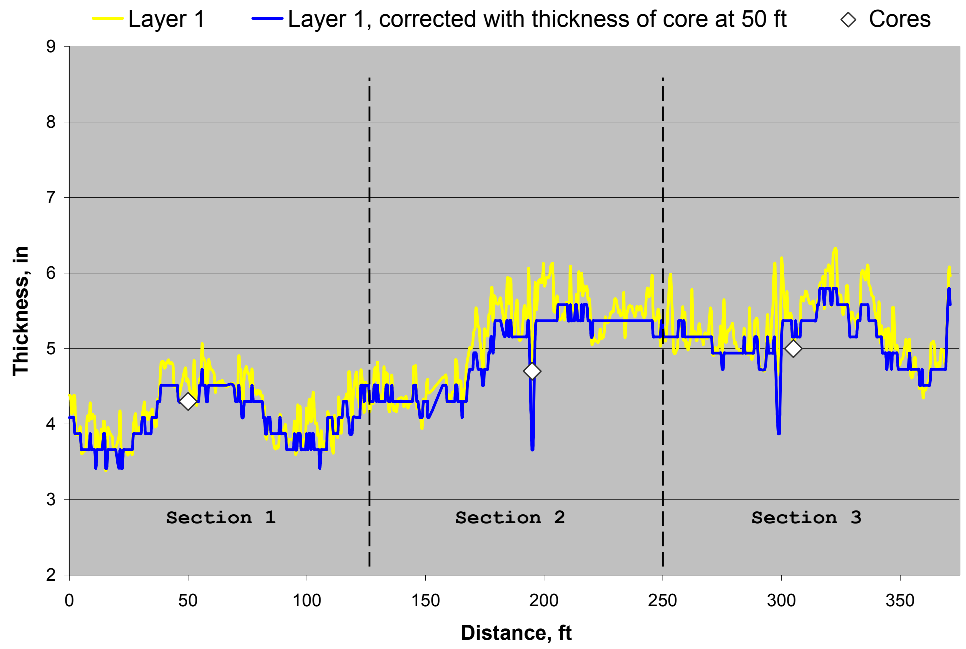

Figure 5: Layer 1 (asphalt) original and corrected thicknesses as determined from the 1 GHz antenna on the ERDC asphalt test pavement.

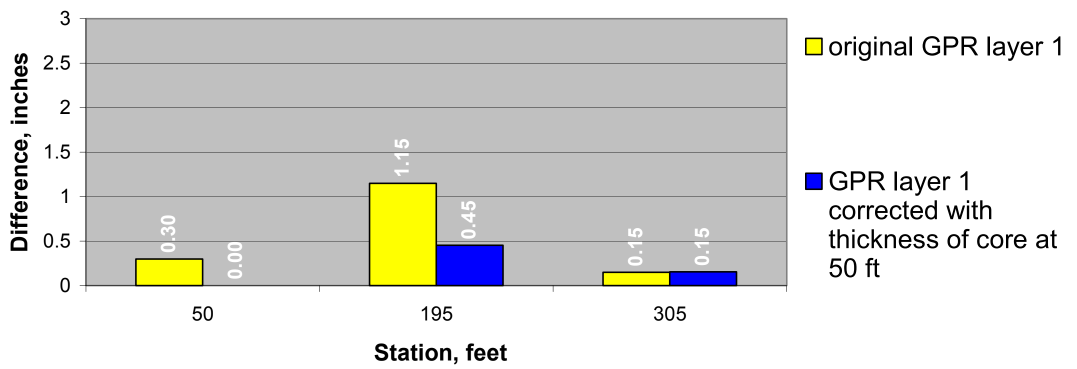

Figure 6: Difference between asphalt core thickness measurements and GPR thicknesses for the 1 GHz antenna on the ERDC asphalt test pavement.

