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16. Abstract COLORMAP is a User friendly window driven software package for processing Ground Penetrating Radar waveforms. It is intended for highway engineers who wish to obtain subsurface information from pavement structures. This report is a User Manual which describes each of COLORMAP's pull down menu options. Also included is a series of case studies which highlight various applications of the package for processing GPR data from a variety of highway applications. Included in these applications are thickness surveys of asphalt and concrete pavements, detections of areas of deterioration within asphalt layers, quality control and pavement evaluations for pavement rehabilitation studies.					
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COLORMAP - USER'S MANUAL WITH CASE STUDIES

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IMPLEMENTATION STATEMENT

The COLORMAP system developed in this study has been implemented by the Texas Department of Transportation. A three-day training school was conducted in December of 1994 to introduce TxDOT personnel to all aspects of GPR data collection and processing. The Pavement Design section now offers GPR services as a routine data collection activity.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or the policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. It is not intended for construction, bidding or permit purposes. The engineer in charge of the project is Tom Scullion, P.E. #62683.

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SUMMARY

COLORMAP is a User friendly window driven software package for processing Ground Penetrating Radar waveforms. It is intended for highway engineers who wish to obtain subsurface information from pavement structures.

This report is a User's manual which describes each of COLORMAP's pull down menu options. Also included is a series of case studies which highlight various applications of the package for processing GPR data from a variety of highway applications. Included in these application are thickness surveys of asphalt and concrete pavements, detections of areas of deterioration within asphalt layers, quality control and pavement evaluations for pavement rehabilitation studies.

CHAPTER 1

INTRODUCTION

Ground Penetrating Radar (GPR) is a nondestructive testing technique used for evaluating the subsurface conditions of pavement systems. The background work on GPR performed by the Texas Transportation Institute for the Texas Department of Transportation has been documented in TTI Research Report 1233-1. Reference should be made to that report for discussion of GPR principles, data collection and data interpretation techniques. In the current study 1341, work has focused on evaluating the capabilities of GPR to assist in a range of new applications, including detecting subsurface problems in hot mix surfacings and asphalt stabilized bases, measuring the thickness of recently constructed concrete pavements and in assisting with the pavement evaluations as the first step in the pavement rehabilitation process. The successful case studies performed in this and earlier studies have convinced the TxDOT to purchase and provide GPR testing as a service to District offices. However, before full implementation of the system can be accomplished, it is necessary to develop a signal processing system so that the masses of waveforms collected in a GPR survey can be readily transformed into information meaningful to highway engineers. The software system described in this report has been developed for this purpose.

The software package known as COLORMAP is a windows based microcomputer system written in Microsoft Quick C for Windows. The system is intended to be simple to use so that non-GPR experts can rapidly review and interpret GPR data after a short introductory training school. Eventually it is hoped that GPR can become a routine District based testing system to assist with the following applications:

1. Quality Control testing of new asphalt layers, which checks thickness, density and uniformity;
2. As the first step in pavement rehabilitation planning where GPR can identify uniform sections, locate areas of surface or base deterioration and give layer thicknesses in advance of structural strength testing and coring;

3. As a forensic engineering tool to investigate unexpected pavement failures; and
4. As part of the States Network Level Pavement Management System, where highways with inadequate or missing plans can be tested for homogeneity and surface thickness.

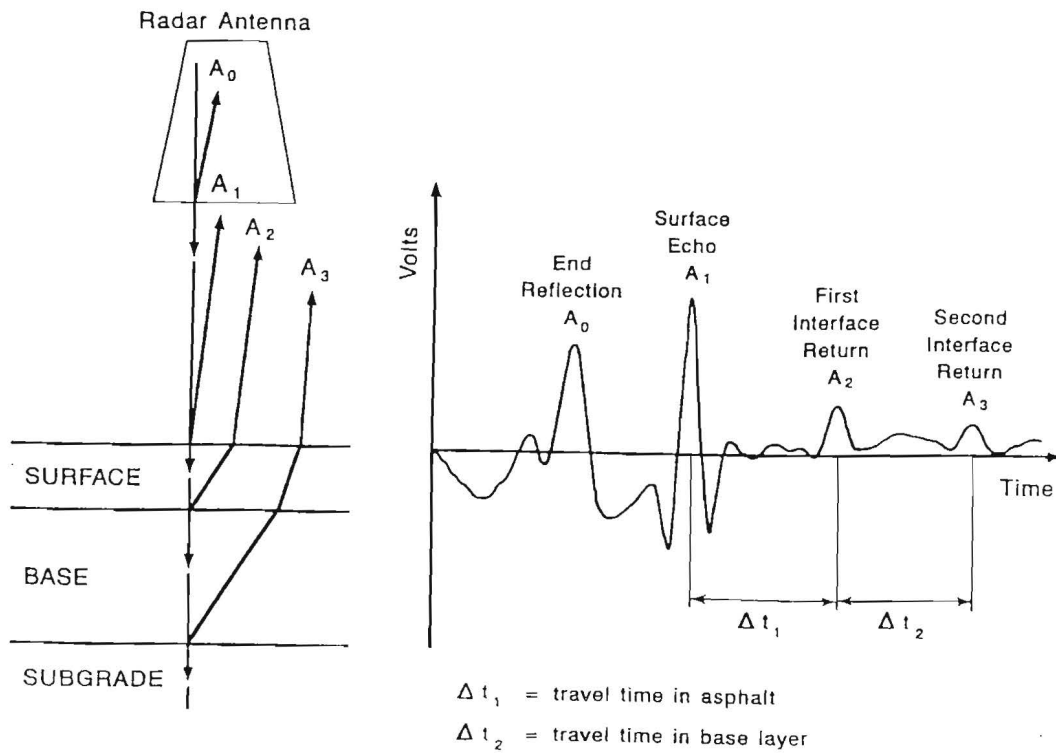
1.1 BASIS OF GPR TESTING

The TTI Ground Penetrating Radar vehicle with the Pulse Radar antenna is shown in the top half of Figure 1. The antenna transmits pulses of radar energy, with a central frequency 1 GHz, into the pavement. This wave is reflected at significant layer interfaces in the pavement. These reflected waves are captured by the system and displayed as a plot of return voltage versus arrival time. As shown in Figure 1 the largest peak is the reflection from the pavement surface, the amplitudes before the surface reflection are internally generated noise and if they are significant they should be removed from the trace prior to signal processing. The reflections of significance to pavement engineers are those that occur after the surface echo. These represent significant interfaces within the pavement, and the measured travel time is related to the thickness of the layer. For example, the time between the surface echo A_1 and A_2 is related to the thickness of the top layer.

The GPR return waveform from a pavement with a homogeneous surface layer and in generally "good" condition is shown in Figure 2. Peaks A, B and C are reflections from the top of the surface, base and subgrade, respectively. The hot mix surfacing is classified as "homogeneous and uniform" because there are no significant peaks between A and B. If the asphalt layer was placed at different times with different aggregates, there may be small positive reflections at each asphalt layer interface. This trace for a "good" asphalt should be contrasted with the trace shown in Figure 3. In this figure a negative peak C occurs between major peaks A and B. This signifies a layer of lower dielectric properties. In Texas, when there are intermittent negative peaks in the surfacing layer, they are usually related to the presence of a low density layer within the asphalt; stripping or some other deterioration is usually the cause of this type of reflection. In this particular case the presence of stripping was confirmed by field coring. Negative peaks such as those shown in Figure 3 may possibly be



a. TTI GPR Equipment.



b. Principles of Ground Penetrating Radar. The Incident Wave is Reflected at Each Layer Interface and Plotted as Return Voltage Against Time of Arrival in Nanoseconds.

Figure 1. GPR Equipment and Principles of Operation.

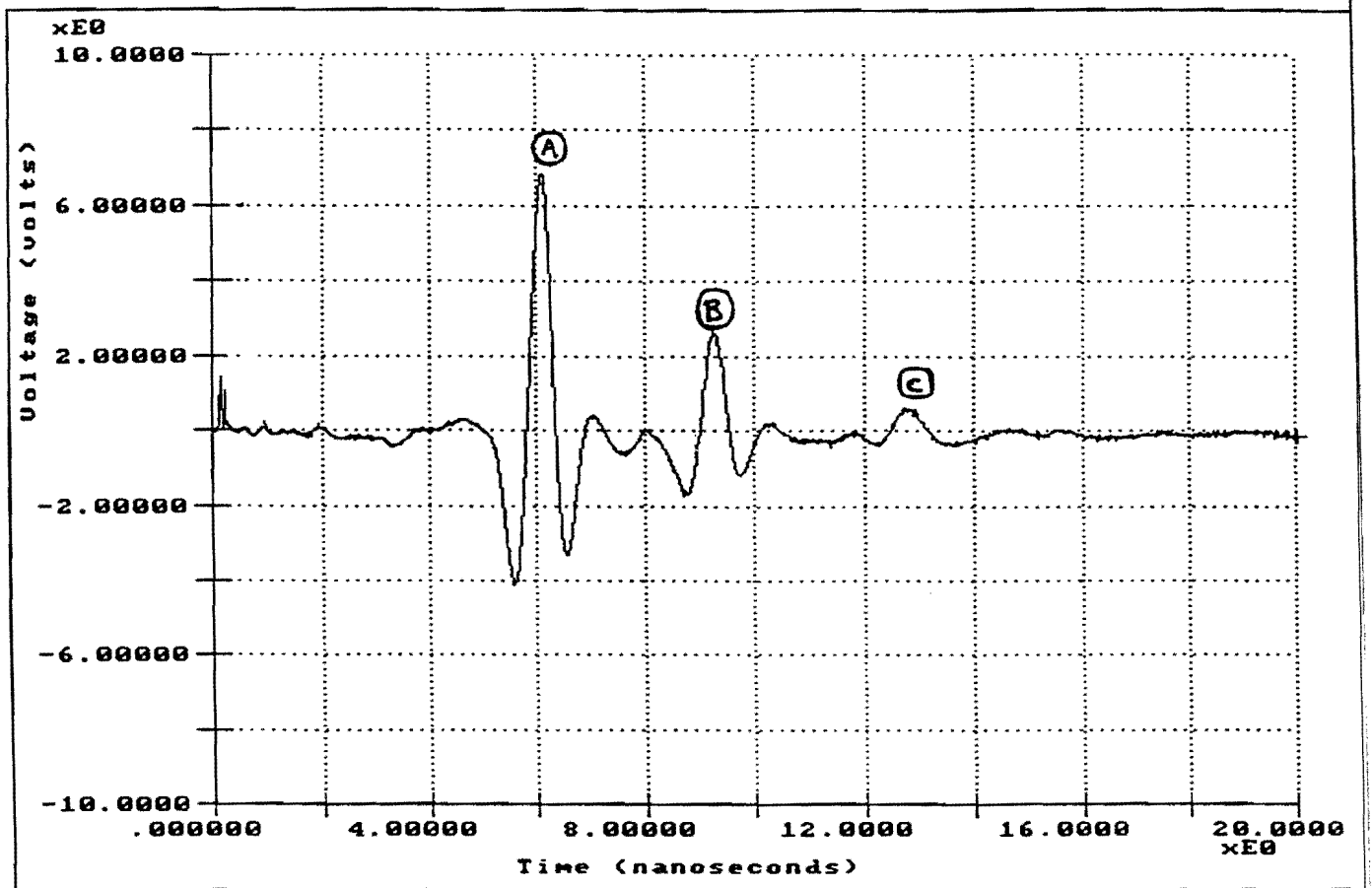


Figure 2. Typical GPR Waveform. Peaks A, B, and C are Reflections from the Surface, Top of the Base and Top of the Subgrade Respectively.

TTI Radar - Single Trace Display
DATA FILE: C:\D21U83\WEST1.DAT # OF TRACES: 7867 DMI Printing...
Draw Trace: 200 Gain: 2.0000 ▶Hard Copy

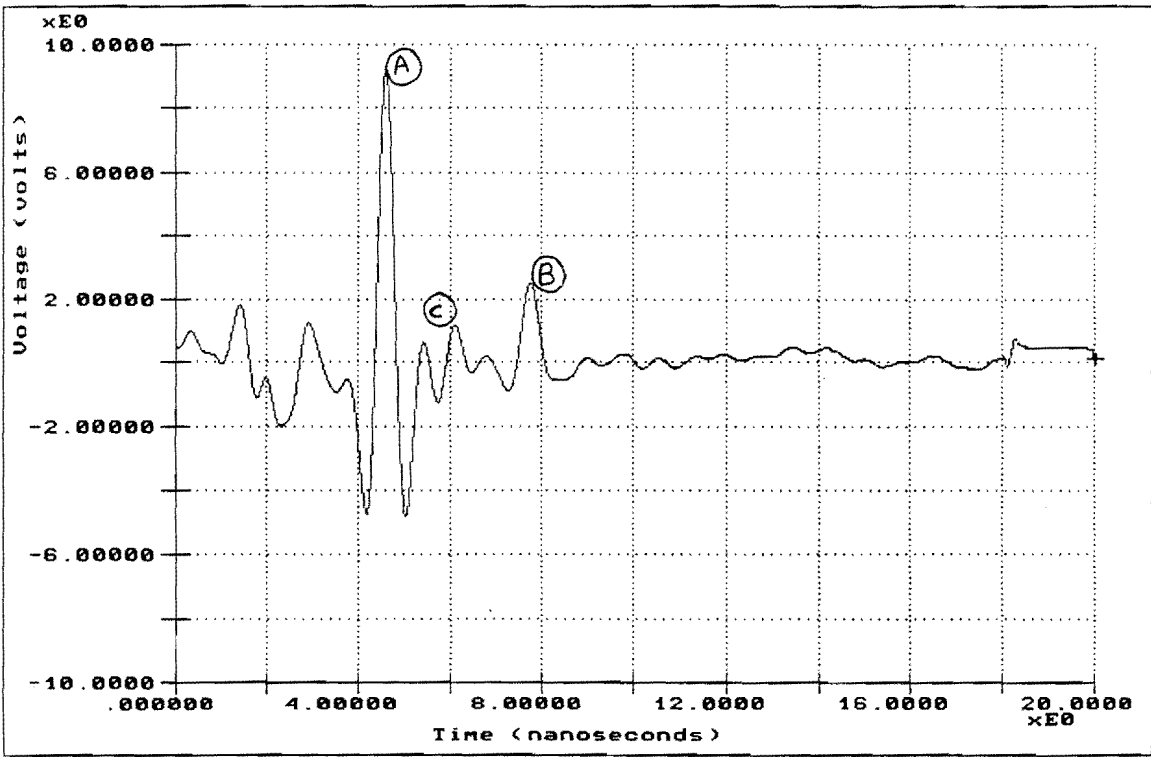


Figure 3. Typical GPR Return Waveform from US83. Reflections A and B are from the Surface and the Top of Base, C is from the Top of the Unstable Stripped Layer.

caused by other factors, such as the use of sand asphalt mixtures containing no large aggregates; however, in all of the cases investigated to date, the presence of intermittent negative peaks within the asphalt layer has been found to be either a construction defect or a significant layer deterioration.

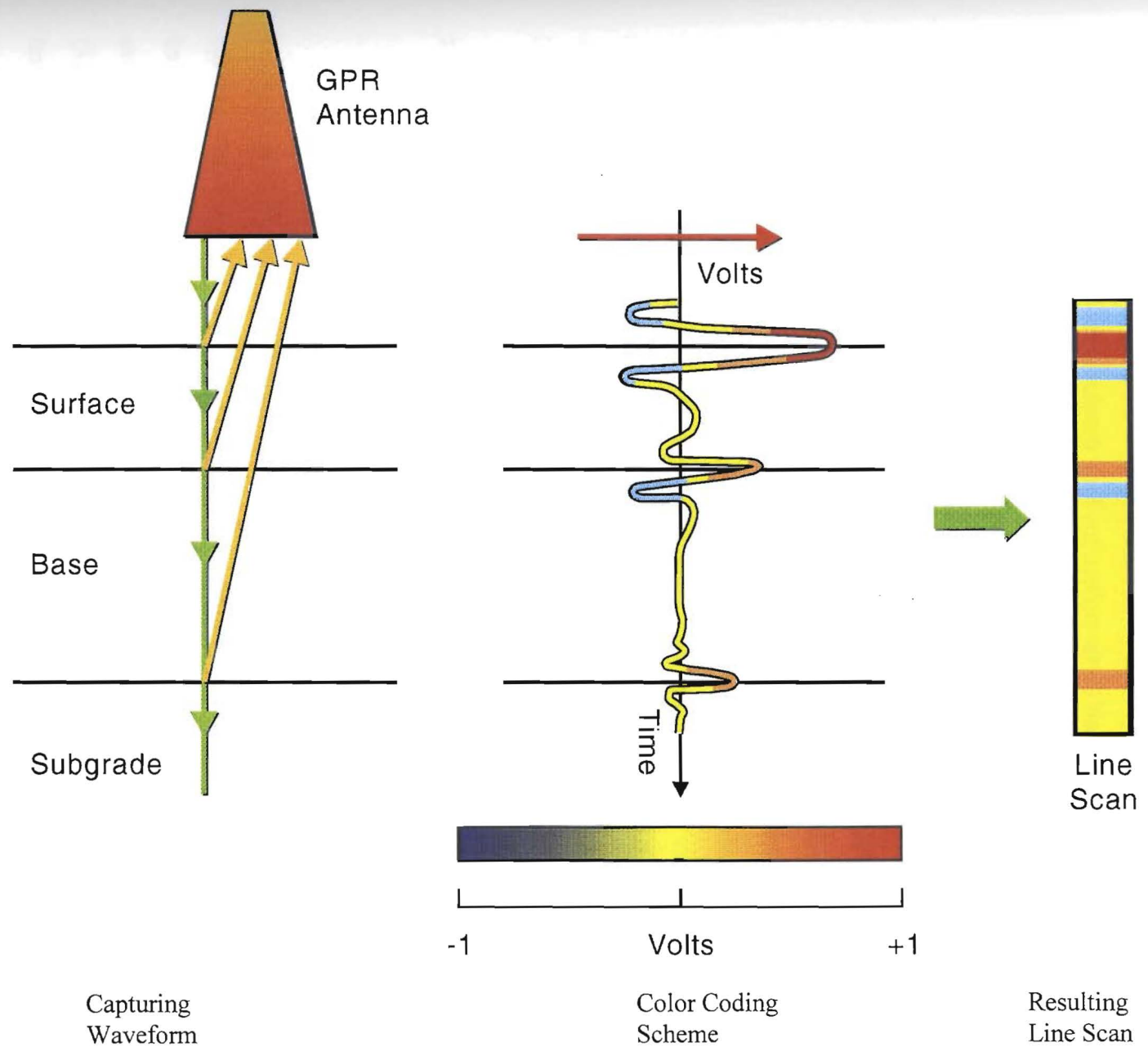
When conducting GPR surveys, traces such as those shown in Figures 2 and 3 are collected at regular intervals along the highway. In most instances several thousand traces will be collected on any particular job. In order to evaluate such a massive amount of data in a timely fashion, COLORMAP employs several innovative data processing techniques. To assist in reviewing the GPR data, each individual trace is color coded into a single line scan. The process of color coding GPR traces is shown in Figure 4. Within COLORMAP, the high positive voltages are colored "red" and the high negative voltages are colored "blue". As will be demonstrated later, the User defines what voltage level is high positive and high negative. Once color coded, the individual traces are then stacked side by side so that several hundred traces can be displayed on a single computer screen. Examples of these color coded stacked traces will be shown later in this report. The benefit of this approach is that it permits the User to quickly and easily identify section breaks, obtain approximate layer thicknesses and locate anomalies within layers.

1.2 DATA COLLECTION REQUIREMENTS

In GPR there are two standard input files used to process data through the COLORMAP system. Typical file names and extensions are shown below; both of these files are included on the COLORMAP distribution diskette:

1. SH30.DAT contains the collected GPR radar traces for State Highway 30 in Texas; this file could be a very large file containing several thousand records, and
2. MTL.DAT contains the metal plate reflection waveform; this is a small file containing a few records collected while stationary over a large metal plate.

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Capturing
Waveform

Color Coding
Scheme

Resulting
Line Scan

Figure 4. Color Coding of Individual GPR Waveforms.

These two files are required in all cases where layer thickness computations are to be made. For GPR systems with low levels of system noise, these two files are adequate; however, on some monostatic GPR systems, a third file, the "end reflection" file, is often required. As explained in detail in Report 1233-1, monostatic systems can generate significant internal noise which may superimpose itself on the reflections from the pavement layers. The end reflection file is obtained by turning the antenna towards the sky and capturing the no reflection wave, which only contains internally generated system noise. If required, COLORMAP contains procedures to scale, align and subtract these internal reflections from the collected waveform. In general, bistatic GPR systems do not require "end reflection" subtraction.

A fourth input file is needed for special applications in which the top layer is very thin or consists of multiple significantly different asphalt layers. The GPR pulse has a known time width (1 nanosecond); this causes reflection overlap for layers less than 70 mm thick. For example, on many miles of Texas pavements, the surfacing thickness is 37 mm or less. On these sections the reflection from the surface will merge with the reflection from the top of the base. This overlap may contaminate both amplitude and time delay estimates. To address the overlap problem, a Template file is used which contains a representative trace from a thick homogeneous asphalt layer. The use of the Template file to address the thin layer issue will be discussed later in this report.

COLORMAP uses the first record in the metal plate, end reflection and template file for computation purposes.

