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

Electronic Communications Laboratory

University of Florida

To

Dr. Bouzid Choubane

Pavement Evaluation Engineer

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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.

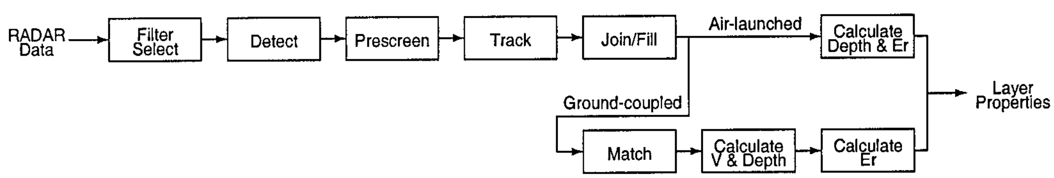
3.0 Ground-truthed Measurements

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.

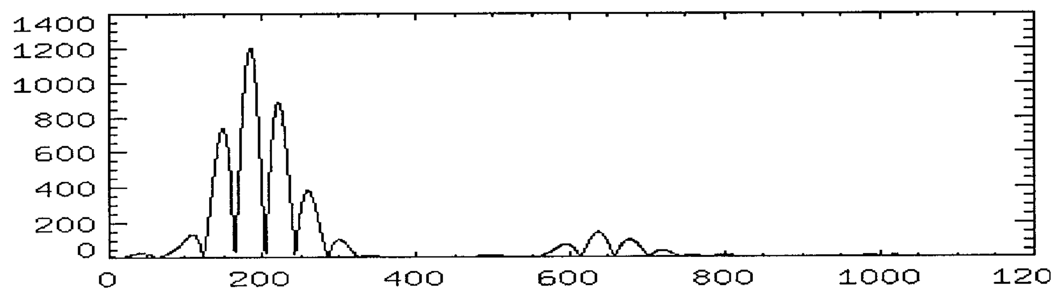


FIGURE 3. Enveloped response with peaks indicated.

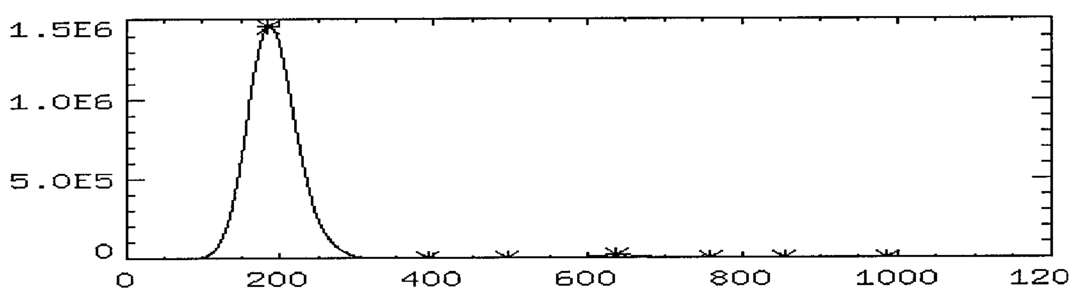
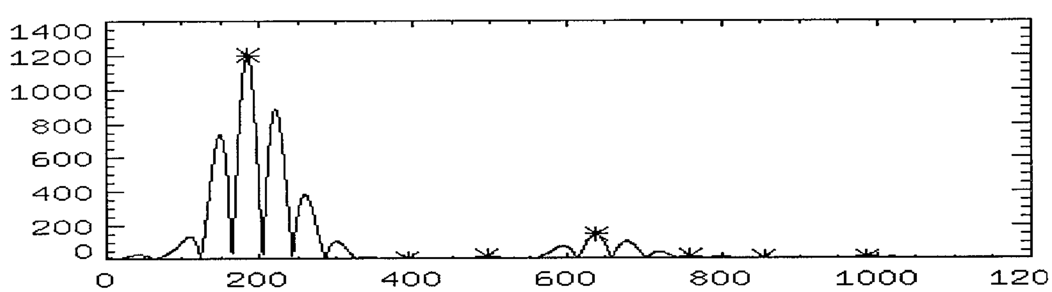


FIGURE 4. Matched filter response with peaks that correspond to peaks in the envelope response.



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.

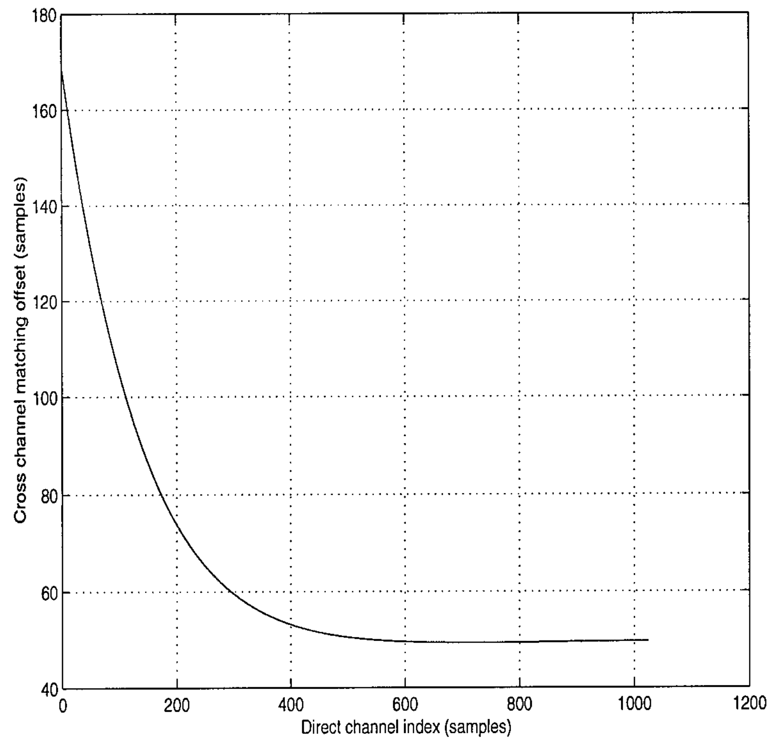
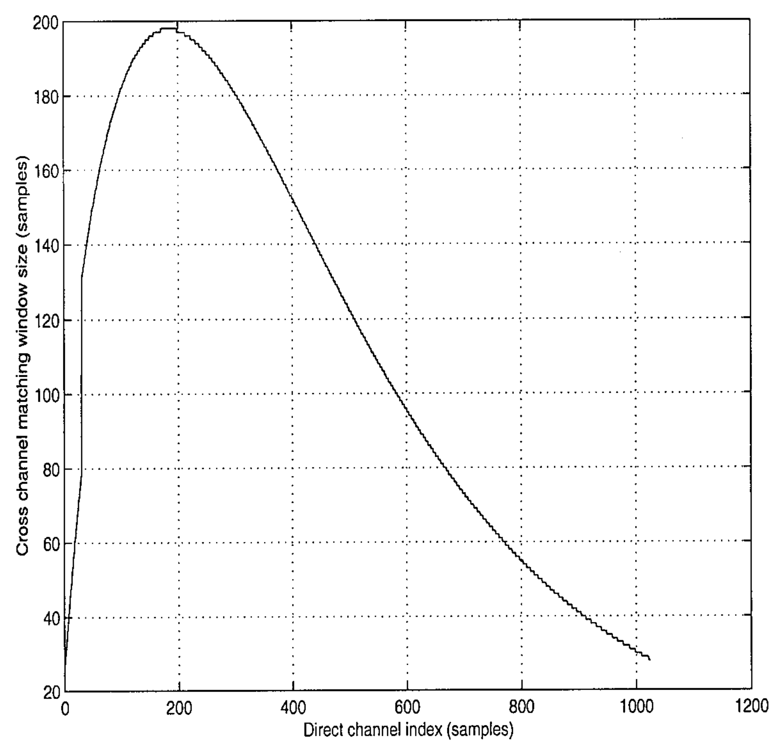


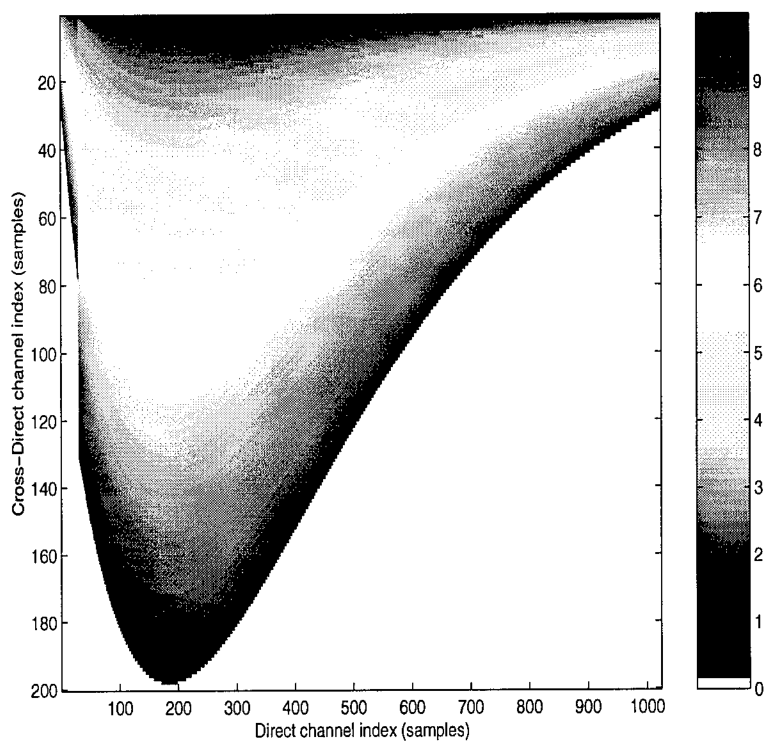
FIGURE 6. Matching window width versus direct channel sample index.



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.

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

$$\varepsilon_r(n) = \left[\frac{3.00\times10^{8}}{v(n)}\right]^2 \quad \text{, where } \varepsilon_r \text{ is the dielectric constant for layer } n \tag{2}$$

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.

