Final Report

Improved Roadway Subsurface Thickness Measurements and Anomaly Identification with Ground Penetrating Radar

Florida Department of Transportation Research Project
Work Order #6, Contract #BC354

Submitted by

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To

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Executive Summary

The University of Florida Electronic Communications Laboratory has performed a research project for the Florida Department of Transportation (FDOT) designed to improve roadway subsurface thickness measurements and anomaly identification with the use of ground penetrating radar (GPR). The project began September 20 1999, was completed June 20 2001, and has resulted in a multisystem roadway analysis system, improved in-the-field data analysis capabilities, and an enhanced GPR evaluation software tool which organizes and processes multisystem GPR data for improved thickness measurements and roadway analysis capabilities. This final report summarizes work performed on the project in developing the system and software. An Operator's Manual for the software tool is included as an appendix.

Several significant accomplishments have been achieved on this project. The primary goals of the project, to develop an improved GPR data collection configuration, signal processing techniques, and software tools to detect and measure thickness of roadway surfaces and allow identification of anomalous regions using ground penetrating radar, have substantially been met. Collection and processing speed limitations for the multiple system configuration place emphasis on project level roadway analysis. The outputs of the software include time location, depths, and dielectric constants to layer interfaces. This type of information can be of significant use to operators who assess the nature of subsurface pavement anomalies and potential problem areas.

In summary, the new GPR data collection configuration and the GPR software and analysis tool will improve FDOT capabilities for the non-destructive evaluation of potentially serious roadway problems at primarily the project level so they can be corrected before they become costly. The software environment will also aid in future road designs and improvements by providing rapid non-invasive measurements of new subsurface roadway designs.

1.0 Introduction

The University of Florida Electronic Communications Laboratory has performed a project for the Florida Department of Transportation (FDOT) to improve the performance of the department's ground penetrating radar (GPR) for non-destructive evaluation of roadways. The project title is "Improved Roadway Subsurface Thickness Measurements and Anomaly Identification with Ground Penetrating Radar", contract #BC354, work order #6. This is the final report.

Specific improvements were needed in the accuracy of subsurface thickness measurements, anomaly identification, and techniques to reduce operator interaction in GPR data collection and processing. This project addressed this need with modest improvements to the hardware and signal processing software of the existing department equipment and assets. To achieve these goals a two-antenna, ground-coupled array was added to the existing air-launched antenna on the GPR van for multi-path data collection. Fusion of data from both antenna configurations provides more accurate velocity and time measurements, resulting in improved subsurface measurements and identification of certain anomalies.

This final report lists the overall tasks for the project and then details the work completed to implement these tasks.

The specific objectives and accomplishments of this project are as follows:

Task 1. Establish a working multiple antenna GPR system using the current FDOT radar vehicle.

A pair of ground-coupled antennas were added to the current FDOT Geophysical Survey Systems, Incorporated (GSSI) SIR 10-B radar system for operation in parallel with the Pulse Radar air-launched system. Two ground-coupled antennas are attached on skids behind the survey vehicle to provide the necessary multiple propagation paths and extend penetration depth while, at the same time, the Pulse Radar horn antenna gives the surface response and near-surface time resolution. The added GPR equipment was tested to ensure operation with the existing FDOT GPR equipment. Data collection methods to synchronize the operation of the Pulse Radar and GSSI systems were designed and installed so that data is co-located between the Pulse Radar and the GSSI system. Details of this task are discussed in Section 2.0.

Task 2. Obtain GPR data with accurate ground truthing using the implemented multiple antenna hardware.

GPR data from actual roadways is difficult to utilize in the development of layer interface detection algorithms. When cores are taken, the data from actual roadways is usually collected statically over non-homogeneous layers. The non-homogeneous layers often contain large rocks (relative to the thickness of the individual layers) that will disturb the accuracy of the results. To mitigate these and other problems, the ECL used a testing area at the ECL that allows for the stacking of clean, homogenous slabs of three different mediums in approximately 0.5” increments. The test area was used to:

- Determine the proper setup of the internal triggering of the GSSI radar for the two separate channels
- Calibrate GSSI and Pulse Radar detection algorithms for calculating depth and dielectric constant
- Provide a surface without large internal disturbances (rocks)
- Provide a variable layer thickness greater than the wavelength of the radar
- Provide a known and repeatable test setup

Details of this task are discussed in Section 3.0.

Task 3. Develop signal processing algorithms that fuse the data from the multiple antenna systems.

Signal processing research, using data collected with the new combined system configuration and the test area at the ECL, was performed and algorithms were developed to accurately calculate dielectric constant estimates and make subsurface layer thickness estimates. Details of this task are discussed in Section 4.0.

Task 4. Develop signal processing algorithms to integrate the fused data into existing roadway GPR software for analysis.

With the implementation of Task 3, the fused data was integrated into a new roadway GPR software environment so that roadway layer interfaces can be identified and tracked. Once the layer interfaces are tracked, they can be graphically edited and physical parameters of the data extracted and viewed for pavement analysis or management. The new software environment has many new features that are outlined further in this document. Details of this task are discussed in Section 5.0.

Task 5. Achieve signal processing capabilities on board the current FDOT radar vehicle to allow for in-the-field measurements and analysis of both roadway and geophysical GPR data.

An on-board PentiumIII class computer was added to the GPR van, with a year 2000 compliant operating system, large hard disk storage, and improved GPR signal processing software. This new computer now provides the FDOT with the ability to do in-the-field signal processing for GPR. The new computer is capable of advanced signal processing tasks and provides a hard disk sufficient to accommodate more than 10,000 miles of unprocessed road data. Data is transferred between computers and radar systems via Iomega zip disks and data can be downloaded from the new computer to other FDOT computers for off-line analysis. In addition to providing significant upgrades to the roadway GPR system, the addition of the on-board computer allows improvements to the field analyses of geophysical data obtained with the SIR-10 GPR. This permits the hardware added on this project to have dual uses and significantly leverages the FDOT GPR resources. Details of this task are discussed in Section 6.0.

Task 6. Establish tests to verify the operation of the designs and investigate techniques for thickness measurement, void, and anomaly identification.

Upon the completion of the previous tasks, verification of the complete system was conducted. As a part of the verification of the system, the collected data was investigated for correlation of extracted parameters to physical characteristics, such as pavement layer thickness, that is used for roadway design and maintenance planning. Details of this task are discussed in Section 7.0 and Section 8.0.

2.0 Multiple System Hardware Integration

In order to establish a working multiple antenna GPR system, it was necessary to modify the current FDOT GPR van and radars. Great care was taken to ensure that none of the changes would negatively affect or limit the previous capabilities of the FDOT GPR assets. The multiple system hardware integration included the mounting of the new antennas, adding an alternate power supply, and synchronization of the Pulse Radar and GSSI systems.

2.1 Mounting of New Antennas

The two GSSI antennas are mounted on skids that are designed to be pulled across paved or unpaved surfaces. The antennas and skids were joined together by the ECL at a fixed separation to maximize the accuracy of measured GPR data. The antennas are attached to the rear of the van using one of two standard trailer hitch receiver tubes located in the wheel path. The antennas are detachable and can be used with any standard tailer hitch that utilizes a receiver tube. When the antennas are attached, a rod is passed through the receiver tube and pinned securely in place. The placement of the two antennas in the wheel path allows for the Pulse Radar and the GSSI radar system to be attached at the same time and data collected from the same physical location. The co-location of the data is accomplished by placing the Pulse Radar and GSSI antennas three feet apart and triggering the radars every foot. The ECL developed software takes the antenna offset into account when importing two-radar system data and aligns the traces from both radars such that they correspond to the same physical location.

Crosstalk between the two systems was a concern and testing was done to ensure that no interference between the two systems occurred. Details of these studies are detailed in the progress reports.

2.2 Power Supply

Errors in the Distance Measuring Instrument (DMI) circuit were observed when the power system in the van was under a heavy load. The power system in the van does not appear to be capable of powering all the systems at once without causing the to DMI measure distance incorrectly. The ECL worked with the FDOT SMO and two solutions were proposed. The GSSI system is to be run off of a 12 volt marine battery or other non-essential systems in the van will be turned off when operating the GSSI and Pulse radars. Both of these methods of power management allow for collection of GPR data with the two radar systems at the same time. The ECL purchased a 12 volt marine battery with a case and a trickle charger for use in the FDOT GPR van. The ECL also purchased and modified a special cable from GSSI in order to operate the GSSI system from battery power.

2.3 Synchronization

In order to co-locate GPR data from the same physical location, it was necessary that both radars be triggered at the same time. The ECL designed a special circuit that adapts the triggering signal from the DMI used by the Pulse Radar so that it can be used by the GSSI system. The trigger signal is fed into the survey wheel input of the GSSI system. A special buffer circuit ensures that the Pulse Radar triggering signal is not corrupted by the GSSI system. The offset of the two system antenna positions is accounted for in ECL developed software, which takes the antenna offset into account when importing two-radar system data. The software aligns the traces from both radars such that they correspond to the same physical location.

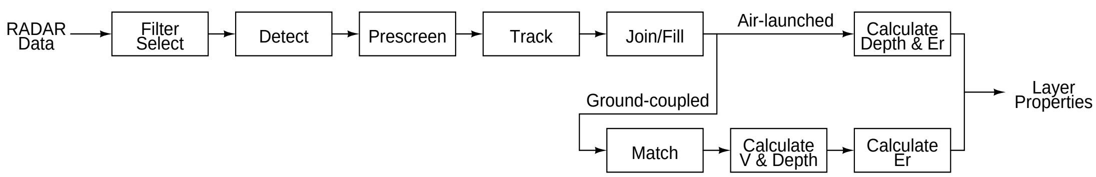
3.0 Ground-truthed Measurements

Development of signal processing algorithms and calibration of the GSSI system required precisely ground-truthed data collections from a range of homogenous dielectric materials over a range of thicknesses. The necessary ground-truthed data was manufactured in an ECL GPR test area using three homogenous materials having three different dielectric constants. Sections of 0.5” thick thin-wall concrete were stacked and measured in 0.5” steps up to 10”. Sections of 0.625” thick, fine-grain particle board were stacked and measured in 0.625” steps up to approximately 15”. The third material used was wallboard, which was stacked and measured in 1.0” intervals up to 24.0”. These three materials provided a homogenous medium which was easily varied in small, accurate thickness intervals for collection of data from a precisely ground-truthed configuration.

4.0 Signal Processing Development

Processing of GPR system profiles (measured GPR response that represents the subsurface) involves many steps to automate the computation and presentation of the results discussed previously. Many of these steps are similar in nature, independent of radar type or configuration, and may therefore be utilized with calibration as a general purpose functional processing block. Other steps require algorithms that are tailored for specific systems or configurations. The processing flow, as indicated in Figure 1, has been designed and implemented in a modular fashion to facilitate algorithm development and comparison in a flexible structured format. Steps are described in the following sections.

FIGURE 1. GPR Processing Flow Diagram



4.1 GSSI Dual-antenna Processing

Steps in the processing of GPR data from the dual-antenna ground-coupled GSSI system are described in the following sections. Some of these are similar or identical in nature to the processing of air-launched data, but several steps require unique processing due to the dual-antenna method of velocity estimation.

4.1.1 Filter Selection

Filter selection involves acquiring a model of the transmitted waveform for use in detection processing. While this is easy for air-launched systems, since the reflection from a metal plate may be used as the necessary waveform, ground-coupled systems present more of a challenge due to problems with making such measurements with an antenna that is sitting directly on the surface. To solve these problems, an adaptive filter and modeled data generated from ground-truthed testbed data were used to optimize an estimate of the measured waveform. Estimates were also made by collecting nearly isolated returns from a metal plate under the homogenous materials used for ground-truthed collections. This estimate and the adaptive filter estimate produced similar results. The adaptive filter estimate was selected and is used for ground-coupled detection processing.

4.1.2 Detection

Detection is the process of determining the location of legitimate returns from subsurface objects in the measured radar return. Matched filtering is used for this stage of the GPR processing. A matched filter is used to maximize the signal-to-noise ratio (SNR) of the received GPR waveform. The matched filter response, as shown in Figure 2, exhibits peaks which correspond to returns from each layer; however, there are also peaks resulting from sidelobes of the transmitted waveform. Valid peaks are considered to be the “peak of the peaks" in the matched filter response. To autonomously determine the appropriate detect locations, a Hilbert envelope of the matched filter response is calculated (Figure 3). This enveloped signal has only one peak for each valid detect. These locations are determined by finding the zero crossings of the signal's derivative (Figure 3). The peaks of the matched filter response are found using the same derivative-based technique. Peaks in the matched filter response that correspond to peaks in the envelope response are determined to be the desired interface detect locations, as demonstrated in Figure 4.

FIGURE 2. Matched filter response.