1.3 SIGNAL PROCESSING PHILOSOPHY

TTI report 1233-1 (Scullion, et al., 1994) describes a signal processing system named DACQ. The main feature of this package was an automated peak tracking system in which the User identified significant peaks within the GPR trace and the software automatically traced these peaks throughout the entire file. For each peak, the amplitude and arrival time was calculated and the layer dielectrics and thicknesses were computed for each trace. The DACQ system had many advanced features including accounting for antenna bounce and several signal clean-up routines which could be applied prior to processing. The DACQ package was successfully used on several projects, but it did have a number of limitations. The data

processing was slow primarily if long lengths of highway were to be processed. It was difficult to use the package to identify section breaks, and the peak tracing systems were difficult to use on several projects. The peak detection system had problems with badly distressed pavements where severe transverse cracking would generate one or two distorted GPR waveforms. It also had difficulty tracking faint interfaces which often happens at the base subgrade interface. The system was expanded to handle many of these problem cases; however, the conclusion was that the DACQ system was an excellent research tool although it may not be adequate for routine measurements. The Texas Department of Transportation has purchased their own GPR system and is hoping to supply GPR testing as a routine service to their Districts.

Because of the limitations of DACQ, it was decided to develop a new processing package to more closely meet TxDOT's needs. These needs included the capability of rapidly evaluating long sections of highway, of defining changes in section, of estimating layer thickness and of locating subsurface problem areas. Based on these needs, the COLORMAP system was developed. This system relies on color graphic displays of GPR data to identify section breaks and subsurface problems and manual tracking of layer interfaces in the layer thickness computation routine. Dielectrics are not estimated for each trace, rather representative values are computed and averaged for each section.

1.4 HARDWARE REQUIREMENTS

The recommended hardware requirements for COLORMAP are shown in Figure 5. A color printer is recommended so that the color coded GPR traces can be output. The system will work with a regular black and white printer; however, color is recommended to more easily identify defects and layer interfaces.

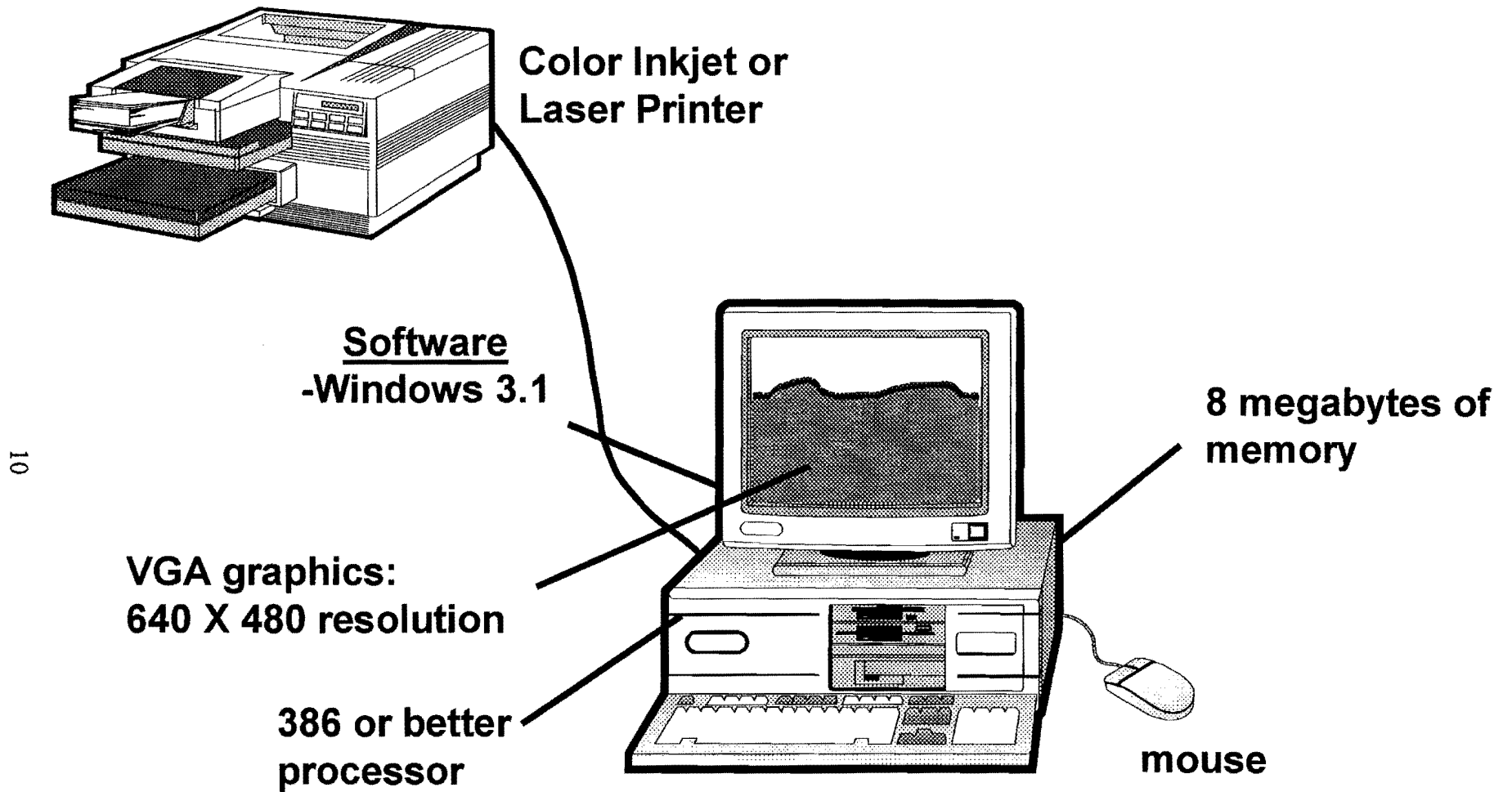


Figure 5. Computer Requirements to Run COLORMAP.

1.5 GETTING STARTED

The Distribution Diskette contains the following four files:

1. SH30.DAT, which contains several hundred GPR traces from a highway in Texas;
2. MTL.DAT, the metal plate reflection collected after testing SH30;
3. END.DAT, the end reflection for SH30; and
4. COLORMAP.EXE, the executable program.

These files should be copied into a RADAR directory and a Windows icon should be created for COLORMAP.

CHAPTER 2

COLORMAP USER'S MANUAL

2.1 MAIN MENU SCREEN

An example of the main COLORMAP screen is shown in figure 6. This is taken from a section of concrete pavement which has a variable thickness asphalt overlay. At the left side of the figure there is no asphalt; the asphalt overlay begins at milepost 0 +141 and gradually increases in thickness. A description of each of the denoted elements in this figure is given on the next page.

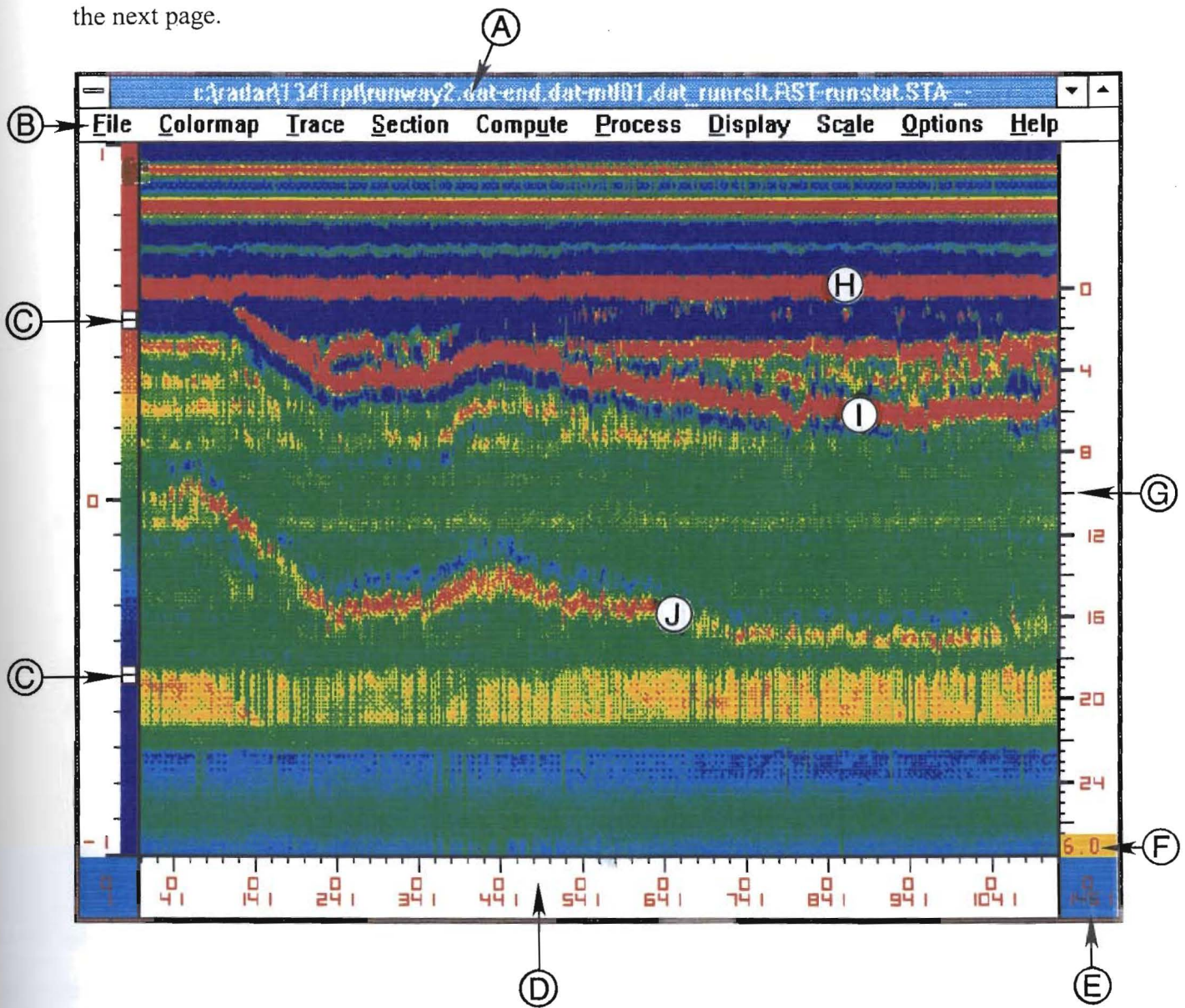


Figure 6. COLORMAP's Color Coded GPR Traces.

- A. Header information showing the directory in use and the list of files that have been opened for either data processing or for storing results.
- B. Main pull down menu bar in COLORMAP. The use of the pull down options will be described in detail in the remainder of this section of the report.
- C. User defined color control buttons, the procedures by which the individual GPR waveforms are color coded and transformed into line scans was shown in Figure 4. The +1 and -1 at the top and bottom of this scale are in units of volts. The upper box indicates the voltage level at which all segments of the GPR trace above this level will be colored "red," the lower button indicates the level at which all negative voltage will be colored "blue." All voltages between the two boxes are assigned the color shown on this scale.

The User can change the color coding scheme by moving these boxes up or down. Click on the box with the mouse and drag it to the desired level. Options within the COLORMAP pull down menu permit the User to assign different scales, changing the +1 and -1 volt range to whatever range is required. Normally, for 1 GHz antenna data, the +1 to -1 volts is recommended.

- D. Distance scale in miles and feet as collected by the GPR's distance measuring instrument (DMI). Distance in feet is coded into each GPR trace collected along the highway. In the OPTIONS pull down menu the User can change this designation to represent the actual highway milepost designation. Another option available is to have this scale represent GPR trace numbers rather than distance.
- E. Total distance in miles and feet within the data file.
- F. User input dielectric value used to generate the thickness scale is at right of figure. This is intended as a first order estimate of layer thickness of the top layer. For asphalt, a value of 6 is recommended, for concrete pavements a value of 8 should be used. The User can change this value in the OPTIONS pull down menu.
- G. This is the thickness scale in inches. By clicking on any part of this scale, the User can drag it vertically to align the surface reflection with zero on the depth scale.
- H. This solid red line represents the surface of the pavement. This figure shows the influence of an overlay on a concrete pavement. At the left of the figure the surface is

concrete, the asphalt overlay tapers into the section from milepost 0 + 144. The figure shows the surface as a horizontal line; in reality the surface of the existing concrete layer is horizontal and the varying thickness of asphalt has been placed on top.

- I. This is the top of the concrete.
- J. This is the bottom of the concrete layer/ top of the subgrade .

2.2 DESCRIPTION OF COLORMAP'S PULL DOWN MENUS

2.2.1 FILE Pull Down Menu

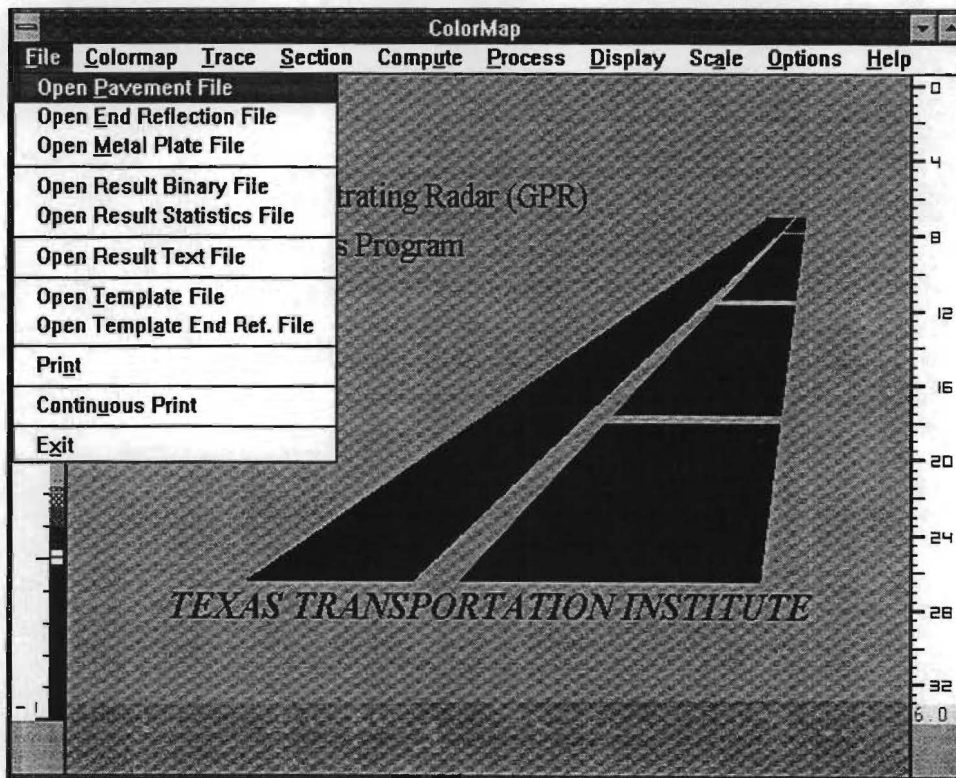


Figure 7. FILE Pull Down Menu Screen.

Objective

This is used to open the files containing the GPR data and to declare the output files. This menu controls the printing of all screens.

Open Pavement File

This is a mandatory file containing the GPR waveforms collected with the Texas Transportation Institute's data acquisition software. Although not essential, it is recommended that the file be given the *.DAT extension, the file name is User supplied and should include the highway and lane under test.

Once this file has been selected, its name will appear in the Header information at the top of the screen.

Open End Reflection File

This is an optional file collected by pointing the antenna to the sky and recording one or more traces. This "sky wave" or "end reflection" is internally generated noise which is superimposed on every trace collected. The selection of this file will automatically set the "Remove End Reflection" flag in the OPTIONS pull down menu. During the end reflection removal process, the software locates the largest positive peak in the end reflection trace. COLORMAP then aligns this peak with the positive peak preceding the surface reflection. The end reflection trace is then subtracted from the GPR data trace. The default option is for aligning positive peaks; however, in the OPTIONS pull down menu, the User can specify a positive or negative peak for aligning the two traces. Although this is not an essential file or process, and the system will work without removing the end reflection, this process is recommended for data collected with the monostatic Penetradar antenna. The end reflection subtraction is not essential with Bistatic GPR systems such as the Pulse Radar system.

Open Metal Plate File

This is a mandatory file if layer thicknesses are to be computed. It is generated by capturing one or more GPR reflections from a large metal plate, typically 1.2 m x 1.2 m, with the antenna operating at the same height as used to collect the Pavement File. It is recommended that the metal plate reflection be collected after the pavement data with the antenna directly above the center of the metal plate. The amplitude of the metal plate reflection is used in the layer dielectric calculations.

Under normal operations this file is always present. However, it can be excluded if the User inputs a metal plate amplitude in the COMPUTE pull down menu or directly inputs layer dielectrics in the PROCESS pull down menu.

Open Result Binary File

This file is mandatory if and only if the the PROCESS menu is to be used. This resulting binary file is a storage file for the computed layer dielectrics and thicknesses. These values are calculated in the Thickness Computing option under the PROCESS pull down menu. This file stores all the information necessary to generate the graphical and statistical outputs. The User is requested to assign a name so that it can be permanently saved for later processing.

Open Result Statistics File

This file is mandatory if and only if the Statistic Computing option in PROCESS menu is to be used. This Result Statistics File contains the statistical summary data generated from the Binary file. It contains the low, high and average layer thicknesses for layer thicknesses at User specified intervals along the highway. These statistical values and data are calculated in the Statistical Computing option under the PROCESS pull down menu.

Open Result Text File

Opening this file is optional. If data is required in an ASCII format, a text file must be opened before computing thicknesses. The computed thickness and dielectrics will be stored in this file. During the thickness calculation process, the layer thicknesses are computed for each section. The text file only retains the last section processed.

Open Template File

This file is optional and may be selected to minimize problems caused by thin surfacings in which reflection overlaps can make true reflections from the top of the base layer difficult to identify . With 1 GHz antennas, reflection overlap will occur with layers less than 75 mm thick. The selection of this file will automatically set the “Remove Template” flag in the options menu. The template file should contain traces from either a metal plate reflection

or from a pavement with a known thick homogeneous surface layer. It is the shape of the reflected waveform that is important. This template subtraction process will align, scale, and subtract the template file surface reflection from the surface reflection collected on the pavement with a suspected thin surfacing. Template subtraction permits the amplitude of the reflection from the top of the base to be more clearly determined.

Open Template End Ref. File

This file is optional. It serves the same function as the end reflection file described above. Even if the template is to be removed, it is not mandatory to remove the end reflection from the Template file. This option is useful for monostatic antennae.

Print

This print option is used to print the color coded trace such as Figure 6, individual traces, statistical graphics and tabular outputs on a page by page basis. When the color coded traces are printed, the printout includes the pavement thickness scales and file characteristics, all features which are not available through the Continuous Print mode.

Continuous Print

When used, Continuous Print will print successive COLORMAP screens without page separation. The User must select a starting position and then choose Continuous Print to print the screen in landscape format. Once the first screen has been printed, scroll to the next full screen and again select Continuous Print. Continue until all desired screens have been printed. A thickness scale will not be printed, but one may be obtained through the single page Print mode described above. To use this option it is essential to have a printer with continuous feed operation.

Exit

Use the Exit command to quit COLORMAP.

2.2.2 COLORMAP Pull Down Menu

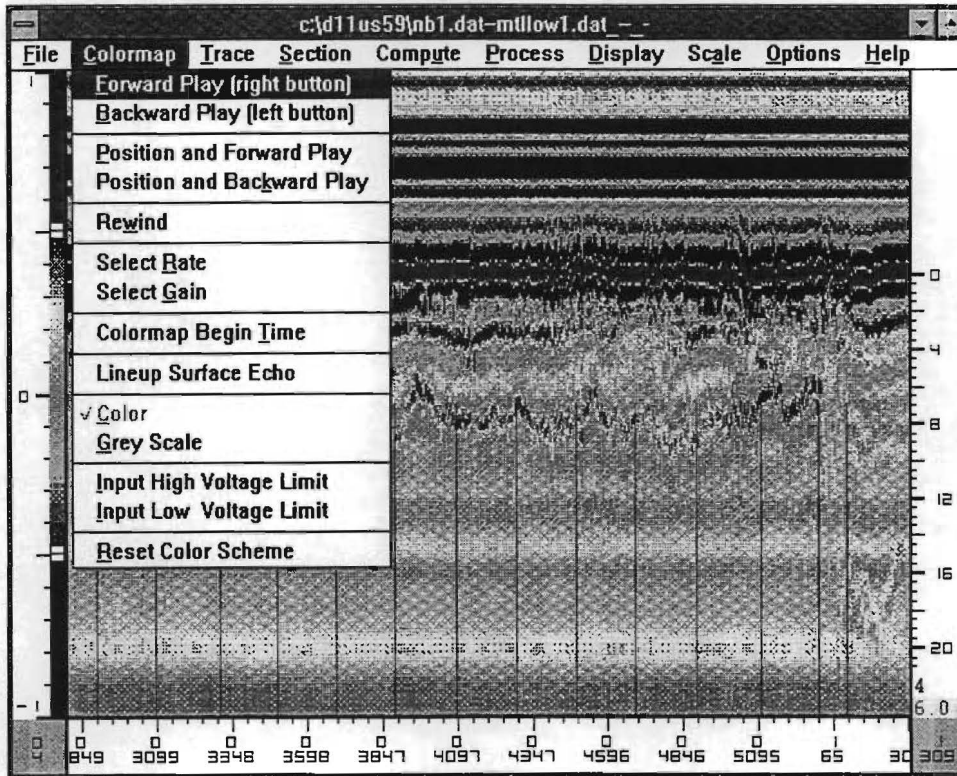


Figure 8. COLORMAP Pull Down Menu Screen.