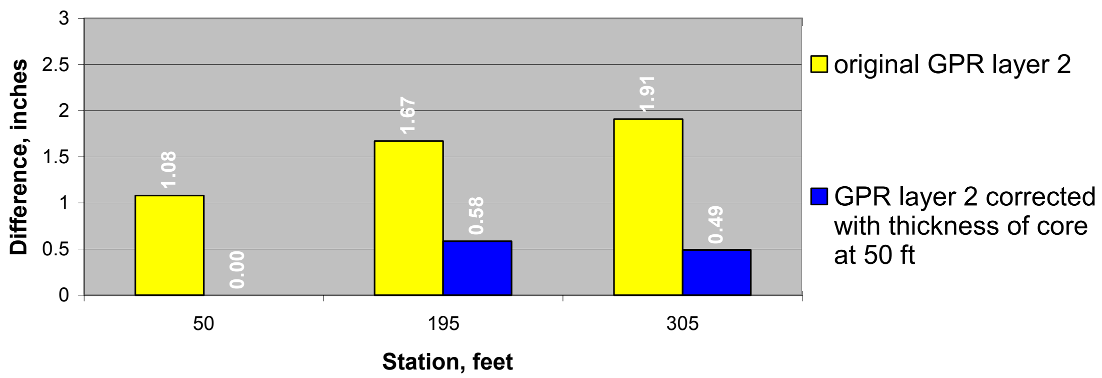

Figure 7: Difference between base layer core hole thickness measurements and GPR thicknesses for the 1 GHz antenna on the ERDC asphalt test pavement.

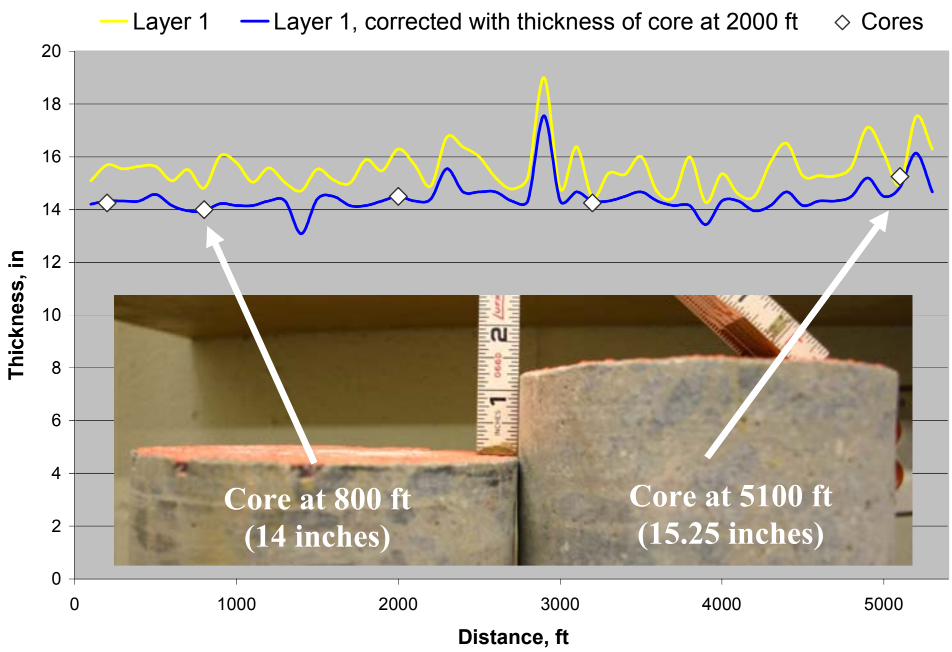

Figure 8: Layer 1 thicknesses as determined from the 1 GHz antenna on the PCC airfield pavement.

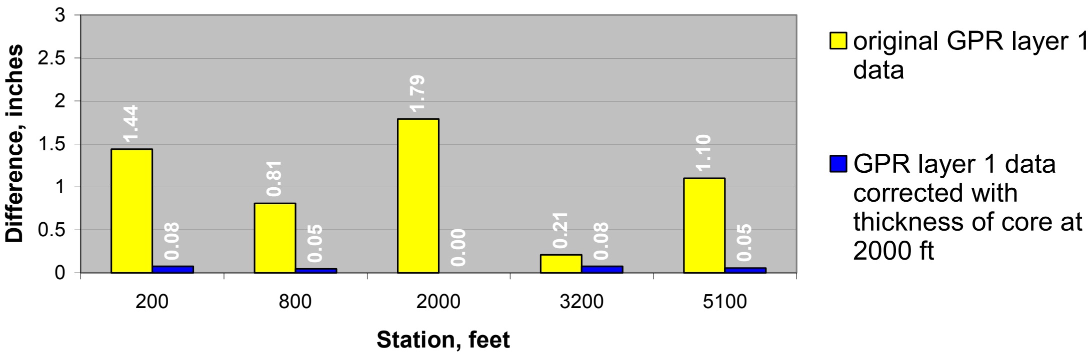

Figure 9: Difference between core thickness measurements and GPR thicknesses for the 1 GHz antenna on the PCC airfield pavement.