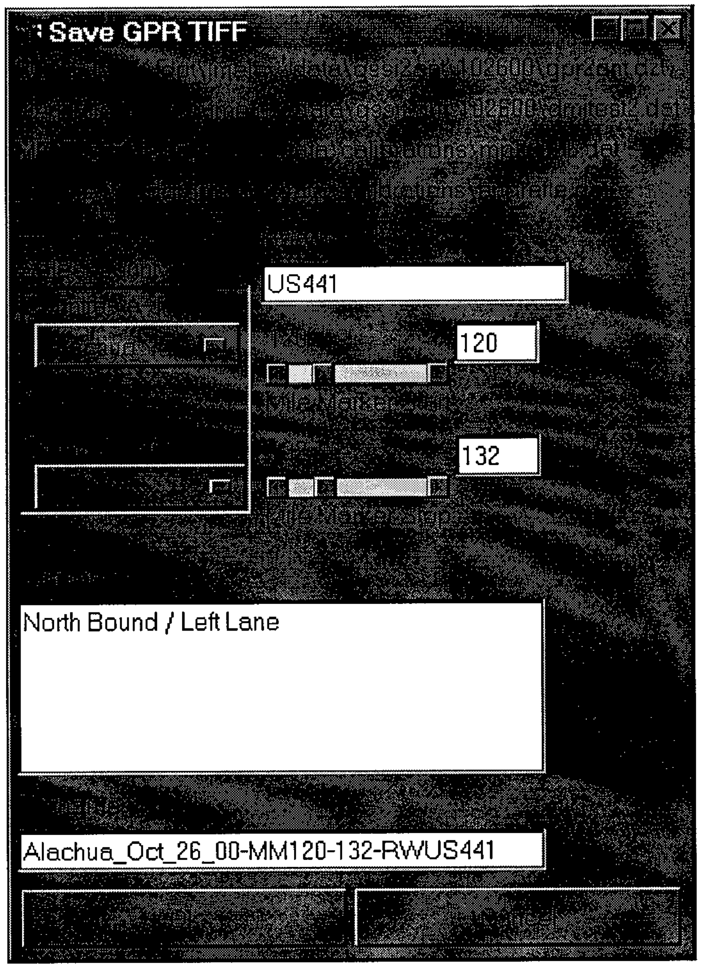


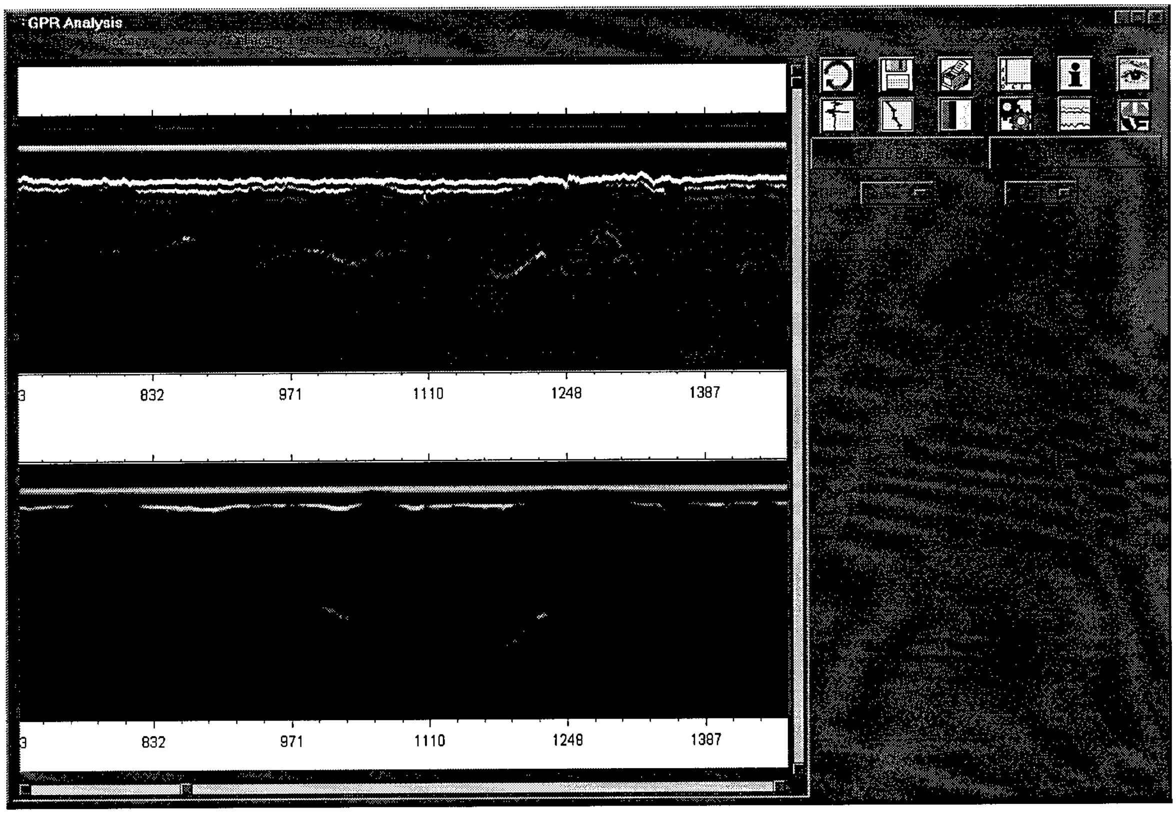
FIGURE 8. GPR Data Conversion Interface

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.

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.

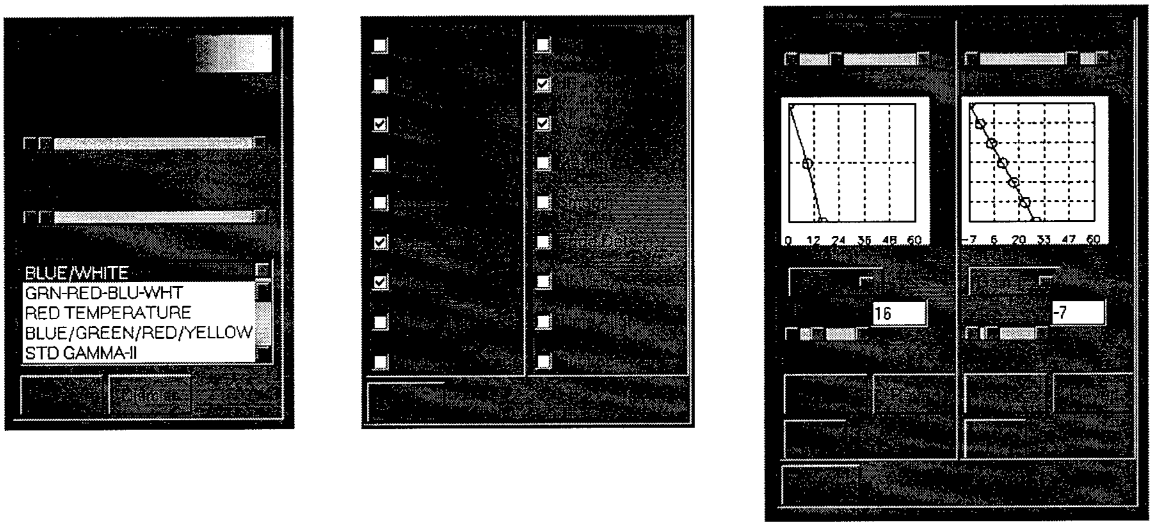
FIGURE 9. GPR Analysis Software



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.

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 rescales 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.

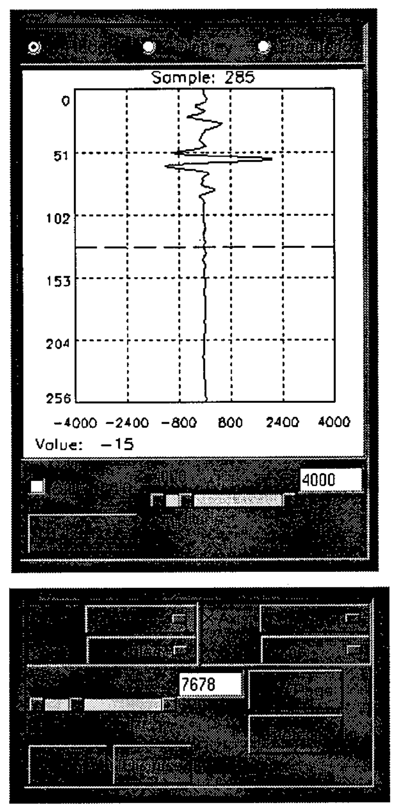


FIGURE 11. Profile and Frequency Spectrum Interface, and Axis Scaling and Labeling Interface

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.

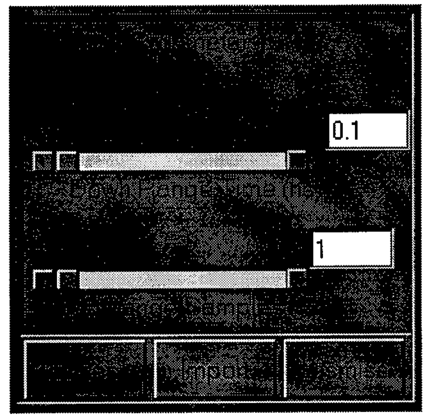


FIGURE 12. Processing Control

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.

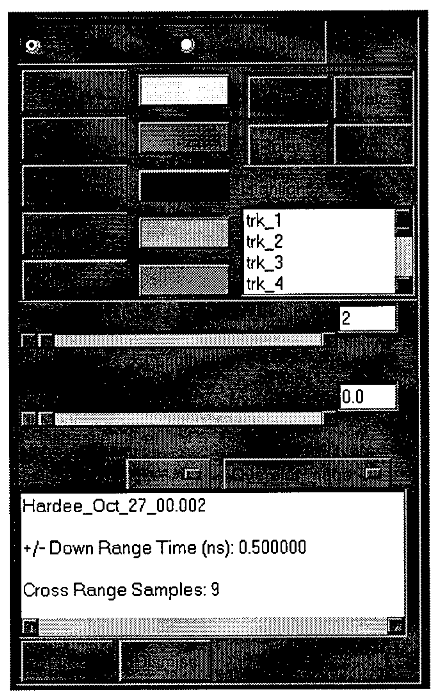


FIGURE 13. Results Presentation

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,

- 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.

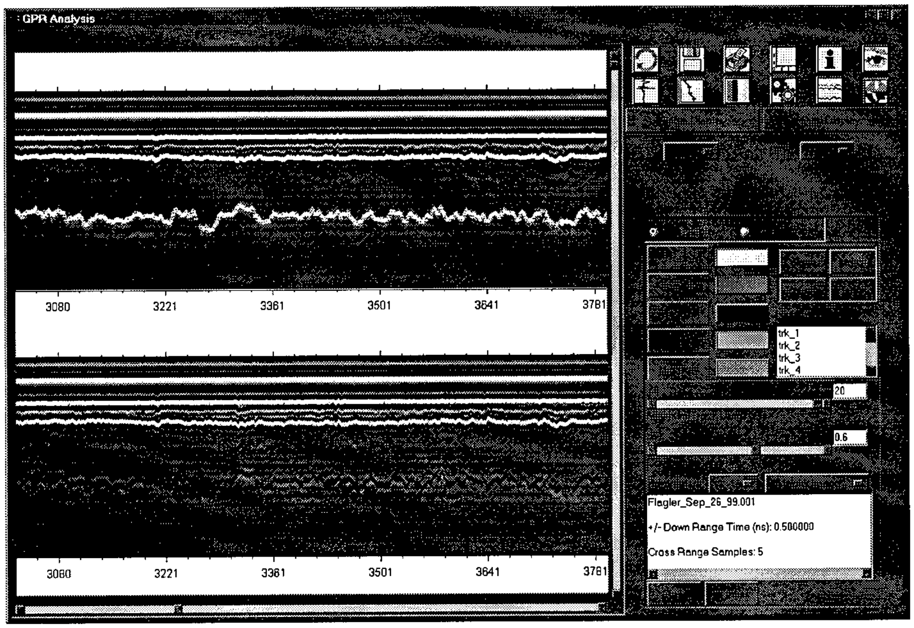


FIGURE 14. Tracks are overlaid on GPR image in yellow on top. Anomalies are overlaid in GPR image in red on the bottom.

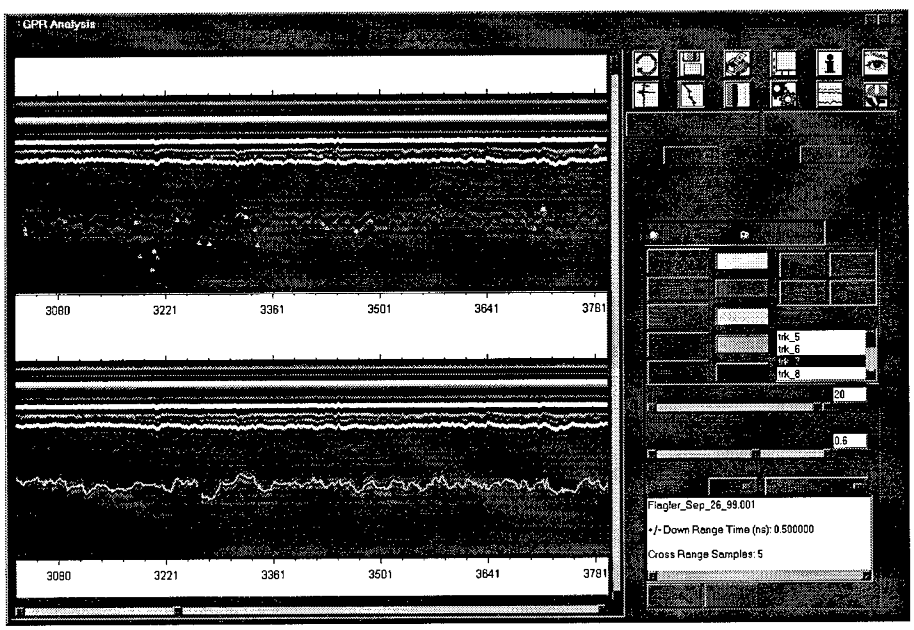


FIGURE 15. Non-tracked detects are shown in green in the top display. The track representing the base layer has been highlighted and linked and is shown in orange in the bottom display.

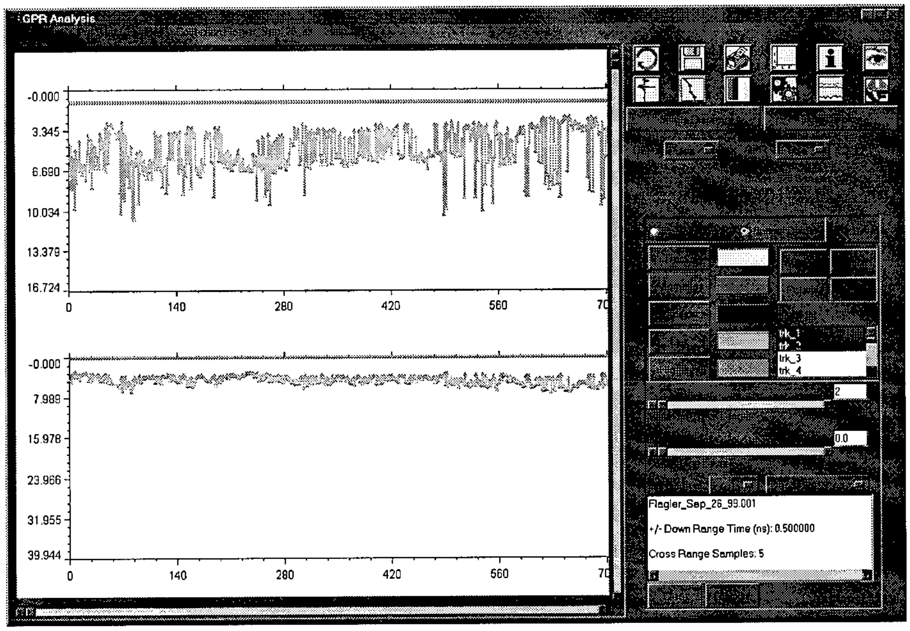


FIGURE 16. Plots for the surface and bottom of surface are shown above. The relative dielectric permittivity is plotted in the top display, the resulting calculated depth is plotted in the bottom display.