Objective

This option permits the User to generate the color coded displays, an example of which is shown above. Various options permit the User to line up the surface echoes, to start the display at a certain position and to change the color coding scheme.

Forward Play

Single click on right mouse button to begin to scroll screen to the right. The screen will scroll until it is full and display similar to that shown in Figure 6 will be shown. Once the screen is full or the display is paused, the User can change the color scheme by clicking and sliding the buttons at the left side of the screen. The thickness scale at the right should be adjusted so that the zero depth on the scale is alongside the surface reflection. To pause the scroll, click any mouse button.

Backward Play

Single click on left mouse button to begin to scroll the screen to the left. The screen will scroll until the screen is full. To pause the scroll, click any mouse button.

Position and Forward Play

Opens up an additional window so that the User can select a starting location, by distance in miles and feet. When you select this location, COLORMAP will advance to that position in the data file and begin to scroll the screen forward.

Position and Backward Play

Allows you to select a starting location, by distance in miles and feet. When you select this location, COLORMAP will advance to that point and begin to scroll the screen backwards.

Rewind

Repositions location to the beginning of the file.

Select Rate

Select Rate will designate the interval of displayed traces. For example, a 1 will display every trace, and a 2 will display every second trace. This command allows a large file to be reduced for ease of analysis. The rate must be inputted as a whole number. The default value is preset at 1 to display all traces.

Select Gain

The Gain linearly amplifies the entire waveform for visual color clarity. Personal preference controls the amount of gain used. If the trace contains small peaks, it may be necessary to amplify them so that they will be easier to detect in the color display. The Gain default value is preset at 1 and can be changed to any number greater than zero.

COLORMAP Begin Time

The typical GPR trace was shown earlier in Figure 3. The total time scale is 20 nanoseconds and the important pavement layer information occurs after the surface reflection. The information prior to the surface echo is system noise and of no significance. This Begin Time option lets the User specify at which point in time the COLORMAP display will begin.

Lineup Surface Echo

The Lineup command automatically detects the largest peak in the waveform and positions it at the top of the COLORMAP screen. This option sets the surface reflection at the top of the screen; this is then the zero depth position.

Color

This option is automatically selected and it ensures that the display is in color.

Grey Scale

If data is desired to be viewed in Black and White, then select this option.

Input High Voltage Limit

This value is the voltage level above which all segments of the GPR trace will be colored Red. The voltage limit may be increased to enhance the color display of the GPR data. It is used if the GPR signals are very big or very small, or if the base line of the GPR data file is not zero. Before adjusting these limits, it is beneficial to look at an individual trace using the pull down TRACE menu. The Default value is +1 volts.

Input Low Voltage Limit

This value is the voltage level below which all segments of the GPR trace will be colored Blue. The voltage limit may be decreased to enhance the clarity of the color display; the default value is -1 volts.

Reset Color Scheme - If the voltage in the color scheme scale has been altered, the values are automatically returned to the default value (+1 and -1 volts).

2.2.3 TRACE Pull Down Menu

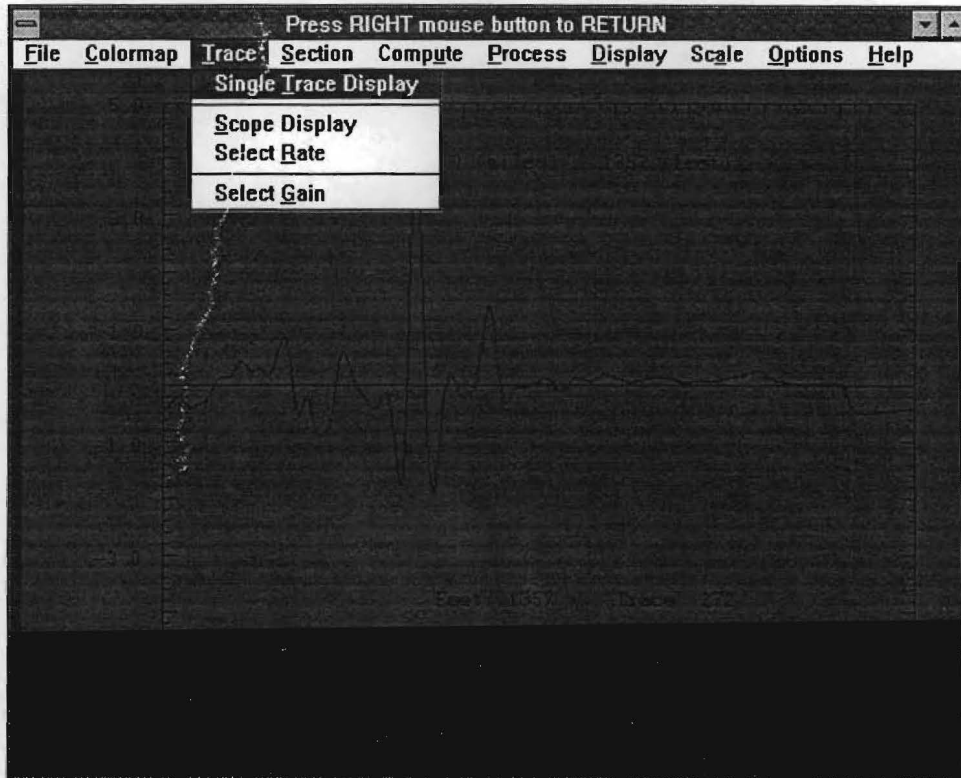


Figure 9. TRACE Pull Down Menu Screen.

Objective

This option permits the User to view individual GPR waveforms from any position in the data file or to review the entire data file.

Single Trace Display

The single trace display will show one waveform, but will not allow computation of thickness and dielectrics. Once selected, a vertical line will appear on the color coded display; this is moved by the mouse to the required location. A single click on the right mouse button and the actual GPR waveform for that location will be displayed. The vertical scale is in volts and the horizontal scale is time in nanoseconds. To end, click on the right mouse button.

Scope Display

If you desire to look at all the collected GPR waveforms, the Scope Display option will open a window in the screen and each trace will flash onto the window. Press the right mouse button and a vertical line will appear on the color display; move this line to the required starting position and click again. The window will open as shown in Figure 10, and the traces will be displayed. To pause, click the left mouse button once. To continue, click the left mouse button again. To quit the scope display mode, click the right mouse button while the display is in the paused position.

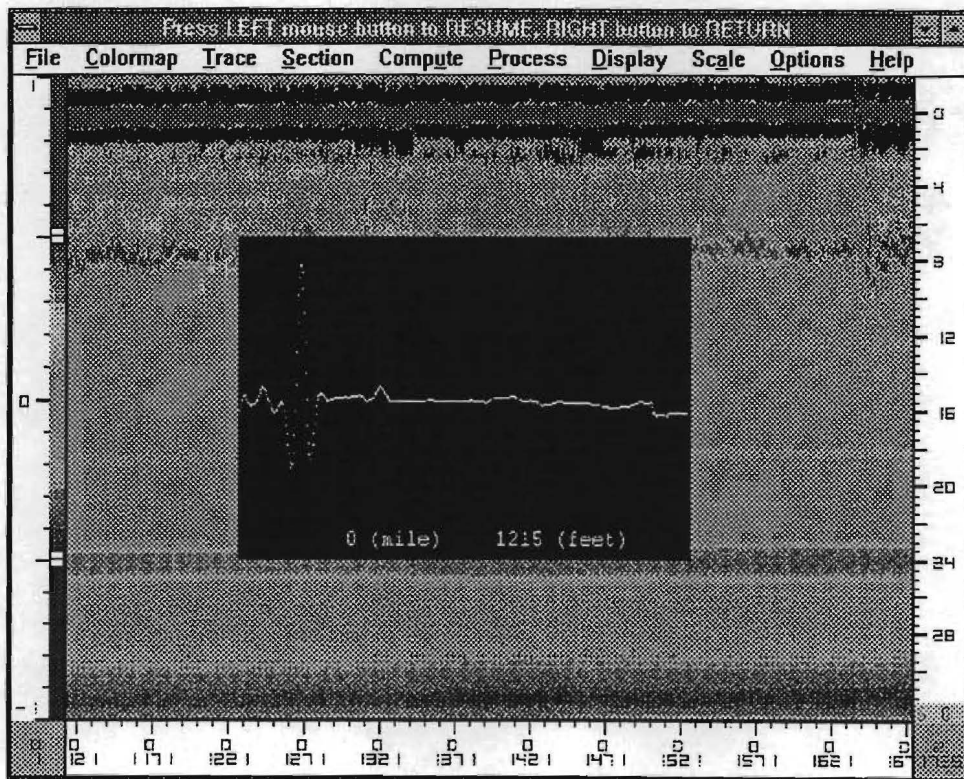


Figure 10. Scope Display Continuously Showing GPR Waveforms for Entire File.

Select Rate

Select Rate will designate the interval between traces. Enter a 2 and every second trace will be displayed. This command allows a large file to be reduced for ease of analysis. The rate must be inputted as a whole number. The default value is preset at 1 to display all traces. This Select Rate command is independent of the other COLORMAP menu Select Rate. This Select Rate is only for use with the Scope Display function.

Select Gain

The Gain factor linearly amplifies the waveform. Personal preference controls the amount of gain to use. The Gain default value is preset at 1 and can be changed to any number greater than zero. The TRACE-Select Gain is independent of the COLORMAP-Select Gain.

2.2.4 SECTION Pull Down Menu

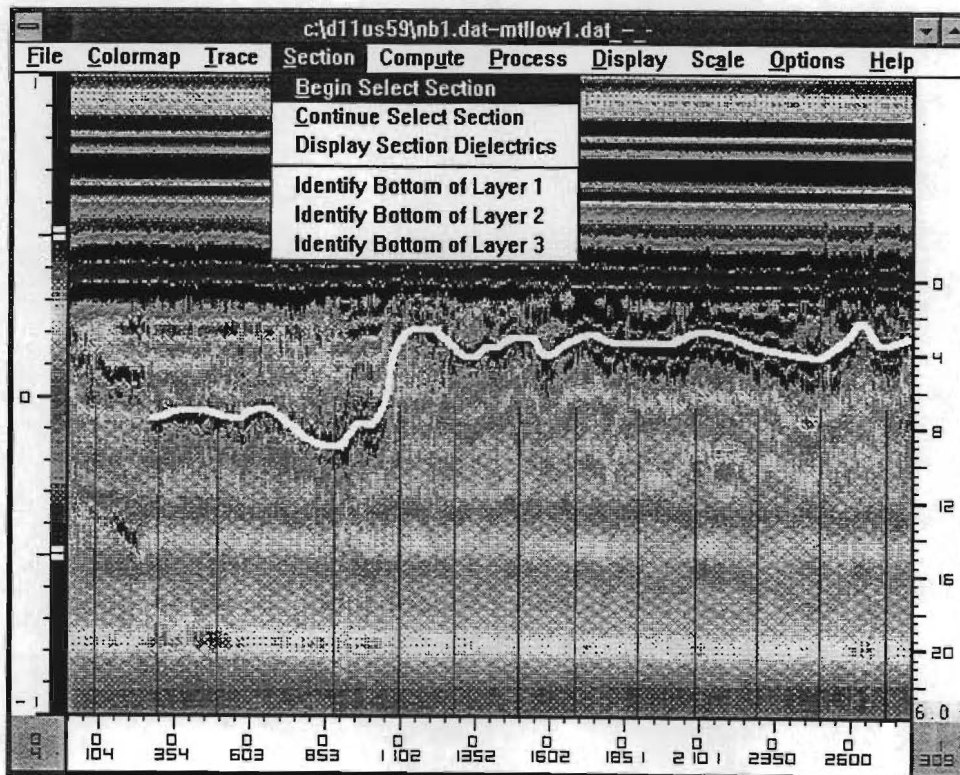


Figure 11. SECTION Pull Down Menu Screen.

Objective

In this option the User manually breaks the GPR file into a number of homogeneous sections. The operator reviews the entire file, then uses this option to define the section breaks usually based on significant changes in layer thicknesses. The processing and layer thickness computations, to be described later, are all section specific.

Begin Select Section

Once this option has been selected the left button of the mouse is used to mark section breaks on the color coded screen display. Once clicked, a vertical line or marker is shown on the screen. Each time the button is clicked a new section break is established. Clicking the right mouse button will quit the Begin Select Section. Note that each time this option is selected, all previous section breaks for this data file are cleared. For long files which continue onto many screens, the User must exit this option, advance the color display to the next significant section break, then use the Continue Select Option.

Continue Select Section

This option permits the User to continue adding section breaks to the GPR file without clearing previous selections. When the next section break is to be added, use this Continue Select Section option. The left button is used to enter the markers, the right button is used to end the session. Figure 12 is an example of the screen that the User will see when creating section breaks with either the Begin Select or Continue Select options.

A section break is automatically included at the beginning and end of each file. Therefore, if the User selects a single section of interest in the middle of the file by entering two markers, one at the beginning and one at the end of the section, the data file will be divided as follows: the selected segment will become Section #2, while from the beginning of the file to the first section marker will be section #1, and the segment from the second marker to the end of the data file will become Section #3. No matter how many markers are added to the file the first and last sections will be automatically added.

The User must put all of the section breaks in the pavement file prior to any thickness calculation. No more section selection is allowed if the User opens an existing data and Binary file. To change the breaks in an existing file the User must open a new Binary file.

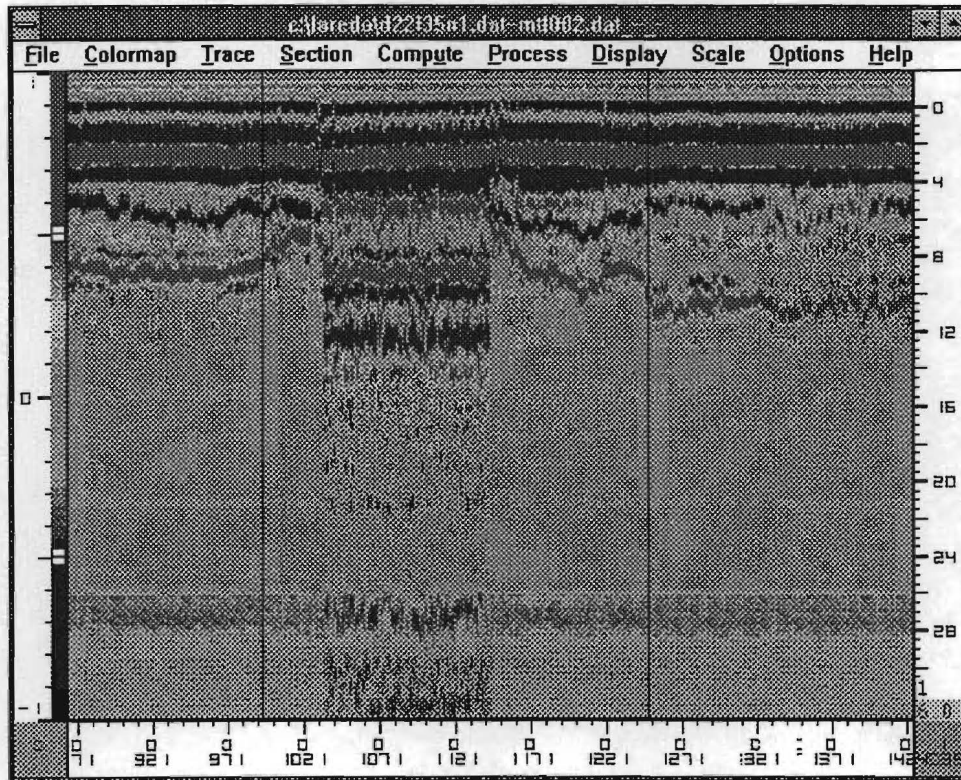


Figure 12. Color Display with User Defined Section Breaks.

Display Section Dielectrics

In the COMPUTE pull down menu, to be described later, the User performs dielectric calculations for selected GPR traces from each section. The function will show the mean of the dielectrics for each layer of each section calculated using COMPUTE-Select Location mode that has been chosen as OK. If the file being processed is broken into sections, each section will be represented in the Display Section Dielectrics mode. If more than one trace is processed for any section, the average dielectric value is shown in this table. A typical table produced in this option is shown below in Figure 13.

Press RIGHT button to EXIT									
File	Colormap	Trace	Section	Compute	Process	Display	Scale	Options	Help
Section	E1	E2	E3	Begin Mile. Feet	End Mile. Feet				
1	7.4	10.6	11.0	0. 2	0. 199				
2	6.2	8.6	11.0	0. 199	0. 996				
3	6.0	8.2	11.0	0. 996	0. 1254				
4	5.8	6.4	8.7	0. 1254	1. 3153				
5	5.5	6.4	8.3	1. 3153	1. 4035				

Figure 13. Computer Dielectrics for Each Section.

Identify Bottom of Layer 1, 2, 3

In this option, the User is allowed to manually trace up to three subsurface layer interfaces. The surface of the pavement is automatically detected by the system. These interfaces are used to define the time of travel within the pavement layer, and this together with the layer dielectric is used to compute the layer thickness. To perform the manual tracing of the first subsurface layer interface, select "Identify Bottom of Layer 1," position the cross hair at the beginning of the section at the first layer interface. Then click the left mouse button and hold it down, while dragging the cross hairs along the interface. The User will observe a continuous line being drawn along the interface. Repeat this operation for Layers 2 and 3.

Perform this tracing one screen at a time. To move to the next screen, click the right button to end the tracing function. Repeat the same process until all sections have been done. The traced area will disappear when the right button is clicked, but will reappear when the User reselects the "Identify Bottom of Layer" option.

It is important to ensure that there are not breaks in the traced line. The User can trace over an earlier error or omission; the system will accept only the last line traced. An example of a traced line is shown in Figure 11.

2.2.5 COMPUTE Pull Down Menu

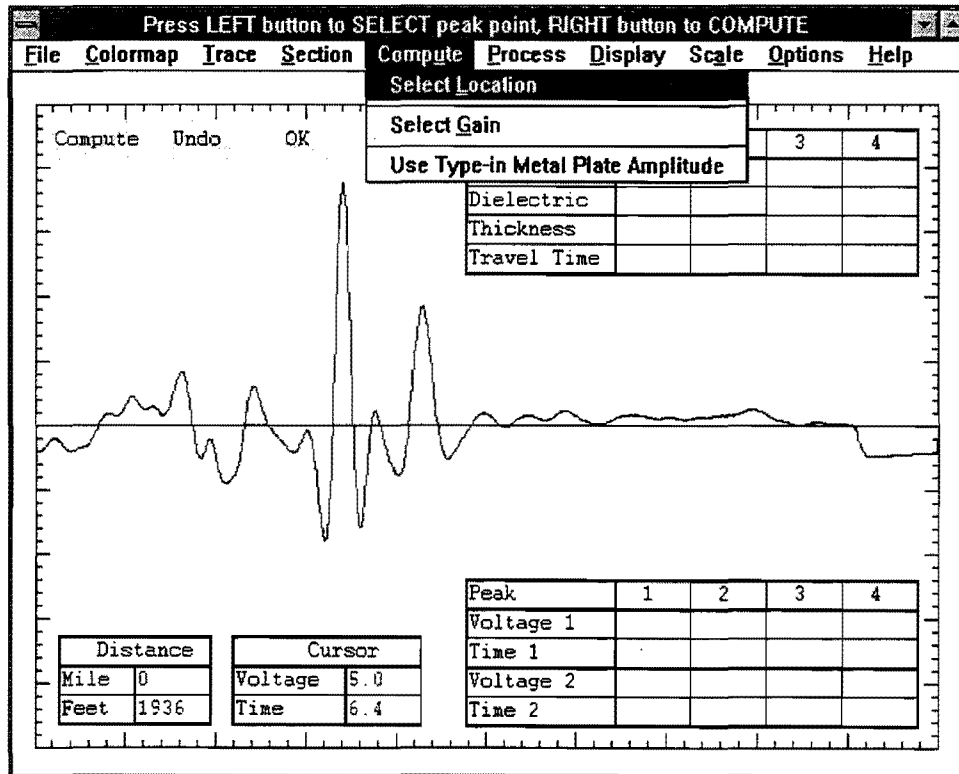


Figure 14. COMPUTE Pull Down Menu Screen.

Objective

This menu permits the User to select and process any single GPR trace within a selected section. Once selected, the trace is displayed on the screen and the User defines the peaks to be used in the dielectric and thickness computation. The computed values will be displayed in the box at the top of the screen. The User decides if these values are reasonable and representative of the section. The accepted dielectric results are stored and used in the computation of thickness the entire section.

Select Location

An open metal plate file or a manually entered metal plate amplitude is a requirement to run this function. Once selected, the User moves the cursor to the trace to be processed. When the left mouse button is clicked, the individual GPR return waveform is displayed. The screen will look similar to Figure 14. The User then uses the mouse to move the crosshair to the peaks to be used in the dielectric calculation process. For each peak a maxima and a minima must be identified so that the amplitude of reflection can be calculated. This amplitude will be compared with the metal plate amplitude to perform the dielectric calculation. The time between selected peaks is used in the thickness calculation.