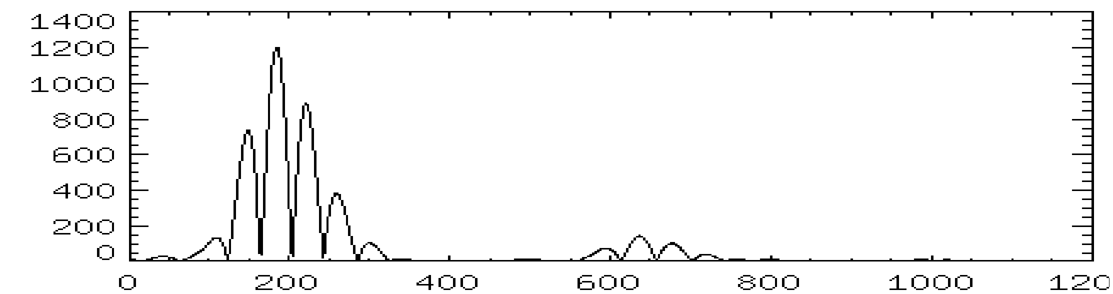


FIGURE 3. Enveloped response with peaks indicated.

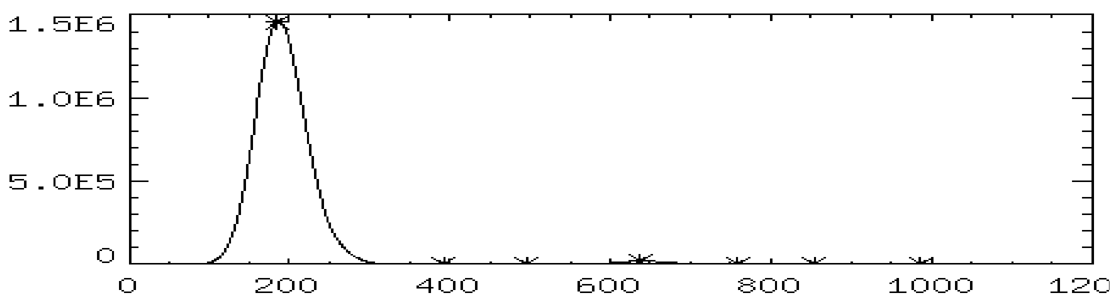
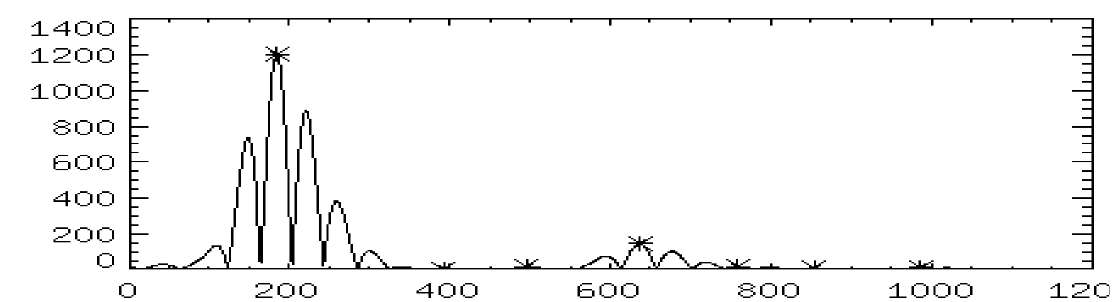


FIGURE 4. Matched filter response with peaks that correspond to peaks in the envelope response.



4.1.3 Prescreening

Detects of interest in the roadway processing application are from layers of the roadway. Once detection has been completed, detections must be segmented according to the layer interfaces that caused them. However, to improve the computational efficiency and performance of the segmentation/tracking algorithms, methods of rejecting detects that do not belong to any substantial layer interface are utilized. These rejected detects are considered to be clutter. To reject clutter, features of each detect are computed. A classifier is then used to determine which detects do not have properties of legitimate layers and are, therefore, clutter.

Classifier performance is dependent on the separability of classes in some feature space. It is, therefore, desirable to achieve some set of features which provide easy separation of layer detects from detects resulting from clutter. Two features have been chosen for GPR detect classification/clutter rejection. A detection confidence feature is calculated to provide an indication of the validity of each detect based on returned signal strength with accommodation for signal attenuation through the subsurface medium. The second feature considers the spatial characteristics of the surrounding detect pattern and indicates the degree to which the shape fits that of a layer. The two features provide clustering in the 2-D feature space which allows separation of clutter. The features are supplied to a K-means Classifier which autonomously separates the clusters by maximizing the average distance between an assumed number of cluster centers.

Detects classified as unlikely returns from a well-defined layer are considered clutter and rejected, while the good detects are retained for further processing. This improves processing results and speed of succeeding processing stages.

4.1.4 Tracking

To facilitate the goal of processing layers as distinct artifacts, detects must be segmented and labeled according to layers. This is the function of the tracking algorithm. Detects which were not rejected as clutter are grouped together by layer. This is a very labor intensive task in manual GPR interpretation. Automation by computer greatly improves the efficiency of GPR analysis.

The tracking algorithm iterates through each detect in the GPR data and looks to associate other detects from the same anomaly or layer interface. Other detects are found by looking ahead (increasing cross-range distance) of and above and below (down-range time) the current detect being tracked. The distance/time that the algorithm looks in cross-range and down-range is defined by the operator. If another detect is found in the box created by the cross-range and down-range parameters, the two detects are assigned the same track number and the newly associated detect is used as a starting point to look for additional detects to associate. If another detect is not found, the tracking of the interface or feature is considered complete and the current track number is incremented so that the next detect used by the tracking algorithm begins a new track with a unique numeric identifier. This process continues until all of the detects are tracked.

4.1.5 Fill/Joining

After tracking is completed, there are often several separate tracks that can be identified as belonging to one consistent layer interface. Breaks in the tracks are often due to misclassification of detects by the clutter rejection algorithm because tracking assigns track labels only to those detects that are not classified as clutter. Fill and join algorithms were designed to improve the results of succeeding processing stages by improving the continuity of tracked layers. Track joining and filling works by considering the clutter detects as potential layer interfaces and assigning track labels where appropriate. By reassigning labels to these misclassified detects, track segments can be automatically joined together and filled in. The joining algorithm starts by performing an euclidian distance search for nearby detects at the end of each track segment. The search is performed inside a windowed area determined by the tracking parameters selected. If non-tracked detects are found, the search begins again at the closest detect location. When another track segment is found it is relabeled with the track number belonging to the segment where the search was initiated. If no detects or tracks are found, the search moves to the next track segment. Track filling uses a windowed search from the start to end of each track segment to attempt to fill in any discontinuities along the length of the track segment with either shorter tracks or detects classified as clutter. The algorithms automatically correct many imperfections in the tracked layer interfaces, thus creating longer more continuous layers.

4.1.6 Matching

Matching is a processing stage that is unique to the dual-antenna system. Layer dielectric constant is determined by utilizing time measurements through two wave propagation paths in the two-antenna system. This requires detected layers in the data from one antenna to be paired together with the corresponding detected layer in the data from the second antenna. This process has been dubbed "matching". An algorithm has been designed which autonomously performs this pairing based upon acceptable locations according to a range of possible dielectric values.

Calculations, given the system geometry, were performed to determine the range of acceptable delays between channels versus direct channel sample time for an assumed range of dielectric values. From this range of acceptable delays between channels, the minimum cross channel offset, as shown in Figure 5, was determined. This curve illustrates the offset position of the matching window in the cross channel with respect to the sample position in the direct channel. The matching window size is also determined from the range of acceptable delays (Figure 6). The position of tracked detects in the direct versus cross channels is compared to determine match pairs. The algorithm biases matching toward the lowest dielectric value possible when finding the detect pairs.

FIGURE 5. Cross channel offset versus direct channel sample index.

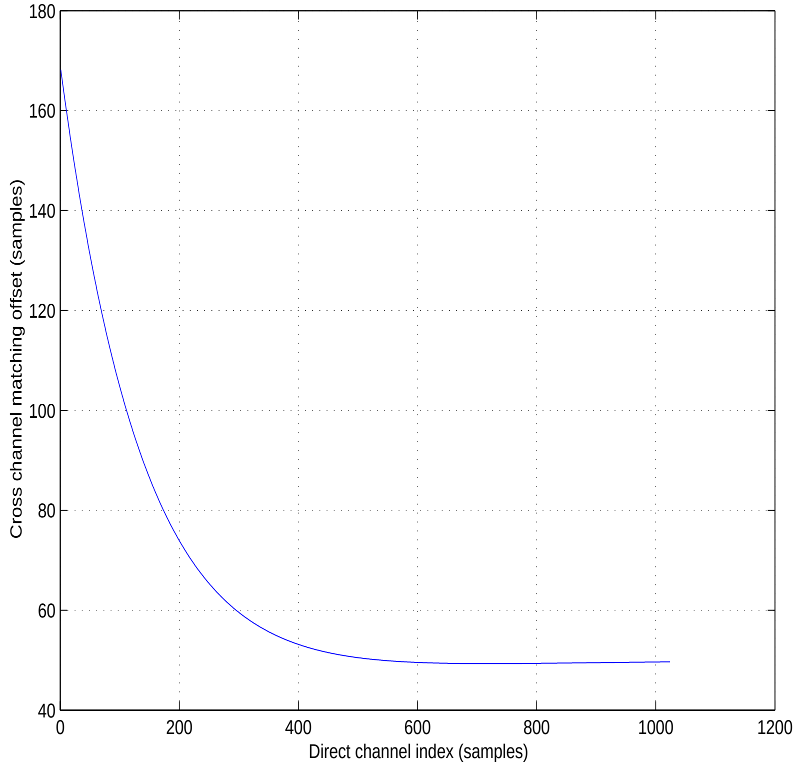
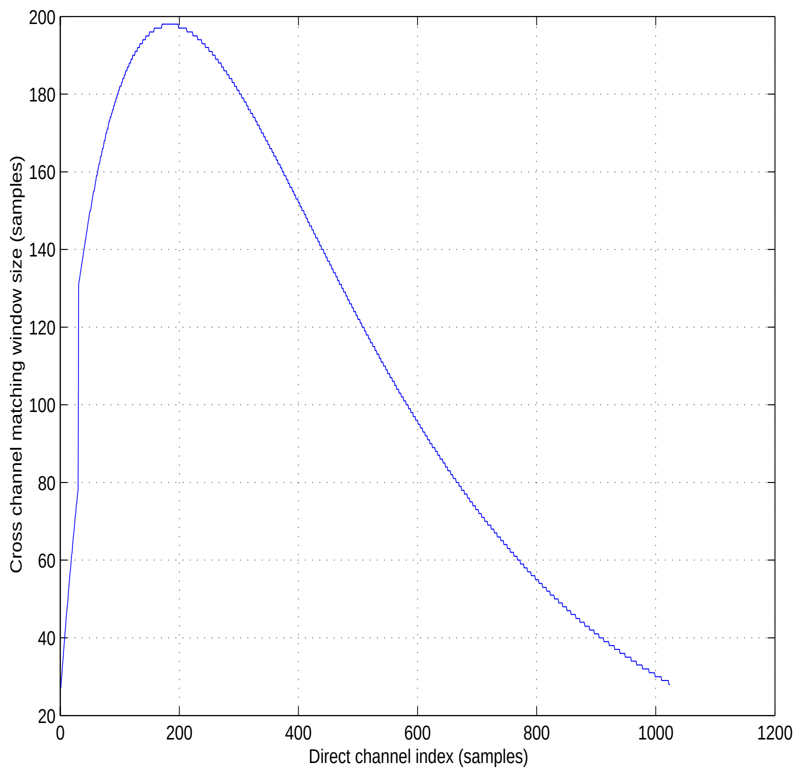


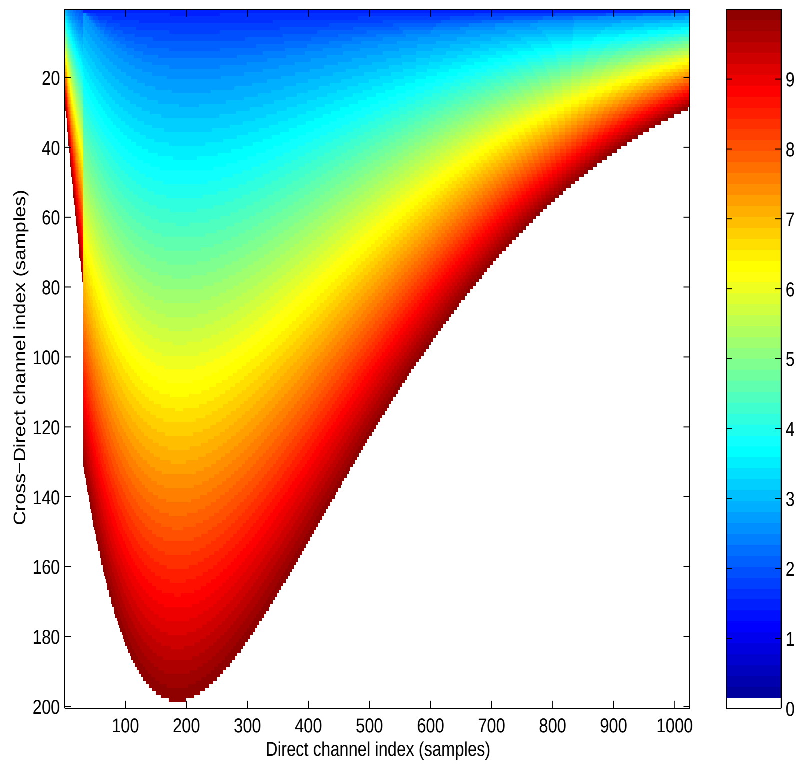
FIGURE 6. Matching window width versus direct channel sample index.