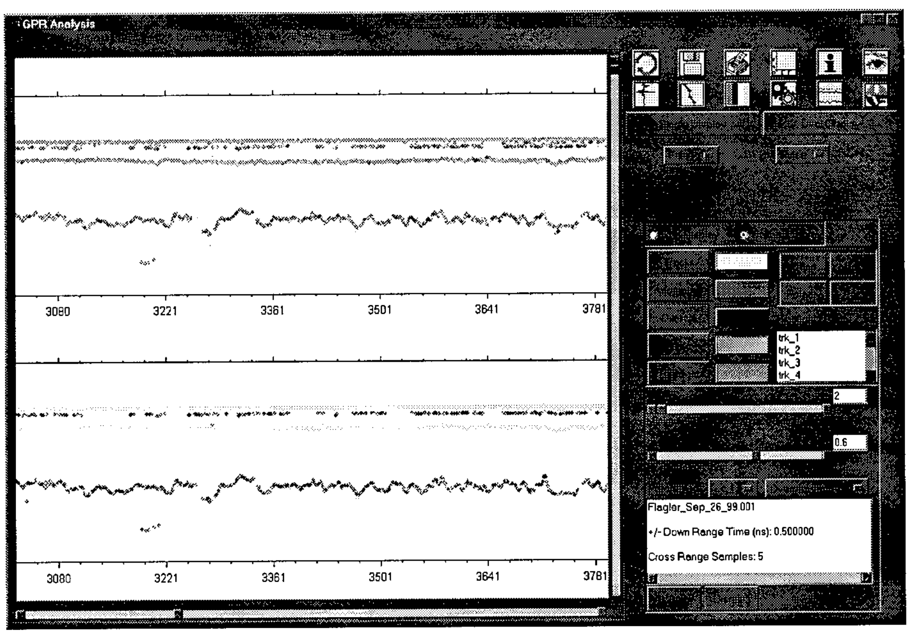


FIGURE 17. The top display illustrates the class assigned by the clustering algorithm. The bottom display shows the signals polarity, green is positive, red is negative.

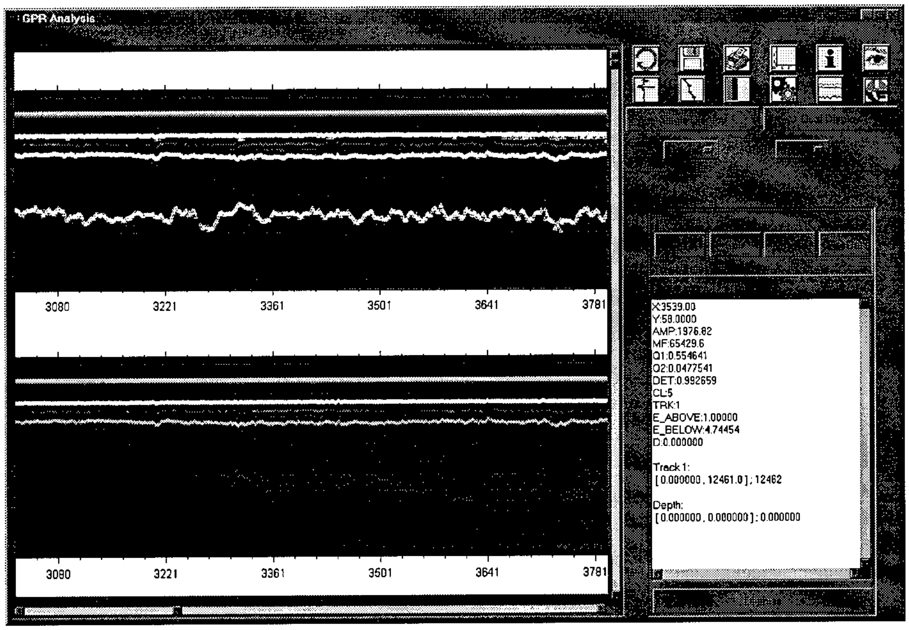


FIGURE 18. The manual editing dialog is activated by mouse-clicking on the plot at the desired location. The text window provides details of the track, anomaly, or detect selected.

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.

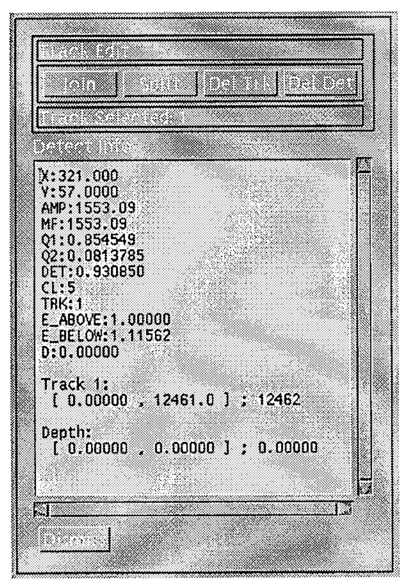


FIGURE 19. Manual Editing

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

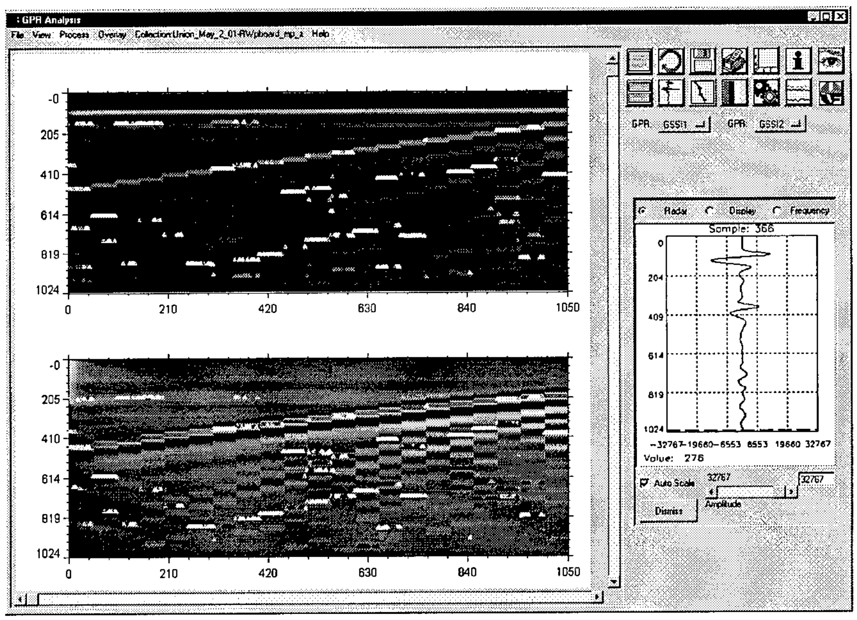


FIGURE 20. Matches for ground-truthed measurements collected from particle board for a range of thicknesses.

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

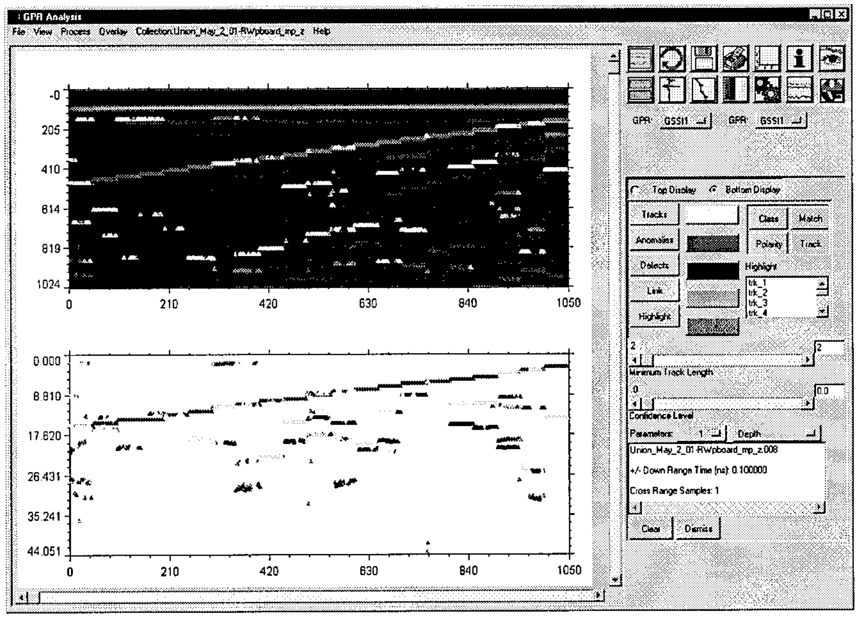


FIGURE 21. Results of depth calculations for particle board layer (bottom window of software display).

