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Final Report

Ground Penetrating Radar Signal Processing Enhancements for Geophysical Anomaly Identification

Contract HPR Study No. 860, WPI 0510860

Submitted by

Electronic Communications Laboratory

University of Florida

To

Dr. Jamshid Armaghani

Pavement Evaluation Engineer

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Executive Summary

The University of Florida Electronic Communications Laboratory has performed a research project for the Florida Department of Transportation (FDOT) designed to enhance the capability of the FDOT to utilize ground penetrating radar (GPR) for surveying subsurface characteristics. The project began in September 1997, has a completion date of September 30, 1999 (with a no-cost time extension), and has resulted in a new graphical software environment that improves FDOT ability to process and analyze GPR data. Recommendations have also been provided concerning data collection practices. This final report summarizes the work performed on the project. A User's Manual for the software tool has been included as an appendix.

The FDOT State Materials Office provided the University of Florida with a response and evaluation letter for the draft final report and the GPR software tool on July 13, 1999. As requested in the FDOT/SMO letter, this final version of the report contains this executive summary, a summary of the salient project accomplishments, limitations of the resulting GPR software tool, and recommended areas for future work.

Several significant accomplishments have been achieved during the course of this project. The major contribution takes the form of a graphical software environment that enhances FDOT productivity concerning GPR use in several beneficial ways. The software provides intuitive use through graphical controls. Visualization of results is significantly improved with respect to previous FDOT capabilities. The software includes a selection of modern processing algorithms which enhance the profile data and aid in visual interpretation of subsurface features. Means of efficient data manipulation and file storage have been included in the package to simplify FDOT efforts. Finally, results of profile editing and processing may be output in several forms for compatibility with commercial software packages, allowing integration of processed images into FDOT results documentation. Another project contribution includes recommendations for radar system configuration and data collection techniques, both of which help ensure the quality of collected data for analysis.

In summary, the GPR software and analysis tool provided by the Electronic Communications Laboratory will improve the FDOT capacity for beneficial use of GPR radar for non-destructive analysis of subsurface anomalies for geophysical applications. Utilization of GPR and this software tool offers the potential for FDOT cost savings when used for pre-construction surveying, maintenance evaluations, and post-construction subsurface analysis.

1.0 Introduction

This report serves to document research conducted by the Electronic Communications Laboratory at the University of Florida for the Florida Department of Transportation under HPR Study No. 860, WPI # 0510860, State Job 99700-3558-119, Contract No. BB-260. The project title was "Ground Penetrating Radar (GPR) Signal Processing Enhancements for Geophysical Anomaly Identification." The initiation date of the project was September 8, 1997 and the project completion date is September 30, 1999 (with no-cost time extension). This report describes progress throughout the course of the project.

The purpose of this project was to improve GPR utility for Florida Department of Transportation (FDOT) geophysical applications, such as anomaly identification, by improving measurement techniques and signal processing techniques. The project had several specific objectives. A primary objective was to develop a capability to use GPR data and signal processing techniques to generate improved display of subsurface areas. This capability will allow the FDOT staff to better identify and locate subsurface artifacts and anomalies than was previously possible. A secondary objective was to develop measurement techniques that will provide more information about subsurface material properties, i.e., moisture content, dielectric constant, and possibly other properties.

Signal processing algorithms which were found to provide significant improvements in GPR analysis were coded into an efficient GPR processing software environment. This environment was customized to maximize utility for the FDOT geophysical application. A graphical user interface (GUI) has been provided to ensure intuitive operation with minimal operator training required. The software package allows display of enhanced GPR profiles which benefit subsurface interpretation and reduce the experience necessary for an informative analysis.

2.0 GPR Challenges

Processing of ground penetrating radar signals provides quite a challenge due to specific issues inherent in the data collection methods and in the use of radar for the specific purpose of imaging objects at close range underground.

2.1 Collection of Data

For geophysical applications, the radar is typically used by the FDOT to survey an area which is marked off in a grid. The radar antenna is usually pulled by hand along the gridlines while a button on the antenna is pressed every time an intersecting gridline is crossed. Each such pass is called a traverse. During each traverse, the GPR transmits and receives a series of pulses into the ground. The measurements of the pulses, also called traces, are stacked next to each other to form a ground profile--an image of the subsurface response for a single traverse. This data collection method introduces two errors in the data. First, the radar samples at a constant rate; however, as the operator walks pulling the antenna, the pace of walking cannot be entirely consistent. The sample interval in cross-range of the radar is, therefore, not constant. This problem distorts objects in a profile and cannot be corrected. Second, the markers set in the data at crossing gridlines are set when

the antenna marker button is pressed. This measurement, once again, introduces human error since the crossing of gridlines is judged "by eye". These problems created by the method of data collection cannot realistically be avoided; although, they may be kept to a minimum by careful, meticulous collection efforts.