4.1.7 Depth Calculation

To calculate the depth of each matched pair of detects, the detect index location in the two channels are used to reference a calibrated matrix--generated from testbed measurement calculations--of average dielectric values, which are unique for a given pair of channel propagation times. This average dielectric constant is then used to determine the average velocity of the radar signal to the interface of interest. From this velocity and the time through either channel, the depth to the interface is computed.

FIGURE 7. Dielectric reference matrix.



4.1.8 Layer Dielectric Constant Calculation

A parameter of interest is the dielectric constant, Er, of each detected layer. Only the average dielectric constant to each interface has been computed (to this point in the signal processing chain) because the time to each interface, as measured by the GPR, is a function of the average velocity of wave propagation to the interface of interest. The dielectric of the medium above an interface is, however, often more useful information than the average dielectric of all mediums above the interface. For this reason, an algorithm has been written that uses an iterative method, starting with the first layer and working down, to calculate an estimate of the dielectric of each individual layer. The algorithm assumes that the first matched pair in a given trace (a single GPR measurement of the subsurface at one location--sometimes called a profile; although, a profile may sometimes refer to a succession of traces stacked together to represent an area of the subsurface) is from the first-to-second layer interface; thus the average dielectric constant is equal to the actual dielectric of the first layer. Once the first layer parameters have been established, the next layer (matched pair) is addressed. Given the depth and average dielectric to the each interface and preceding layer, the dielectric constant of the layer may be calculated using equation 1 and equation 2. This process is successively followed for each interface in a trace.

$$v(n) = \frac{[d(n) - d(n-1)] \times v_{avg}(n) \times v_{avg}(n-1)}{d(n) \times v_{avg}(n-1) - d(n-1) \times v_{avg}(n)} \qquad \text{, where } v \text{ is velocity and } d \text{ is depth} \tag{1}$$

$$\varepsilon_r(n) = \left[\frac{3.00 \times 10^8}{v(n)}\right]^2 \qquad \text{, where } \varepsilon_r \text{ is the dielectric constant for layer } n \tag{2}$$

4.2 Pulse Radar Air-launched Processing

Many of the processing stages for the air-launched Pulse Radar system are similar to those of the ground-coupled system. However, there are some differences that will be noted.

4.2.1 Filter Selection

Filter selection for the air-launched system may be determined by directly measuring the transmitted radar waveform. This is easily accomplished by placing a flat metal plate on the roadway surface and collecting a GPR return. The measured signal is an excellent representation of the waveform for use as a matched filter.

4.2.2 Detection Improvements

Detection uses matched filtering similar to the processing for the ground-coupled system. The algorithm is also similar to that used in a previous FDOT air-launched system project; however, improvements in performance of the detection processing stage were made during this project. The algorithm no longer assumes some fixed number of returns. Modifications were made to automatically determine the number of detects in each trace.

4.2.3 Prescreening

Prescreening is performed in an identical manner to that used in the ground-coupled system. This stage improves the performance of the air-launched processing over previously used software by rejecting clutter returns before the tracking processing stage.

4.2.4 Tracking

Tracking for both the ground-coupled system and the air-launched system are identical (processing mentioned in earlier section) and use a derivative of the technique developed and employed for a previous FDOT air-launched system project. Improvements on the technique during the course of this project have improved the performance of the algorithm. Tracking speed has been improved, and modifications were made that reduce the number of erroneous tracking phenomena.

4.2.5 Fill/Joining

Fill and Join algorithms are identical to those used in the ground-coupled system processing. These algorithms greatly improve analysis efficiency and system performance due to the improvement in track continuity.

4.2.6 Calculation of Dielectric Constant

Calculation of dielectric constants and depths of layers is performed using algorithms that were initially developed under a previous FDOT air-launched GPR system development project. The code utilizes amplitude ratios of the detected returns to estimate dielectric constants and subsequently propagation velocity.

5.0 Multiple System Software Integration

Data from multiple radar systems are fused into a single distance-synchronized collection for processing and analysis. This is accomplished through a common file format and a multiple data set, integrated software environment.

5.1 Common Data Format

Data from the GSSI and Pulse Radar systems has been translated into a common data file format based on the standard tagged image file format (TIFF). TIFF provides a platform independent standard image format and is extendable to allow the inclusion of an unlimited amount of special purpose GPR specific data. Conversion from the native GPR formats to TIFF is performed automatically when cataloging GPR data with the software tools provided to the FDOT. This file format allows complex image manipulation to be performed without compromising the integrity of the GPR data. TIFF also has the benefit of being compatible with most image viewing software.

5.2 Software Environment Enhancement

The GPR Signal Processing Environment is designed to provide intuitive handling, visualization, processing, and analysis of GPR data acquired from multiple radar systems. The software facilitates intelligent database storage of the vast amounts of multi-radar data collected for each GPR analysis project. It provides for enhanced display of GPR profiles and processing results. The GPR environment also provides graphical control of GPR processing algorithms. Image and text based output capabilities are included for efficient documentation of GPR analysis results.

5.2.1 Collection Management

The ECL designed GPR software environment utilizes a database to store and catalog data collections. This database aids the users in organizing the data so that it can be located and processed easily, and allows for systematic evaluation. This is especially important for collections that contain data from multiple GPR sources. Additionally, when GPR data is imported into the database, it is converted from its native format to TIFF. TIFF provides a standard image format yet allows inclusion of an unlimited amount of special purpose GPR specific data.

The database is organized by county, date, roadway ID, and mile markers. Comments can also be added that further describe any other desired collection condition information. The software tool provided to the FDOT, for importing GPR data into the database is shown in Figure 8.

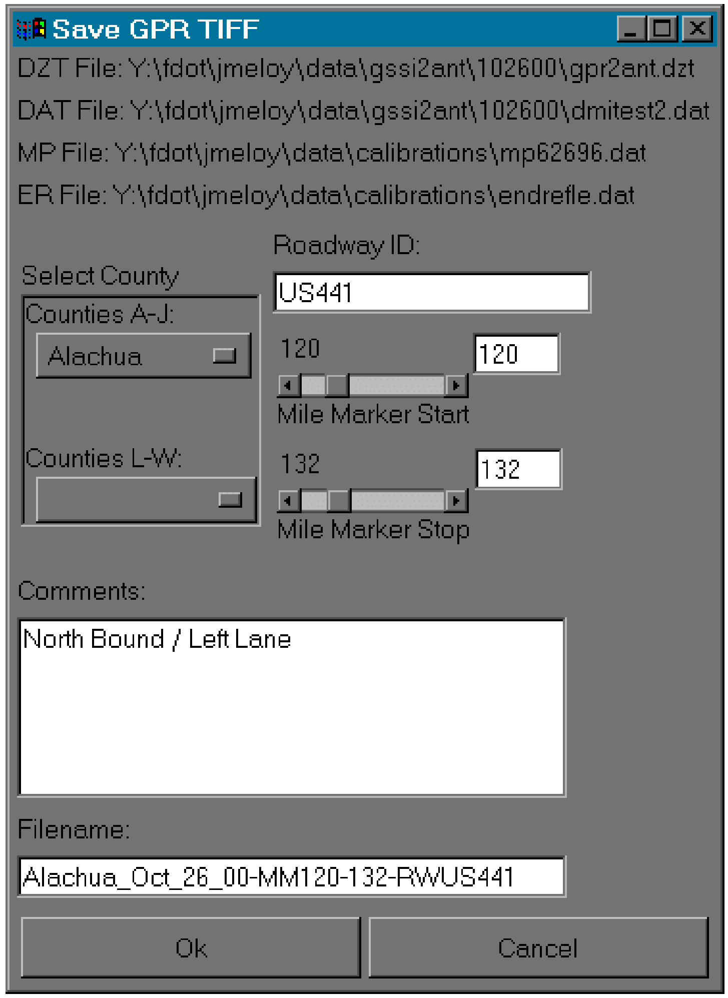
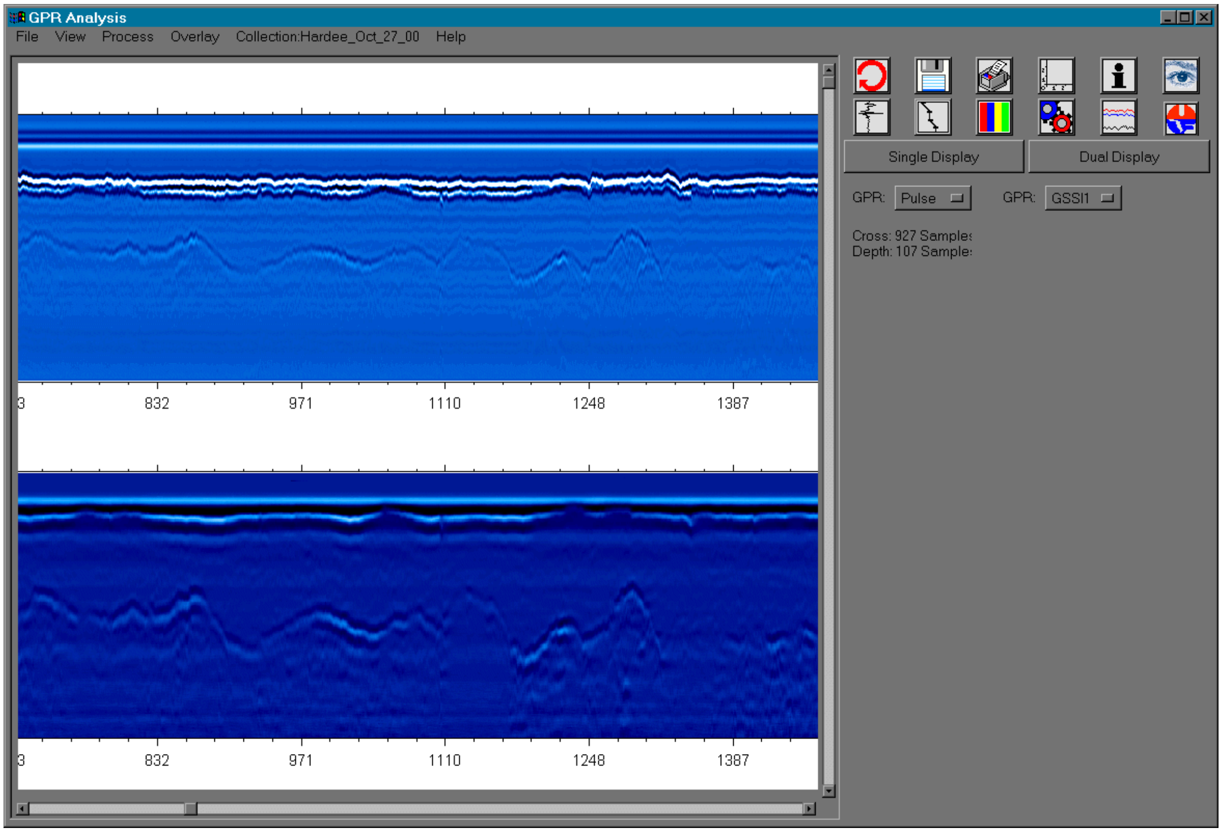


FIGURE 8. GPR Data Conversion Interface

5.2.2 GPR Visualization

The most prominent feature of the GPR analysis software is the GPR image display. GPR images are formed by aligning the received waveforms. Separate TIFF files are generated for cataloging data from all GPR systems used for each collection. Each TIFF file allows the raw waveforms to be saved along with a lower resolution image that is used for display purposes only. Software users can manipulate the images in a number of different ways as needed to better visualize subsurface features in the GPR data. The single display provides GPR image detail enhancement, while the dual display allows for GPR image comparison as shown in Figure 9.