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

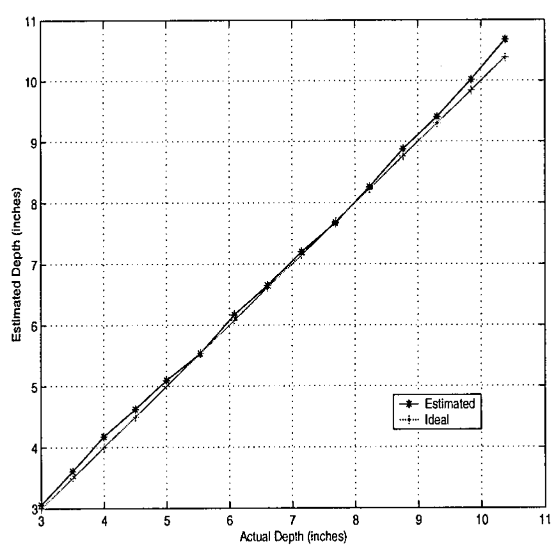


FIGURE 23. Percent Error in Depth Calculated vs. Detect Depth for Concrete Board

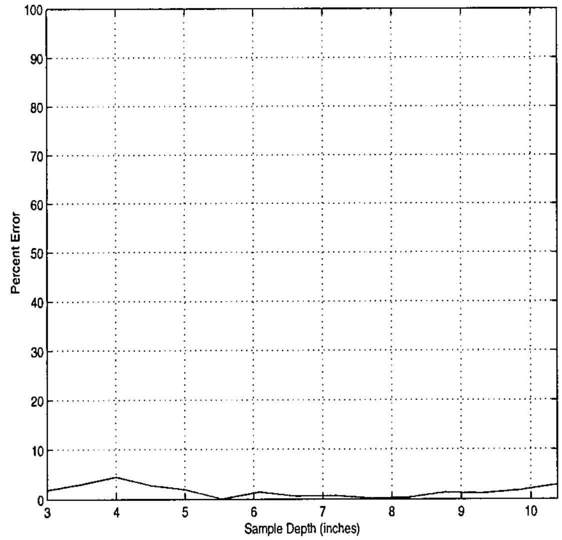


FIGURE 24. Calculated Depth and Ideal Result vs. Detect Depth for Particle Board

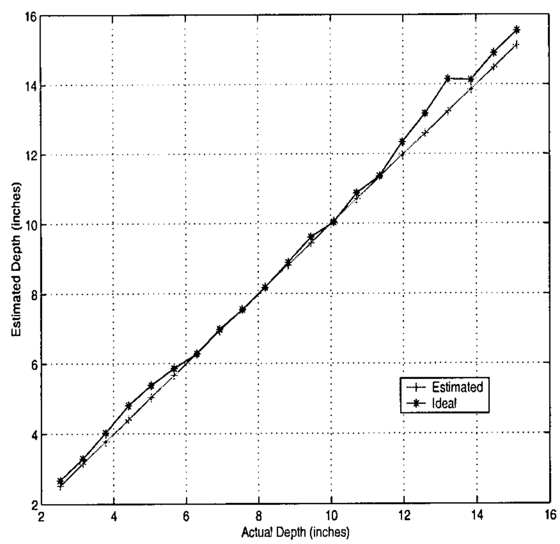


FIGURE 25. Percent Error in Depth Calculated vs. Detect Depth for Particle Board

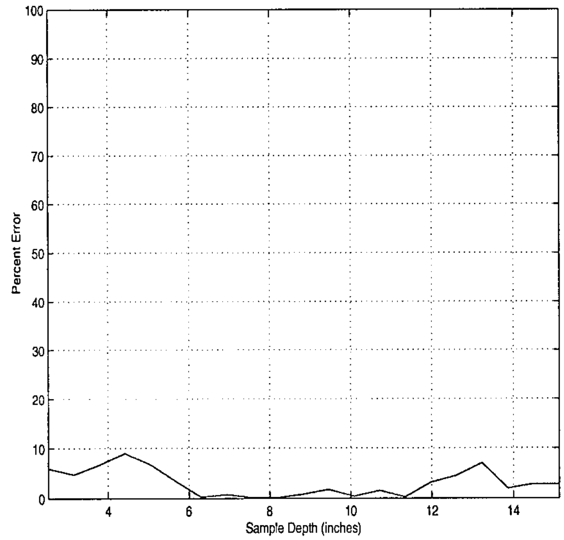


FIGURE 26. Calculated Depth and Ideal Result vs. Detect Depth for Wallboard

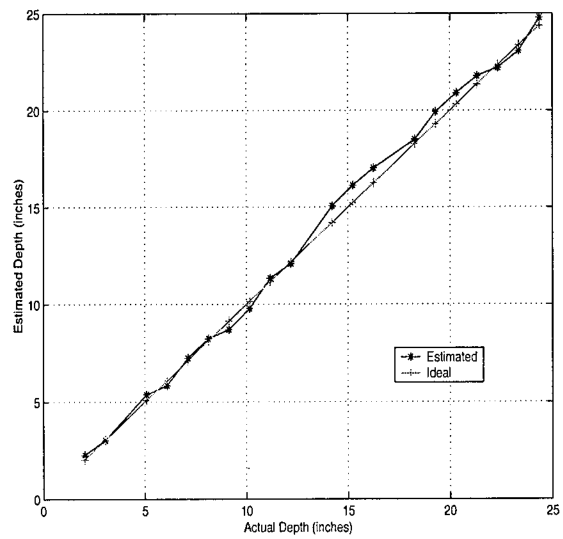


FIGURE 27. Percent Error in Depth Calculated vs. Detect Depth for Wallboard

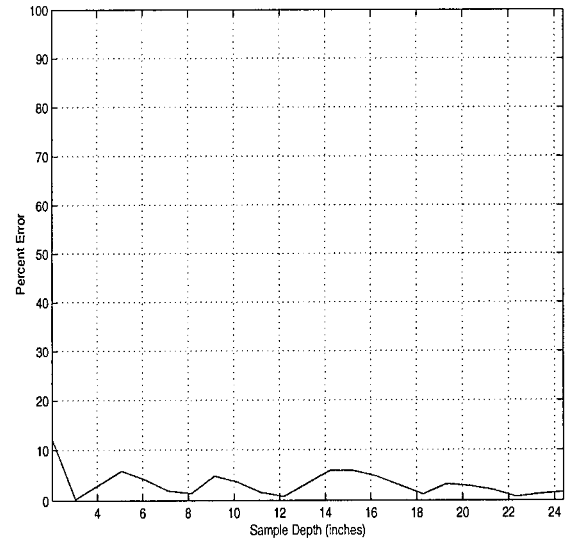


TABLE 1. Summary of testbed calculation results.

	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.

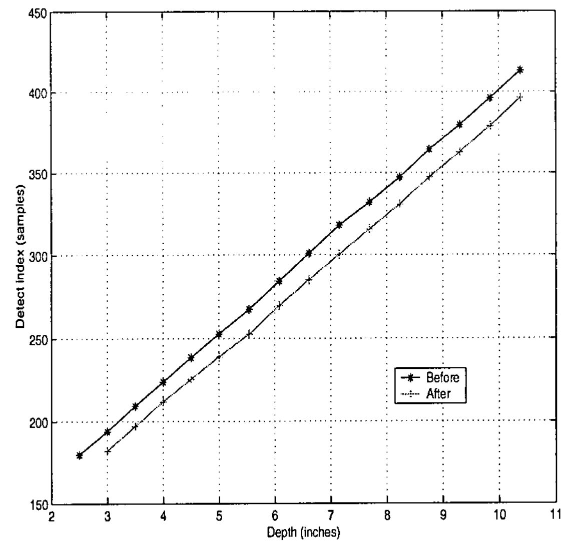


FIGURE 29. Index shifts for cross channel in thin-wall concrete.

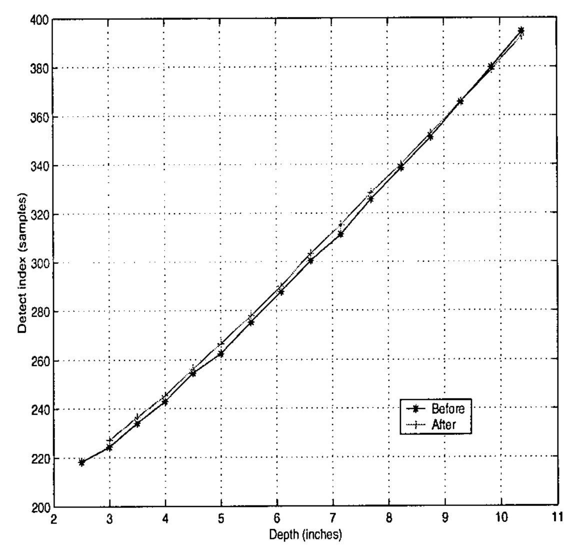


FIGURE 30. Index shifts for direct channel in particle board.

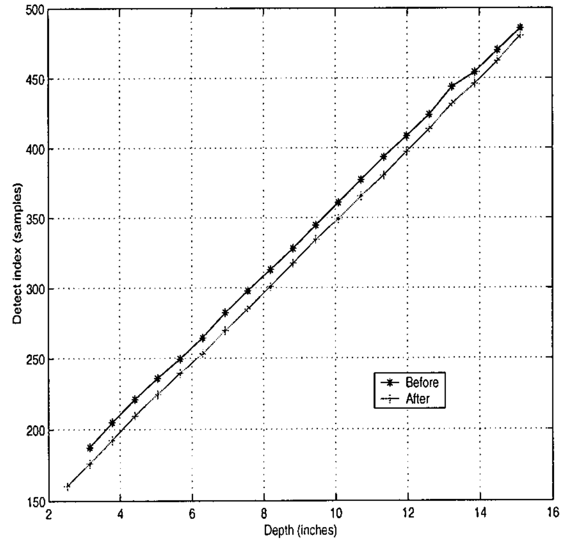


FIGURE 31. Index shifts for cross channel in particle board.

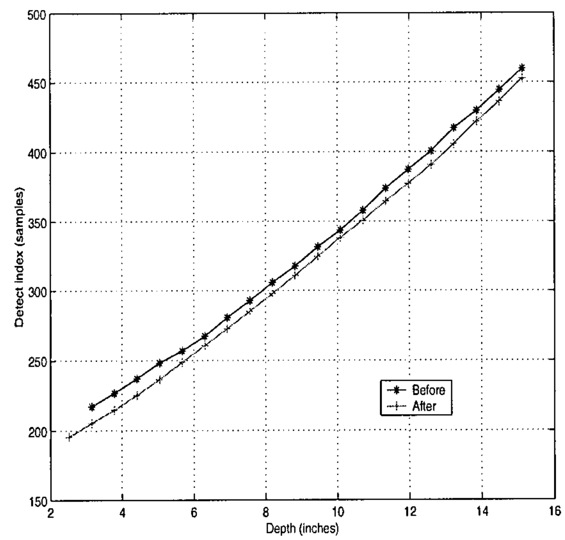


FIGURE 32. Index shifts for direct channel in wallboard.

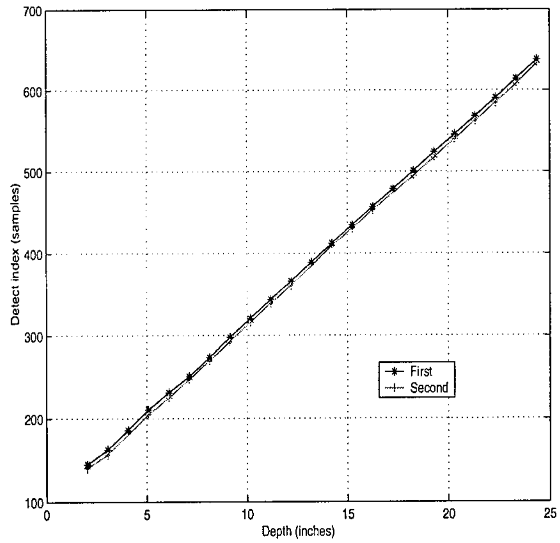


FIGURE 33. Index shifts for cross channel in wallboard.

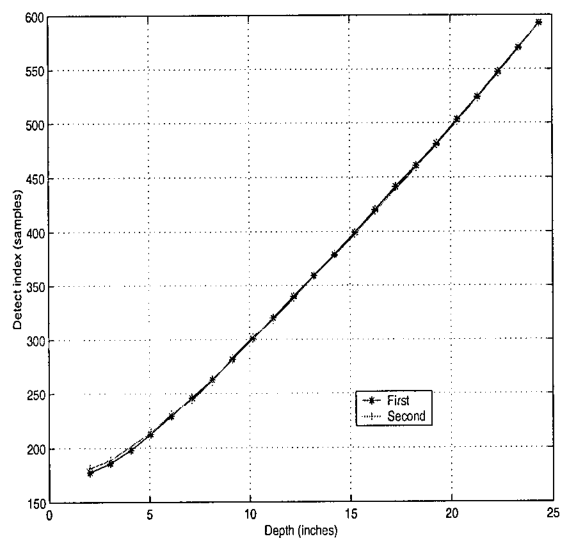


FIGURE 34. Calculated Depth and Ideal Result vs. Detect Depth for Particle Board using data collected before re-seating of the radar board.

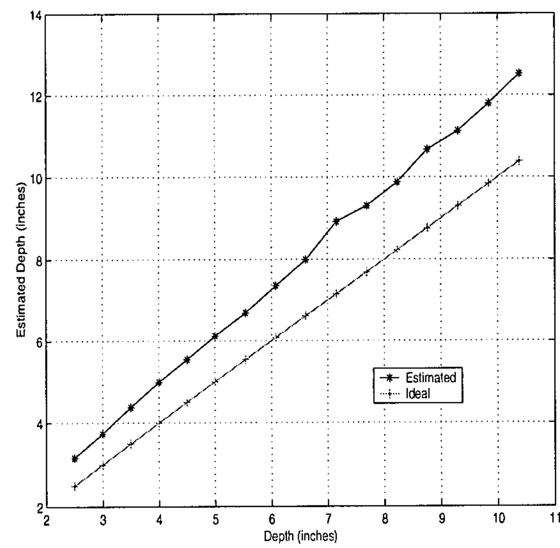
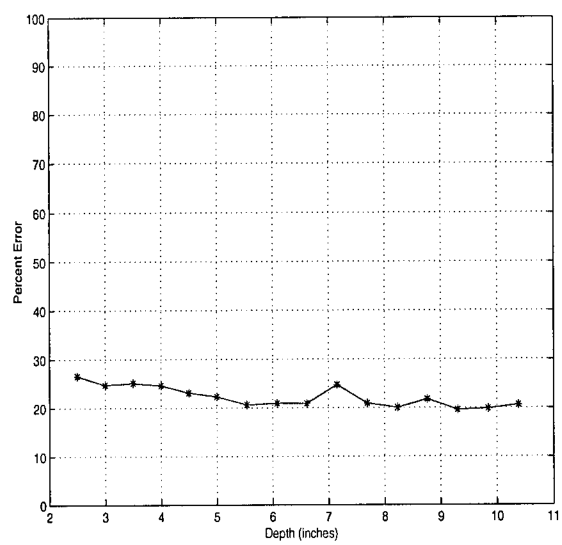


FIGURE 35. Percent Error in Depth Calculated vs. Detect Depth for Particle Board using data collected before re-seating of the radar board.



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”.

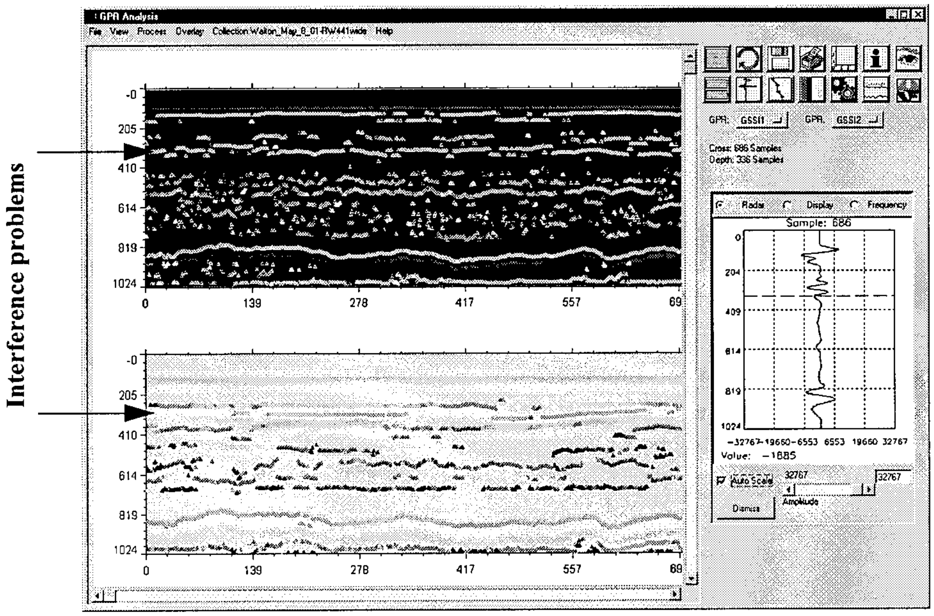


FIGURE 36. Detection results for HWY441 from the GSSI system shown with color designated by classification of each detect. Regions of detection complications due to interference are shown. The major pavement interface should be in these regions.