Under normal operating conditions, when the layer dielectrics increase with depth, the positive peak is identified first, followed by the negative peak. The left button is used to mark the peaks. Once all the peaks are selected, the right button is pressed and the computed dielectrics and thicknesses are displayed in the box in the upper right-hand corner on the display. For the surface reflection, it is recommended that the minima be selected on the left side of the surface peak; for all subsequent peaks the minima should be selected on the right side of the maxima. An example of this together with the computed values is shown in Figure 15. These recommendations on side selection are intended to minimize problems with thin surfacings where the surface and first layer reflections are close enough together to distort the overlapping portions of the wave.

In some rare instances the layer dielectrics do not increase with depth. Sometimes a negative reflection is observed in the trace. This has been observed with some unusual asphalt layers such as sand asphalt. For negative reflections, the negative peak must be identified first followed by the positive peak. In this instance, the computed layer dielectric will be less than calculated for the upper layer.

If the Remove Template has been selected in the OPTIONS pull down menu, then after the surface reflection has been identified, the template will be subtracted from the waveform. The resulting waveform will be displayed on the screen; all subsequent peaks must be defined on this waveform.

Once the calculations have been made, the User must decide whether the calculated dielectrics are acceptable. If the OK button is chosen, these values will be used to update the

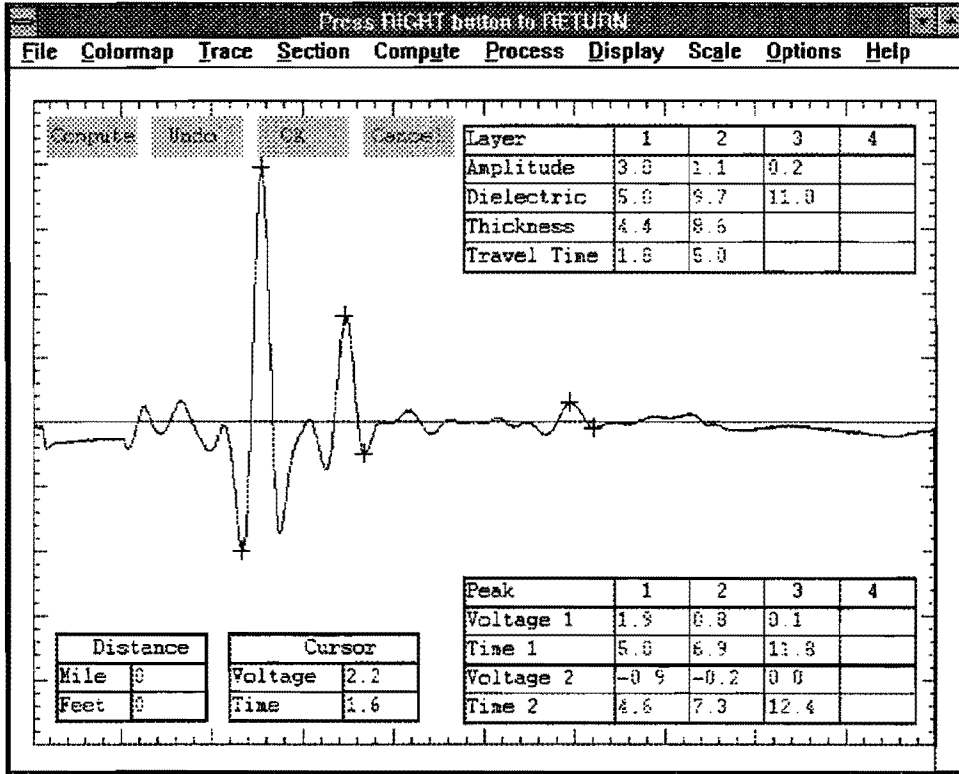


Figure 15. GPR Trace with User Defined Peaks with the Computed Dielectrics and Thickness.

Section Layer Dielectrics table discussed earlier. With experience, the User will recognize reasonable values for layer dielectrics. From Texas experience, the dielectric for an Hot Mix Asphaltic Concrete layer should be between 4.5 and 6.5 , and Portland Cement Concrete should be between 6 and 8. Dielectrics outside these ranges should be reviewed.

Select Gain

The COMPUTE-Select Gain is only used for amplifying the individual GPR trace. It may be easier to identify the peaks in the amplified signal. The default gain value is set at 1.0. This gain value will not affect the gains set in any other menus.

Use Type-in Metal Plate Amplitude

The dielectric calculation requires an amplitude of reflection from a large metal plate. This is normally obtained from the Metal Plate file opened in the FILE pull down menu. However, this option permits the User to type in a value for the metal plate reflection amplitude in volts.

2.2.6 PROCESS Pull Down Menu

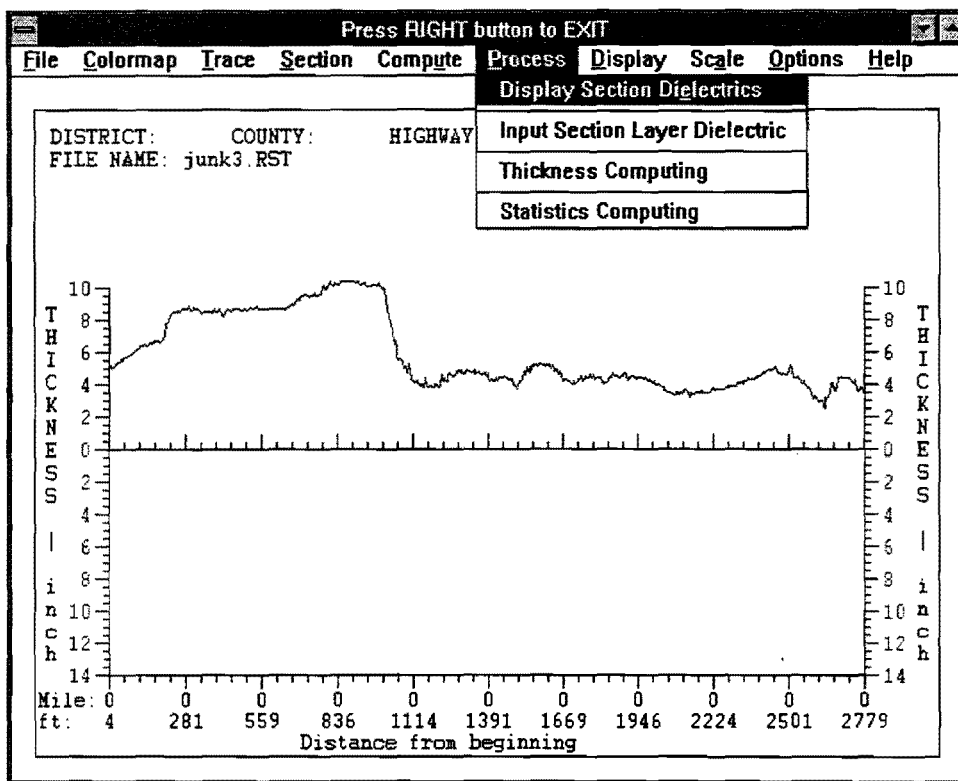


Figure 16. PROCESS Pull Down Menu Screen.

Objective

To calculate the layer thickness using the dielectric values stored in the Section Dielectrics table and the layer travel times manually defined in the "Identify Bottom of Layer 1, 2 or 3" routine.

Display Section Dielectrics

This, when used in conjunction with the Compute-Select Location command, will allow the calculated value of the dielectrics to be displayed. There will be a prompt to ask what section number in case there is more than one section.

Input Section Layer Dielectric

The dielectric of a layer in a section may be inputted manually. When selecting the Input Section Layer Dielectric command there will be a prompt to input section number. Then, there will be a prompt to input layer number. Finally, the dielectrics can be inserted. This value will replace values computed in COMPUTE menu. This option would only be used if there was a problem with the metal plate file which caused the automatic layer dielectric calculation procedure to give unreasonable values. In general, the asphalt layer dielectrics should be between 4.5 and 6.5, concrete between 6 and 8, flexible base between 8 and 12. The User should carefully review numbers outside of these ranges.

Thickness Computing

To use the Thickness Computing command, the File-Open Results Binary File must be opened and the Section Layer Dielectrics table must be complete. Once these requirements are met, the Thickness Computing will ask for a section to compute. COLORMAP processes the data and stores the results in the .BIN file and in the optional .TXT file if opened. The User can view these thicknesses by using the Display Thickness Curve option in the DISPLAY menu.

To create the .TXT file the User should have opened the file in the File Open Results Text File option. An example of this .TXT file is shown in Figure 17.

Statistics Computing

The statistics option permits the User to define reporting intervals in the data file; for example, every 500 m or 0.5 mile. The system then calculates the low, mean and high values of layer thickness and dielectric within these intervals. The computed values are stored in the .STA file which was defined in the FILE pull down menu. An example of a typical .STA file is shown below in Figure 18.

Trace	Feet	Time1	Time2	Time3	Thick1	Thick2	Thick3	E1	E2	E3
193	47	3.4	0.0	0.0	8.3	0.0	0.0	5.7	11.3	0.0
194	48	3.3	0.0	0.0	8.2	0.0	0.0	5.7	11.3	0.0
195	48	3.3	0.0	0.0	8.1	0.0	0.0	5.7	11.3	0.0
196	48	3.2	0.0	0.0	7.8	0.0	0.0	5.7	11.3	0.0
197	49	3.2	0.0	0.0	7.9	0.0	0.0	5.7	11.3	0.0
198	49	3.2	0.0	0.0	7.8	0.0	0.0	5.7	11.3	0.0
199	50	3.1	0.0	0.0	7.7	0.0	0.0	5.7	11.3	0.0
200	50	3.1	0.0	0.0	7.6	0.0	0.0	5.7	11.3	0.0
201	51	3.0	0.0	0.0	7.5	0.0	0.0	5.7	11.3	0.0
202	51	3.0	0.0	0.0	7.4	0.0	0.0	5.7	11.3	0.0
203	52	3.0	0.0	0.0	7.4	0.0	0.0	5.7	11.3	0.0
204	52	3.0	0.0	0.0	7.3	0.0	0.0	5.7	11.3	0.0
205	52	3.0	0.0	0.0	7.4	0.0	0.0	5.7	11.3	0.0
206	53	3.0	0.0	0.0	7.4	0.0	0.0	5.7	11.3	0.0
207	53	2.9	0.0	0.0	7.3	0.0	0.0	5.7	11.3	0.0
208	54	2.9	0.0	0.0	7.3	0.0	0.0	5.7	11.3	0.0
209	54	2.9	0.0	0.0	7.3	0.0	0.0	5.7	11.3	0.0
210	55	2.9	0.0	0.0	7.3	0.0	0.0	5.7	11.3	0.0
211	55	2.9	0.0	0.0	7.3	0.0	0.0	5.7	11.3	0.0
212	56	2.9	0.0	0.0	7.3	0.0	0.0	5.7	11.3	0.0

Figure 17. Typical .TXT File Created in the Thickness Computing Option.

Distance (Ft)	Layer 1 Thickness			Layer 2 Thickness			Layer 3 Thickness		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
0- 50	6.8	7.5	7.3	0.0	0.0	0.0	0.0	0.0	0.0
50- 100	6.5	7.4	6.8	0.0	0.0	0.0	0.0	0.0	0.0
100- 150	6.7	7.5	7.0	0.0	0.0	0.0	0.0	0.0	0.0
150- 200	7.0	7.6	7.4	0.0	0.0	0.0	0.0	0.0	0.0
200- 250	7.2	8.4	7.9	0.0	0.0	0.0	0.0	0.0	0.0
250- 300	7.1	8.3	7.5	0.0	0.0	0.0	0.0	0.0	0.0
300- 350	8.4	8.9	8.7	0.0	0.0	0.0	0.0	0.0	0.0
350- 400	7.7	8.5	8.2	0.0	0.0	0.0	0.0	0.0	0.0
400- 450	7.5	7.9	7.8	0.0	0.0	0.0	0.0	0.0	0.0
450- 500	6.9	7.3	7.1	0.0	0.0	0.0	0.0	0.0	0.0
500- 550	7.4	7.8	7.7	0.0	0.0	0.0	0.0	0.0	0.0
550- 600	7.1	7.5	7.3	0.0	0.0	0.0	0.0	0.0	0.0
600- 650	7.0	7.8	7.4	0.0	0.0	0.0	0.0	0.0	0.0

Figure 18. Example of Output from the Statistical Computing Option.

2.2.7 DISPLAY Pull Down Menu

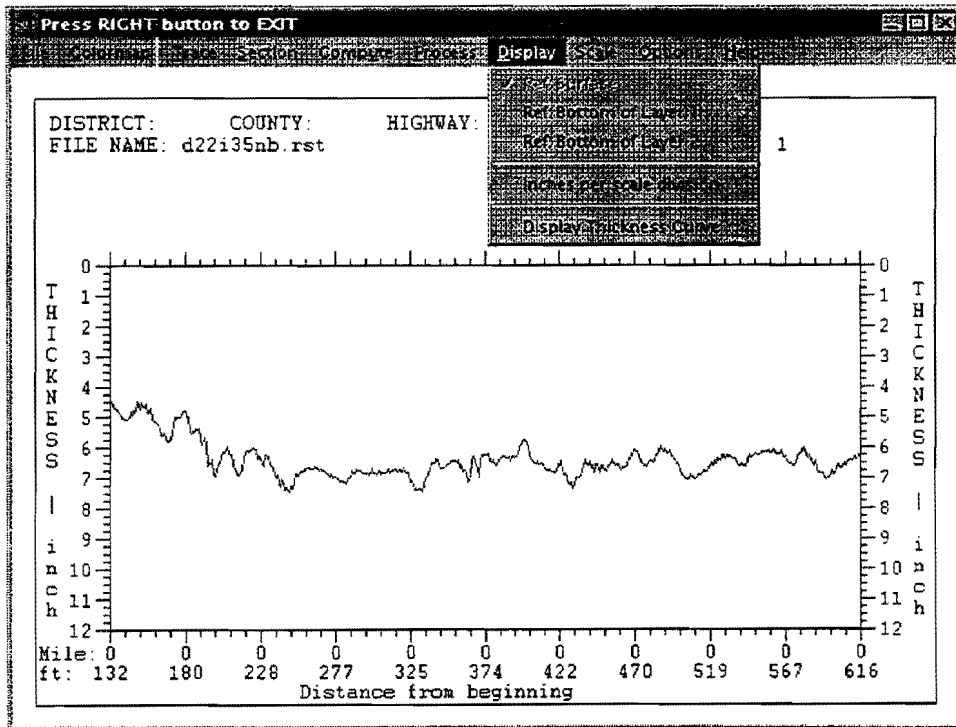


Figure 19. DISPLAY Pull Down Menu Screen.

Objective

This option provides the User with flexibility in printing the thickness plots and viewing the plots and statistics information prior to printing.

Ref: Surface

Clicking on this command will cause all thickness and statistical computing to be referenced to the surface reflection. The pavement surface will appear as a horizontal line at the top of the plot.

Ref: Bottom of Layer 1

Clicking on this command will cause all thickness and statistical computing to be referenced to the bottom of the first layer. The bottom of the first layer (top of the base) will appear as a horizontal line in the middle of the plot.

Ref: Bottom of Layer 2

Clicking on this command will cause all thickness and statistical computing to be referenced to the bottom of the second layer. The bottom of the base layer will appear as a horizontal line at the bottom of the plot.

Inches Per Scale Division

This option permits the User to change the thickness scale along the vertical axis of the Display Thickness curve.

Display Thickness Curve

After doing the PROCESS-Thickness Computing, the Display Thickness Curve option will cause the graph similar to Figure 19 to appear on the screen of the section desired. Clicking the right mouse button will return to the COLORMAP main screen. If a printed copy is desired, use the print option in the FILE menu.

2.2.8 SCALE Pull Down Menu

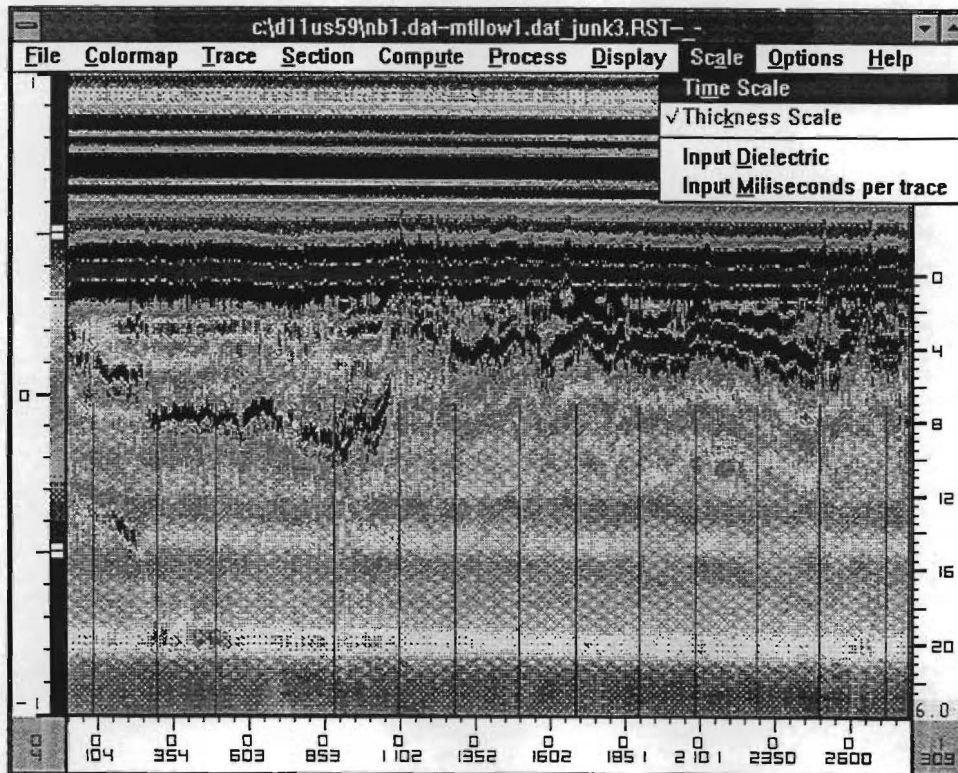


Figure 20. SCALE Pull Down Menu Screen.

Objective

To provide flexibility in modifying the color graphics display. The changes made in this menu only influence the color display screen.

Time Scale

The default setting for the vertical scale at the right of the color display is depth in inches. By selecting this option, this scale will become time in nanoseconds. The scale can be moved up and down by clicking and holding down the left mouse button and moving it up or down. The zero position on both the time or thickness scale is normally aligned with the surface reflection, which is a solid red line near the top of the screen.

Thickness Scale

This is the default setting where the vertical scale is in terms of depth in inches. The depth scale is calculated by using the two parameters input on this menu, namely the Input Dielectric value and the Input Milli-seconds per Trace. The scale can be moved up and down by clicking and holding on it with the left mouse button and moving it up or down.

Input Dielectric

The default value of this dielectric is preset to 6, which is a reasonable value for an asphalt pavement. However, if the scale on the right needs to be adjusted, it is done by changing the dielectric value.

Input Milliseconds Per Trace

The default value is set to 20 nanoseconds. If the collected GPR trace has a different time scale, then this new scale can be entered in this option. This will change the scale at the right hand side of the color display; it will also affect all thickness calculations.

2.2.9 OPTIONS Pull Down Menu

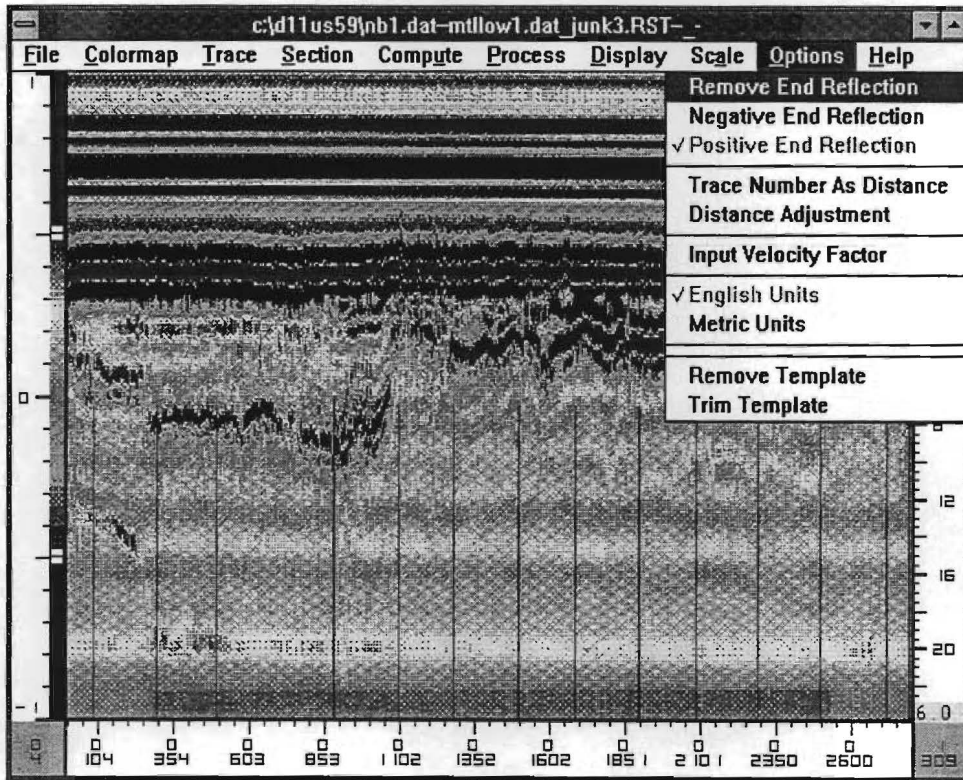


Figure 21. OPTIONS Pull Down Menu Screen.