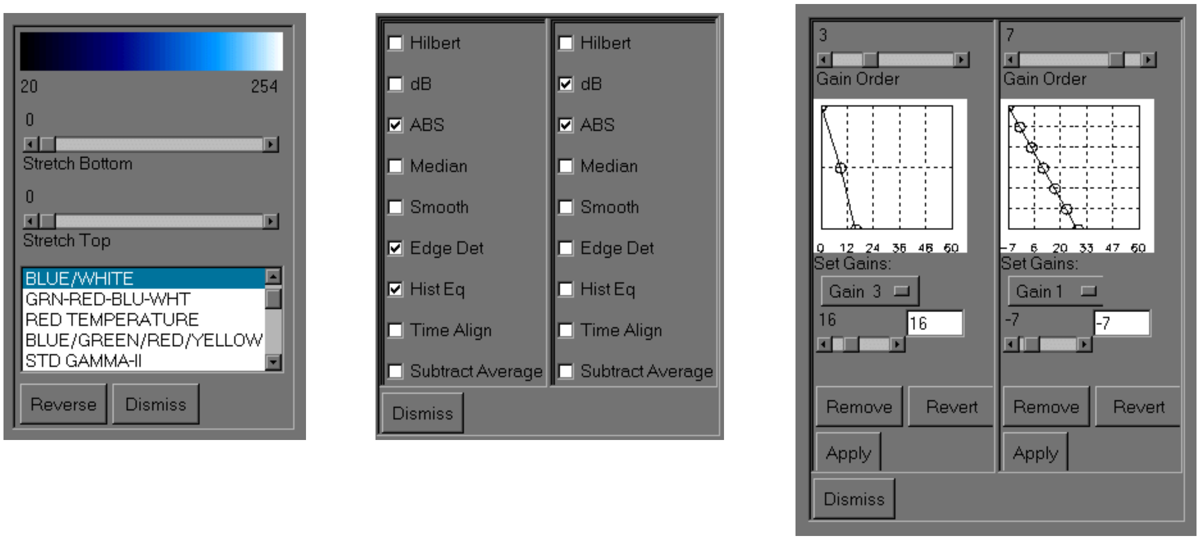
FIGURE 9. GPR Analysis Software



5.2.2.1 Color, Image Enhancement, and Gain Adjustment Options

Skilled GPR operators can often identify subsurface features using GPR by recognizing specific characteristics in the data. Computer algorithms are good at assigning numerical values, such as depth, to GPR data, but the trained GPR operator can usually outperform the best algorithms at recognizing structures and trends in the data. The GPR analysis software provides tools to allow color contrast adjustment, image enhancement, and gain function manipulation. These tools can assist so that subsurface features can be recognized more easily. These tools modify the appearance of the GPR image, but do not affect the saved GPR waveforms. The interfaces for these and most other functions provided with the GPR analysis software are provided as plug-in modules that are displayed to the right of the GPR image display. The interfaces for the color, image enhancement, and gain adjustments are shown in Figure 10.

FIGURE 10. Interfaces for Color Manipulation, Image Enhancement, and Gain Adjustments



5.2.2.2 Profile and Frequency Plots

Another plug-in component, Figure 11, allows profile and frequency spectrum plots. To display plots of the profile of the radar waveform, the image display, or the frequency spectrum of the radar waveform, the mouse is used to position the cursor on the desired location of interest in the GPR image display. The amplitude scale slider can be used with the profile plots to set the range of the x-axis. The autoscale option simply sets the slider to the maximum amplitude possible for the profile selected.

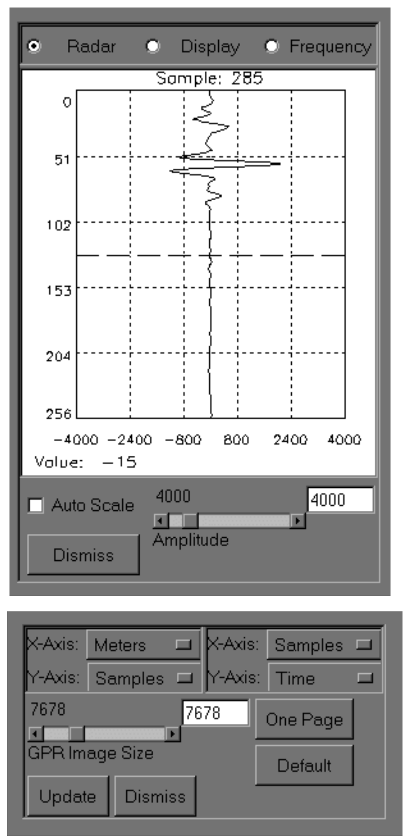


FIGURE 11. Profile and Frequency Spectrum Interface, and Axis Scaling and Labeling Interface

5.2.2.3 Axis Scaling and Labeling

Axis-scaling and labeling is controlled using another plug-in component, Figure 11. By default, the size of the GPR image displayed is in proportion to the number of received waveforms collected, one column of pixels represents one received waveform. Software users can scale the axis to control the size of the image, which can be useful when interpreting processing results. The one-page button re-scales the entire GPR image to fit on a single page, which can be useful when obtaining snapshots of the GPR image. The units used for axis labeling are controlled by a series of menus.

5.2.3 Processing Control

Interface layer detection and tracking is performed using a number of different algorithms that operate on the GPR data in a sequential order. Tracking performance is controlled largely by the two parameters that control the search space used for the tracking algorithm. The ideal settings for these parameters are largely dependent on the structure and spacing of the subsurface layers in the ground, so allowing user adjustment of the parameters can provide for better tracking performance. When processing GPR data the software user is presented with two sliders, as seen in Figure 12, to control the cross range and down range search widths. After processing, the parameters used are saved as a processing control file and the processing results are saved to a file. The parameter settings for subsequent data processing can be set automatically by importing the parameters from previously saved control files.

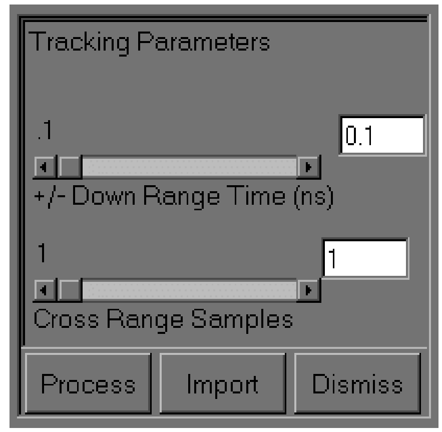


FIGURE 12. Processing Control

5.2.4 Results Presentation

Another plug-in component, Figure 13, is used to display processing results. This plug-in allows the software user to display processing results overlaid on the GPR image, plotted versus depth or plotted versus relative dielectric permittivity. If the data set has been processed a number of different times using different tracking parameters, the parameter menu is used to select which processing results file to use. The text window near the bottom of the plug-in displays the tracking parameters used for the parameter set selected.

Several different buttons and sliders are used to display the processing results. The confidence slider and minimum track length sliders are used to pare the results displayed. Buttons are used to select the display desired and the associated color, and are defined as follows:

- Tracks - Displays detects classified as tracks by the clustering algorithm that have an extent greater than the setting for minimum track length,

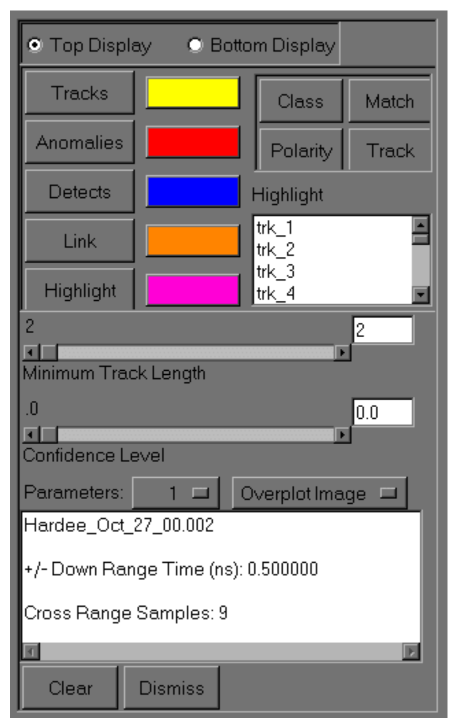


FIGURE 13. Results Presentation

- Anomalies - Displays detects classified as tracks by the clustering algorithm that have an extent less than the setting for minimum track length,
- Detects - Displays detects not classified as tracks by the clustering algorithm,
- Link - Displays a connecting line between all detects in each displayed track,
- Highlight - Displays the selected tracks from the list to the right of the “Highlight” button (Figure 13).

A secondary set of buttons can be used to display the results from the intermediate processing stages and are defined as follows:

- Class - Displays detects color coded according to classification assigned by clustering algorithm, green and cyan are clutter (non tracks),
- Match - Multi-channel GPR only, displays the match used for determining time difference measurements in a rotating color scheme,
- Polarity - Displays the detects according to polarity, green for positive, red for negative.
- Track - Displays all tracks in a rotating color scheme.

Figure 14 - Figure 18 show examples of each of the presentation display features in more detail. Each figure gives an explanation of the displayed feature in its caption.

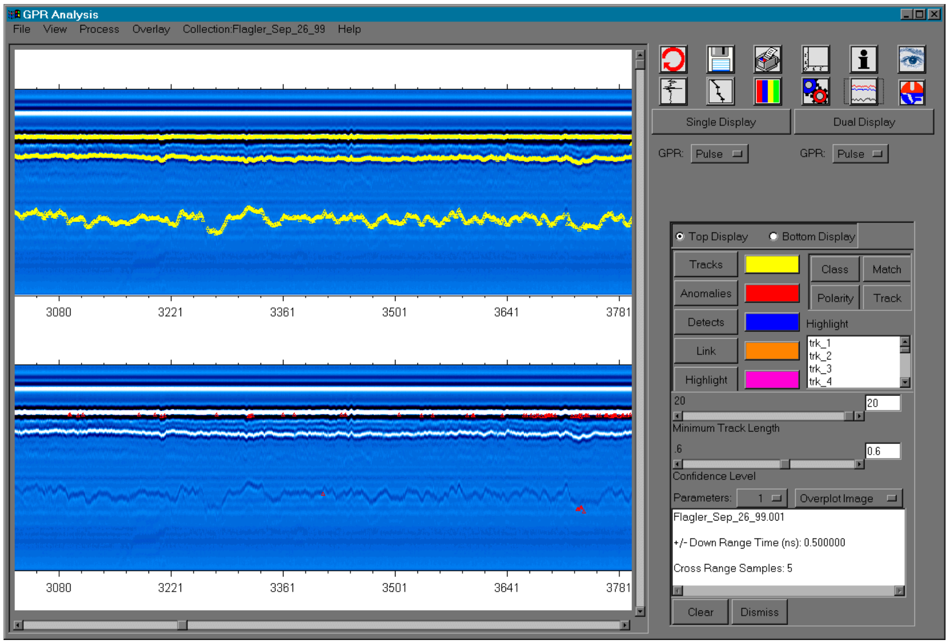


FIGURE 14. Tracks are overlaid on GPR image in yellow on top. Anomalies are overlaid in GPR image in red on the bottom.

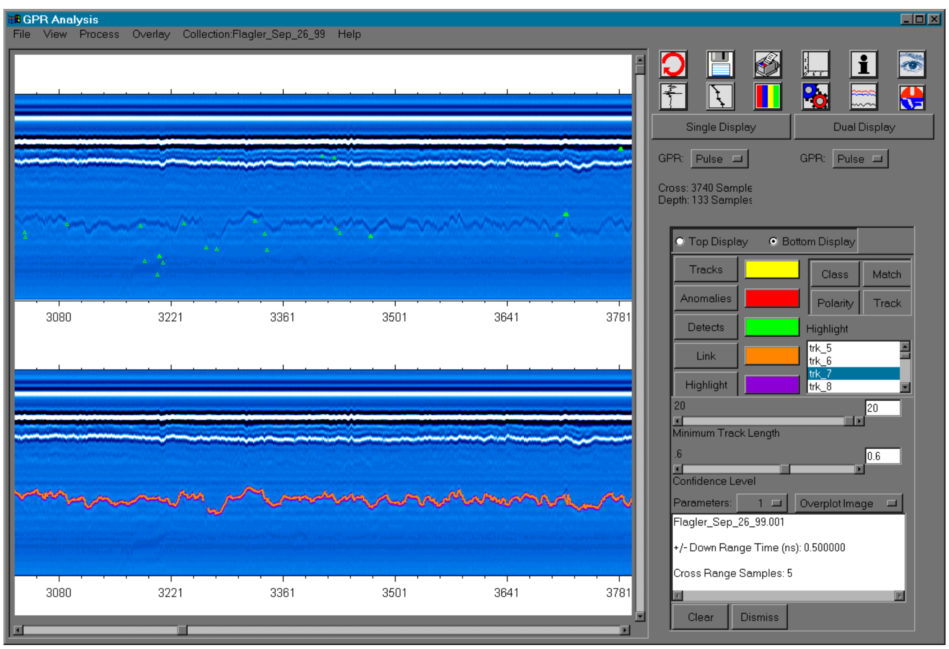


FIGURE 15. Non-tracked detects are shown in green in the top display. The track representing the base layer has been highlighted and linked and is shown in orange in the bottom display.

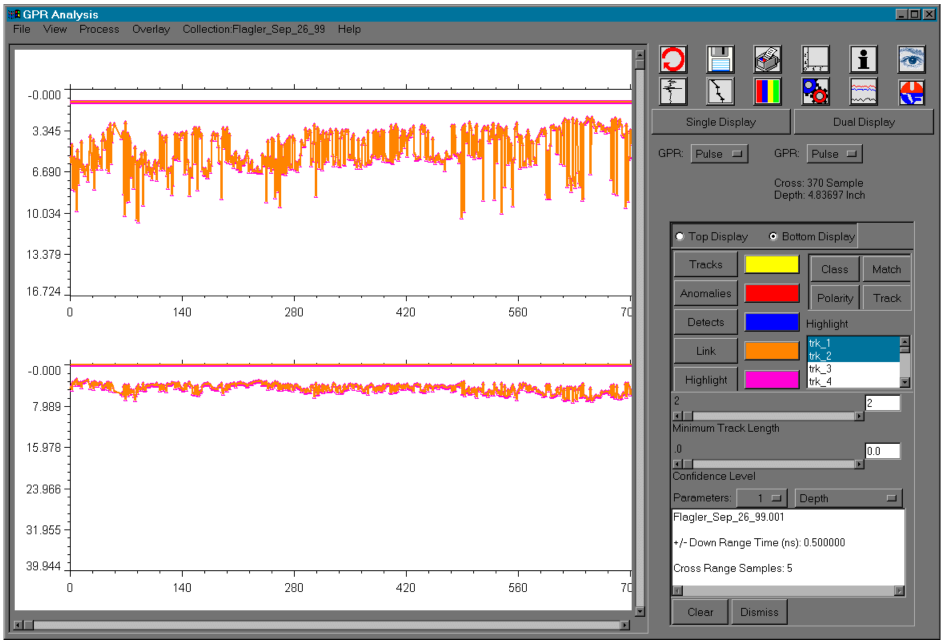


FIGURE 16. Plots for the surface and bottom of surface are shown above. The relative dielectric permittivity is plotted in the top display, the resulting calculated depth is plotted in the bottom display.