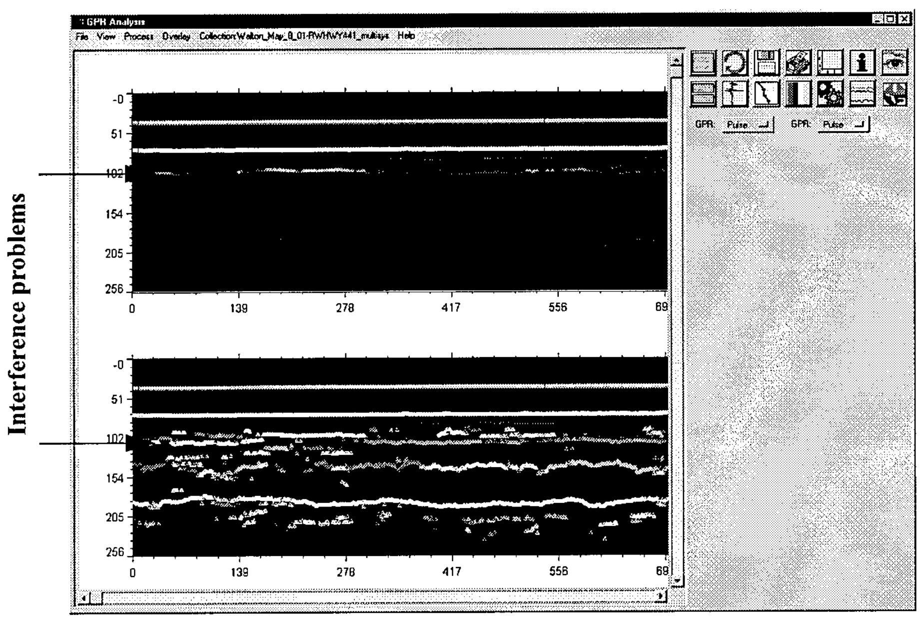
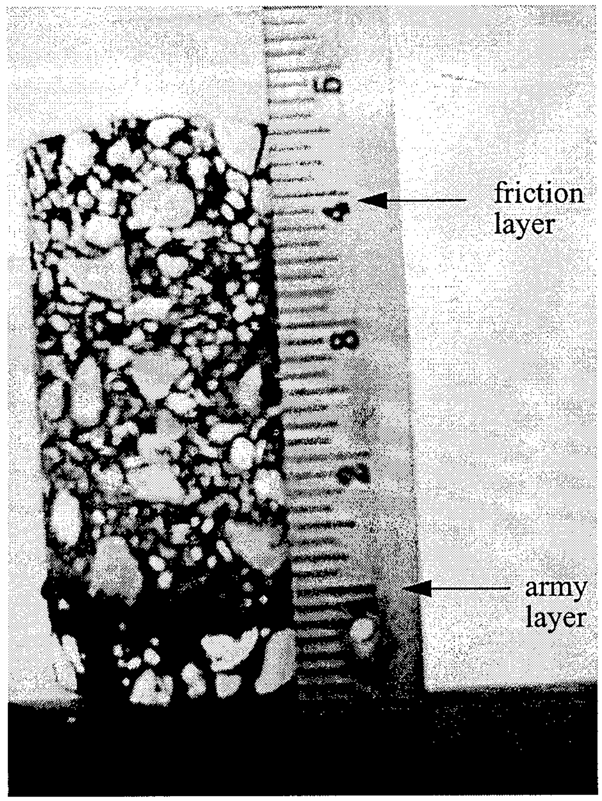


FIGURE 37. Detection results for HWY441 from the Pulse Radar system shown with color designated by detect track number. Regions of detection complications due to interference are shown. The major pavement interface should be in these regions.

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.

Prepared in cooperation with the State of Florida Department of Transportation and the U. S. Department of Transportation.

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.

GPR Roadway Analysis Tool - User's Manual

Electronic Communications Laboratory
University of Florida
Gainesville, FL

for: Florida Department of Transportation

Prepared for:
Florida Department of Transportation under Research Project Work Order #6, Contract #BC354 entitled: Improved Roadway Subsurface Thickness Measurements and Anomaly Identification with Ground Penetrating Radar

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PO Box 140245
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May 2001

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CHAPTER 1

Overview

This chapter serves as an introduction to the Ground Penetrating Radar (GPR) Roadway Analysis system and software. It covers the following:

- GPR Utility
- Manual Structure

GPR Utility

The Florida Department of Transportation (FDOT) and other DOTs have recognized significant potential advantages of ground penetrating radar for nondestructive subsurface road measurements for some time. These potential advantages include the ability of GPR to measure the thickness of thin overlays and subsurface layers, the reduction or elimination of destructive coring, and the identification of certain subsurface anomalies that may cause road surface failures. These advantages, in turn, allow for significant potential cost savings through fewer corings, less road down-time, more accurate road inspections, and more informed maintenance/repair decisions. The potential utility of GPR for roadway measurements has been only partially realized for both project and network level applications. Limitations have occurred due to the large amounts of data that are collected by the GPR for longer road sections, the significant amount of operator interaction and interpretation required, and the vast amount of signal processing that is required. These limitations have tended to make GPR under-utilized even in those cases where adequate measurement accuracies have been possible.

This manual illustrates the capabilities and use of processing algorithms and a dedicated GPR processing software tool designed and constructed for the FDOT to improve GPR analysis accuracy and efficiency through improved layer parameter estimates and reduced operator interaction. The tool provides increased utility of the FDOT GPR assets with processing of new calibrated system configurations, database collection management, and more informative access to the results of enhanced signal processing algorithms.

Manual Structure

The manual will explain the use of the multisystem GPR system and the signal processing and visualization tool. The basics of the software package, use of the hardware system, management of the database, and use of the software for GPR analysis will be explained. The manual will be contain the following sections:

Basics
- Covers software issues and graphical user interface (GUI) fundamental components.

Multisystem Collection Methodology
- Covers use of the multiradar system hardware and collection techniques.

Collection Management
- Covers the database structure and its use.

Profile Visualization
- Covers the GPR data visualization capabilities of the tool.

Data Processing
- Covers use of the GPR signal processing algorithms.

Results Visualization
- Covers the capabilities of the software for display of analysis results.

Report Generation
- Covers output capabilities of the software for easy documentation purposes.

GPR Interpretation
- Covers additional information obtained through evaluation of processing results.

CHAPTER 2

Basics

This chapter describes general operational functionality of the GPR analysis software environment. It covers the following topics:

- Software Issues
- Graphical User Interface (GUI) Fundamentals

Note: For the GPR analysis software to display correctly, the computer monitor's display resolution must be set to **1024x768** or higher.

Software Issues

This software was designed to improve the capacity of the Florida Department of Transportation (FDOT) in making meaningful interpretations of ground penetrating radar (GPR) profiles through enhanced signal processing techniques. With this goal in mind, methods of signal processing were studied and analyzed for applicability to GPR processing tasks. Procedures which were determined to provide suitable utility were coded for use in Visual Numerics' PV-Wave mathematical analysis software. These algorithms process the radar data; however, it was imperative that a graphical environment, or Graphical User Interface (GUI), be developed to facilitate the manipulation of GPR files and data, to provide intuitive access and operation of processing routines, and to display results in a visually beneficial format. This User's Manual serves to document and demonstrate the appropriate use of the graphical environment designed to fulfill that purpose.

GUI Fundamentals

The GPR analysis software is comprised of Graphical User Interface (GUI) components that are used for GPR display, user feedback, and interactive control. These GUI components are contained within the software's main-display, shown below.

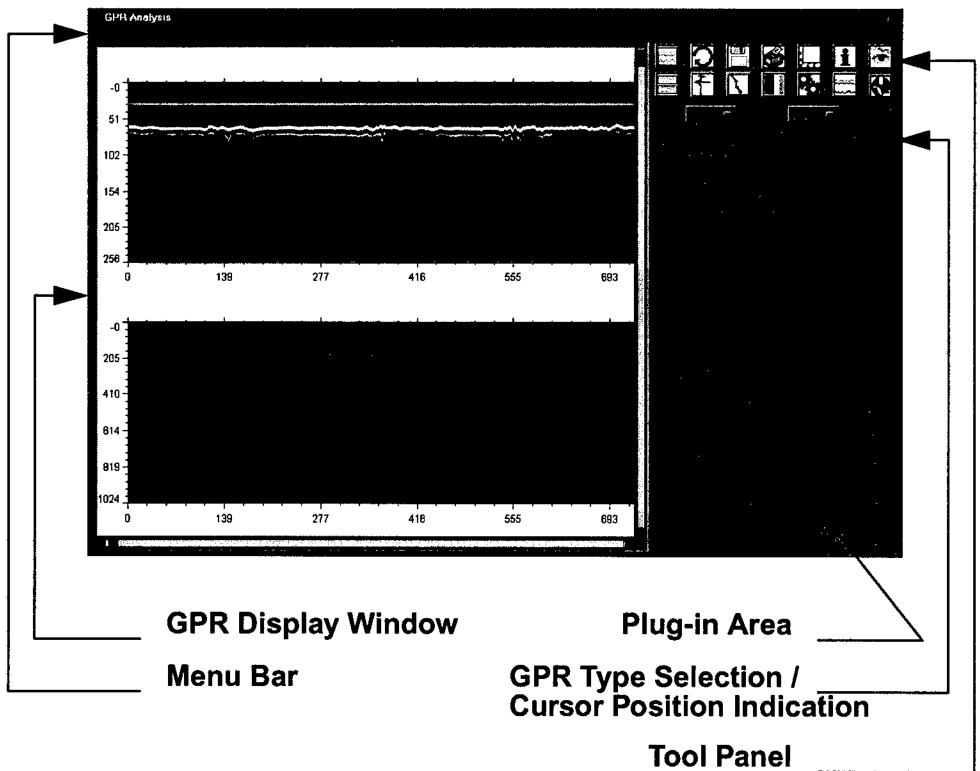


FIGURE 2.1: **GPR Analysis Software Components**

GPR Display Window

Images formed by sequentially aligning the received GPR waveforms, are displayed in the GPR display window. Images can be shown in full window width for detail enhancement or can be viewed in a dual display mode, as shown in FIgure 1, to make comparisons easy. The dual display mode is useful when the GPR collection is comprised of data from multiple GPR sources or channels.

Plug-in Area

The interfaces for most functions provided with the GPR analysis software are provided as plug-in modules. The area to the right of the GPR display window is reserved for displaying plug-in component interfaces. The modular nature of these plug-ins allow extended functionality to be added to the software, without affecting existing functionality. Plug-in components are activated using the menus or tool buttons. Details of existing plug-ins will be discussed in the following sections of the manual.

Menu Bar / Pop-up Menu

The menu bar, located in the top left hand corner, provides access to available functions and plug-ins, and also displays the name of the currently loaded GPR data collection. An identical pop-up menu is activated with the right mouse button when the mouse cursor is located anywhere within the software's main display. Software operations are divided into appropriate categories so that desired functions may be located intuitively.

Tool Panel

A tool panel consists of two rows of iconic buttons and is provided for quick access to commonly used functions.

GPR Type Selector

Drop down menus are used for the selection of the GPR radar type displayed in the GPR display window. The menus are useful when GPR data collection is comprised of data from multiple GPR sources or channels.

Cursor Position Indicator

Mouse cursor position inside the GPR display window is continually updated. The cursor position indicator is displayed in the axis units selected for the GPR image display.

CHAPTER 3

Multisystem Collection Methodology

The GPR roadway analysis system is capable of utilizing dual radar systems for data collection and analysis. The two-system configuration used by the Florida Department of Transportation includes a 1 GHz air-launched system and a Geophysical Survey Systems Incorporated (GSSI) dual 1.5 GHz ground-coupled antenna system. Benefits exist from the comparison and contrast of results from both radars; however, the hardware and software assets are not limited to a dual-system configuration. Data may be collected and processed from the systems individually. Various frequency antennas may also be used with the GSSI system. Collection of data using the radars independently is accomplished using the same procedures previously used by the FDOT for data collection. This chapter covers issues relating to operation of the multisystem configuration:

- Dual System Hardware Assembly
- Dual System Initialization and Collection
- System Limitations

Dual System Hardware Assembly

Pulse Radar. The Pulse Radar is assembled as previously described in FDOT manuals and procedures. The only addition is the connection of the wire for the triggering for the GSSI radar to the Pulse Radar. This cable can be left connected to the Pulse Radar without effecting the operation of the system even when the GSSI system is not being utilized.

GSSI. The GSSI antennas are attached to the FDOT GPR van via a standard trailer hitch as shown in Figure 1. It should be noted that the hitch should be fully inserted into the receiver tube so that the antennas will be properly spaced.