2.2 Ground Coupling

GPR may be used for several specific applications. It is often used for thin layer pavement evaluation and thickness measurements. However, this report focuses on the department's use of the radar for analysis of deeper artifacts and anomalies. This application requires significantly greater signal penetration than that of thin layer evaluation. For this reason, ground coupled antennas are used rather than air-launched versions. Ground coupled antennas are placed directly on the surface, allowing electromagnetic coupling of the ground with the antenna. The antenna no longer sees the surface as a reflecting interface because the ground is now considered part of the antenna. The large loss of transmitted radiation due to reflection from the air-surface interface is, therefore, not experienced. Hence, a greater magnitude of the transmitted signal actually enters the ground for returns from subsurface objects. This advantage does not come without a cost. The surface reflection is not as obvious in the GPR profile as with air-launched antennas. Estimation is now required for the first layer. Another cost involves the electromagnetic coupling of the antenna with the ground. The transmitted signal may no longer be measured for use in matched filtering, inversion, or other signal processing methods. In fact, since the antenna is being pulled across the ground, the source signal is modified in a different manner by each surface the antenna contacts. So, ground coupling allows sufficient penetration for analysis of deeper objects, but it creates challenges to GPR processing development for ground coupled applications.

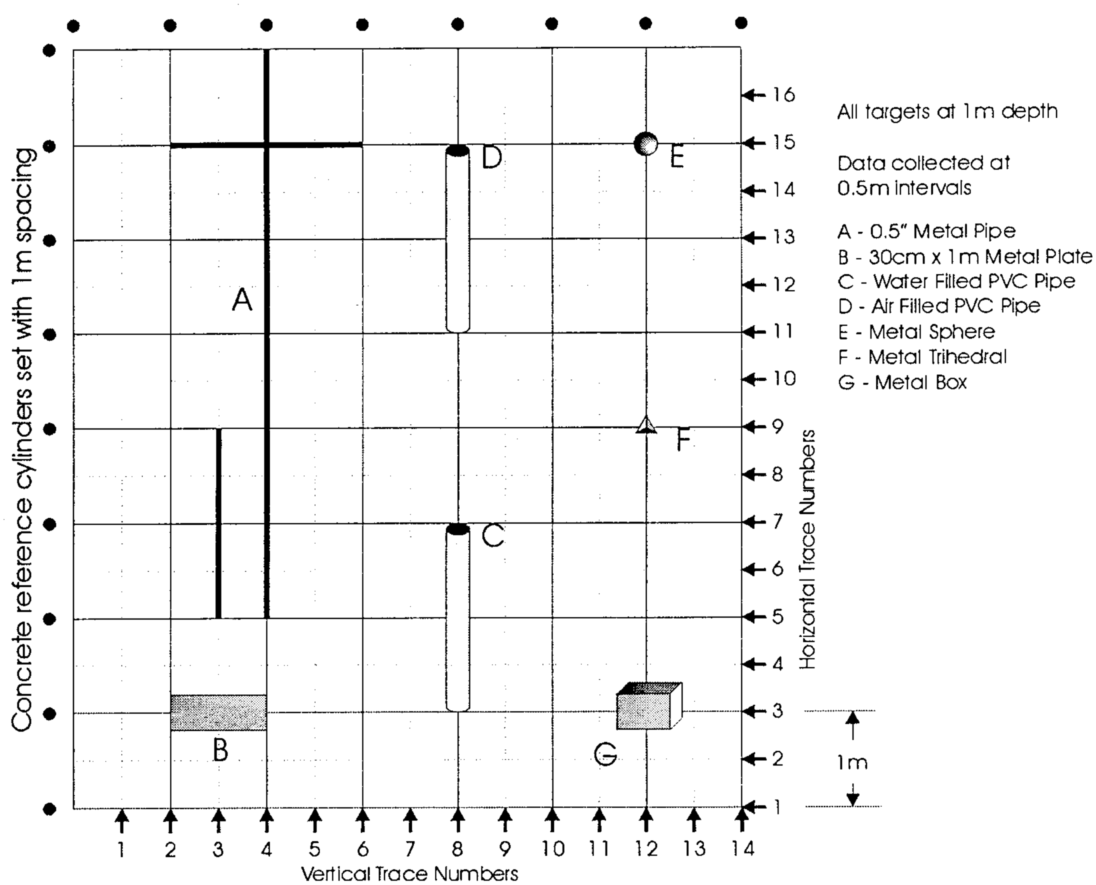
2.3 Hyperbolic Effect

Ground penetrating radars have a beamwidth of approximately 90 degrees or more. Because of this wide beamwidth, the radar is able to "see" an object and register a return before the radar is directly over the object. In fact, the radar integrates all the returns from surfaces perpendicular to the wave propagation for each time location within the antenna beamwidth. The time (and therefore the distance) to a target appears in a GPR profile to be greatest when the GPR first "sees" the target, but it is actually the correct value when the artifact is directly below the antenna. As the antenna passes the target, the time measurement to the target response increases again. Once again, only responses from surfaces which are perpendicular to the wavefront propagation reflect electromagnetic radiation back to the antenna and are "seen". Point targets, which are omni-directional having perpendicular surfaces in all directions, produce a hyperbolic shaped response, as can be seen in many profiles. Due to the same phenomenon, objects with extent that do not contain horizontal surfaces appear to be shifted horizontally because their returns were measured when the antenna was not directly overhead. This hyperbolic effect spreads the energy or information in the return from an object into a complex pattern which is often capable of rendering features in a profile indistinguishable. Objects in a profile which are in close proximity to each other demonstrate returns that overlap and add together, causing even more difficulty in interpretation of the patterns found in GPR profiles.

3.0 Progress

The progression of research throughout this project evolves from the pursuit of three main tasks. This first of these tasks is the collection of relevant data from the system of interest. In this case the FDOT department's GSSI SIR-10B ground penetrating radar must be used to acquire data from ground truthed regions in order to provide measurements for analysis of the applicability of new signal processing methods. The second task involves the study and development of signal processing algorithms which may benefit GPR profile visualization and interpretation. These algorithms must enhance features of objects in subsurface profiles to ease the uncertainty which currently plagues GPR analysis. Due to the volumes of data involved in this application, the routines must be written to work efficiently if they are to operate with reasonable analysis times. Finally, the third task is comprised of the development of a software environment which facilitates intuitive use of the advanced signal processing and efficient completion of routine GPR analysis. These three tasks have been carried out somewhat in parallel during the course of this project.