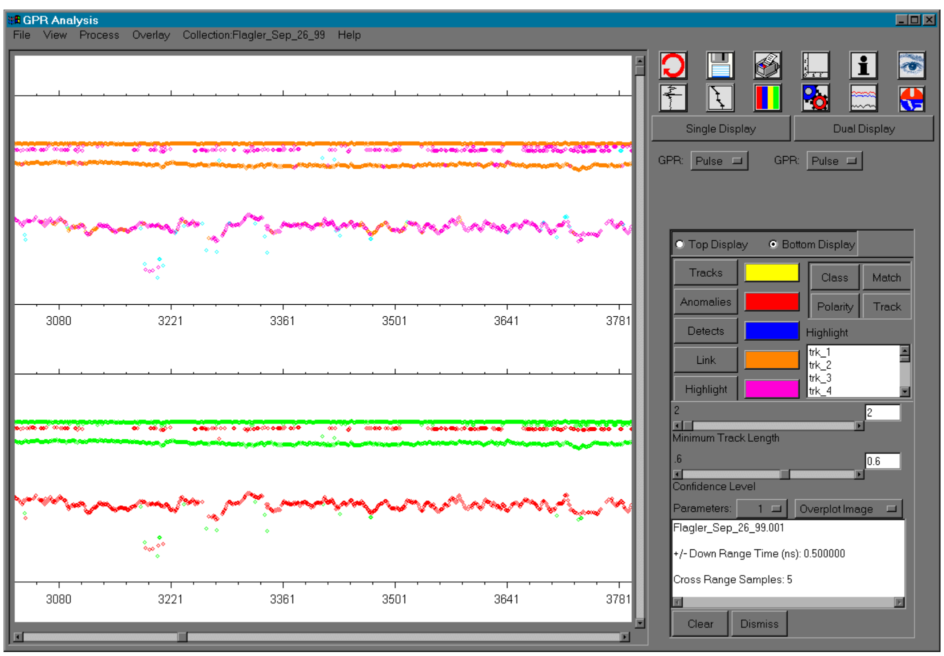


FIGURE 17. The top display illustrates the class assigned by the clustering algorithm. The bottom display shows the signals polarity, green is positive, red is negative.

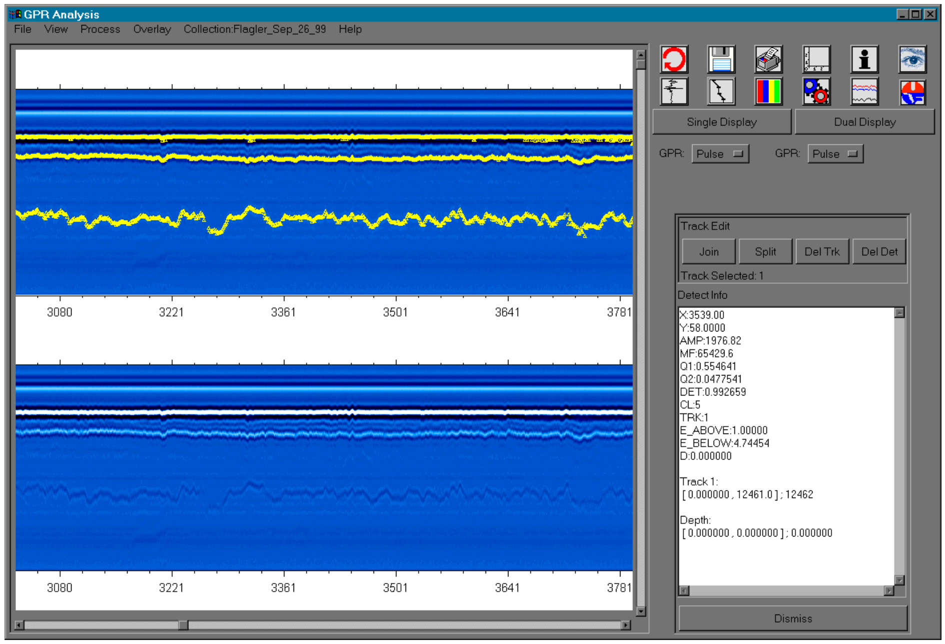


FIGURE 18. The manual editing dialog is activated by mouse-clicking on the plot at the desired location. The text window provides details of the track, anomaly, or detect selected.

5.2.5 Manual Editing

Tracking layer interfaces is a difficult problem due to inconsistent subsurface layer composition or strong interference caused by two or more closely separated layers. Manual editing allows the software user to correct many errors made by the automatic tracking algorithm. The manual editing plug-in, Figure 19, is activated by selecting a plotted track or detect using the mouse. The actions occur at the location selected. The editing options are as follows:

- Join - Joins two non-overlapping disconnected tracks,
- Split - Splits a continuous track segment into two separate segments,
- Del Trk - Deletes track, relabels all detects along the track to clutter designation,
- Del Det - Deletes detect, relabels single tracked detect to clutter designation.

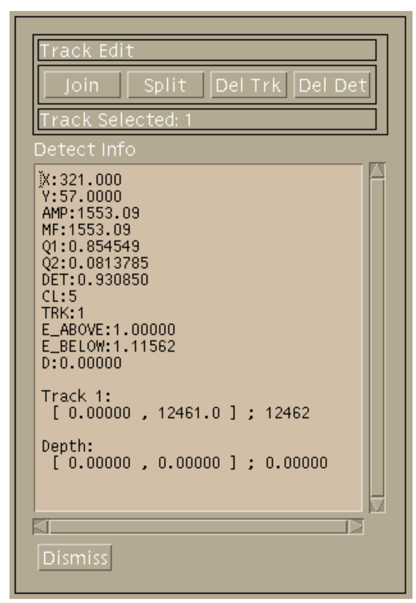


FIGURE 19. Manual Editing

6.0 On-board Processing Capacity Enhancements

A signal processing computer was procured and installed in the FDOT GPR van to allow in-the-field analysis and measurements of both roadway and geophysical radar data. The computer is year 2000 compliant for both hardware and software. The fixed disk storage in the computer is capable of storing more than four weeks of GPR data collection (500 miles of data per day). The new computer can be used to process GPR data from previous collections while simultaneously collecting roadway GPR data. The ability to process data rapidly in the field should shorten the time required to get results back to roadway engineers. This feature is especially important when GPR tasks involve emergency subsurface surveys in remote locations.

A summary of the specifications and benefits for the new computer includes:

- WindowsNT operating system (Y2K compliant)
- 733 MHz PentiumIII processor (fast GPR data processing)
- 256 MByte RAM (allows for processing very large data files)
- 30 GByte hard drive (online storage of large data collection trips or historical data storage)
- 250 MByte zip drive (data transfer and backup)
- 100 Mbps network interface (high speed data transfer between van and office)

The addition of a KVM (keyboard, video, mouse) switch allows a single keyboard, mouse, and monitor to control the existing computer, the new computer, and the SIR-10 GPR. The switch reduces the power requirements of the FDOT van to efficiently utilize current assets in the limited interior space.

7.0 System Utility

The multiple-radar system assembled as part of this project provides increased utility to the FDOT radar assets. It accomplishes this task without imposing any limitations or changes to the operation of the two independent radar systems as previously used by the FDOT.

7.1 Single System Operation

Both radar systems may be operated independently. No modifications of the system hardware have been made to change operating methods or capabilities of the radar units. The systems may be used in exactly the same way they were used prior to this project. Processing and analysis for single system operation is also possible in the current software environment. Utility also been added with the addition of the independently operated, dual-antenna, ground-coupled GSSI system, which may now be connected to the tow hitch of nearly any vehicle for roadway analysis. The vehicle must provide a power supply from either a marine battery or a power inverter system. If a compatible DMI system is not available, the data may be taken in continuous mode.

7.2 Multiple System Operation

Collection of roadway data using the multisystem configuration adds utility to the data collection system. Processing may allow additional information to be withdrawn from GPR data in addition to depths, thicknesses, and dielectric constants. Several concepts are discussed below.

7.2.1 System Comparison

Roadway analysis with the multiple radar system allows comparison of radar results and processing from two distinctly different techniques. This allows for error checking of the results from processing of the data from two systems, reducing improper analysis and improving information for maintenance decisions.

7.2.2 Surface Roughness Evaluation

The use of both an air-launched and a ground-coupled system presents opportunities for evaluation of roadway surface roughness. Air-launched systems determine layer dielectric constants based on ratios of return amplitudes. The dielectric constant of the first layer is calculated from the ratio of the return amplitude from a metal plate to that of the air-surface interface. The air-surface interface measurement is, however, corrupted by the roughness of the road surface, which scatters the signal and lowers the effective returned amplitude. This introduces error in the computation of the first layer dielectric constant, which is also propagated to successive layers. Ground-coupled systems are not affected by corrupted amplitude measurements, since they use time through multiple signal propagation paths rather than amplitude to calculate dielectric constants. This should remove errors due to surface roughness. A comparison of the results from the two systems gives some indication of the roughness of the surface, which should be proportional to the error induced by surface roughness.

7.2.3 Void Content Monitoring

Studies have demonstrated [1] the ability to non-destructively monitor the deterioration of roadways based upon void content analysis using ground penetrating radar. It has been shown that changes in void content of roadways are correlated to changes in the dielectric constant of the roadway. GPR may be used to track these changes in dielectric constant, which may then be used to infer the approximate percentage void content relative to the value measured after construction. This process requires initial measurements of the actual void content and GPR calculated dielectric constant immediately following roadway construction. Correlations of the void content versus dielectric for the given roadway material must also be determined using laboratory measurements made prior to roadway evaluation. The void content changes may then be referenced using successive dielectric analysis from the GPR [1].

The software and algorithms provided to the FDOT will allow the measurement of dielectric constants with both radar systems. Further laboratory and field measurements will need to be made by the FDOT to correlate dielectric constant and void content. Based on feedback form FDOT, work on this project focused on improved thickness and dielectric constant measurements. FDOT may explore void measurements in the future.

7.2.4 Anomaly Identification

Features of detects may be used to infer some sort of classification of the reflecting object. For example, continuous layers typically create detects that are relatively continuous in cross-range extent and have calculated dielectric constants which are consistent with those of concrete or asphalt. Such detects would not be considered anomalous, but detects which do not meet these criteria would be considered anomalous. Anomalies, which are considered to be any subsurface artifacts that are not part of a typical roadway interface, might present themselves in a variety of ways in a GPR profile, depending on the type of anomaly and conditions present. Detects from objects with very limited extent could be determined to be anomalies. Such anomalies might be utilities, rebar, crossdrains, large rocks, air or water pockets, etc. Discontinuities in tracked layers may also indicate an anomaly, particularly if the break is due to a polarity inversion that clearly indicates a material change. These anomalies might indicate a void under an interface or just a change in the material under an interface. Continuous detects from an apparent layer might also be considered anomalous if the dielectric is determined to be abnormally high or low, or if the return amplitude has an unusually high magnitude for a typical roadway interface. This would also indicate an anomalous situation under a layer which could be an air or water filled void, a metallic object, areas of high moisture content under a road layer, etc.

The multisystem radar configuration and software tool provide indications of anomalous regions and information that might be used to determine anomaly type under some circumstances. Air-launched system results estimate the dielectric under an interface, which may indicate air, water, or metal below an interface. The dual-channel ground-coupled system provides better resolution, better stability under van bounce conditions, and better thickness measurements of at least the first layer, which is often the most significant, for a better representation of roadway thickness abnormalities. Both systems indicate, for comparison and contrast, areas of tracking discontinuity and polarity inversion. Utilizing information derived from both systems can assist in the analysis of anomalous regions.

The GPR analysis software may be used to visually identify and analyze possible anomalies. Three situations in particular should be noted:

7.2.4.1 Short Extent

Detects from objects with limited extent may be displayed in two ways from the overlay tool plug-in. The “Class” display function may be used for either radar system to show the classification of each detect according to spatial characteristics as determined by the prescreening algorithm. Anomalous detects, which are rejected from the tracking algorithm are shown in green and light-blue. Tracked detects from short extent objects may be displayed with the "Anomalies: Short Track" display function. The slider may be set to determine how short the track has to be to be considered anomalous. Detects of interest as possibly significant anomalies may be inquired by clicking on the detect in the profile display. Parameters of the detect are displayed. The air-launched system is particularly useful for this feature. The dielectric calculated for the medium below the detect may indicate whether air, water, or metal is present. The presence of an anomalous region in both radar system profiles may provide some indication of the validity of the existence of the artifact.