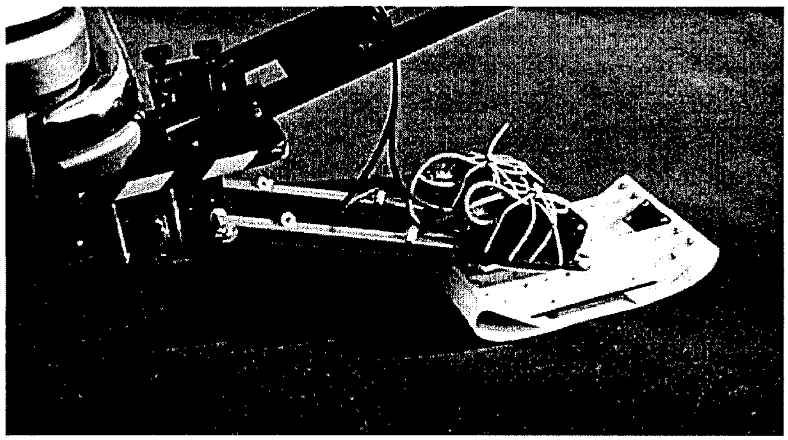


FIGURE 1. **GSSI antenna mounting**

The antennas can be mounted in either wheel path or the center of the van. If the GSSI antennas are mounted in the center of the van, the GSSI and Pulse radar data will not be co-located as the Pulse Radar antenna can not be mounted in the center of the van. The cables for the two GSSI antennas are run out of the window of the GPR van as shown in Figure 2. Rain is not a problem as GPR data can not be collected in the rain so the window will not be open in the rain. The operator should pay special attention to the numbering on the cables as the cables are not electrically the same length and swapping cables will induce errors in the data collection.

The GSSI two antenna data collection methodologies can be utilized with any vehicle that has a standard trailer hitch if the Pulse Radar system in not available.

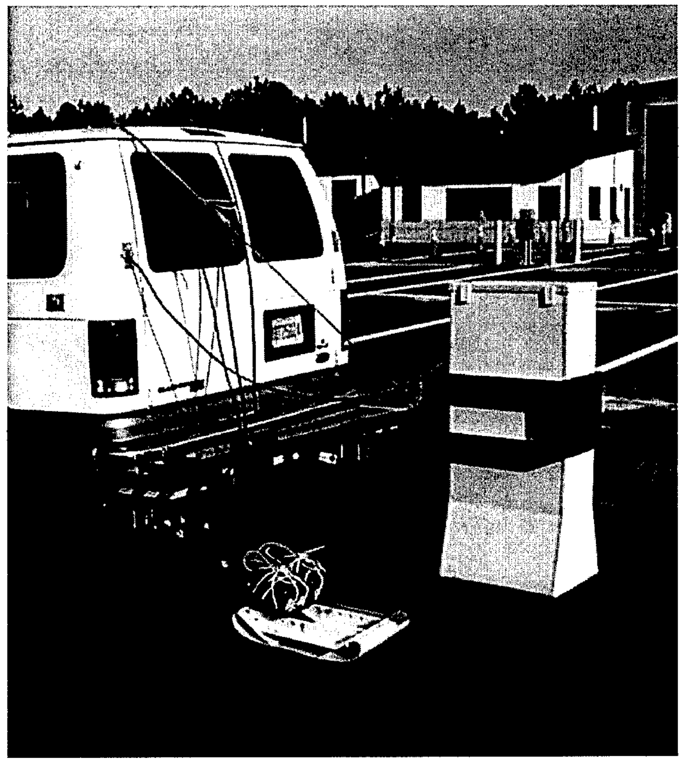


FIGURE 2. **Antenna positioning and GSSI cables routed out of back window of GPR van**

Dual System Initialization and Collection

The Pulse Radar system is powered and initialized as described previously in FDOT manuals and procedures. The Pulse Radar system should be configured for data collection at 1 foot spacing. The GSSI should be operated under system setup number 05. The cable from the Pulse Radar triggering should be connected to the Survey Wheel input of the GSSI. The triggering signal conditioning box should be turned on after the GSSI is powered and before the system setup is completed. Once the Pulse and DMI are configured and ready to collect data, the GSSI collection should be initiated. When the survey vehicle is moved, synchronized collection from the two radars should result.

System Limitations

- 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.

CHAPTER 4

Collection Management

The GPR Roadway Analysis Software was designed to assist in the management of collection data from the multiple radar systems as well as individual radar collections. A common radar file format was created, and a collection database was generated to associate files from each collection. This chapter describes collection management in the following sections:

- Common File Format
- Collection Database Structure
- File Converting and Importing
- File Loading
- GPR Filename Convention

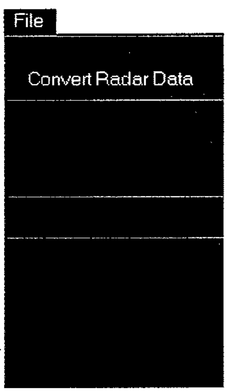
Common File Format

Each different GPR system uses a specialized data format storing the received GPR waveforms and the corresponding parameters relating to the data collection. To simplify data input/output operations and overcome limitations inherent in the native GPR data formats, a common file format called TIFF is used for storing all GPR data. TIFF provides a standard portable image format, yet allows inclusion of an unlimited amount of special purpose GPR specific data. In addition, each TIFF file provides storage of a lower resolution GPR image used for display. This allows image manipulation and enhancement, while maintaining GPR data integrity.

Collection Database Structure

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. The database is organized by the collection conditions provided. The software uses simple and intuitive interfaces to import GPR data into the database, and load GPR data from the database.

File Converting and Importing



When importing GPR data into the database, conversion to TIFF is performed automatically. A dialog box provides selection of the data collection identifiers used for importing GPR data into the database. Counties, dates, roadways, and mile markers are grouped together to uniquely identify the imported GPR data. Only the date and county fields are mandatory. In addition, comments can be added that further describe any other desired collection condition information.

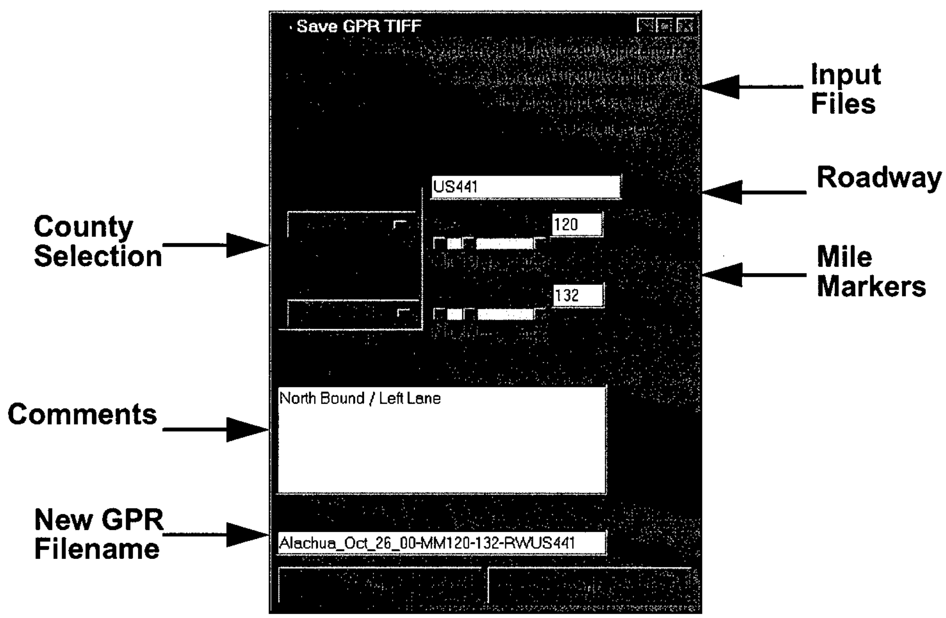
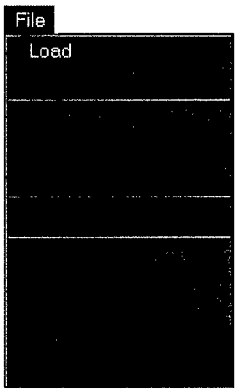


FIGURE 4.1: **File Converting and Importing**



File Loading

When loading GPR data for viewing or processing, the software scans through all available files in database and presents users with a graphical interface for data selection, shown below.

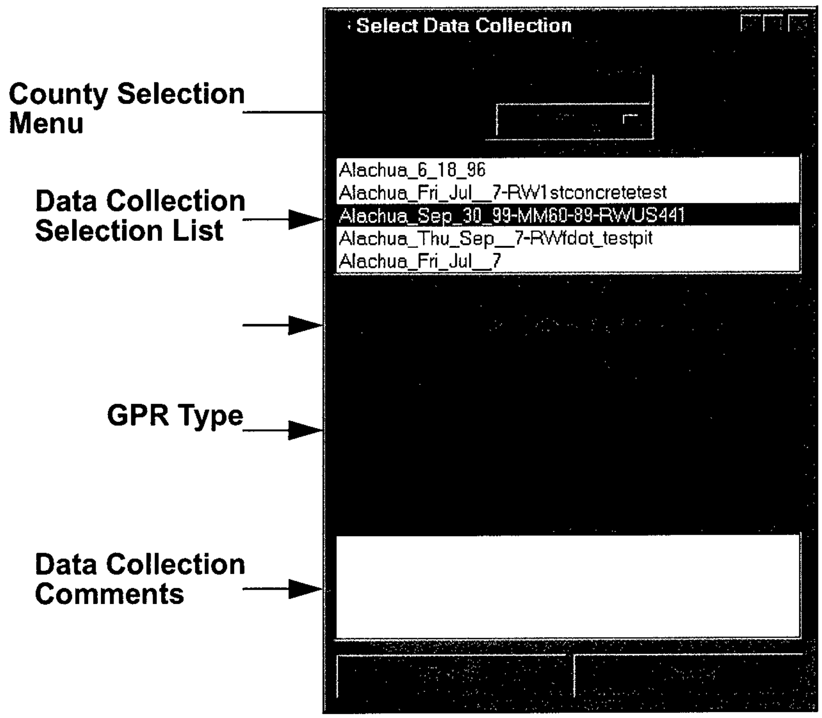


FIGURE 4.2: **File Loading**

GPR Filename Convention

The filenames for GPR files are constructed from the collection identifiers used when GPR data is imported into the database. The fields used are county, date, roadway, and mile marker start and stop. Only the date and county fields are mandatory. Filenames are constructed using the data collection identifiers, as illustrated below.

County: Alachua
Date: 02_11_98
Mile Marker Start: 60
Mile Marker Stop: 80
Roadway: US441

GPR Filename: Alachua_02_11_98-MM60-80-RWUS441

FIGURE 4.3: **GPR Filename Convention**

CHAPTER 5

Profile Visualization

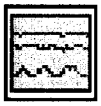
Skilled GPR operators can often identify subsurface features using GPR by recognizing specific characteristics in the data. Computer algorithms are good at assigning numerical values, such as depth, to GPR data, but the trained GPR operator can usually outperform the best algorithms at recognizing structures and trends in the data. The GPR Roadway Analysis Software provides a powerful and intuitive visualization environment for ground penetrating radar data. Display capabilities of the software are described in the following sections:

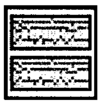
- Image Display
- Profile Display

Image Display

This section explains the display capabilities of the software for GPR images. These capabilities include:

- Single/Dual Display
- Axis Control
- Image Enhancement
- Color Selection and Contrast Adjustment
- Gain Control





Single/Dual Display

GPR images can be displayed in either single or dual display modes. In single display mode, GPR images and plots are shown using the full display window width for detail enhancement. Dual display mode splits the display window vertically, and is useful for making comparisons. Both nodes are illustrated below.

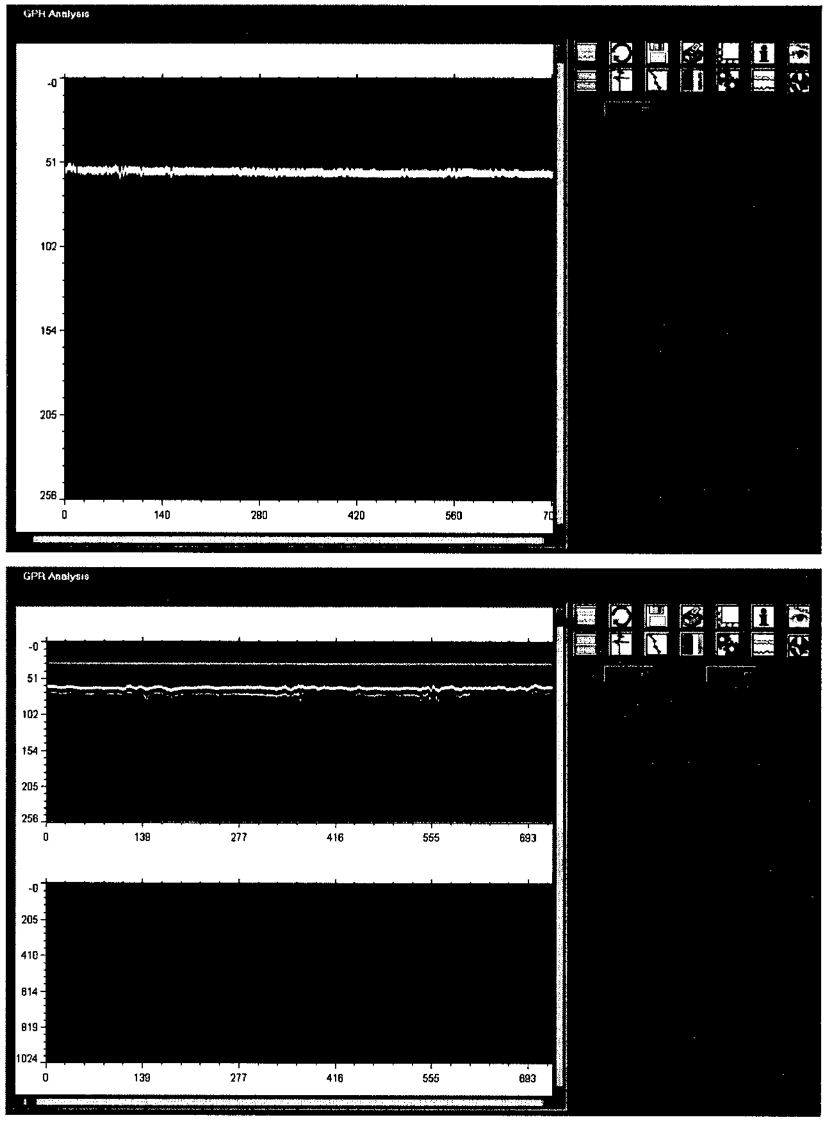
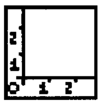


FIGURE 5.1: Single and Dual Display Modes



Axis Control

Axis-scaling and labeling is controlled using a plug-in component. 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 rescales the entire GPR image to fit on page which can be useful when obtaining snapshots of the GPR image. The units used for axis labelling is controlled by a series of menus. The interface for the axis control is shown below.