FIGURE 1. GPR Test Pit

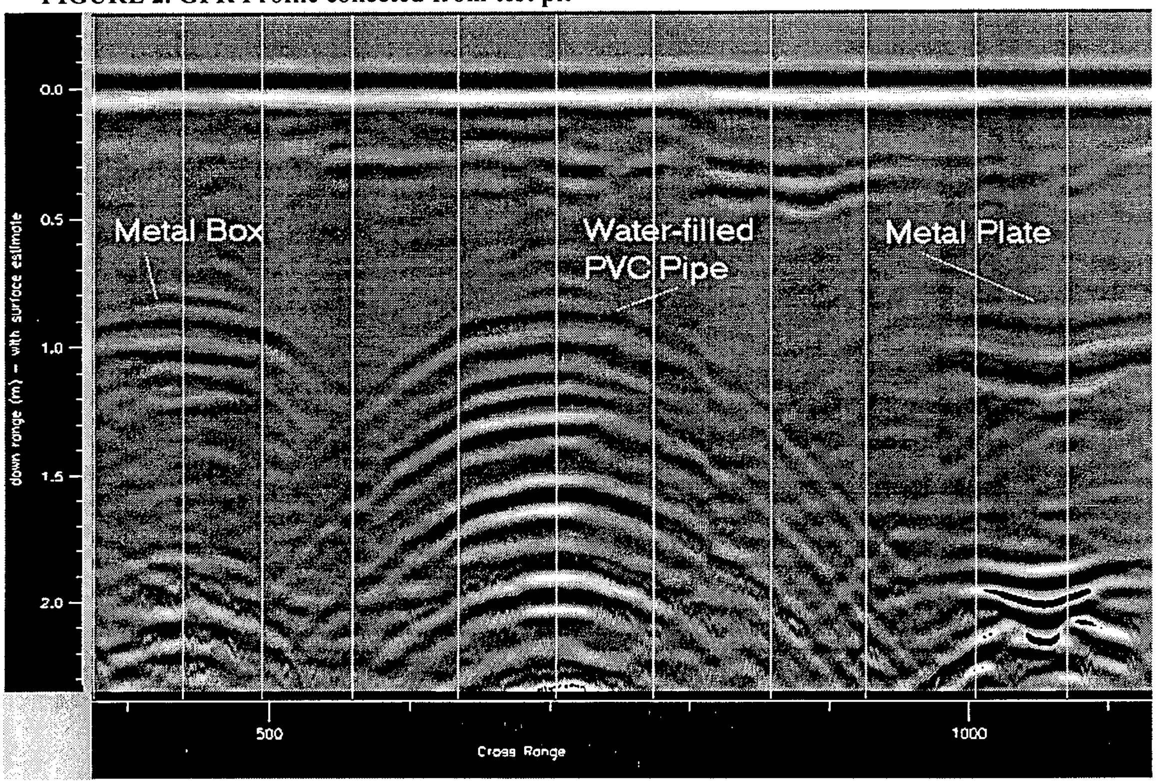


3.1 Acquisition of Meaningful Data

In order to effectively determine the usefulness of signal processing algorithms for GPR, data from the radar must be provided for study. It is critical that the data represent a known subsurface such that the appropriate correlations may be made between algorithm results and the responses from actual physical artifacts. In order to collect the required

data from a ground truthed area, a GPR test pit was constructed with a collaborative effort between the ECL and the FDOT at a location provided on FDOT property. This pit was designed by the ECL to provide radar responses from a set of specific, known targets which are typically used for radar system development. The targets were buried in the pit in known locations so that collection could be efficiently taken and appropriately documented. A diagram of the pit follows in Figure 1. Upon construction of the GPR test pit, the radar was used to survey the area. Traces were recorded in a grid-like fashion as documented in the Figure 1 illustration. Data was collected first using the 500MHz antenna, which provides good resolution and penetration for imaging objects buried to one meter depth, as those placed in the test pit. Data was later collected using the 900MHz antenna to provide greater resolution with less penetration. The test pit provided an acceptable set of ground truthed data for analysis and algorithm evaluation.

FIGURE 2. GPR Profile collected from test pit



3.2 Development of GPR Processing Algorithms

3.2.1 Background Removal

Horizontal bands frequently obscure more important information in a GPR profile. These bands sometimes result from ringing of the antenna, ground coupling effects, or the response from some artifact maintaining a constant distance from a poorly shielded antenna. Routines have been written which remove banding in a response profile. The algorithms assume that any response which is constant for the entire profile, or for a user selected range, is useless information. The algorithms, therefore, average the traces over the given cross-range and subtract the result from each trace in the profile. This procedure effectively removes the banding and quite often reveals pertinent data. The routine must

be used with caution due the possibility of removing responses from anomalies with significant horizontal extent.

3.2.2 Median Filter