Objective

To provide the User with several options to clean up the input GPR waveforms prior to display. The User should decide whether end reflection subtraction is required. Typically with Monostatic antenna systems, end reflection subtraction should be used. Bistatic systems may not require end reflection subtraction. This decision is based on the size of the end reflection and the degree of overlap with the pavement information.

Using OPTIONS it is also possible to modify both the horizontal distance scale and the vertical depth scale on the color graphics display. A template subtraction can also be specified to remove the surface reflection so that thin layers can be detected.

Remove End Reflection

With some horn antennas it is essential to clean up the GPR waveform prior to signal processing. The simplest method is by use of the end reflection subtraction technique. An end reflection file contains one or more "sky wave" traces where the antenna is pointed towards the sky and the no reflection waveform is captured and declared in the FILE pull down menu. This waveform therefore contains only the internally generated system noise. If an end reflection file is identified then this "Remove End Reflection" option will be automatically activated. When activated, the end reflection trace is aligned and subtracted from each waveform.

Negative End Reflection

This option is used to specify how the end reflection will be aligned with the pavement GPR waveform. In performing the end reflection subtraction, the software automatically locates the maximum positive reflection from the pavement data file which is assumed to be the surface reflection. In this option, the software then aligns the largest negative reflection prior to the surface reflection with the largest negative peak in the end reflection trace.

The User must decide whether end reflection subtraction is warranted and whether a positive or negative peak match should be used. This second decision is based on the shape of the end reflection waveform.

Positive End Reflection

This option is identical to the Negative End Reflection option discussed above, but this time the software looks for a positive end reflection match. The Positive match is the default setting.

Trace Number As Distance

Under normal operations, the horizontal scale on the color display is the distance along the highway as measured by the system DMI device. However, in some instances, if a DMI is not available, the User must use trace numbers as the distance scale.

Distance Adjustment

This option changes the distance markers at the bottom of the color graphic display to match the actual field mileposts. For example, the starting position in the GPR file may correspond to Reference Milepost 634 +00 in the field. With the current system, the DMI is measured in feet from a known starting location. When using this option, the User must input for two locations in the file the old and new location information (miles and feet). The program automatically offsets and linearly rescales the DMI information on the output color display. Note that this is for display and output purposes only; it makes the referencing system match the field referencing system. The data in the GPR file is not changed.

Note that if the User only inputs one set of old and new reference information, the program will only apply the offset.

Input Velocity Factor

This factor is the system measured speed of the GPR wave in air in inches per nanosecond of two-way travel. The speed of an electromagnetic wave in air is 5.9 inches per nanosecond (two-way travel). The velocity as measured by the system should be close to this value. It is calculated using the time calibration procedure described in TTI Report 1233-1, which involves capturing metal plate reflections at different heights and comparing the increased travel time to the distance traveled.

As a systems check, this calibration factor should be collected every month; however, this factor should not change significantly from month to month.

English Units

Select the English units for the thickness and statistical data to be in English units. The default is preset to be English.

Metric Units

If the desired units to be used are Metric, select the Metric Units option. It will override the default English units.

Remove Template

The template file contains a GPR trace from either a pavement with a thick homogeneous surface layer or from the metal plate reflection. The shape of the trace in the template file is used to remove the surface reflection from a pavement data file suspected of having a thin surfacing layer. If a template file is opened, this option will be automatically activated. To turn the subtraction off, the User must click on the Remove Template option.

When the Remove Template is activated, the User will observe the following two changes to the system:

1. In the COMPUTE pull down menu, once the surface reflection maxima and minima have been located, the template reflection is automatically subtracted and the new trace displayed. All subsurface peaks are then located on the resulting trace.
2. On the color graphics display, the display will show the waveforms after subtraction. The surface of the pavement will be positioned at the top of the screen.

Trim Template

This option permits the User to decide what amount of the Template trace to use in the subtraction process. Once activated, the template trace will be displayed. To trim a template trace, click the left mouse button on the left side of the trace and click again on the right side of the trace; after this the trace outside of the identified area will be set to zero volts. An example of a trimmed template is shown in Figure 22. Click the right mouse button to exit the command.

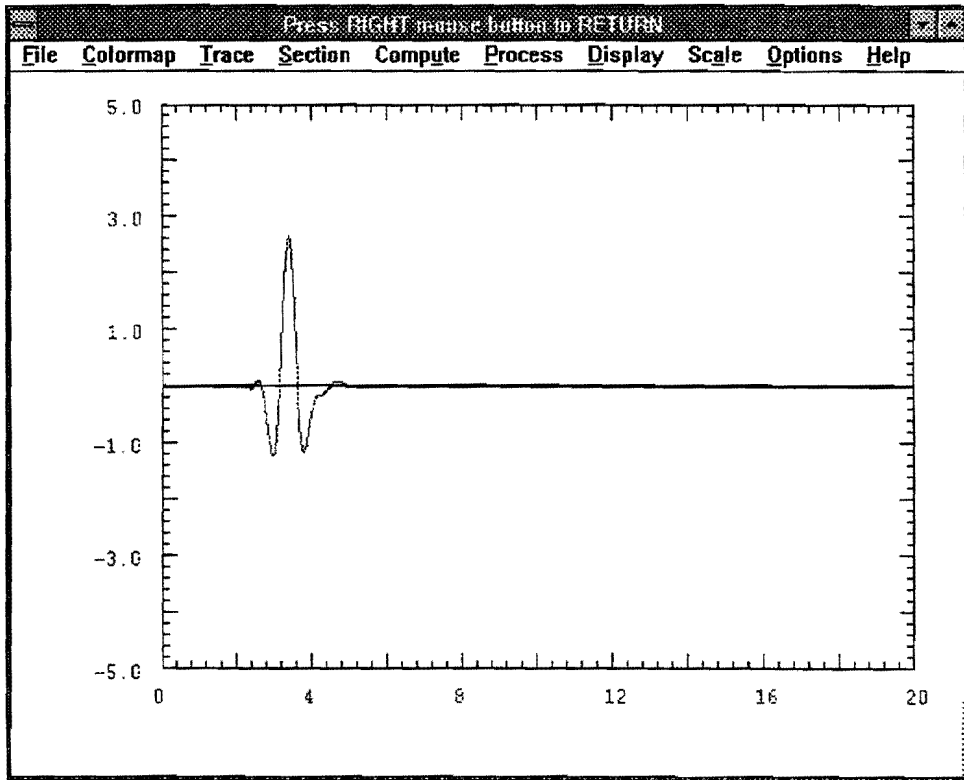


Figure 22. Typical Trimmed Waveform Used in Template Subtraction Process.

CHAPTER 3

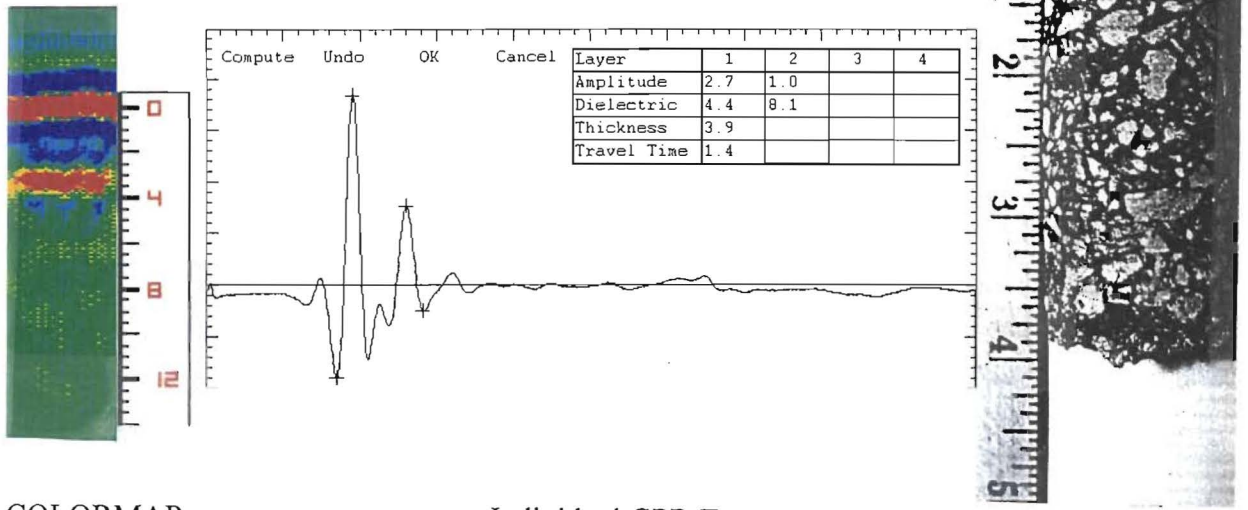
CASE STUDIES

During study 1341, several case studies were conducted on in service pavements in Texas. The GPR system used was the Pulse Radar unit, data was collected with the TTI data acquisition software and processed with COLORMAP. In most instances Ground truth testing was conducted after the GPR data had been interpreted. In this section of the report, a discussion will be presented highlighting which applications were successful and which were not, and typical GPR traces will be shown together with the outputs from COLORMAP. As a general rule, GPR works well on asphalt pavements, and applications involving evaluation of the surfacing or base layer were generally successful. The results on rigid pavements are generally less satisfactory.

3.1 ASPHALT LAYER THICKNESS SURVEYS

Using GPR for determining the thickness of asphalt layers has been documented in detail elsewhere (Maser and Scullion, 1992, Scullion, 1994). What will be described here are the typical outputs that can be anticipated from COLORMAP. Figure 23 shows the color profiles for two short sections of asphalt pavements, together with individual GPR waveforms and photographs of the calibration cores that were obtained from these locations. As can be observed, the computed thicknesses are in close agreement to the core thicknesses. The accuracy of thickness prediction is a subject of interest to DOT personnel. For asphalt pavements containing a single homogeneous layer, a new construction for example, the average error has been found to be less than 2.5%. For older pavements with multiple layers laid at different times the accuracy reduces to about 5%. However, if a single calibration core is obtained the accuracy can be improved by a factor of 2. With the air launched GPR systems such as the 1 GHz Pulse Radar unit, there is no limitation on speed of data acquisition; therefore, most network level surveys in Texas are conducted at a speed of in excess of 80 kph (50 mph). If a clear interface exists between surfacing and base, then asphalt thickness in excess of 500 mm can be accurately measured.

Section 1

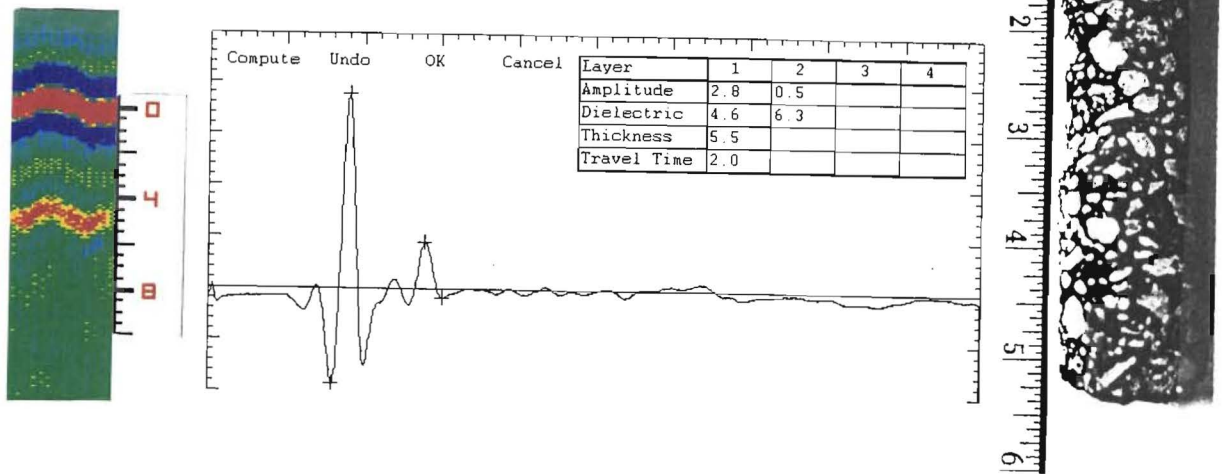


COLORMAP
Display

Individual GPR Trace

Core

Section 2



COLORMAP
Display

Individual GPR Trace

Core

Figure 23. Typical COLORMAP Display Individual Traces and the Validation Cores.

A typical COLORMAP output from a network level thickness survey is shown in Figure 24. This is from Interstate 45 near Centerville, Texas. The pavement consists of varying thicknesses of asphalt over a continuously reinforced concrete pavement. The scale at the left of the figure is depth in inches. The red line near the top of the figure at depth equal to zero is the surface reflection, the lower lines are the reflections from the bottom of the asphalt layer and the bottom of the concrete layer. In this example, the CRCP layer was 200 mm thick and this was bonded to a 100 mm thick heavily stabilized cement treated base. The lower interface in Figure 24 is actually the bottom of the cement treated base. There is a good dielectric contrast between the bottom of this treated base and the underlying subgrade. There is very little contrast between the dielectric of the concrete and the cement treated layer, so no major reflection of GPR energy occurs at that interface. Therefore the thickness of the concrete layer cannot be computed for this section.

Another important point regarding Figure 24 is the uniformity of the asphalt layer. There are strong reflections at the surface and bottom of the asphalt, but no major reflectors between these two. This implies that the material is homogeneous with no major subsurface deterioration, and as will be shown later in this section, areas of subsurface deterioration are usually observed as negative peaks in the GPR trace. With the color coding scheme used, this would appear as areas of blue at some depth below the surface.

As a final step in processing the GPR data shown in Figure 24, the interfaces would be manually traced using the techniques described earlier in this report, the typical layer dielectrics would be calculated and the layer thicknesses computed. This would generate a layer thickness strip map such as shown in Figure 25. Figure 25 is from another section of IH 45, where the thickness of the asphalt surfacing and concrete and CTB base are graphed.

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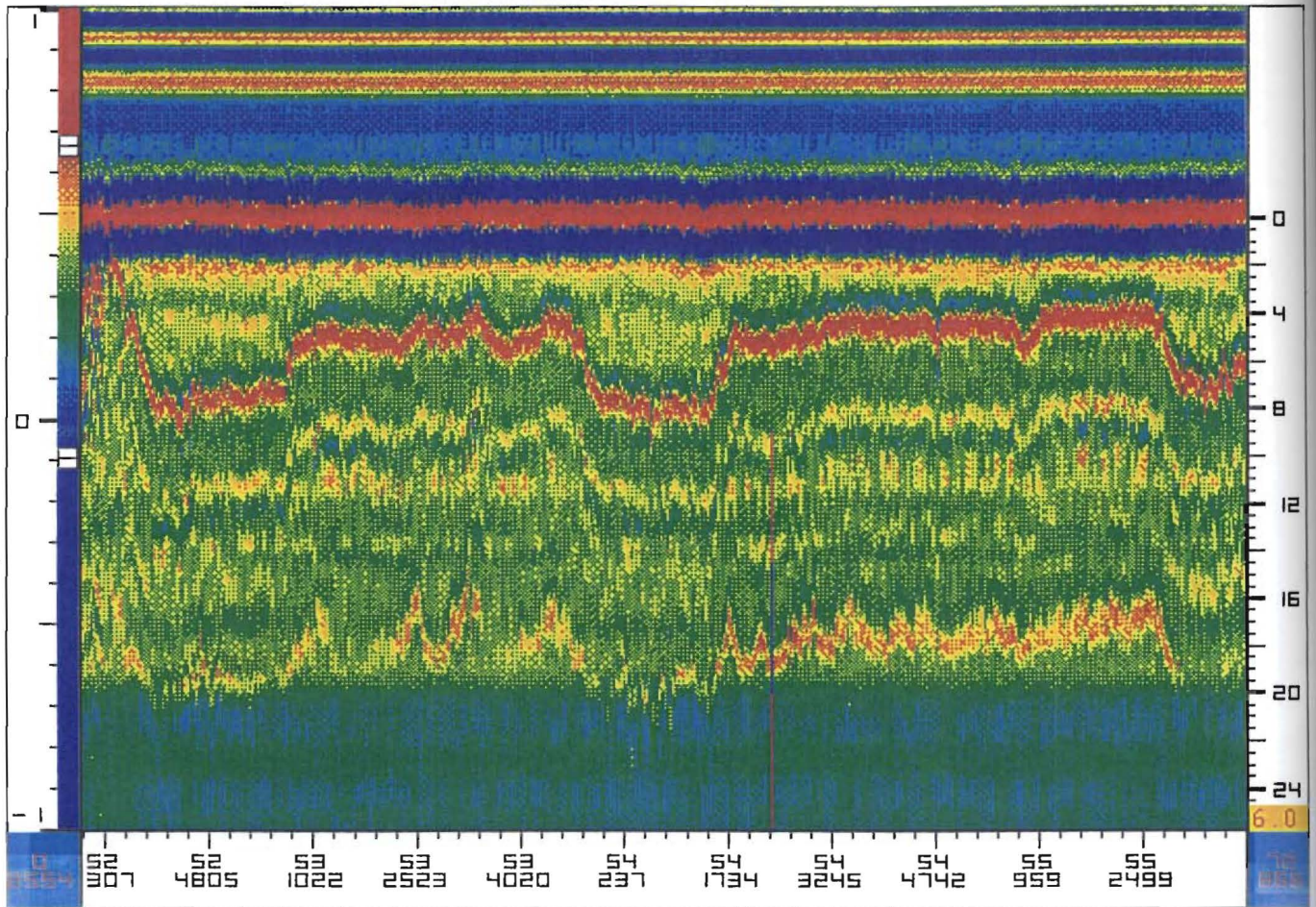


Figure 24. COLORMAP Display of Layer Thickness Variations. The Surfacing is Homogeneous Asphalt Over a Concrete.

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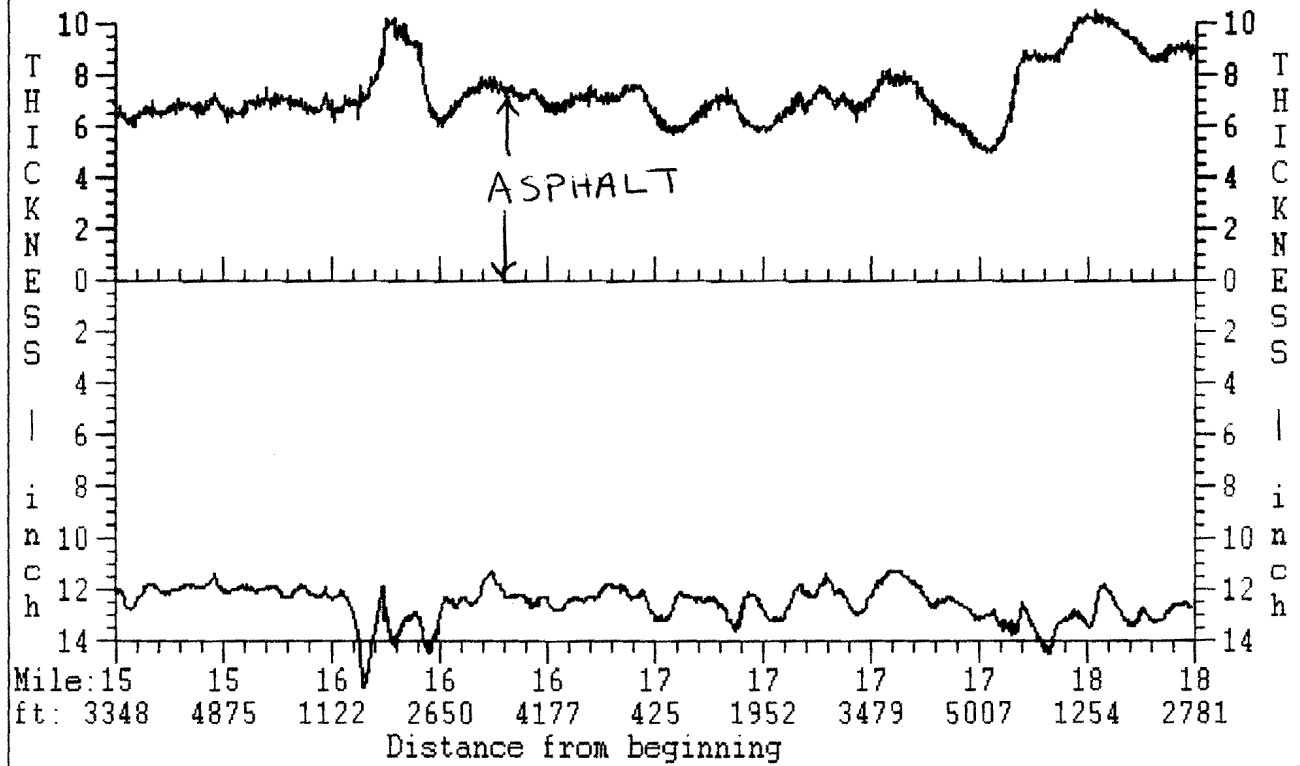


Figure 25. Thickness of Asphalt and Concrete Base Generated Within the PROCESS Menu.

3.2 CONCRETE LAYER THICKNESS SURVEYS

TxDOT had hoped that GPR could be used as a quality control check for thickness of new concrete pavement. Currently new pavements are cored every 305 m (1000 ft) in every lane. If the actual thickness is 6.3 mm (0.25 in) below the design thickness the coring interval is changed to every 92 m (300 ft) so that a penalty can be calculated. If the actual thickness is 19 mm (0.75 in) below design then the coring interval is changed to every 3 m (10 ft) as this is the no-pay or replace situation. The coring is expensive and destructive. TxDOT is interested in evaluating if any of the nondestructive technologies can assist in this area. Coring would not be eliminated, but minimized and restricted to the suspected thin areas.