7.2.4.2 Broken Tracks

Discontinuities in tracked layers may indicate a possible roadway problem, and thus an anomaly. Starting and ending points of tracked interfaces may be investigated to determine the possible cause of the discontinuity. If tracking halted because the return from the interface changed polarity, this could indicate a change of material under the layer or a void. The "Polarity" display function in the overlay tool plug-in will show the polarity of detects. This may be used to analyze polarity changes at track edges in either radar system display. This task may be simplified by placing the same data in both display windows. The tracks may then be displayed in one window while the polarity of detects is displayed in the other. The presence of an anomalous region in both radar system profiles may provide some indication of the validity of the existence of the artifact.

7.2.4.3 Interface Return Abnormality

Detects within a track with abnormally high return amplitude may indicate an area of interest and are reflected by extreme dielectric constant estimates. The software "Anomalies" display function in the overlay tool plug-in allows display of detects with dielectric constants below them that are both abnormally high or abnormally low for roadway layers. These detects may be shown on top of display of the detected tracks, thereby illustrating anomaly location with respect to tracked interfaces. The estimated dielectrics below anomalous detects may indicate an air or water filled void, a metallic object, areas of high moisture content under a road layer, etc. Air-launched GPR results should typically be used for this type of analysis since the amplitude-based nature of the calculations are conducive to estimation of dielectrics below interfaces. The presence of an anomalous region in both radar system profiles may provide some indication of the validity of the existence of the artifact.

Visual inspection of the radar profile and individual trace plots at anomalous locations should be conducted. Often changes in the returned signal may be noticed that validate the existence of an artifact. The separation of layers due to the onset of large voids may also be visually identifiable in some cases.

8.0 Verification of Operation

Verification of the performance of both the system hardware and software was conducted. The results of these tests is discussed in the following sections.

8.1 Hardware

Two GSSI antennas were configured so that they could be attached to the FDOT GPR van. Signals necessary to synchronize the data from the GSSI and Pulse Radar systems were generated and a synchronization circuit has been installed and tested in the FDOT GPR van. All hardware and software have been verified as operational in the FDOT GPR van. Errors in the DMI circuit have been observed when the power system in the van is under a heavy load. The power system in the van did not appear to be capable of powering all the systems at once without causing the DMI to measure distance incorrectly. The FDOT SMO replaced the batteries in the van and subsequent testing has not shown the DMI errors. The ECL has worked with the FDOT SMO and two solutions were implemented in case the DMI has errors when the van has low power reserves. The GSSI system will be run off of a 12 volt marine battery or other non-essential systems in the van will be turned off when operating the GSSI and Pulse radars (VCR, TV, tape drive, etc.). Both of these methods of power management allow for collection of GPR data with the two radar systems at the same time.

Care was taken to ensure that the modifications to the FDOT GPR van would enhance and not deter from the functionality of the previous FDOT GPR assets. While no functionality of the individual systems was limited, when operating the two radar system together, certain limitations apply.

- The maximum radar scanning rate limits the GPR van's velocity to less than 15mph for data collection in 1 foot intervals.
- GSSI antennas are ground contacting and therefore are susceptible to damage if drug over large obstacles or dropped from appreciable heights.
- GPR data can not be co-located if the GSSI and Pulse Radar systems are operated in a continuous sampling mode.
- The Pulse Radar GPR antenna must be mounted on the van and therefore collections are limited to areas accessible by the van.

8.2 Processing

Evaluation of the performance of the system algorithms was conducted on controlled testbed measurements and roadway data collections. The results and system limitations will be discussed.

8.2.1 Performance

Performance is evaluated by comparison of the actual depths to material interfaces with the estimated depths acquired using the GPR analysis algorithms. The average percent error in depth calculation has been determined from controlled ground truth measurements in the ECL testbed and from measurement of roadways that were cored to provide ground truth.

Testbed Data Tests

The ECL GPR testbed allows data collection from interface depths which may be accurately controlled. Collection of data using the dual-antenna GSSI SIR10 system was taken for a range depths using three materials: thin-wall concrete, fine-grain particle board, and wallboard. These three homogenous materials were available in approximately 0.5” sheets, which were stacked and measured over a range of thickness. Thin-wall concrete was measured up to approximately 10”. Particle board was measured to approximately 15”. Wallboard was measured to approximately 24”. Detection and matching functioned properly for all three materials at interface depths from approximately 2.0” and deeper. Figure 20 shows the matched pairs between the direct and

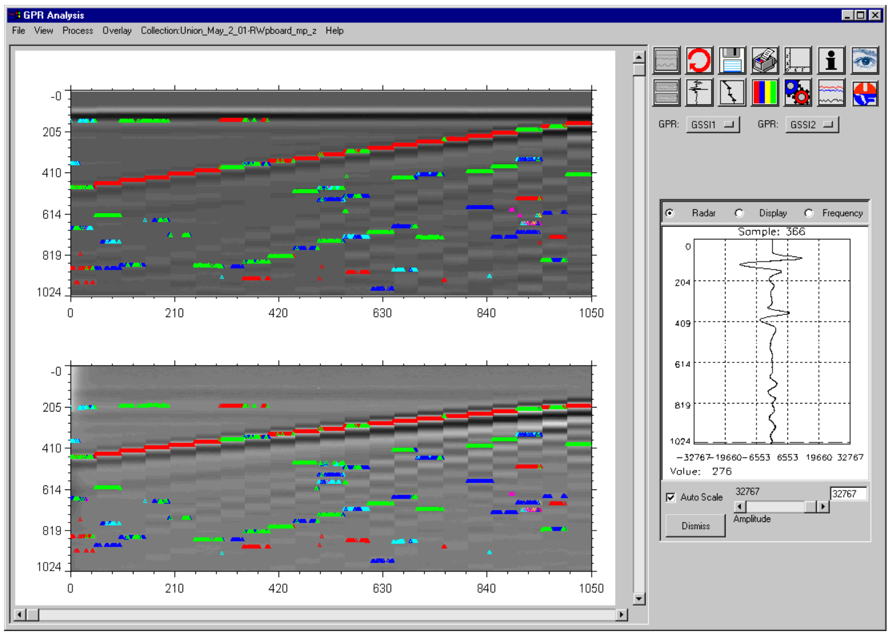


FIGURE 20. Matches for ground-truthed measurements collected from particle board for a range of thicknesses.

cross channels for the particle board collection. The staircased detects from the bottom of the medium are visible in both channels. Figure 21 shows the results of depth calculations

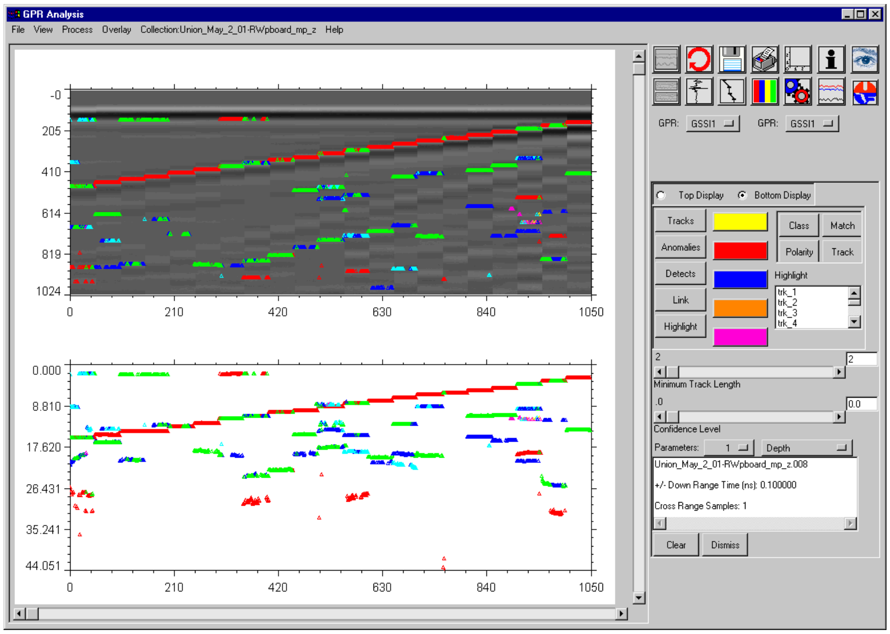


FIGURE 21. Results of depth calculations for particle board layer (bottom window of software display).

for the particle board interface. Processing was completed on all three mediums. Figure 22, Figure 24, and Figure 26 compare the results of the GPR calculations of depth and the ideal result for the three mediums. Figure 23, Figure 25, and Figure 27 show the percent error in the GPR calculations. Table 1 summaries the performance of the dual-antenna measurements for the three ground-truthed, testbed mediums.