On occasion, profile displays contain a significant amount of what is called "salt and pepper" noise before or after processing. The phenomenon exerts itself as high valued, outlying points in an image. These points seldom truly represent meaningful points in a data set and often cloud the image with a grainy appearance and/or an inappropriate color scaling. One solution to this problem, which is often used in many image processing applications, is a median filter. Median filters take all the points within an area around a pixel and return the median of the points as the pixel's new value. This effectively removes any outlying points and produces a less corrupted display. To improve the appearance and produce a truer representation of GPR data, a median filter has been added to the list of GPR signal processing options.

3.2.3 Signed dB Display

Data collected by the GPR may typically range in amplitude over several orders of magnitude. This makes visualization of many profiles difficult, if not impossible, using a linear scale. A linear scale distributes the allocated colors evenly between the lowest value in a data set to the highest value in a data set. Very high values often cause small values to be indistinguishable when the data is displayed. This is usually true of GPR data due to the exponential attenuation of the electromagnetic signal during propagation through the subsurface. Returns from near-surface objects will be very high when compared to reflections from deeper objects. To improve the display of such large dynamic range profiles, the signals are often displayed in decibels(dB), which is computed by taking twenty times the LOG_{10} of the data. The displayed dynamic range is, therefore, compressed allowing both high amplitude and low amplitude returns to be seen. However, computing the LOG_{10} requires taking the absolute value, since LOG_{10} of negative numbers does not exist. It is, therefore, common practice to just take the absolute value of the data before displaying in decibels. While this method often helps provide a better display, any information contained in the sign of the data is discarded. When interpreting GPR profiles, the sign of the peaks of the returned reflections are quite often very beneficial for understanding subsurface artifacts. With the goal of improving the display of wide dynamic range data without losing information contained in the sign of the data, a new method of display was employed. This new method takes the typical unsigned dB data and gives it the appropriate sign, which is obtained from the sign of the original data. The resulting display provides for effective visualization of GPR in many instances without loss of sign information.