GPR is a good candidate for this work as it can rapidly and continuously scan long lengths of highway. In the evaluation process GPR surveys were made on three recently constructed projects in the Houston area. The GPR data was collected at the same time as the validation coring. The GPR data was collected before coring and used to predict the actual core thicknesses. The goal was to be able to predict the core thicknesses to within 6 mm (0.25 in) of the actual thickness. Both air launched and ground coupled antennae were used for this task. The air launched antennas included TTI's 1 GHz horn antenna and a new 500 MHz horn antenna supplied for this evaluation by Pulse Radar of Houston. The ground coupled included both a 500 MHz and a 1000 MHz unit manufactured by GSSI.

The results of these tests were less than promising. On only one of the projects were the concrete thicknesses computed with sufficient accuracy. On the other two projects, no clear reflections were identified in the GPR traces from any of the antennae. The failure of GPR in two of the cases is attributed to the following two factors:

- a. CRCP Pavement Design, the common practice in Houston is to construct Continuously Reinforced pavements with the following layers: a concrete slab with a double mat of longitudinal rebar (thickness 250 mm to 375 mm), over a 25 mm asphalt bond breaker, over a heavily stabilized cement treated base. In order to measure the thickness of the top layer of concrete the GPR system must be capable of detecting the very thin layer of asphalt that is sandwiched between two electrically similar materials. In one of the pavements tested, the

bondbreaker was only 12 mm thick and laid directly on top of an existing concrete pavement. From the studies conducted, it is concluded that GPR will not work consistently with this pavement design. Results from the one successful test are shown in Figure 26. The bottom of the concrete is identified as a blue line which signifies a negative reflection. As the concrete has a higher dielectric than the asphalt, a negative reflection is to be anticipated. The practice of using a thin bond breaker over a cement stabilized base is widespread in Texas; therefore, it is concluded that GPR is not capable of obtaining reliable thicknesses information with this type of structure. There may be potential for enhancing the reflection from the asphalt bond breaker by using metallic paint; only limited work was done in this area, but the results were not too promising, particularly in the early life of the concrete slab.

- b. Complexity of Concrete, Portland Cement Concrete is a very electrically complex material, particularly as the material cures in the first few day after placement. Unlike asphalt, portland cement concrete substantially attenuates GPR energy. Furthermore, in its early life, the concrete slab will not have homogeneous electrical properties with depth. The variation in electrical properties soon after placement is shown in Figure 27. These are laboratory determined values obtained using an HP surface probe and Network Analyzer. The real part of the dielectric defines how fast the GPR wave will travel in the concrete, the imaginary part is used to calculate the attenuation of the signal as it passes through the concrete. In the early days of concrete, the attenuation of GPR energy is very high. This means that very little signal would be reflected from any subslab interface. The change in attenuation is shown in Figure 28, these are traces captured at the same position on a full size concrete slab as it cures. In this position a large 1.2 x 1.2 m metal plate was placed beneath the concrete. The metal plate is a perfect reflector and as can be seen from Figure 28, early in the life of the slab it was difficult to detect the metal plate. If the GPR cannot detect a metal plate, it would be impossible to detect an asphalt layer whose dielectric properties are relatively similar to concrete.

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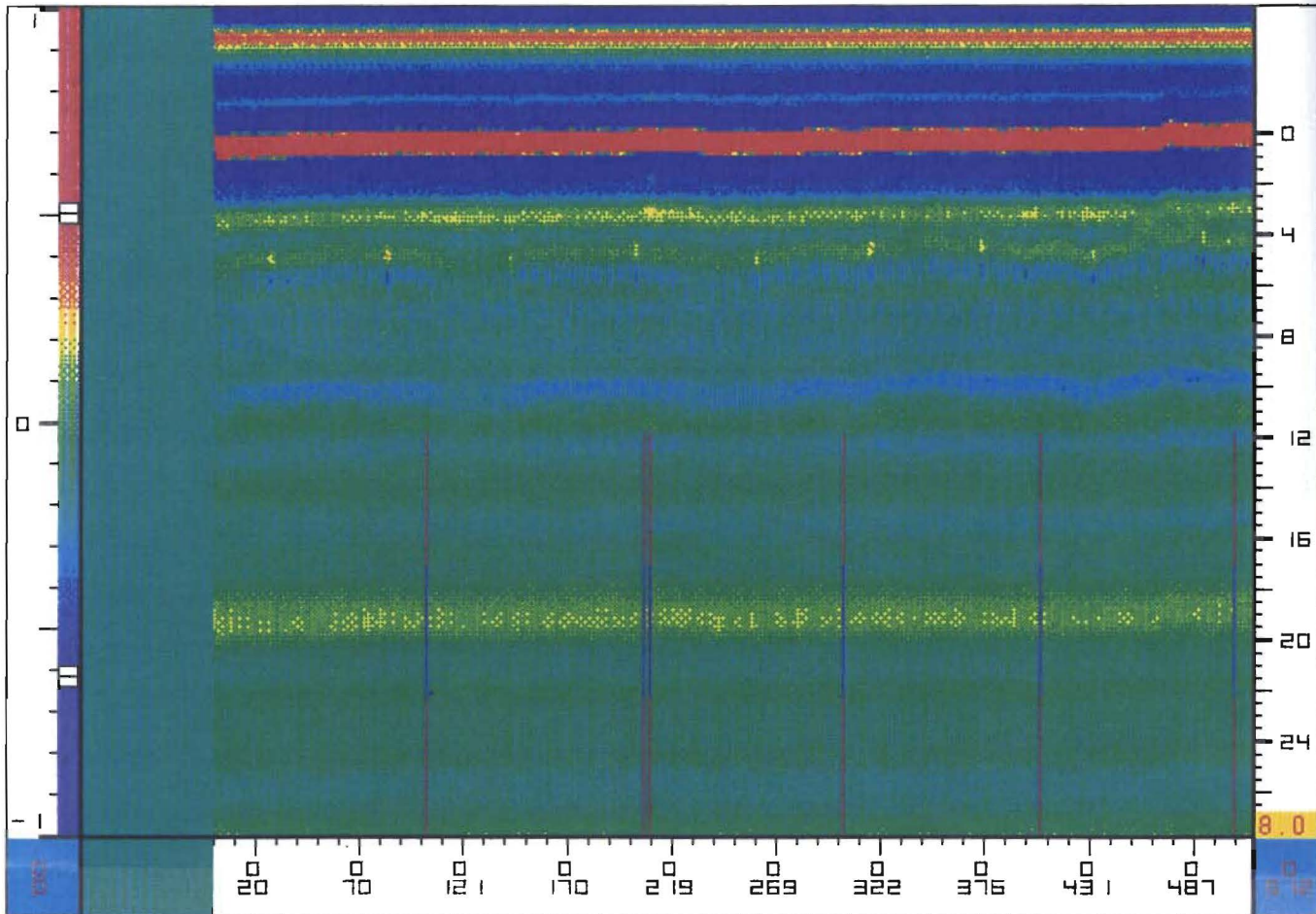


Figure 26. Thickness Measurements on US290, a Newly Constructed CRCP Pavement Near Hempstead, Texas. The Bottom of the Concrete is Indicated By the Faint Blue Line at a Depth of 250 mm (10 ins).

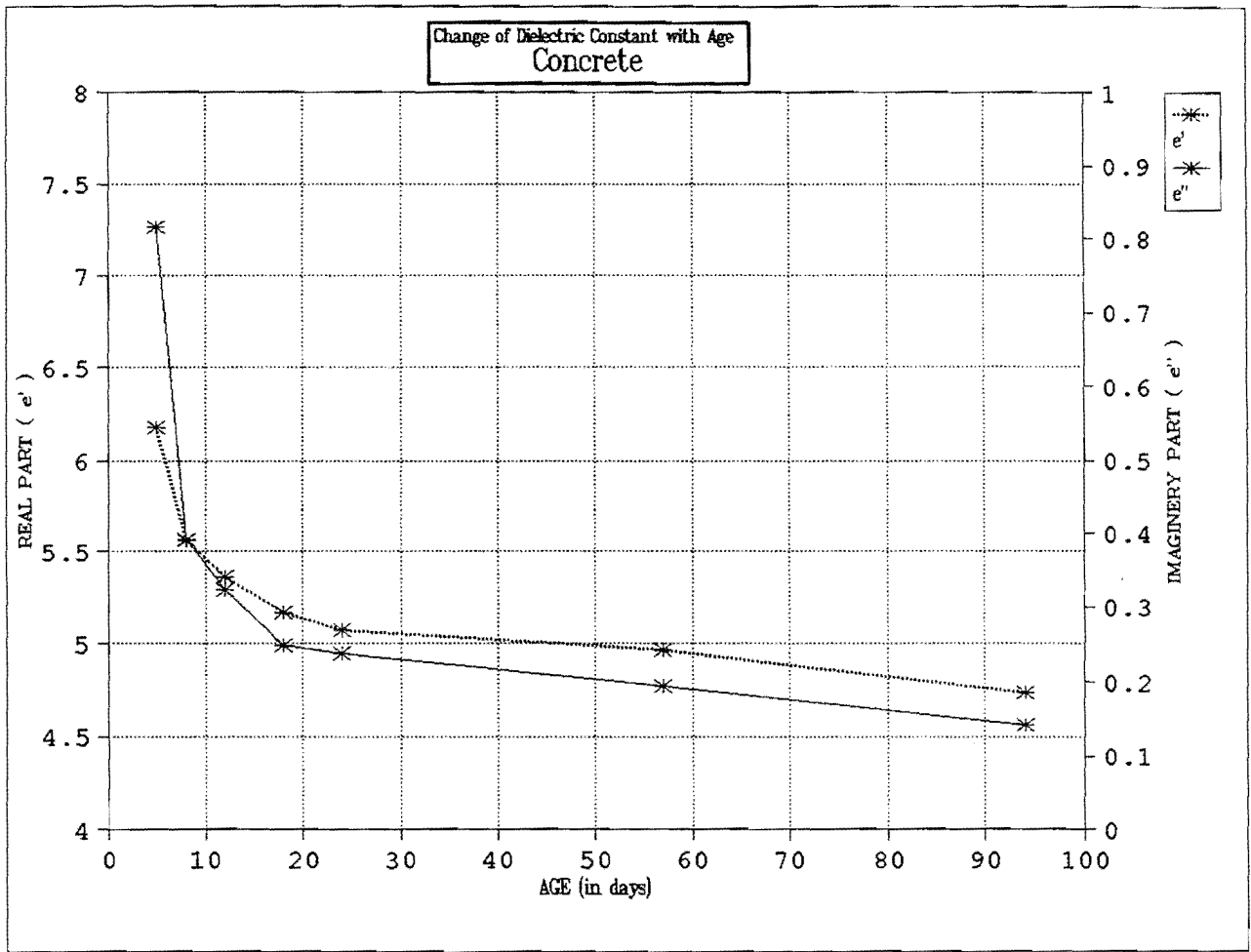
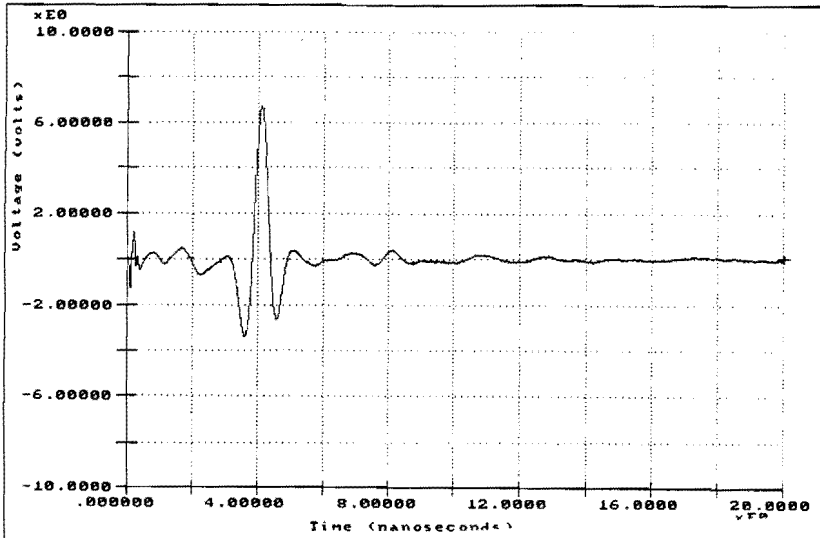


Figure 27. Variation in Electrical Properties of Concrete with Time.

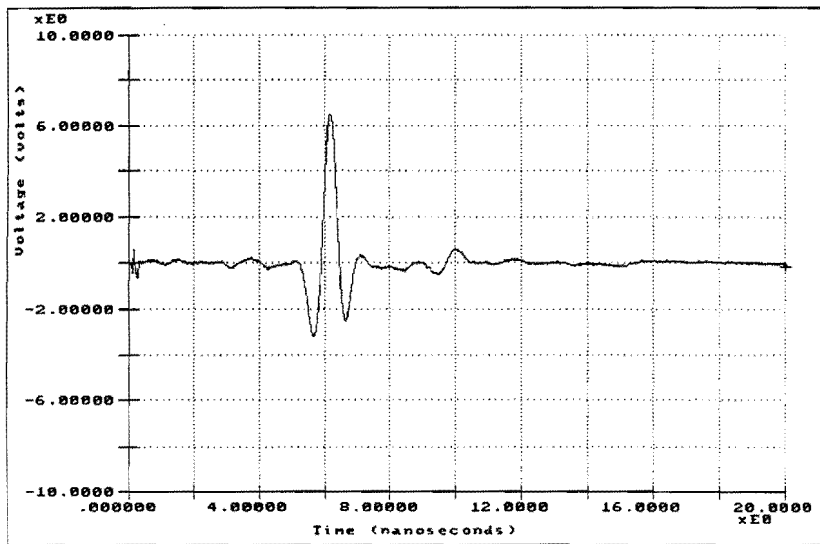
ϵ' is the real part of the dielectric which influences the speed of travel in the concrete.

ϵ'' is the imaginary part of the dielectric which influences the attenuation of GPR energy within the concrete.

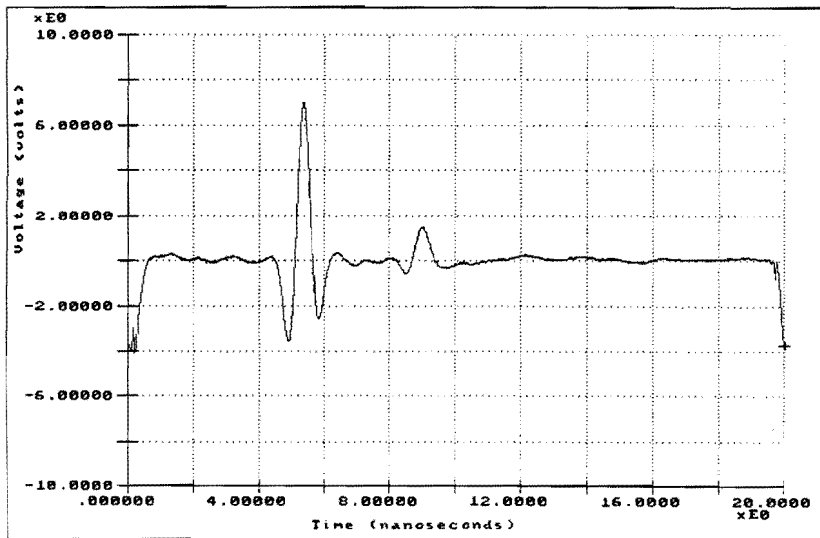


Days After Placement

a) 7 Days



b) 30 Days



c) 100 Days

Figure 28. Changes in GPR Return Waveforms Resting from a Concrete Slab 175 mm (6.9 ins) Thick on a Large Metal Plate.

As a contrast to PCC, asphaltic materials have close to zero attenuation of GPR energy. PCC material is relatively impermeable, and inside a concrete slab there is a significant amount of moisture. It is this moisture which causes the attenuation problem with PCC materials.

3.3 DETECTING STRIPPING IN ASPHALT LAYERS

Many miles of highways in Texas were constructed with aggregates that are now known to be moisture susceptible and prone to stripping; the rounded river gravels used in the 1970's and early 1980's are often identified a "strippers." Stripping is accelerated by repeated wetting and drying cycles, and it is observed as the total disintegration of an asphalt layer where the aggregate and asphalt bond is broken leaving a weak unstable layer. Over time these weak layers are often buried under overlays. However, continuing to resurface these pavements with severe stripping is not cost effective; the surface cracking problems often reoccur in a very short period of time. Recent changes to the TxDOT specification, including specifying the number of crushed faces, the use of anti stripping agents, and the introduction of stripping tests such as the Lottmann procedure have greatly reduced the likelihood of future problems. However, there are still many miles of pavement in Texas with severely deteriorated lower asphalt layers.

TxDOT is interested in determining if GPR could be used to detect these subsurface deteriorated layers. Often TxDOT engineers suspect that stripping may be present in sections under consideration for rehabilitation. They are interested in using GPR to determine:

- a. at what depth the deterioration is present;
- b. how severe the deterioration is; and
- c. how widespread the problem is throughout the section. If the deterioration is concentrated in a small area, then limited milling and patching may be sufficient. However, if the problem is found throughout the section, then the decision is whether to mill and totally remove the problem area or whether to apply a temporary repair until more funds become available.

Several case studies have been completed in Study 1341 to determine if GPR can detect stripping. The results to date have been very promising. In all cases investigated, the stripping has caused a negative peak in the GPR return waveform. A positive reflection is generated as the GPR wave travels from one layer to a layer with a higher dielectric; this is the normal case for flexible pavements. The higher dielectrics are associated with an increase in moisture content. Negative peaks in the GPR return waveform are generated when the GPR wave travels from a high to a low dielectric material. Under normal circumstances this is rare, but it can occur in the transition from concrete to asphalt, or from regular asphalt to low density asphalt or from regular asphalt to a sand asphalt. Examples of positive and negative reflections are shown in Figure 29. These are individual GPR reflections from areas of good and bad hot mix. Peak A is the surface reflection, peak B is the top of the flexible base, the intermediate peaks are from different layers with the asphalt layer. Traces a) and c) represent the normal cases of “good” hot mix; trace b) was taken from a section with a moderately deteriorated layer found 35 mm beneath the surface. The negative peak at 6 nanoseconds in trace b) is caused by a low density stripped layer. The core shown in Figure 30 is the best core obtained from one of the problem areas of the pavement; many of the other cores taken either broke or disintegrated in the problem layer.

COLORMAP provides a good tool for locating potential stripped areas. Figure 31 shows the color coded output for a section of Interstate 45 near Huntsville, Texas. The pavement has varying thicknesses of asphalt overlay (150 to 200 mm) over the original concrete pavement. The interesting part of this figure is the blue areas observed at mid depth in the asphalt centered around mile 17 + 3900. Upon coring of the sections, the cores completely disintegrated at this depth; the top 100 mm of asphalt was fine but the latest 37 mm overlay had cracked prematurely due to the poor support from the unstable stripped layer.

In the case of asphalt overlays on concrete pavements, deterioration of the asphalt layer sometimes originates at the asphalt/PCC interface. With good asphaltic materials, this interface should generate a small positive reflection. When deterioration of the hot mix occurs, the interface becomes unclear and sometimes a small negative peak overlaps with the positive peak from the concrete.