FIGURE 22. Calculated Depth and Ideal Result vs. Detect Depth for Concrete Board

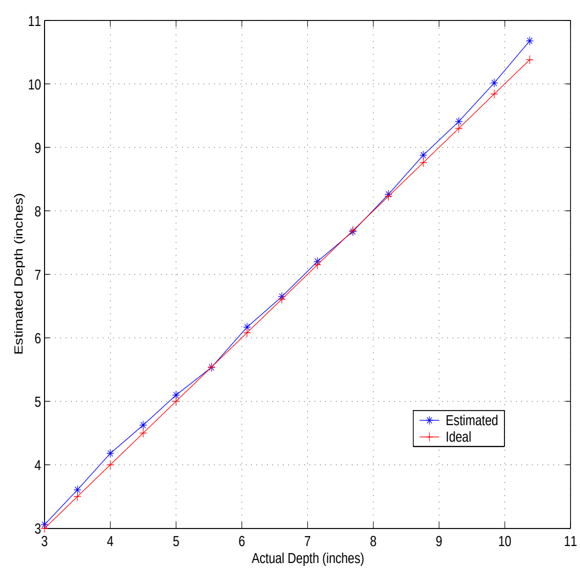


FIGURE 23. Percent Error in Depth Calculated vs. Detect Depth for Concrete Board

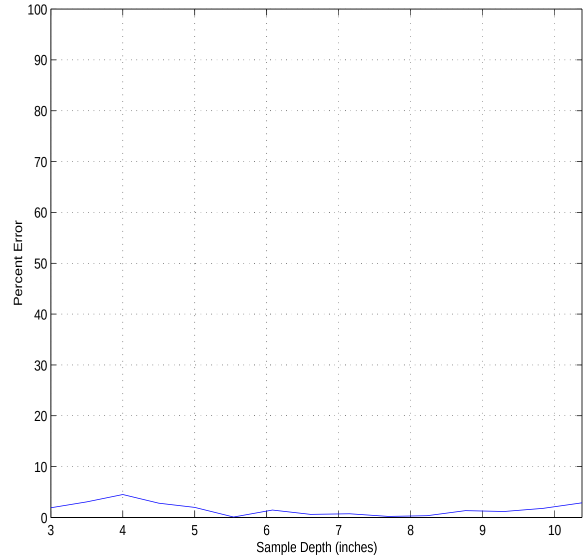


FIGURE 24. Calculated Depth and Ideal Result vs. Detect Depth for Particle Board

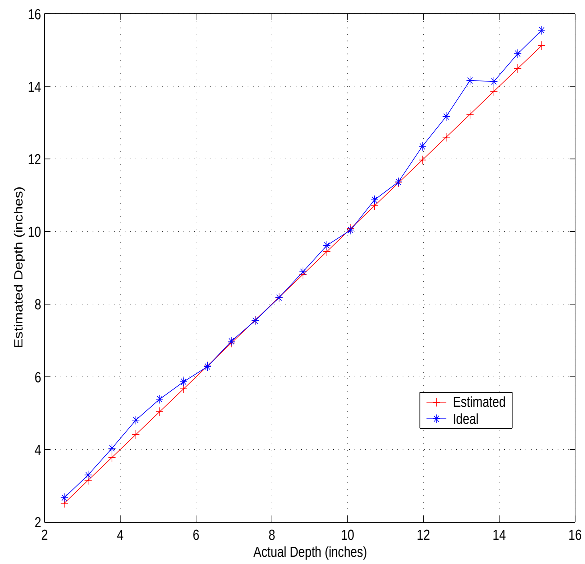


FIGURE 25. Percent Error in Depth Calculated vs. Detect Depth for Particle Board

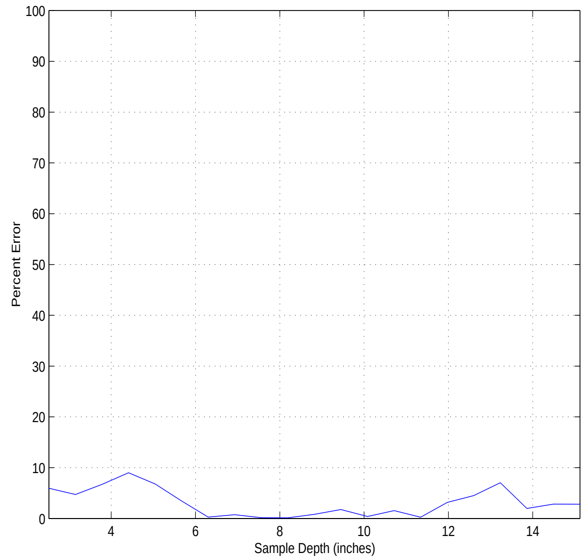


FIGURE 26. Calculated Depth and Ideal Result vs. Detect Depth for Wallboard

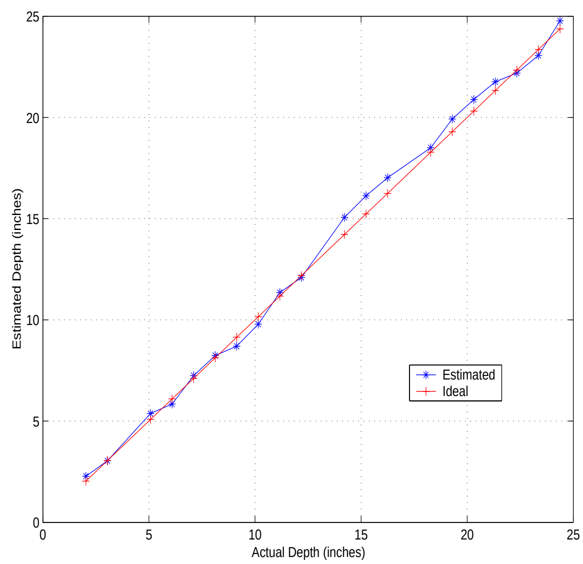


FIGURE 27. Percent Error in Depth Calculated vs. Detect Depth for Wallboard

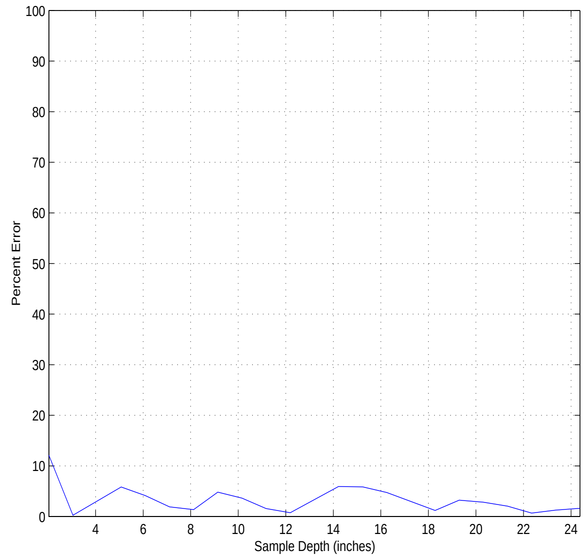


TABLE 1. Summary of testbed calculation results.

	Concrete Board	Particle Board	Wallboard	Total
Average Percent Error	1.65	3.09	3.29	2.78
Error Standard Deviation	0.08	0.24	0.40	0.28

Errors in estimates, particularly those with higher percentage error, are due to detection shifts which might be attributed to interference from multipath effects in the closed testbed system or to interference from returns from small separations between the testbed layers.

These results prove the validity of the dual-antenna measurement system for evaluation of material thicknesses. Low error in the calculated results from the software closes the loop in the algorithm development and demonstrates operation of the system for a range of dielectrics and depths.

The GSSI system experienced board failures between some of the collections of verification data. The radar boards were re-seated by the FDOT. This seems to have alleviated most of these problems, but at least one board failure occurred even after re-seating of the boards. Ground-truthed data from the ECL testbed indicated bizarre results which led to the discovery of unexplained apparently somewhat random time shifts in data collections from one use of the radar to the next. Figure 28-Figure 33 illustrate time shifts in ground-truthed measurements take before and after the re-seating of the radar board. Both collections for the wallboard were taken after re-seating of the board. The data shows changes in the critical timing (seen as timing offsets) used by the software analysis software to compute dielectric constant, and depths. To alleviate these problems for calibration purposes, data was collected for all three ground-truthed materials without ever shutting down the radar system. Problems in repeatability of the collection due to random shifts in system timing will result in erroneous measurements. Such timing issues may be factor in the roadway verification data that was collected. Figure 34 and Figure 35 show the error in calculations from a collection taken before the radar boards were re-seated. The average percent error the corrupted data case was 22.0%.

FIGURE 28. Index shifts for direct channel in thin-wall concrete.

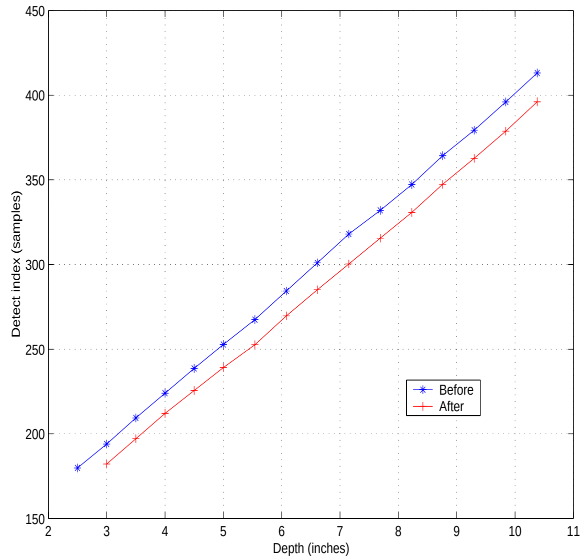


FIGURE 29. Index shifts for cross channel in thin-wall concrete.

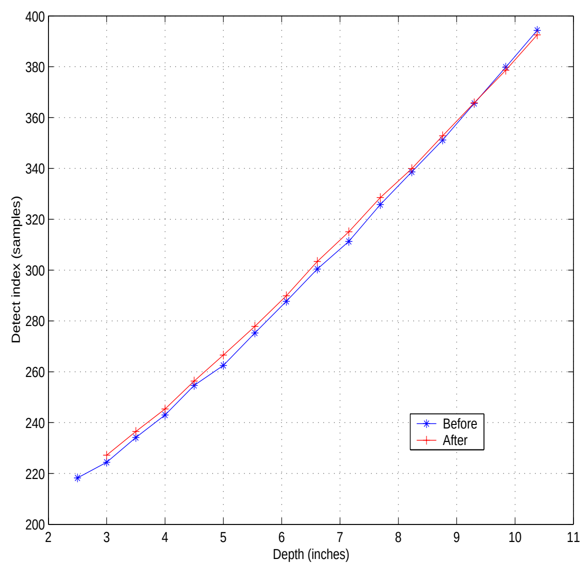


FIGURE 30. Index shifts for direct channel in particle board.

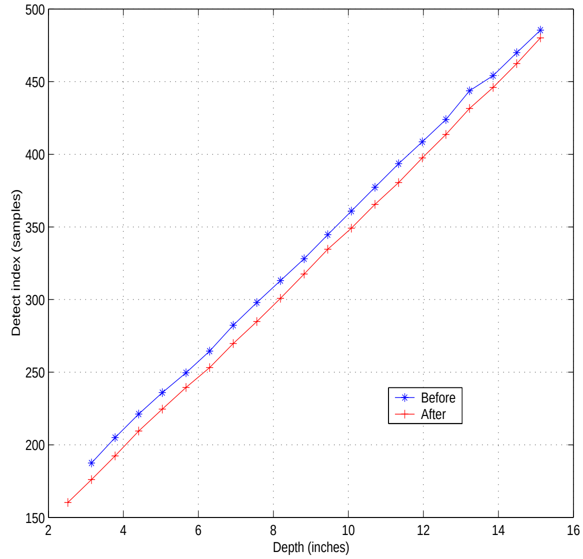


FIGURE 31. Index shifts for cross channel in particle board.

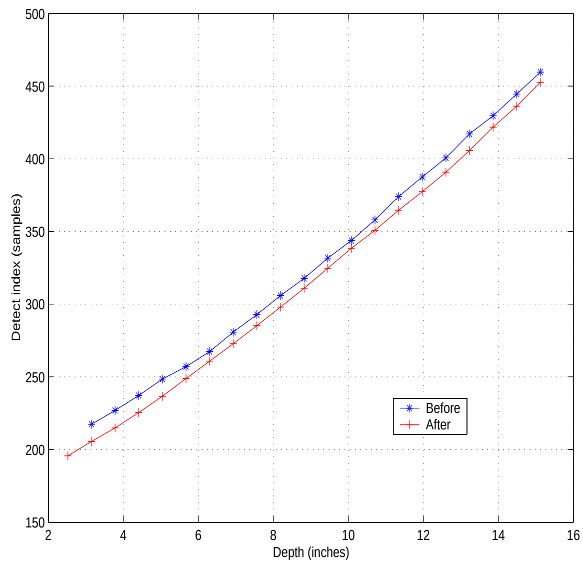


FIGURE 32. Index shifts for direct channel in wallboard.

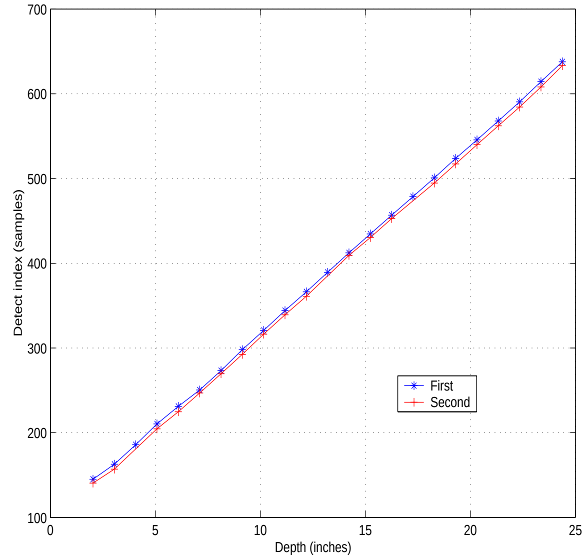


FIGURE 33. Index shifts for cross channel in wallboard.

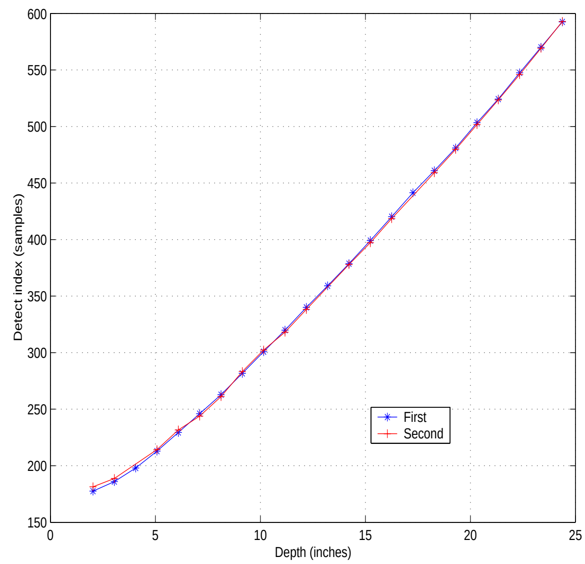


FIGURE 34. Calculated Depth and Ideal Result vs. Detect Depth for Particle Board using data collected before re-seating of the radar board.

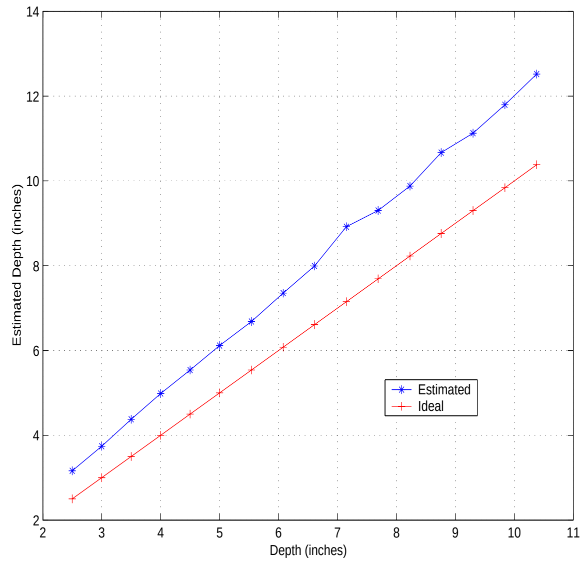
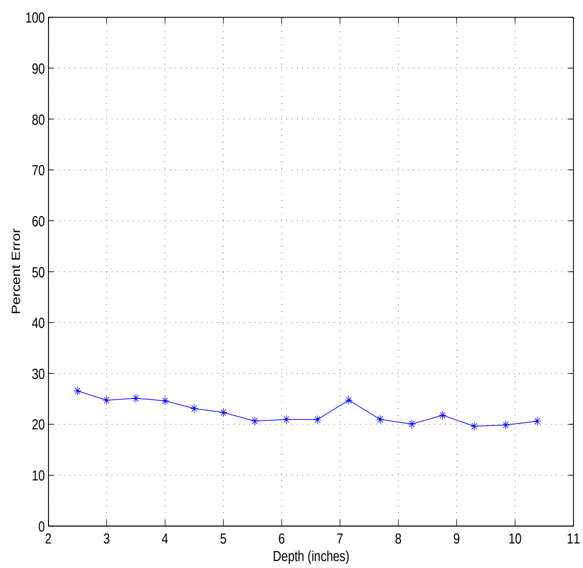


FIGURE 35. Percent Error in Depth Calculated vs. Detect Depth for Particle Board using data collected before re-seating of the radar board.