3.2.4 Histogram Equalization

When colors are allocated for the display of data, they are most often distributed in a linear manner. This means that the colors are ranked in some order according to some predefined colorscale. The top color value is assigned to the highest sample value in the data while the bottom color value is assigned to the lowest sample value in the data. All the colors between the top and bottom are allotted data values which are evenly distributed

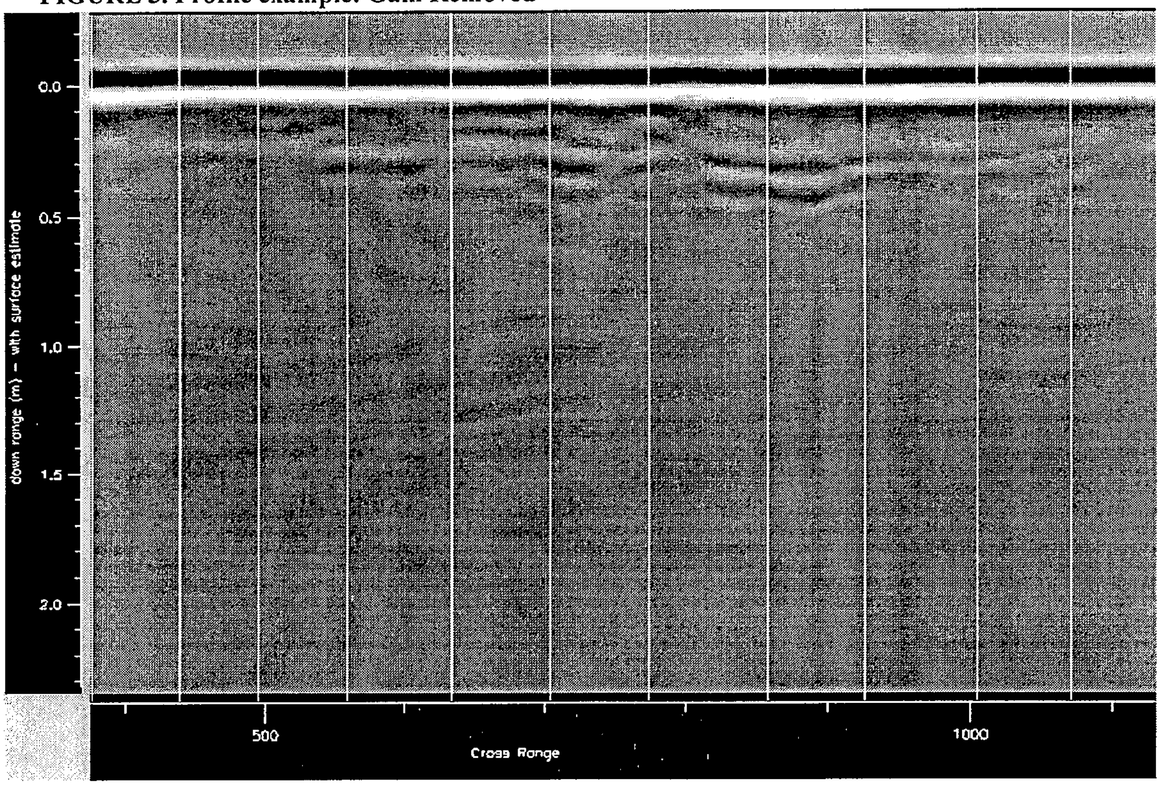
between the highest and the lowest values. The colors are, therefore, allocated without regard for where the data values are most prevalent within the determined range. This method is perfectly acceptable in many instances. In fact, it works very well, and it provides a linear association between the data value and the position of the color within the color range. Generally this linear color association is more natural or intuitive. However, there are many situations when this method provides little to no color separation between features of interest within a data set. For example, suppose there are both a few very high data values and a few very low data values within a given data set. In this set consider also that a majority of the data values are within a much smaller range somewhere in the middle of the set, with no values of data points in the substantial regions between this central group of points and either the small, high group or the small, low group. In the linear allocation scheme, colors will be assigned evenly between the highest group and the lowest group. Many colors will be wasted in the display of the data because they will be assigned to data values which do not exist in the data set: values between the middle group and the high or low groups. There will be few of the limited number of colors available to display the very large middle group of points. These few colors will be distributed evenly over the important middle set of points, and each point will be displayed using the color representing a value which is closest to the actual data value. Small differences in the actual data values, which may represent significant features in the data, may not be visible because they are mapped to the same color as a result of the insufficient number of colors available for their display. A better scheme, in this instance, will allocate the available colors only in the ranges where data values exist within the set. In this way, all colors will be used to visualize the data without wasting colors. Histogram equalization is a method of color assignment which performs just this task. Before determining where colors should be distributed, histogram equalization maps out the number of occurrences of each data value within a given set. It then chooses to assign the colors such that each color is used an equal number of times in displaying the data. Narrow congregations of data with many representative points, having small differences between them, now receive a sufficient number of colors for the mapping of small differences in value to different colors. The important features may now be visible, whereas before they might not have been. Histogram equalization works very well in many instances. Sometimes, however, it applies too many colors and makes interpretation difficult. In these cases, normal color assignment is preferable. Histogram equalization complements the standard linear allocation very well, and with viewer discretion succeeds in significantly improving the visibility, and therefore interpretation, of GPR profiles.