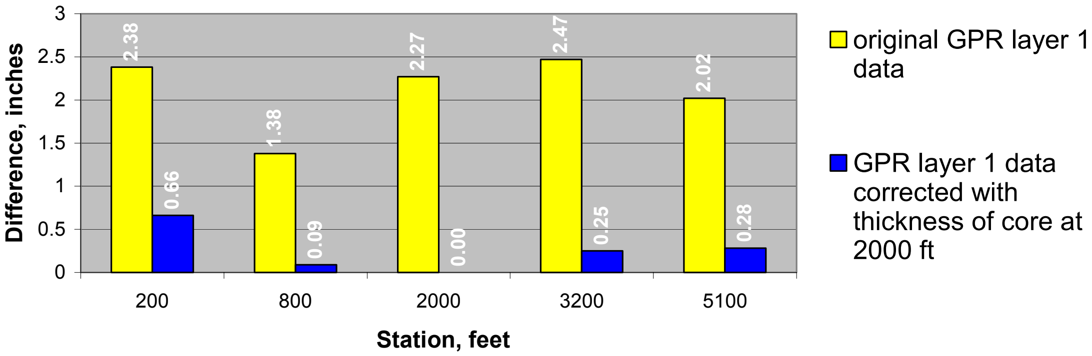

Figure 10: Difference between core thickness measurements and GPR thicknesses for the 500 MHz antenna on the PCC airfield pavement.

4 SUMMARY AND CONCLUSIONS

A multi-antenna GPR system specifically designed for pavement applications has been described in detail. Some conclusions, based on a limited amount of testing on flexible and rigid pavements, are presented below:

- The combination of a 1 GHz and 500 MHz antenna appears to provide both the resolution and penetration necessary for sampling most typical pavement structures.
- GPR has been shown to be a very useful tool in locating utilities. With the addition of the 100 MHz antenna, it is possible to identify drainage structures at depths of 3-10 feet.
- Use of GPR does not eliminate the need for some type of physical measurement of layer thicknesses. While Pulse Radar's proprietary software appears to do a very good job of detecting layers within a pavement structure, the GPR thicknesses can be significantly in error. The GPR thicknesses can be adjusted using a measured thickness (ground truth). The corrected thicknesses from the 1 GHz antenna for the pavements presented herein were very accurate. The flexible pavement surface and base layers were predicted within 0.4 inches and the rigid pavement surface layer was accurate to within 0.1 inches.
- GPR provides a means of collecting continuous information along the entire length of a pavement facility. This sampling resolution provides a high degree of confidence that changes in the layer structure will be detected.
- GPR is a viable tool that can be integrated with the falling weight deflectometer and dynamic cone penetrometer to provide a greatly improved pavement evaluation system. Incorporating GPR would provide the ability to optimize coring/DCP testing based on visual interpretation of the layer structures. This would greatly minimize the time required to conduct an airfield assessment. The use of layer thicknesses from GPR with the falling weight deflectometer data would result in more accurate backcalculated moduli and, therefore, more reliable predictions of structural capacity.

5 ACKNOWLEDGEMENTS

The tests described and the resulting data presented herein, unless otherwise noted, were obtained from research conducted under the Army Airfield Program of the US Army Corps of Engineers by the Airfields and Pavements Branch. Permission was granted by the Director, Geotechnical & Structures Laboratory, to publish this information.

The authors would like to thank Terry Jobe for his assistance with the data acquisition and processing.

REFERENCES

Scullion, T., Lau, C., and Chen, Y., 1994. *Implementation of the Texas Ground Penetrating Radar System.* Research Report 1233-1, Texas Transportation Institute, College Station, TX.

Pulse Radar, 1995. *Unpublished Technical Report*. Houston, TX.