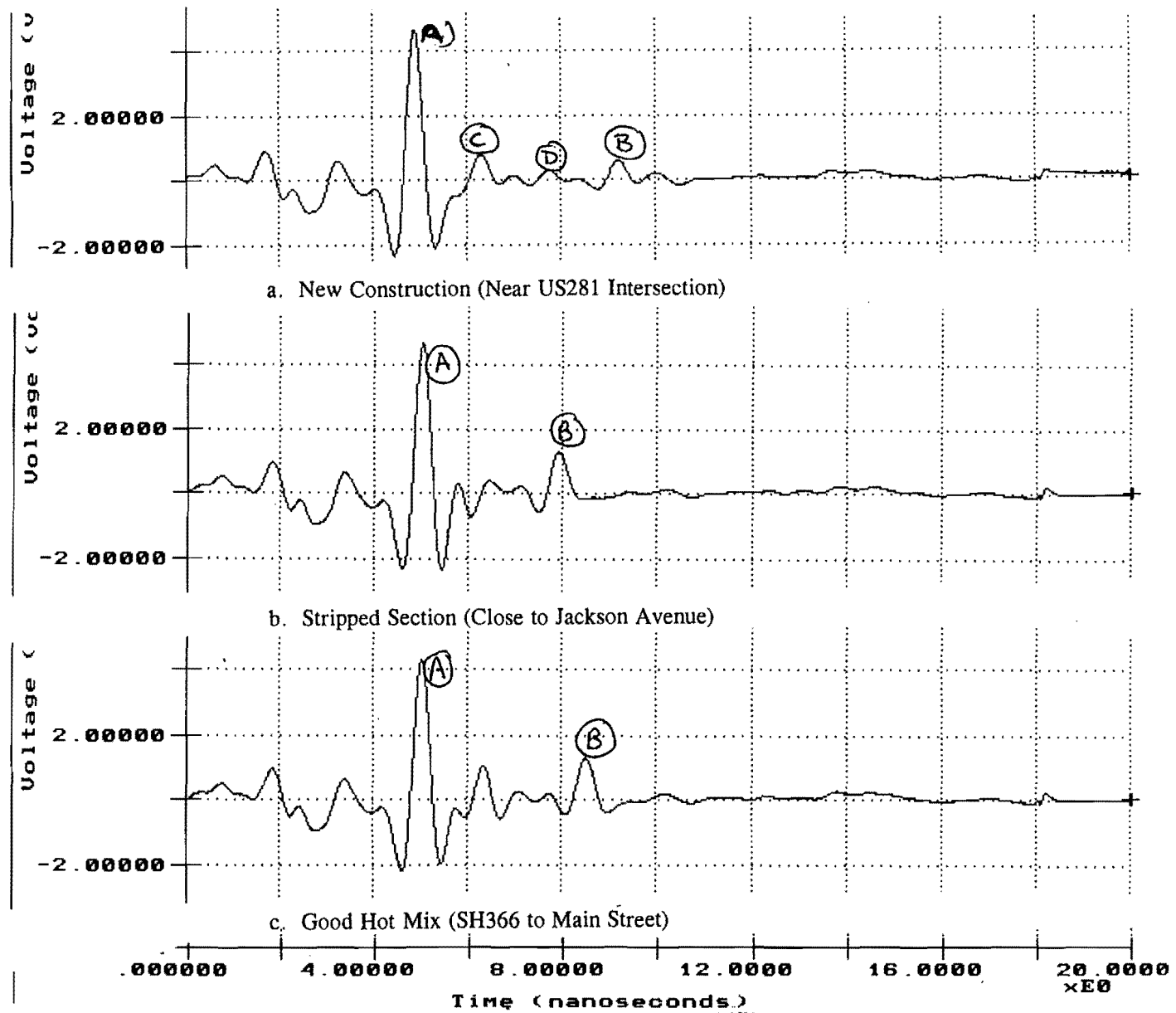


Figure 29. GPR Traces from Both Good Quality Asphalt, Traces (a) and (c) and from Asphalt Layer Containing a Weak Low Density Layer Trace.



Figure 30. Pavement Core from Section Location of Trace (b) in Figure 29. The Top 37 mm and Bottom 75 mm are in Good Condition. The Middle Layer is Low in Rock and High in Binder, and Some Stripping was Evident.

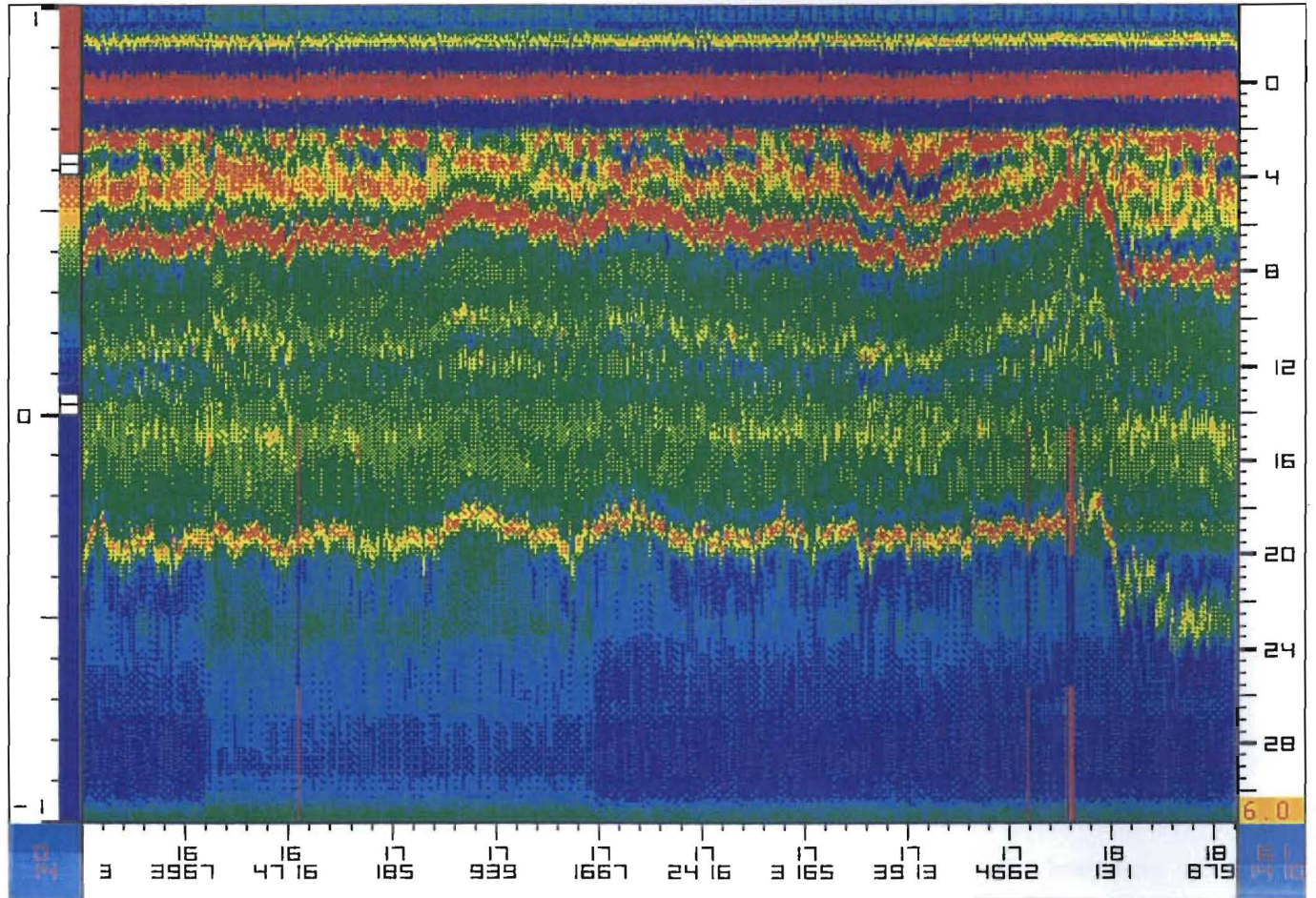


Figure 31. Section of Interstate 45, Asphalt Over Concrete. Stripping Detected at Middepth of Asphalt Around Mile 17 + 3600, Denoted as Deep Blue Areas (Negative Peaks in GPR Return).

Another problem occurs when multiple thin overlays are applied to a pavement. The overlapping reflections from these thin layers may result in apparent negative peaks in the GPR trace. This would appear as a thin blue line just below the surface reflection on the color graphics display. To verify that a true low dielectric layer is present, a Template subtraction should be applied to remove the surface reflection. Using this deconvolution technique, often two positive peaks result. This overlapping reflection problem is shown in Figure 32, the top trace in this figure shows an apparent negative peak a short time after the large surface reflection. In the COLORMAP display this appeared as a thin blue line similar to those shown in Figure 31. However, the bottom trace in Figure 32 shows the result of the Template subtraction. The second trace is the resultant from subtracting the surface reflection as described earlier in section 2 of this report. It now becomes clear that rather than a negative peak, a positive peak is found which is the bottom of the thin overlay/top of existing asphalt interface.

The other problem which could confuse the stripping detection capabilities of GPR is the presence of unusual layers such as sand asphalt, drainage layers, McAdam bases or layers containing lightweight aggregates. The possible existence of any unusual materials should be verified from a review of available records or from a discussion with maintenance personnel.

The stripping detection projects conducted to date have been very successful. On long projects the GPR data was collected at close to highway speed, 60 kph. Once the data has been processed it is essential to verify findings by field coring. GPR can, however, limit the number of cores required to characterize the properties of any section. It is acknowledged that GPR analysts have only limited experience with the wide variety of aggregates, the range of different mix designs and construction and rehabilitation practices that are used today.

Future work should consist of continuing to test sections suspected of containing subsurface deterioration and to perform the ground truth coring. Also, work is required to relate the degree of deterioration to either the amplitude of the negative reflection or the backcalculated layer dielectric. Currently the degree of deterioration is simply related to the amplitude of reflection. If large negatives are present, severe deterioration is found and the material frequently disintegrates upon coring. A limited amount of work has been conducted in Study 1341 relating asphalt density to layer dielectric; this work will be presented in the near future.

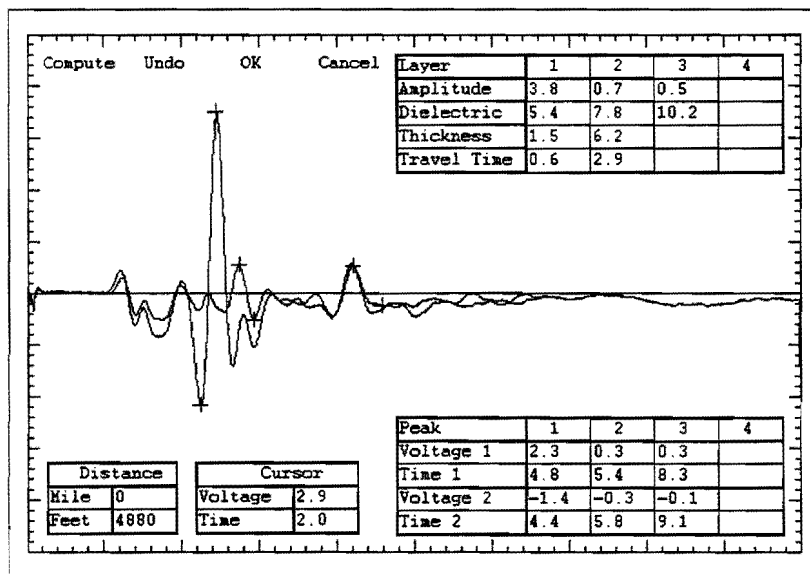
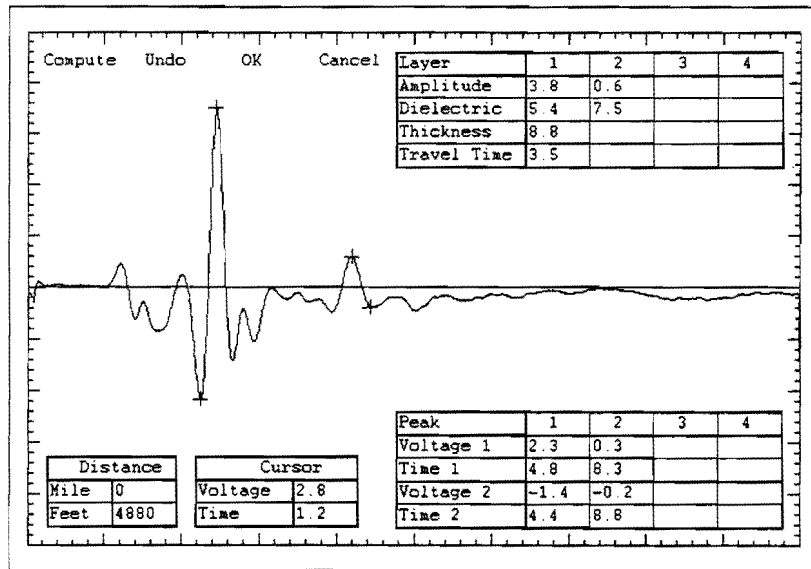


Figure 32. Using Template Subtraction to Identify if a Negative Peak is Present in the GPR Trace.

The Upper Trace shows an apparent negative after the surface reflection. The Lower Trace shows the impact of removing the surface reflection by template subtraction. The remaining peak is actually positive. This is a common occurrence when dealing with thin surfacings < 50 mm thick.

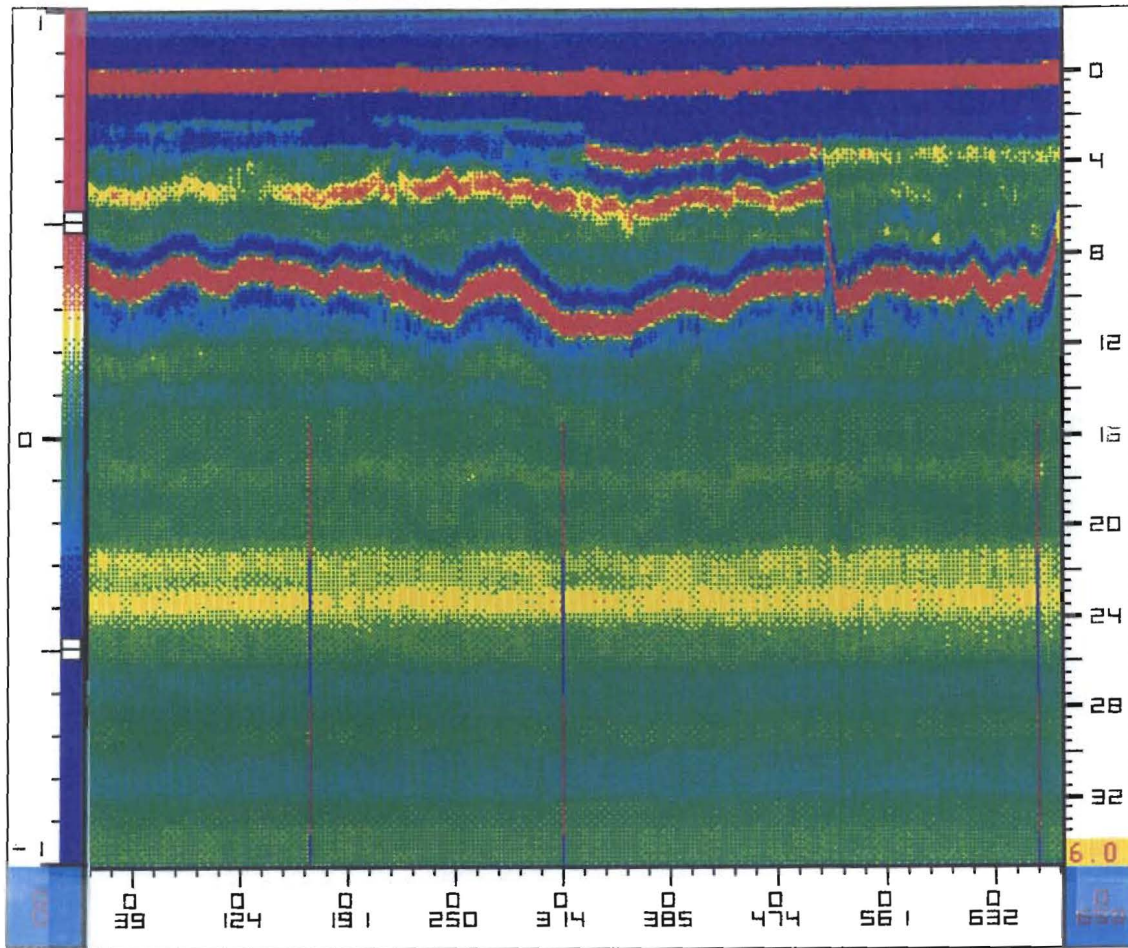
3.4 QUALITY CONTROL OF NEW CONSTRUCTION

GPR shows good potential to assist with quality control testing of newly constructed asphalt layers, particularly thick asphaltic stabilized bases. Only a little amount of testing has been performed, but this is an area in which GPR can provide cost effective nondestructive information on the quality of the finished product. At present, GPR can be used to check final thicknesses and detect defects in the finished section. Work is underway to determine if the measured layer dielectrics can be used to quantify other important properties such as density.

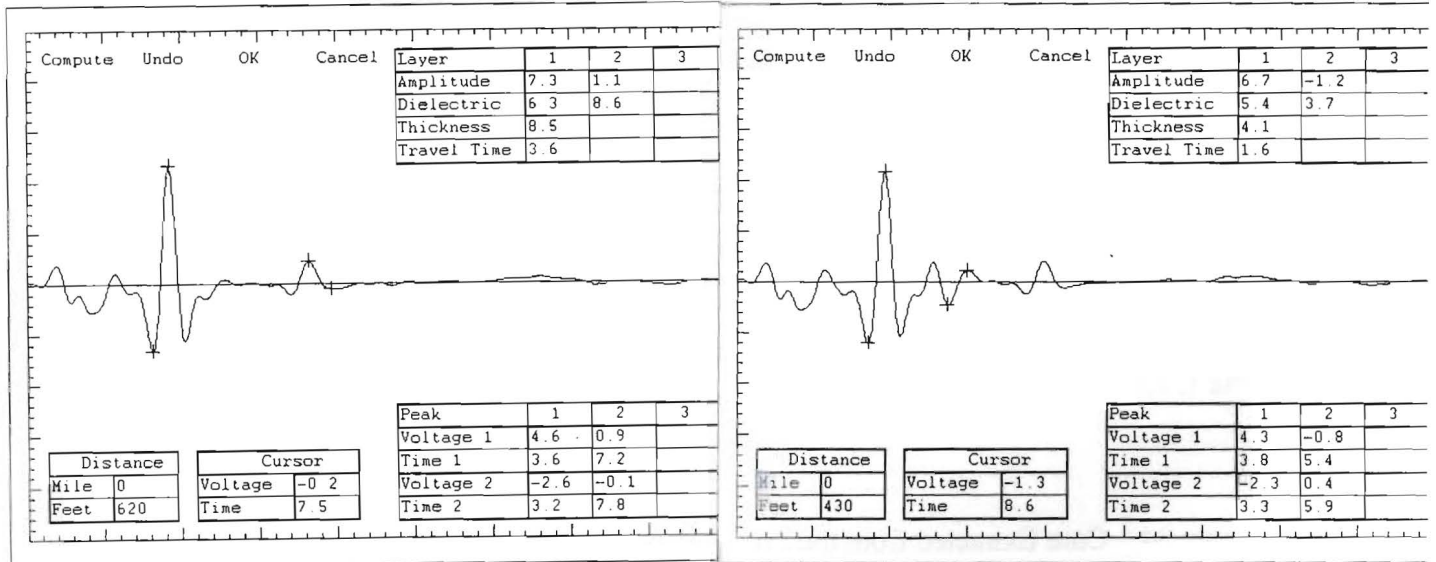
Figure 33 shows a COLORMAP output for a section of newly constructed asphalt pavement. The total thickness of asphalt was specified as 200 mm; what is of interest in this figure is the anomaly that occurs at middepth around mile 0 + 350. This is seen as a blue interface related to a negative peak in the GPR reflection. As described in an earlier section, the negative peak is related to the presence of a low density layer within the asphalt layer. At the time of conducting the GPR test, the section was in service, but less than 6 months old; no apparent problems could be identified at the surface. Upon coring of the problem location, a major defect was located. One of the extracted cores is shown in Figure 34. The core disintegrated at middepth. The problem was eventually traced to a construction problem. The material that disintegrated was cold mix which had been placed by the contractor as a temporary surface during construction. This material was supposed to be replaced prior to placing the final material. In this short section (50 m) the temporary material was not removed. Instead the surfacing layer, approximately 60 mm thick, was placed on top.

3.5 MOISTURE MEASUREMENTS IN BASE LAYERS

Most of the GPR work reported has focused on measuring the properties of the top layer, usually the asphalt surface. A limited amount of work has been conducted on measuring the properties of the granular base layers. Reference should be made to the TRB paper by Maser and Scullion (1991) and to the companion TTI report number 1341-2 by Saarenketo and Scullion (1995). Using GPR data, it is possible to estimate the dielectric properties and thickness of the granular layers. The thickness estimates are subject to error because granular materials violate assumptions used in the computation process



COLORMAP Display 0+450 Problems Around Mile



Individual traces at 620 ft "good" hot mix.

Individual traces at 430 ft subsurface detect.

Figure 33. Quality Control Testing of New Hot Mix.

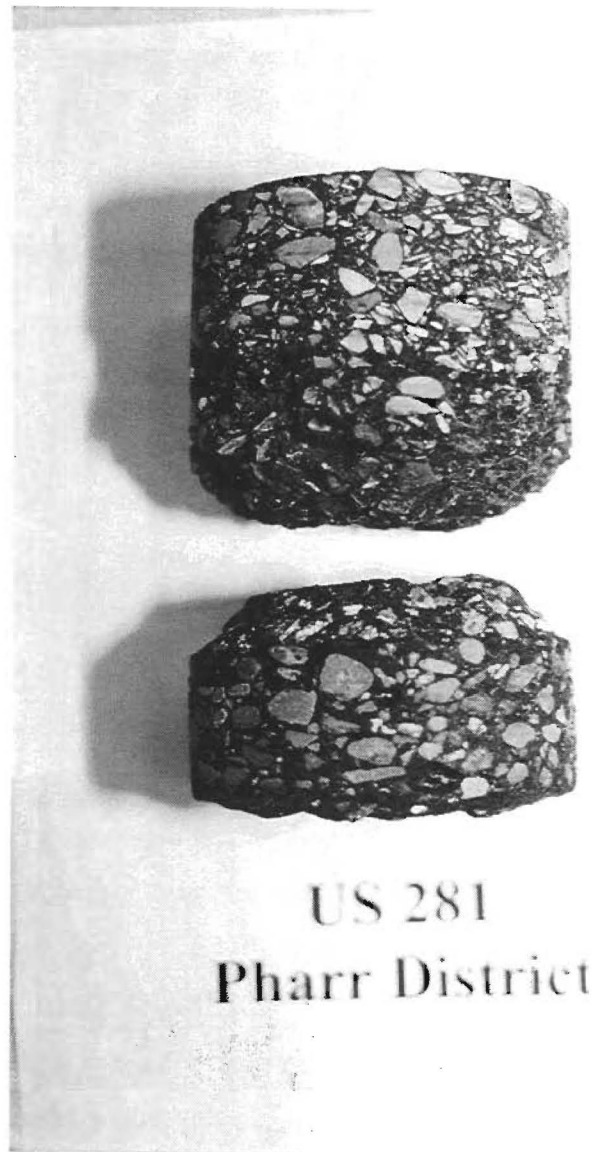


Figure 34. Core Extracted from the Problem Section Shown in Figure 33.

namely, that they are firstly uniform with depth and, secondly non-conductive. Maser and Scullion(1991) reported that the standard error in estimating base thickness was close to 20 mm. One additional problem in determining the thickness of granular bases is that often there is not a consistent substantial reflection from the base/subgrade interface because of either materials mixing or the fact that they are similar materials at similar moisture contents.