3.2.5 Gain Function Removal

Collection of profile data is subject to a gain function which is applied to the received signal. This gain function can be automatically set by the radar, or the function may be manually chosen by the system operator. This gain magnifies the value of the response in an attempt to compensate for the attenuation of the signal moving deeper into the subsurface. Often this procedure makes very small returns from deep artifacts visible. However, there are two potential problems with such a method that can often affect signal processing algorithms adversely. First, the noise level inherent in the system is also amplified with the desired signal. This noise can become significantly large and disrupt processing and visualization. Second, the gain function applied causes an unnatural

response with respect to the inherent properties of the subsurface medium. Processing designed to interpret subsurface characteristics based upon the natural response from object features may not handle the corruption of the response by some arbitrary gain function which is in no way correlated to the features themselves. For these reasons, it is often desired to remove the gain function from the data prior to processing with certain algorithms. The characteristics of the gain function, which was applied to the data upon collection by the radar system, are saved within the header information of the data file. A routine was written which is able to retrieve the appropriate gain function information from the header and then apply the inverse of the function to the profile data. This effectively returns the response of the subsurface without gain corruption for further processing.

FIGURE 3. Profile example: Gain Removed



3.2.6 Simple Migration

Migration is the process of focusing the hyperbolic responses of point targets in GPR profiles to points with the goal of providing a more meaningful representation of the subsurface for interpretation. Fixing the problem, however, is not a simple task. Several difficulties arise. First, not all responses are from point targets and do not, therefore, have a nice hyperbolic shape. Few prior assumptions can be made about the subsurface to remedy this problem. Second, the inconsistent cross-range sample rate corrupts the shape of the responses, so matching hyperbolas to the responses can sometimes prove difficult. Third, the hyperbolic shape depends on the velocity of the electromagnetic wave in the medium, which is not constant for most situations. So, the responses may be distorted by gradients in the dielectric constant, which cannot be determined to a sufficient extent to correct the problem. Finally, interference from multiple nearby targets creates a much

more complex response. With all this said, the possibility of migration in GPR sounds nearly impossible; but, in many situations, it may in fact be helpful. Typical use of the radar often involves locating utilities such as buried pipes and cables, or rebar--all of which respond as point targets in a perpendicular cross-section. The dielectric may vary a significant amount between targets located in different sections of a profile, but it will often be consistent enough in the immediate area around a specific target. If the data is carefully collected such that the cross-range sample rate maintains a relatively constant sample interval, then migration can be of use for improving the interpretation and cross-range localization of the object of interest, particularly point targets.