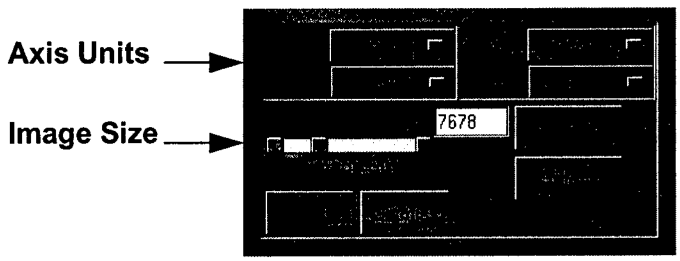


FIGURE 5.2: **Axis Control**

Image Enhancement

Image processing algorithms have been included. These algorithms do not affect the GPR data, but enhance the visual representation of the data in various ways. Often features of the data may be more easily interpreted by the software operator using combinations of these image enhancement options. Image enhancement options are stored in the data file header when the GPR data is saved. Image enhancement options are described below.

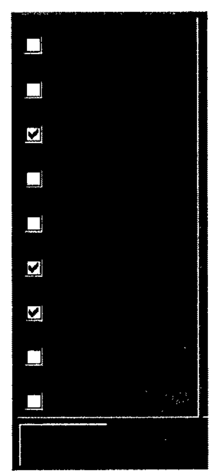


FIGURE 5.3: **Image Enhancement**

Hilbert

Often in GPR images, single interfaces may appear as multiple returns, due to the sidelobes present in the transmitted waveform. The Hilbert Transform is used to obtain the positive envelope of the received waveforms, which effectively removes the multiple responses due to the sidelobes. Unfortunately, enveloping the data also reduces the level of detail, and can cause closely spaced interfaces to disappear entirely.

dB

Data collected by the GPR may typically range in amplitude over several orders of magnitude due to the exponential attenuation of the electromagnetic signal during propagation through the subsurface. This can make visualization of many profiles difficult using a linear scale. Very high values often cause small values to be indistinguishable when the data is displayed. Decibel (dB) scaling, converts the images from a linear to logarithmic scale, and can improve the display of GPR images that have large dynamic ranges.

ABS

Both positive and negative peaks are present in the received GPR waveforms. The polarity of each peak in a received waveform depends on the relative change in dielectric permittivity at each interface encountered. If the relative dielectric change is from lower to higher, the signal peak is positive, when the change is from higher to lower, the peak is negative. The absolute value (ABS) function, allows the magnitude of the GPR waveforms to be displayed without regard to polarity.

Median

On occasion, GPR images contain a significant amount of what is called “salt and pepper” noise. The phenomenon is due to outlying points with high local variance in GPR images. These points seldom truly represent meaningful points in the data, and are often due to sampling errors in the hardware or artifacts induced by other image processing algorithms. A median filter takes all the points within a windowed area around a pixel and returns the *median* of those windowed points as the pixel’s new value. When applying median filtering, users are able to adjust the window sizes to obtain the best visual results.

Smooth

Smoothing is similar to median filtering and can, in some instances, provide better results. A smoothing filter takes all the points within a windowed area around a pixel and returns the *average* of those windowed points as the pixel’s new value. When smoothing, users are able to adjust the window sizes to obtain the best visual results.

Edge Detection

Edge detection attempts to highlight areas where rapid amplitude changes in GPR images occur. Software users have the choice of three different edge detection techniques. The Roberts algorithm performs edge sharpening. The Sobel algorithm performs edge isolation. Finally, unsharp masking discards areas in the image where the change in amplitude is smallest. The Roberts and Sobel algorithms provide the most dramatic results, while unsharp masking gives the user some control through the adjustment of the mask window size.

Histogram Equalization

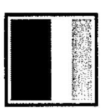
In many GPR images, most pixels reside in a few small subranges of the possible values. Histogram equalization works by spreading the distribution so that each range of pixel values contains an approximately equal number of members, thus improving the contrast of image. The contrast improvement provided by histogram equalization can come at the expense of hiding small details in the image.

Time Align

With air-launched GPR, a rippling effect often appears in the images due to excessive bounce of the GPR collection vehicle. Time aligning attempts to remove this effect by simply shifting each vertical trace in the GPR image such that the maximum value of all traces occur at the same sample delay.

Subtract Average

Locally varying features in the data can be enhanced by removing the background from the image. Background removal in GPR images is done by subtracting all the samples values in each row by the average of all the sample values in the corresponding row.



Color Selection and Contrast Adjustment

Color scheme selection and contrast adjustment for GPR images is performed using another plug-in component. The interface for this plug-in component provides a window to display the current color and contrast settings, sliders for contrast adjustments, and finally, a selectable list of available color schemes.

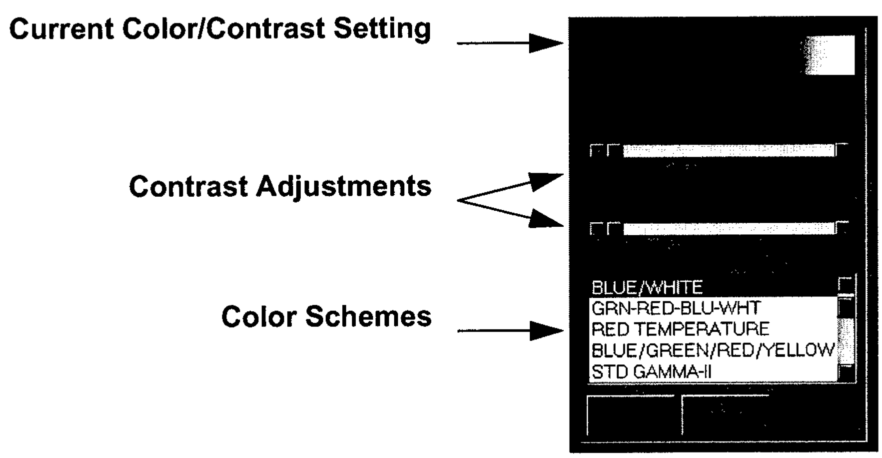
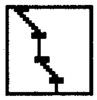


FIGURE 5.4: **Color Selection and Contrast Adjustment**

Gain Control



Sometimes applying a gain function to GPR data will make deeper objects visible. A gain function will often amplify small returns from subsurface features which have been attenuated by long travel distances in the ground. The graphical tool used to modify gain functions has been specifically designed to be compatible with gain functions used in GPR systems. In addition, the tool provides the flexibility to allow the addition and modification of gain functions for data from GPR systems that do not support gain function usage.

Gain functions may contain up to eight points. The value of the gain is linearly interpolated between the gain values at the points. Gain values at each point are set using the graphical tool. New gain functions are stored in the data file headers when GPR data is saved. A revert option is included to allow the user to revert the gain function to the one set at the time of the data collection. The interface for gain function control is shown below.

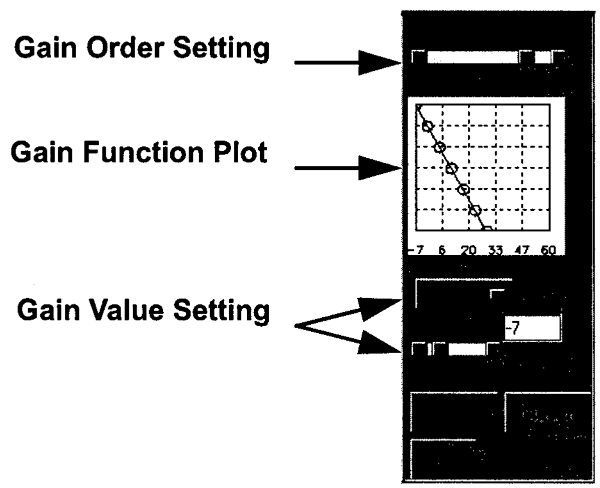
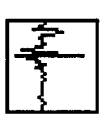
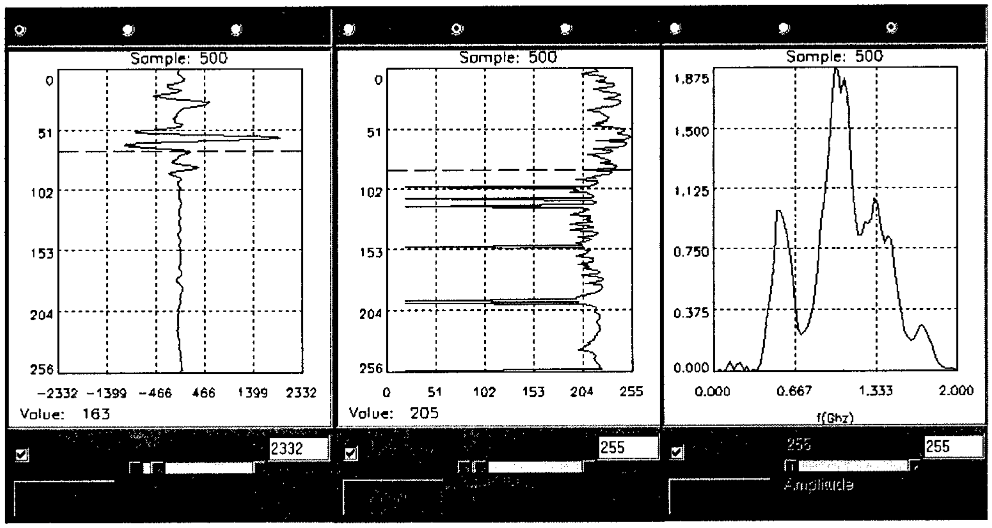


FIGURE 5.5: **Gain Control**

Profile Display



Information may also be displayed for individual traces of a GPR image. Three display modes for profile information are available: radar, display, and spectrum. Displays consist of plots that correspond to data at the mouse cursor position in the GPR image display. The three modes are illustrated in the following figure. The autoscale option sets the x-axis range to the maximum possible value for the entire data set. The *radar profile* displays the received GPR waveform, the *display profile* is obtained from the GPR image display with the image enhancements applied, and the frequency plot represents the estimated frequency spectrum of the received GPR waveform.



Radar -

Received Radar Waveform Profile

Display -

GPR Image Profile

Frequency -

Estimated Frequency Spectrum

FIGURE 5.6: **Profile Display**

CHAPTER 6

Data Processing

The GPR Roadway Analysis Tool software automates the tedious process of GPR interpretation, greatly improving efficiency over more labor intensive software packages. Layer interfaces are detected and segmented autonomously in GPR images, and properties of the layers are calculated. Operation of the processing algorithms is simple and intuitive and is described in the following sections:

- Parameter Selection
- Process Feedback

Parameter Selection

The algorithms used for layer interface detection were designed to operate on GPR data with limited need for user modification of algorithm parameters. The only parameter settings needed when processing are for control of the tracking related algorithms. Control of the tracking parameters is necessary due to the wide variety of subsurface conditions that may be encountered between different GPR data collections. Tracking works using a windowed search technique to link recorded signal detections into continuous tracks. Depending on the subsurface conditions of the particular GPR collection, the tracking parameters used can greatly affect the layer tracking performance.

The tracking parameters are controlled using parameter selection slider bars. For most subsurface conditions, the mid range settings (.5, 10) will yield adequate results. A rule of thumb for selecting tracking parameters is as follows: if tracks are too small and noncontinuous, increase the tracking parameters; if the tracks are connecting unrelated interfaces or exhibit excessive crossings, lower the tracking parameters. Each time a unique set of parameters are used to process the data, the parameter set is saved. The import button allows the software users to automatically set the parameters to a previously used values. The interface for selecting the tracking parameters is shown below.

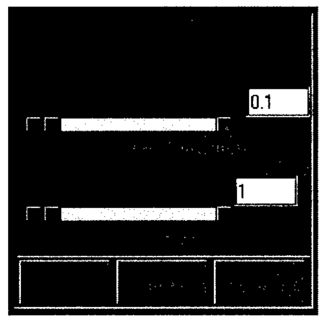


FIGURE 6.1: Processing Parameter Selection

Process Feedback

A series of algorithms process the GPR data sequentially when the layer interface detection and tracking is performed. The time to completion status of these algorithms is displayed in a status bar as the GPR data is processed.