Road Data Tests

Tests of the system were also conducted for road cases that were cored to acquire ground truth. Data was collected from several roadway cases including locations on Highway 441, State Road 20, and the Accelerated Pavement Testing (APT) test tracks at the FDOT pavement evaluation complex in Gainesville, FL. Early collections of the verification data were collected using a narrow spacing of the antennas in an attempt to maximize the signal return strength in the cross-channel. However, it was determined that on roadway cases, the cross-coupling response for the narrow spacing was significantly interfering with detection performance. Increasing the spacing distance between the two GSSI antennas reduced the return signal by a small amount but greatly reduced the strength of the cross-coupling response. Wider spacing should also give better dielectric constant measurement resolution as long as sufficient signal return strength is received in the cross-channel. Widening the separation in the dual-antenna system improved detection performance significantly in the cross channel, making detection possible in many cases which were not feasible with the narrow spaced configuration. Data was collected on a section of Highway 441 with the final, wide antenna spacing, and data was re-collected at the APT testing facility. These data sets were used for performance analysis. Figure 36 shows detection results from the GSSI dual-antenna configuration. Figure 37 shows detection results from the Pulse Radar system. Coring measurements indicate approximately a 5.0” roadway with layers of approximately 1.0”, 3.0”, and 1.0”. One of the cores, typical of the entire set, is shown in Figure 38. The 1.0” army layer, as seen in the figure, is thinner than the resolution of the radar will allow for detection using standard techniques. This cause an interference pattern that corrupts the location of the resulting detects from the bottom of the pavement in the HWY 441 data, making matching and calculations virtually impossible. Both radar systems experienced problems detection the bottom of the core accurately, as would be expected given the roadway construction. Both systems were able to consistently detect, track, etc. a deeper layer, which may be the bottom of the base layer. The GSSI results indicate this layer is an average of 17.22” deep with a standard deviation of 0.9”. The Pulse results report an average of 18.9” with a standard deviation of 2.2”.

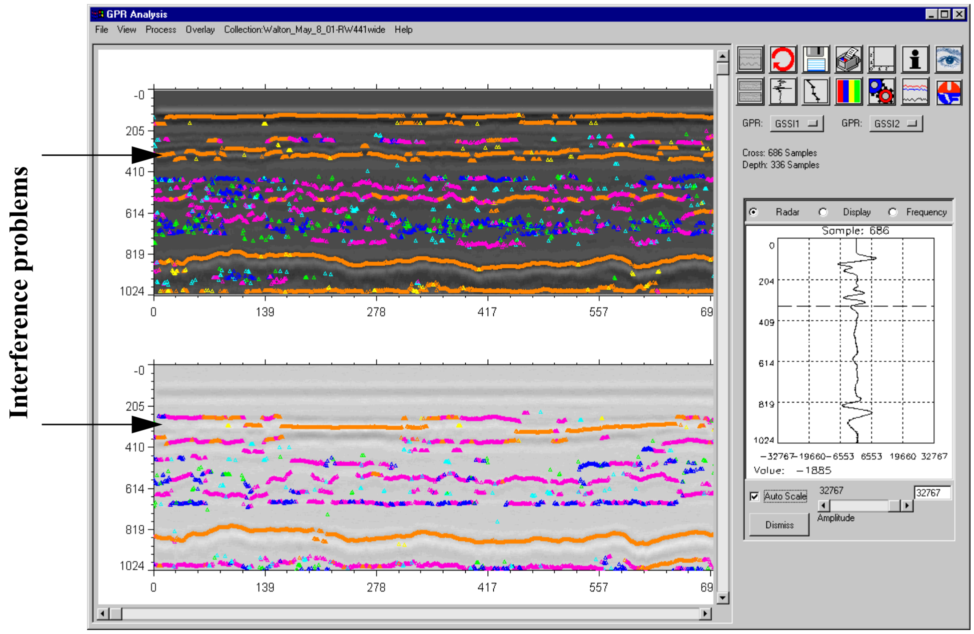


FIGURE 36. Detection results for HWY441 from the GSSI system shown with color designated by classification of each detect. Regions of detection complications due to interference are shown. The major pavement interface should be in these regions.

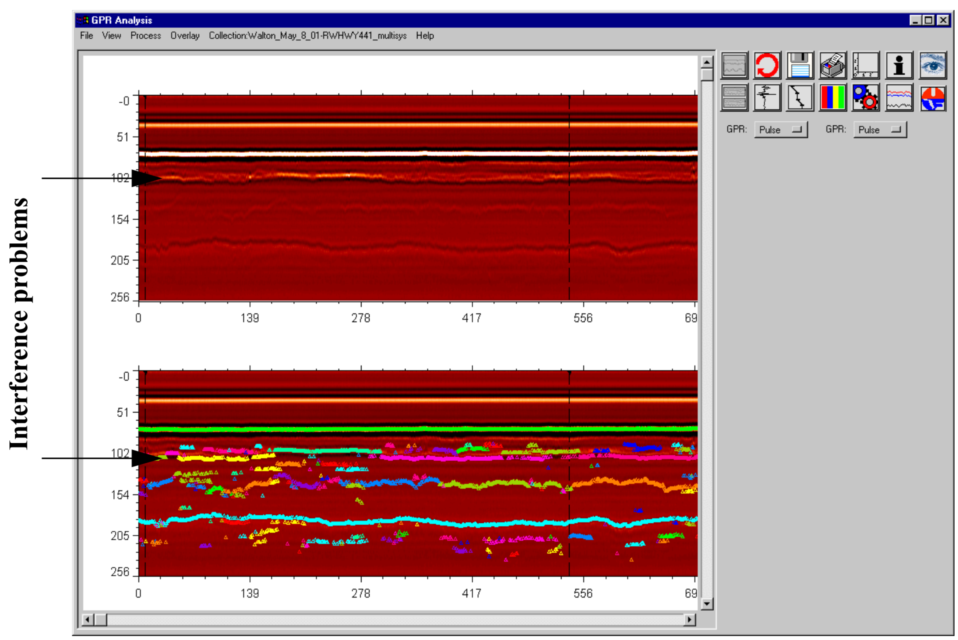
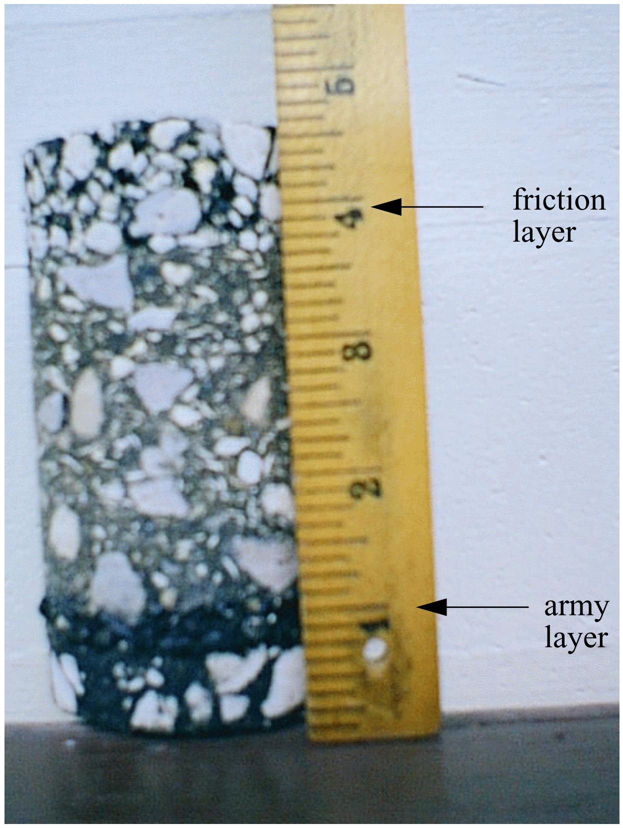


FIGURE 37. Detection results for HWY441 from the Pulse Radar system shown with color designated by detect track number. Regions of detection complications due to interference are shown. The major pavement interface should be in these regions.

FIGURE 38. Typical core from HWY 441 collection w/ interfaces shown.



Data was collected for five of the APT test tracks. The tracks were constructed in two lifts. Cores were taken for each lift in different locations, so a total core thickness can only be estimated by adding together various coring measurements. In all cases the two lifts are in the vicinity of 1.5” - 2.0” thick, which might contribute to some interference problems resulting from minimum radar resolution. This will be more of a factor in the tracks where the two lifts are of different material composition. The average and standard deviation of the coring and radar measurements are compared in Table 2.

TABLE 2. APT test track core and GPR measurement summary.

	Track 1	**Track 2**	**Track 3**	**Track4**	**Track 5**
GSSI average	5.56”	4.88”	4.50”	4.91”	5.22”
GSSI standard deviation	0.24”	0.29”	0.21”	0.13”	0.32”
Pulse average	3.88”	3.36”	3.35”	3.58”	3.78”
Pulse standard deviation	0.27”	0.26”	0.18”	0.17”	0.25”
Core average	3.95”	3.42”	3.43”	3.49”	3.64”
Core standard deviation	0.28”	0.40”	0.40”	0.32”	0.23”

The accuracy of the results from the Pulse Radar system are very well correlated to the core measurements. This indicates a good detection at the bottom of the core and probably indicates errors in the GSSI calculation are due to random time shifts in the collected data similar to those shown in Figure 34 and Figure 35. Measurements in the GSSI system are based on wave travel times and are corrupted by timing problems resulting from GSSI radar problems. The timing offsets appear to change for each collection, but the seem to be relatively constant within each data collection. Timing problems in the GSSI radar system may indicate radar failure that needs to be repaired. It may also indicate sporadic timing changes that are typical of GSSI systems.

9.0 Summary and Conclusions

The University of Florida Electronic Communications Laboratory has performed a research project for the Florida Department of Transportation (FDOT) designed to improve roadway subsurface thickness measurements and anomaly identification with the use of ground penetrating radar (GPR). The project resulted in a multisystem roadway analysis system, improved in-the-field data analysis capabilities, and an enhanced GPR evaluation software tool which organizes and processes multisystem GPR data for improved thickness measurements and roadway analysis capabilities.

Several significant accomplishments have been achieved on this project. The primary goals of the project, to develop an improved GPR data collection configuration, signal processing techniques, and software tools to detect and measure thickness of roadway surfaces and allow identification of anomalous regions using ground penetrating radar, have substantially been met. The operation of a dual-antenna, time-based processing scheme was verified for a range of depths and dielectric constant values. Results show high accuracy and low error variance. Timing problems in the GSSI ground-penetrating radar system have, however, been isolated as a considerable source of error in measurements. This critical issue and “radar board failure” errors experienced during the verification data collections may indicate system problems that must be addressed by the FDOT before the dual-antenna configuration will be capable of functioning to its full capacity.

A limiting factor encountered in roadway analysis involves the radar resolution and the very thin layers sometimes found at the bottom of roadway cores, and shown in Figure 38. Radar resolution is limited by its bandwidth. This project has increased the bandwidth of the radar system with the addition of higher frequency antennas than were previously included in FDOT assets. This has improved the resolution of the system; however, layers on the order of approximately 1.5” and smaller, as seen in some collections, are not resolvable using the current system. Newer “super-resolution” algorithms are being researched throughout the scientific community. These algorithms hope to improve detectable resolution beyond that achievable using matched filter techniques for a given system bandwidth. Although application of such algorithms could be the focus of an entire research effort, modest attempts were made to utilize primitive super-resolution processing methods to improve GPR detection resolution. Development of super-resolution algorithms was not within the scope of the development of a total working implementation of the dual-antenna, multiple-radar system under this project, and the utility of such algorithms has yet to be determined. Matched filter techniques currently produce the best results. However, detection challenges caused by resolution present an area of GPR signal processing that warrants dedicated research efforts. Investment in the study of super-resolution processing for GPR layer detection could significantly benefit the utility of FDOT GPR assets for roadway analysis.

Collection and processing speed limitations for the multiple system configuration place emphasis on project level roadway analysis. The outputs of the software include time location, depths, and dielectric constants to layer interfaces, along with various other subsurface characteristic indicators as discussed previously in this document and in the software user's manual. This type of information can be of significant use to operators who assess the nature of subsurface pavement anomalies and potential problem areas.

In summary, the new GPR data collection configuration and the GPR software and analysis tool will improve FDOT capabilities for the non-destructive evaluation of potentially serious roadway problems at primarily the project level so they can be corrected before they become costly. The software environment will also aid in future road designs and improvements by providing rapid non-invasive measurements of new subsurface roadway designs.

DISCLAIMER

The opinions, findings, and conclusions expressed in this paper are those of the authors and not necessarily those of the Florida Department of Transportation or the U. S. Department of Transportation.

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References

[1] Saarenketo, Timo, and Scullion, Tom, "Road evaluation with ground penetrating radar", Journal of Applied Geophysics, March 2000.

Appendix:

The following appended document is the "GPR Roadway Analysis Tool -- User's Manual". The manual has also been provided to the FDOT as a separate document for reference during use of the GPR analysis software package. Additionally, a PDF file version of the user's manual is directly accessible through a button on the software tool bar.