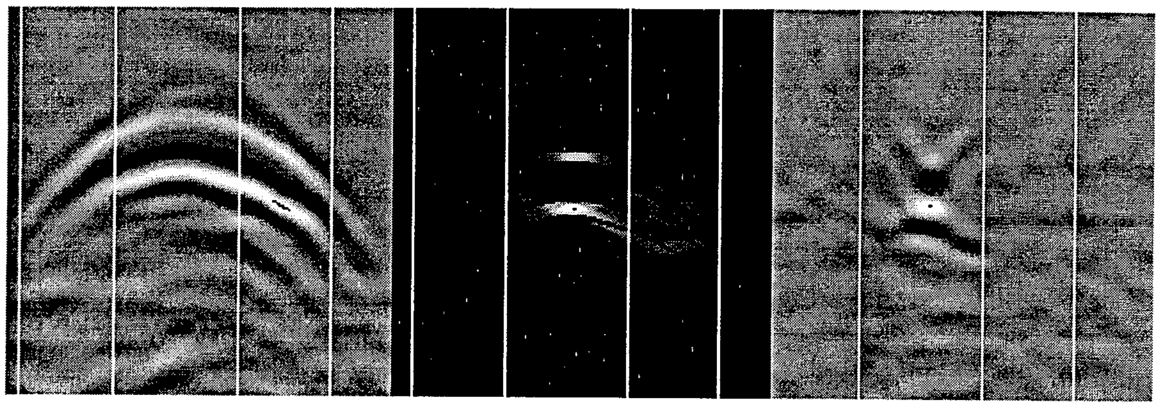
The simple migration algorithm uses the physical geometry of the radar system and the resulting hyperbola associated with an un-migrated point target in a GPR profile image to migrate GPR data. It can be shown that the hyperbolic shape for a point target will be a specific shape for a given target depth, medium dielectric constant, and radar antenna beamwidth. The algorithm uses the assumption that the target is a point object with sufficient returned energy to be discernible from the profile background, where no significant level returns were detected. With this assumption the algorithm thresholds the amplitude data from the GPR and only processes significantly high responses which are considered to be likely candidates for point targets. If the GPR image pixel is above the threshold, the hyperbolic shape is calculated for the specified GPR beamwidth, medium dielectric, and depth of the target. The energy contained along the hyperbola is then integrated or summed to create the new value for the pixel at the hyperbola's apex. This effectively collapses the hyperbolic shape to a more point-like object, as is more appropriate for interpretation. The process is repeated for each pixel in the profile which meets the threshold requirement. Focusing the point targets also narrows the extent of the target response in cross-range, providing a more precise location of the object. The migration algorithm may also be used to estimate the dielectric of the medium surrounding point targets in a profile. The algorithm can be run using a range of dielectric values. When the most accurate dielectric estimate is used for migration, the algorithm will produce the most focused results.

3.2.7 Fast Fourier Transform Migration

Another method of profile migration was originally developed for seismic data processing by Stolt [3]. It has also been used for Synthetic Aperture Radar (SAR) applications, which are similar in nature to the geophysical application of the FDOT. Stolt's algorithm takes advantage of relationships between traveling wavefronts in the frequency domain. This method of processing transforms the time-domain profile into the 2-D frequency domain. It is able to use Fast Fourier Transforms for this conversion, which results in a remarkably efficient algorithm and extremely fast operation. Once in the frequency domain, a spatial transformation, discovered by Stolt, is executed to perform the required focusing, and then the inverse Fast Fourier Transform is performed to return the migrated GPR profile. This method of processing has proven to be very fast when compared to the point processing involved in the simple migration algorithm. Its results are good with objects that are good approximations of true point targets, when the dielectric is chosen appropriately. For other targets, the simple migration method often works a little better. Some of the limitations of the Fast Fourier Transform migration method are perhaps due to the

assumption made that the propagating wavefront is planar. The assumption is valid for far-field analysis in seismic and SAR applications; however, the GPR application is a near-field problem. Nonetheless, the algorithm is fast and may be helpful in many situations. It may be used in a like manner to the simple migration method for estimation of the dielectric constant as well.