CHAPTER 7

Results Visualization

The GPR software has extensive capabilities for visualization of processing results. This chapter explains these capabilities and manual editing of processing errors in the following sections:

- Display Processing Results
- Detect Inquiry

Display Processing Results

Another plug-in component 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. It also provides flexibility in options for displaying processing results. Display options are discussed in the following sections:

- Top/Bottom display selection
- Parameter selection
- Display modes
- Display filters
- Processing results

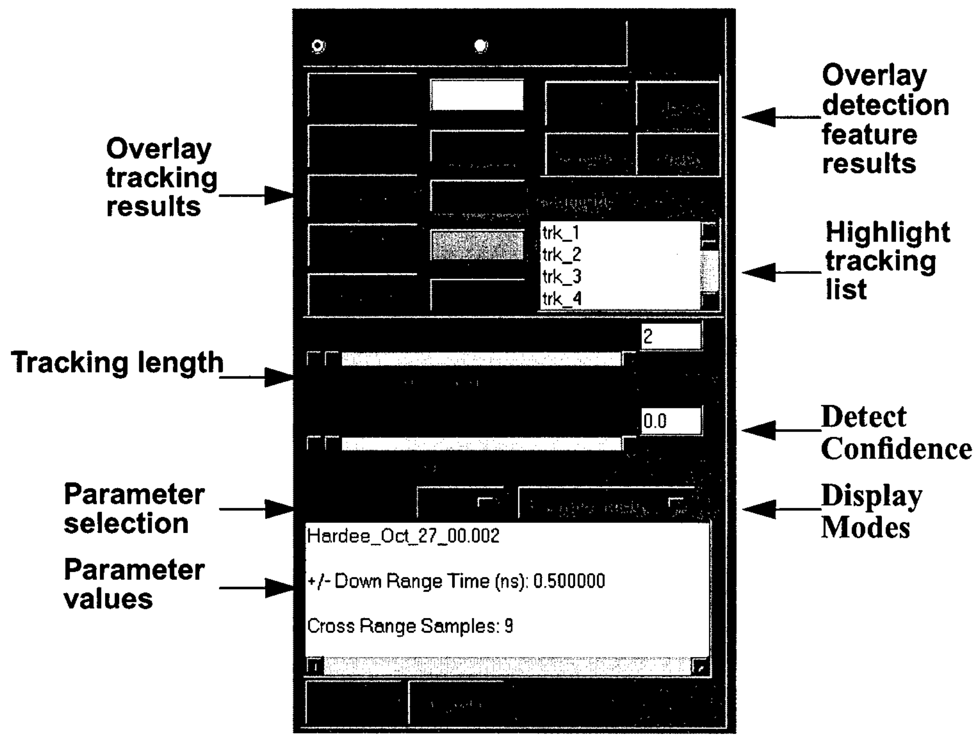


FIGURE 7.1: Overlay

Top/Bottom display selection

This section of the overlay interface is only selectable when the GPR dual display mode is used. Overlays will be plotted inside either the top or bottom axis depending upon the selection made.

Parameter selection

Depending on the subsurface conditions of the particular GPR collection, the tracking parameters used for processing can affect the layer tracking performance. If the loaded 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.

Display modes

Software users can display processing results overlaid on the GPR image, plotted versus depth or plotted versus relative dielectric permittivity.

Display Filters

Two sliders bars are used to set the values for the display filters. The first slider bar is for detection confidence. When displaying processing results, detects and tracks will be plotted only when the calculated confidence value is above the value selected. The second slider bar is for track length. Only tracks that have a greater total number of detects than track length setting will be plotted.

Processing results

Results may be displayed based upon track associations or based upon features of individual detects.

Track association-based

These results are based on assigned tracking labels. The color used for the plots for each of these results is selectable using the color buttons next to each display type. The various display types are described below.

- **Tracks** - Tracking attempts to link together detects from common layer interfaces. Each tracked section is assigned a label. Track labels are assigned to tracks sequentially according to extent, starting with the largest track.
- **Anomalies** - Refers to groups of detects that do not correspond to long layer interfaces, or detects that have abnormally high or low associated relative dielectric values. Users are given the option for plotting anomalies based on detect extent or relative dielectric values.
- **Detects** - Detects that are not classified as tracks are referred to as clutter. These detects either have lower confidence values and linear correlation with surrounding detects than detects associated with layer interfaces (tracks).
- **Link** - After plotting tracks, linking will draw a connecting line between all detects in each track for all of the displayed tracks.
- **Highlight** - Individual tracks to highlight can be selected from the list of all available tracks.

Detect feature-based

Detects have various feature-based properties other than track extent. Display colors used correspond to the feature values associated with each detect.

- **Class** - Prior to tracking, each detect is assigned to a specific class based on detection confidence and the linear spatial correlation between other detects. Tracking is then performed using all detects except those that are classified as clutter (classes 0 and 2). Detect classes are designated as follows:
  Class 0 - low confidence, low correlation - light green
  Class 1 - low confidence, high correlation - dark blue
  Class 2 - medium confidence, low correlation - light blue
  Class 3 - medium confidence, high correlation - magenta
  Class 4 - high confidence, low correlation - yellow
  Class 5 - high confidence, high correlation - orange
- **Match** - Time delay differences between two antennas are needed in order to calculate subsurface properties for GPR data collected using ground launch antennas. When detects are found in both channels, that correspond to the same object or layer interface, a match has occurred. For ground launched GPR data, values for depth and other properties can only be calculated for detects that match in both channels.
- **Polarity** - Signal polarity can often be used as an indication of the relative dielectric change between the various subsurface interfaces. When the change in relative dielectric goes from lower to higher, the received waveform has a positive peak, when the change in relative dielectric goes from higher to lower, the received waveform has a negative peak. When plotting polarity, detects with a positive values are plotted using green, negative values are plotted in red.
- **Track** - All tracks are plotted using different colors to distinguish individual tracks from one another.

Detect Inquiry

Properties of individual detects may be displayed, and detection tracking errors may be manually corrected. This section explains both of these features.

Parameter display

After displaying processing results, parameters of individual detects and tracks can be obtained by clicking the mouse cursor over the desired track or detect plotted in the main display. The plug-in component used to display the detect and track properties is shown below.

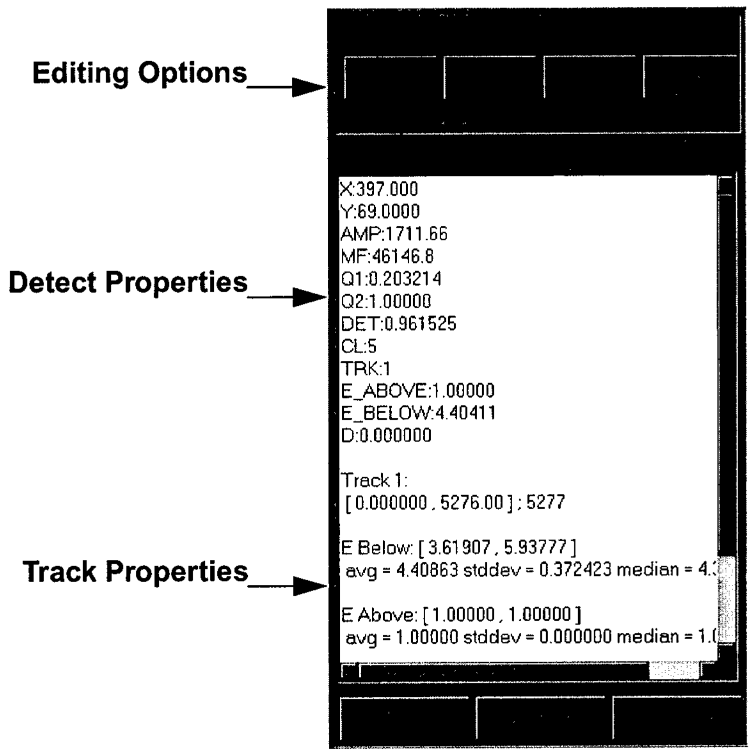


FIGURE 7.2: **Detect and Track Properties**

Manual editing

There may be regions in the GPR data where the detection or tracking algorithms fail to correctly track continuous layer interfaces, or conversely, incorrectly connect layer interfaces. To correct these potential problems, the GPR analysis software allows users to edit the processing results. The interface for editing the processing results is provided as part of the detect and track parameter display plug-in component. The following manual editing options are available:

- **Join** - Used to join nonconnected track segments into a single continuous track. To join two track segments together perform the following steps: 1) select first track segment using the mouse, 2) hit the *Join* button in the detect parameter display plug-in, 3) finally, select the track segment to join together using the mouse.
- **Split** - Used to split a long continuous track into 2 separate track segments. To split a track, use the mouse to select the desired splitting point in a track and then hit the *Split* button in the detect parameter display plug-in.
- **Del Trk** - Used to delete an entire track from the detection list.
- **Del Det** - Used to delete single detects from tracked segments.

After manual editing is performed, the *Recalculate* button is used to recalculate the depth and dielectric values using the new track assignments. The Save Edits buttons permanently commits all edits to the detection file.

CHAPTER 8

Report Generation

Provisions for easy documentation of processing results have been made. This chapter explains the abilities of the GPR Roadway Analysis Tool to export both hardcopies of results and graphics file formats that may be easily used in standard word processing applications. This chapter contains the following topics:

- Tracking Processing Results
- Printing

Tracking Summary

After interface detection and tracking have been performed, summary results can be examined and saved as text files. These text files can be easily incorporated into reports or other documents. The interface for viewing and saving tracking summaries consists of a multi-windowed panel. The number of panels corresponds to the number of radar systems and channels used for the currently loaded GPR collection. Since each GPR collection can be processed using multiple sets of tracking parameters, users must first select the desired parameter set from the list of available parameter sets displayed at the far left of the interface. Once the desired parameter set is selected tracking summaries are displayed for each GPR system and channel. The tracking summaries can then be saved as text files.

Tracking summaries consist of a listing of each track, along with its average depth and extent. Tracks are labeled and listed sequentially from largest to smallest length.

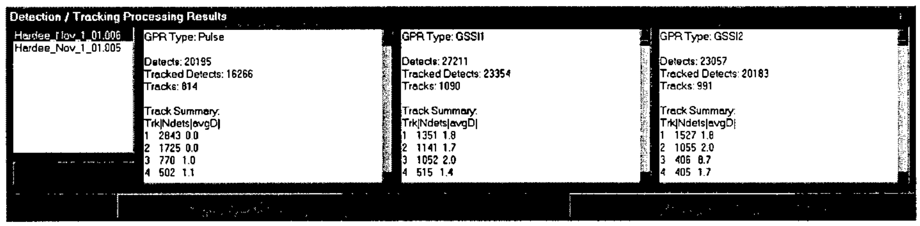


FIGURE 8.1: Tracking Summary

Printing

The windowed portion of the GPR image display can be printed or saved as a standard graphics file. The printing interface is done using a plug-in component that provides a print preview and allows selection of several graphics file formats. By using printing in conjunction with the axis control's *One Page* option, an image representing the entire data collection can be saved or printed. The printing interface is shown below.

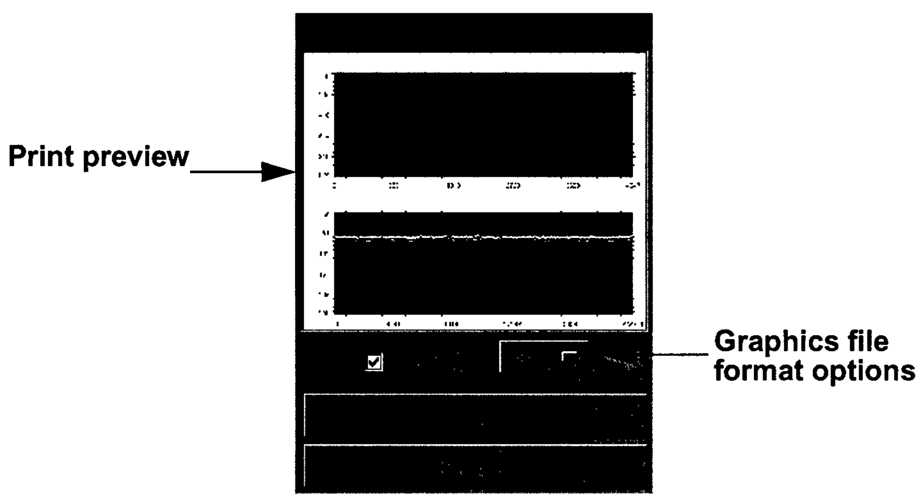


FIGURE 8.2: Printing

CHAPTER 9

GPR Interpretation

This chapter discusses some concepts of GPR interpretation beyond the typical thickness and dielectric measurements of layers. The sections cover:

- Anomaly Identification
- Void Content Analysis
- Surface Roughness Estimation

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 considered 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 and 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:

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" 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.

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.

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 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.

Void Content Analysis

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.

Surface Roughness Estimation

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.

References

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

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