However, the base dielectric values calculated using the surface reflection methods described in TTI report 1233-1 (Scullion, Lau and Chen, 1994) may be used to estimate the moisture conditions at the top of the granular base. In 1991, Dr. Robert L. Lytton of TTI proposed initial derivations for the relationship between volumetric moisture content and measured base dielectric. The first step involves assuming a constitutive model that relates the composite layer dielectric to that of the component materials (air, water and aggregate). The next step is to use standard weight-volume relationships to simplify the equations. In this section it is proposed to lay out the basic equations and assumptions needed to relate layer dielectric to layer moisture content and then to demonstrate their use in a laboratory experiment.

For granular base material, the following Complex Refractive Index Model (CRIM) constitutive model has been proposed:

$$\sqrt{\epsilon_b} = \theta_s \sqrt{\epsilon_s} + \theta_w \sqrt{\epsilon_w} + \theta_a \sqrt{\epsilon_a} \quad (1)$$

where:

- ϵ_b = Dielectric of the base calculated from field measurements
- $\theta_s \theta_w \theta_a$ = Volumetric concentrations of solid, water and air in the base course
- $\epsilon_s \epsilon_w \epsilon_a$ = Dielectrics of the aggregates (typically 4-8), water (81) and air (1), respectively

This equation can then be simplified as

$$\sqrt{\epsilon_b} = \theta_s \sqrt{\epsilon_s} + 9\theta_w + \theta_a \quad (2)$$

The standard weight volume relationships for a unit volume are shown below:

Volume		Weight
θ_a	Air	0
θ_w	Water γ_w	W_w
θ_s	Solid $\gamma_s = G_s \gamma_w$	W_s
1	Total	W_T

where:

W_w, W_s = Weight of water and solids, respectively, in base layer

γ_w, γ_s = Unit weight of water and solids, respectively

The gravimetric moisture content is defined as

$$w = \frac{\text{weight water}}{\text{weight solids}} = \frac{W_w}{W_s} \quad (3)$$

The volumetric moisture content is defined as

$$V_m = \frac{\text{Volume Water}}{\text{Total Volume}} = \theta_w$$

The volume of air in the unit volume is therefore

$$\theta_a = 1 - \theta_w - \theta_s = 1 - \frac{W_w}{\gamma_w} - \frac{W_s}{\gamma_s} \quad (4)$$

By substitution,

$$\theta_a = \left(1 - \frac{W_s w}{\gamma_w} - \frac{W_s}{\gamma_s}\right) \quad (5)$$

Equation (6) then becomes

$$\sqrt{\epsilon_b} = \frac{W_s}{\gamma_s} \sqrt{\epsilon_s} + 9 \frac{w W_s}{\gamma_w} + \left(1 - \frac{W_s w}{\gamma_w} - \frac{W_s}{\gamma_s}\right) \quad (6)$$

Replacing γ_w with γ_s/G_s and collecting terms,

$$\sqrt{\epsilon_b} = \frac{W_s}{\gamma_s} (\sqrt{\epsilon_s} - 1) + 8 w \frac{W_s G_s}{\gamma_s} + 1 \quad (7)$$

$$w = \frac{(\sqrt{\epsilon_b} - 1) - \frac{W_s}{\gamma_s} (\sqrt{\epsilon_s} - 1)}{8 G_s \frac{W_s}{\gamma_s}} \quad (8)$$

The volumetric moisture content then becomes

$$V_w = \frac{(\sqrt{\epsilon_b} - 1) - \frac{W_s}{\gamma_s} (\sqrt{\epsilon_s} - 1)}{8} \quad (9)$$

The above equations are based on the square root dielectric model, equation 2. In practice, ϵ_s can be assumed, and ϵ_b can be estimated from the GPR trace. Another model, which is based on laboratory testing at TTI, appears more appropriate for granular materials. It is a simple linear model, shown in equation 10.

$$\epsilon_b = \theta_s \epsilon_s + \theta_w \epsilon_w + \theta_a \epsilon_a \quad (10)$$

Using this model equations 8 and 9 become

$$w = \frac{\epsilon_b - 1 - \frac{W_s}{\gamma_s} (\epsilon_s - 1)}{80 G_s \frac{W_s}{\gamma_s}} \quad (11)$$

$$V_w = \frac{\epsilon_b - 1 - \frac{W_s}{\gamma_s} (\epsilon_s - 1)}{80} \quad (12)$$

Reasonable guesses can be made about the unknown in equations 11 and 12 (W_s , γ_s , ϵ_s , G_s). For typical aggregates $\gamma_s = 165 \text{ lb/ft}^3$ (2650 Kg/m^3), $G_s = 2.64$, $\epsilon_s = 5$. The only unknown is W_s , which is the weight of the solids in a unit volume of base. In practice this is best achieved by making a calibration measurement of base dielectric at a single location and then taking samples to obtain the in-situ moisture content in the laboratory. The ϵ_b terms and w will be known, and the unknown ratio can be calculated from the information for that location.

In order to evaluate equation 11, a series of laboratory tests were conducted with crushed limestone granular base material which was compacted to the same density at different moisture contents. Moisture contents of 3.1, 5.1, 7.2 and 9.1 by weight were used. The material was compacted in a test box measuring 910 x 910 x 152 mm (36 x 36 x 6 inches). The thickness of the compacted base was fixed at 122 mm (4.8 inches). To clearly locate the reflection from the bottom of the test box a small piece of metal foil was attached to the bottom of the box. GPR tests were conducted with TTI's 1 Ghz horn antenna mounted at 480 mm (19 inches) above the granular material. A total of 50 waveforms were collected from the granular

base and the average amplitude of reflection measured. This amplitude was compared with the amplitude of reflection from a large metal plate. As described earlier in this report, by using this ratio it is possible to calculate the dielectric of the granular layer. The results of this analysis are tabulated below:

% Moisture (by wt)	Amplitude of Reflection (volts)	Base Dielectric
3.1	5.97	7.80
5.1	6.43	10.87
7.1	6.70	13.42
9.1	7.76	20.04

Based on the typical aggregate values discussed above equation 11 reduced to:

$$w = \frac{\epsilon_b - 1 - 4\left(\frac{W_s}{\gamma_s}\right)}{212 \left(\frac{W_s}{\gamma_s}\right)} \quad (13)$$

The unknown in equation 13 is the ratio (W_s/γ_s) . To solve for this unknown, one set of moisture content and dielectric values are used. Using the calculated dielectric of 7.8 at the 3.1% moisture content the value of W_s/γ_s is calculated to be 0.643. This further simplifies equation (13) to

$$w = \frac{\epsilon_b - 3.57}{136.3} \quad (14)$$

By inputting the calculated values of ϵ_b into equation 14 it is possible to calculate the base moisture content w . The comparison of calculated versus measured moisture content is tabulated below:

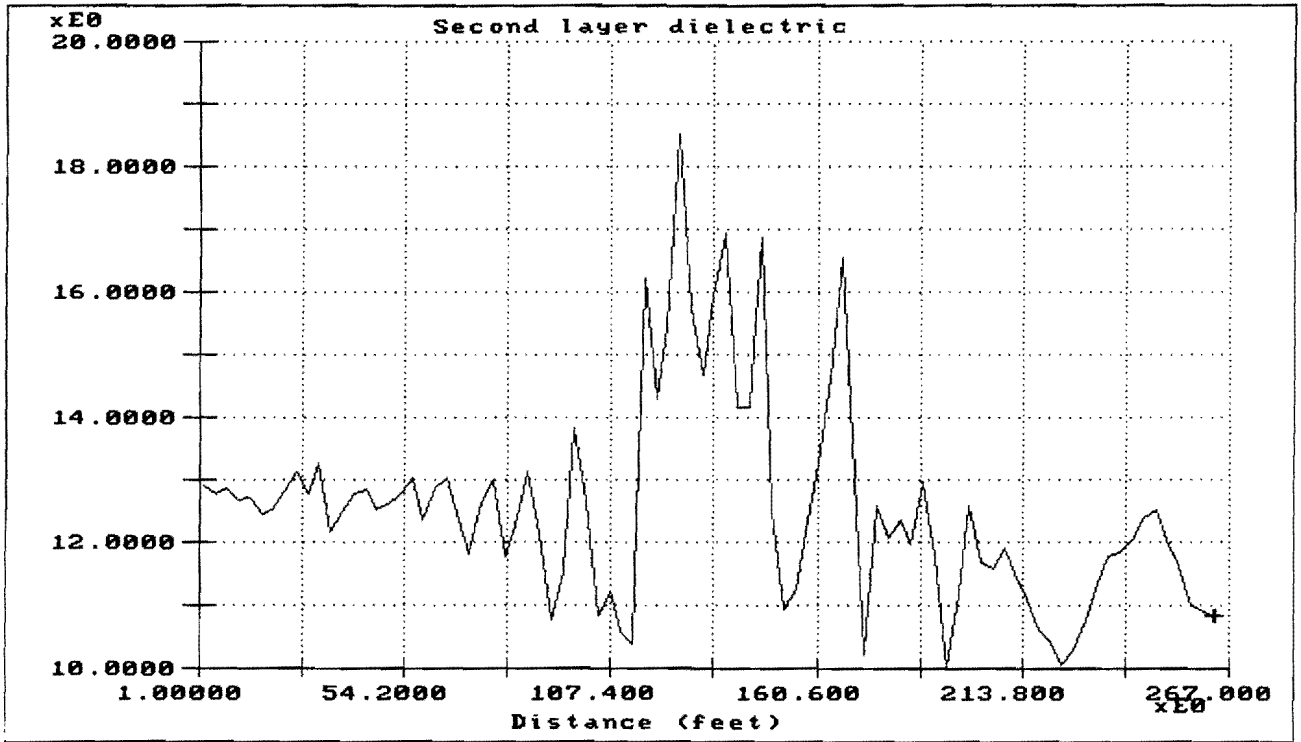
Moisture Content %	
Calculated	Measured
5.3	5.1
7.2	7.1
12.1	9.1

The calculated values are very close to the actual values for two of the three predictions. There is an error at the high moisture content level. However, at the 9.1% moisture level the base was fully saturated with free water standing on the surface of the sample. It is proposed that this moisture level is out of the range typically found in pavements. At the two other moisture content levels, equation 14 made reasonable predictions of the base moisture content.

The above derivations are based on the following assumptions:

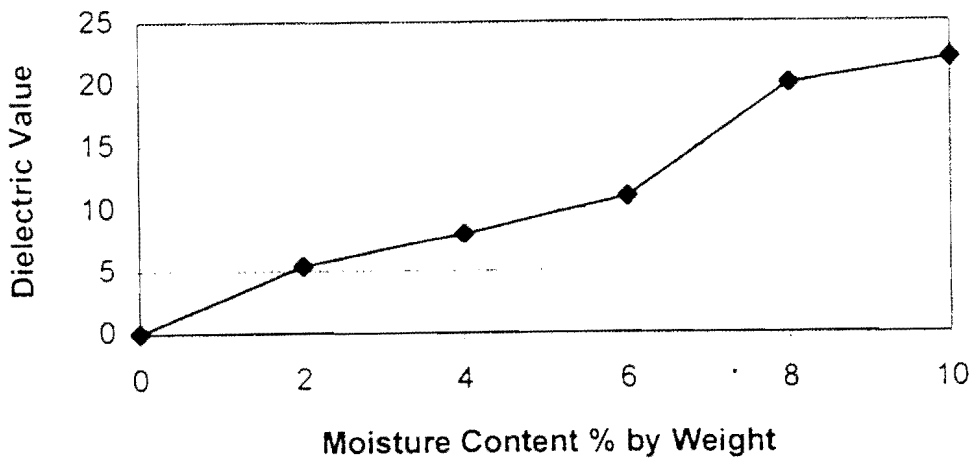
1. The dielectric of the aggregates is a constant (a value 5 was used);
2. The density of the base remains relatively constant; and
3. The linear constitutive model (Equation 10) is valid.

However, if required, a simple alternative method is possible where a laboratory calibration curve is generated for any base material. This is shown in Figure 35. The top curve is the base dielectrics as calculated from the amplitude of reflection from the top of the base layer. The lower curve is the laboratory determined dielectric versus moisture curve as measured using the surface probe equipment manufacture by Adek, Ltd (see TTI report 1341-2 for details). In this test pavement, there is a clear increase in dielectrics in the middle of the section. This can be converted into the equivalent base moisture content using the calibration curve. The saturated base conditions in the middle of this site were also observed in other nondestructive testing conducted with TxDOT's Falling Weight Deflectometer, where the Surface Curvature Index increased substantially and the backcalculated base moduli was found to be less than 10 ksi.



a) Field Dielectric For Granular Base Calculated From GPR.

#7-Caliche Gravel



b) Laboratory Determined Relationship Between Base Dielectric and Moisture Content.

Figure 35. Variation in Calculated Base Dielectric for an Experiment Pavement and the Laboratory Correlation Between Dielectric and Moisture Content.

3.6 PAVEMENT REHABILITATION STUDIES

Perhaps one of the best uses of GPR analysis is in the area of developing pavement rehabilitation plans. In this case, the GPR analysis is performed prior to coring and structural strength testing using deflection testing equipment such as the Falling Weight Deflectometer. GPR testing therefore becomes an integral part of the pavement rehabilitation process. GPR is needed because, in many instances, the as-built plans are often missing or not up to date. GPR's main advantage is that it is fast and safe. The surveys can be conducted at close to highway speed, and by using the software package described in this report the large volumes of data collected in network level surveys can be processed very soon after collection. GPR is also unique in that it can be used to look beneath the pavement surface and locate defects within the pavement layers, be it deterioration within the asphalt layer or trapped moisture within the base. All of this information can be used to assist in modulus backcalculation and in determining the appropriate level of pavement rehabilitation required.

Two major evaluations have been conducted in Texas, both involving testing substantial lengths of Interstate pavement. The first involved testing the entire Length of Interstate in Lasalle County, a total 176 km of asphalt surfacing over either flexible or asphalt stabilized base. The second was a survey of the entire Interstate system in the Bryan District, approximately 280 km of asphalt overlays over the original concrete pavement. In both instances, the objective were to:

- a. Locate section breaks;
- b. Define layer thicknesses within each section;
- c. Identify any subsurface defects which could be use to explain the observed distresses; and
- d. Make plans for ground truth testing and subsequent FWD testing.

The GPR analysis was made using the COLORMAP system and the techniques described in this report. One of the summary reports produced for the Bryan district is a map, shown in Figure 36, in which rehabilitation priorities are assigned. The assigned priorities are described as follows:

- Priority 1 GPR data indicated significant problems within the asphalt layer. Mostly, this appears to be stripping beginning at 2-4" beneath the surface.
- Priority 2 GPR data was not clear; no clear interfaces were found. The GPR signature was not as would have been expected from a good hot mix. These sections may have deterioration at the Asphalt/Concrete interface. Coring is required to confirm the potential problem.
- Priority 3 Hot mix looks good; no significant problem areas identified.

Within each of the priority one sections, subsections are identified and the thicknesses and the presence of subsurface anomalies identified. For example the southbound section from MP 147 to MP 132 was subdivided into two sections.

In another project, SH10 in the Fort Worth District, the benefits of merging GPR and structural strength testing with FWD's were clearly demonstrated. The as-built plans indicated that the surfacing thickness was constant at 200 mm for an entire 8 km section. In performing the backcalculation of layer moduli it was initially concluded that the granular base on a subsection was poor. However, upon reviewing the GPR data, it was observed that the surfacing thickness on the subsection was only 100 mm, not 200 mm. Upon reanalyzing the FWD data, the base strength now appeared to be reasonable. The problem with the section was in the surface, not the base as the earlier deflection analysis had indicated. In this case the FWD data provided false results because the layer thicknesses were wrongly assumed.

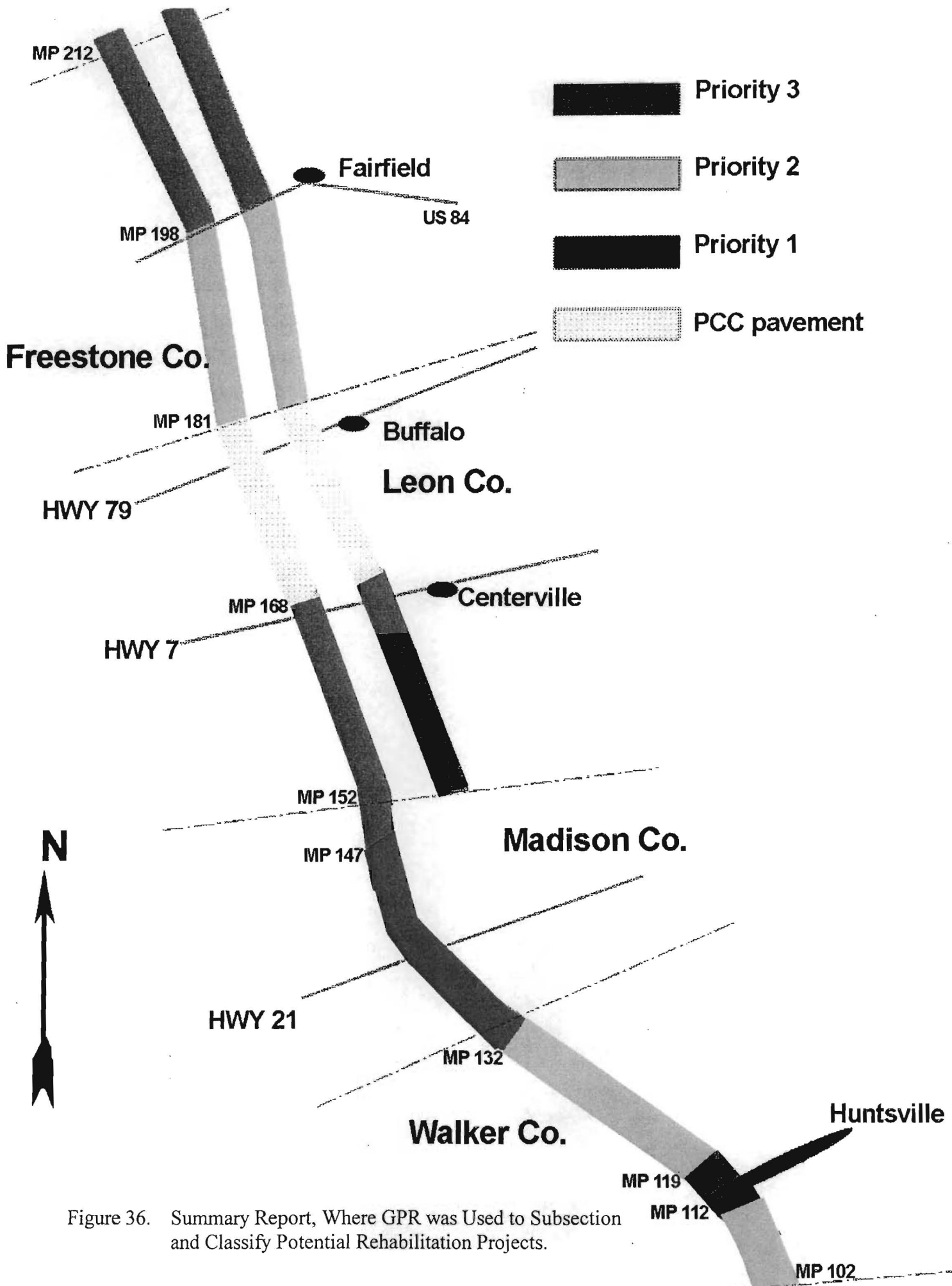


Figure 36. Summary Report, Where GPR was Used to Subsection and Classify Potential Rehabilitation Projects.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

This report has presented the COLORMAP system which has been developed by the Texas Transportation Institute for the Texas Department of Transportation for converting the GPR waveforms into information of use to highway engineers. The system was developed to improve the productivity of existing GPR processing software which currently relies on automated peak tracking. By combining the manual peak tracking capability with the automated computations, color displays and graphic outputs, the system is ready for implementation and the User need not be a “radar expert.” The system is currently being used by the Texas DOT to process GPR data on a routine basis.

This report also presents a series of case studies where GPR has been evaluated on an experimental basis. The ultimate goal was to identify applications within the pavement testing area where GPR could be effective. In general, GPR was successful in testing pavements with asphalt surfacings; it was not successful in testing the thick concrete pavements currently being constructed in Texas. The most effective application of GPR is as an integral part of a pavement rehabilitation design system. GPR should be used as the first step in any major pavement rehabilitation survey. It can be used to define homogeneous pavement sections, to measure thicknesses within these sections and to identify any subsurface defects that could be used to determine the cause of distresses observed at the surface. A GPR survey should be performed prior to coring and structural strength testing with the FWD. The FWD data is of little value if either the layer thicknesses or the section breaks are not known.

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