FIGURE 4. Migration examples: Unmigrated, Simple Method, FFT Method

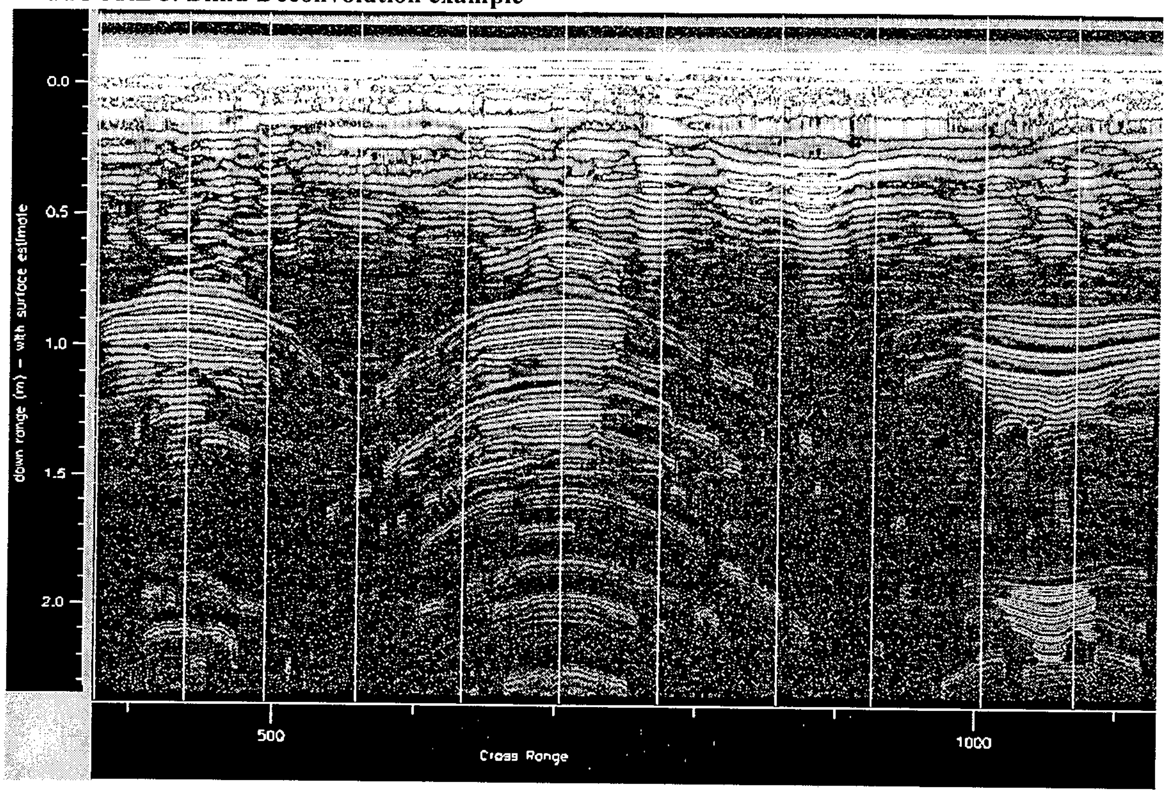


3.2.8 Blind Deconvolution

One way of considering the GPR subsurface imaging problem is to interpret the ground as a filter. The source waveform from the radar would be the input to the filter, and the received signal would be the output from the filter. This filter could be generalized as a series of impulses, having an impulse at each interface between layers of differing dielectrics. What is seen as the output in a GPR profile is the result of the source waveform being filtered by, or convolved with, the ground response. This response appears similar to a "mexican hat" waveform at each interface. The "mexican hat" has a high main lobe and two smaller, negative sidelobes. One reason GPR profiles are difficult to interpret is that each interface returns a waveform with multiple lobes of alternating sign. Ideally, it would be easier to interpret a profile if the profile were more like the original subsurface response, which consists of one high amplitude, narrow peak at each interface. The desired profile, the impulse response of the ground, can be attained by separating, or mathematically speaking, deconvolving the source waveform from the returned response. However, this filtering cannot be done when a ground coupled radar is used because the input signal is a function of the ground coupling and, therefore, is not accurately known or measurable. Resolving this problem calls for more creative methods. One such method is known as blind deconvolution. The deconvolution procedure is considered "blind" because it must separate both signals without knowing either one of them. In order to do this, one of the signals is modeled as a white noise process, while the other is modeled as linearly predictable. Both the additive noise and the subsurface impulse response may be modeled as a white noise process due to their random nature; no combination of previous values of the samples tells anything about the next samples. The input signal, however, may be approximately modeled as the impulse response of an all-pole, minimum-phase filter. This means that each sample value is a linear combination of previous samples, and the next sample may be effectively predicted from the current sample and previous ones. In summary, the input signal may be predicted, with an

appropriate filter, from current and previous samples while the ground response and additive noise may not. This assumption is very beneficial and allows for an estimated deconvolution of the two signals. To perform this blind deconvolution, an adaptive filter is utilized. The filter is designed to predict the next value of each sample in a trace as it filters the trace. After each prediction, the error between the predicted value of the trace and the actual value is used to modify the values of the filter such that it is more capable of predicting the next value. Hence, the filter adapts to minimize the error between what it predicts as the next sample in a trace and the measured sample.

FIGURE 5. Blind Deconvolution example



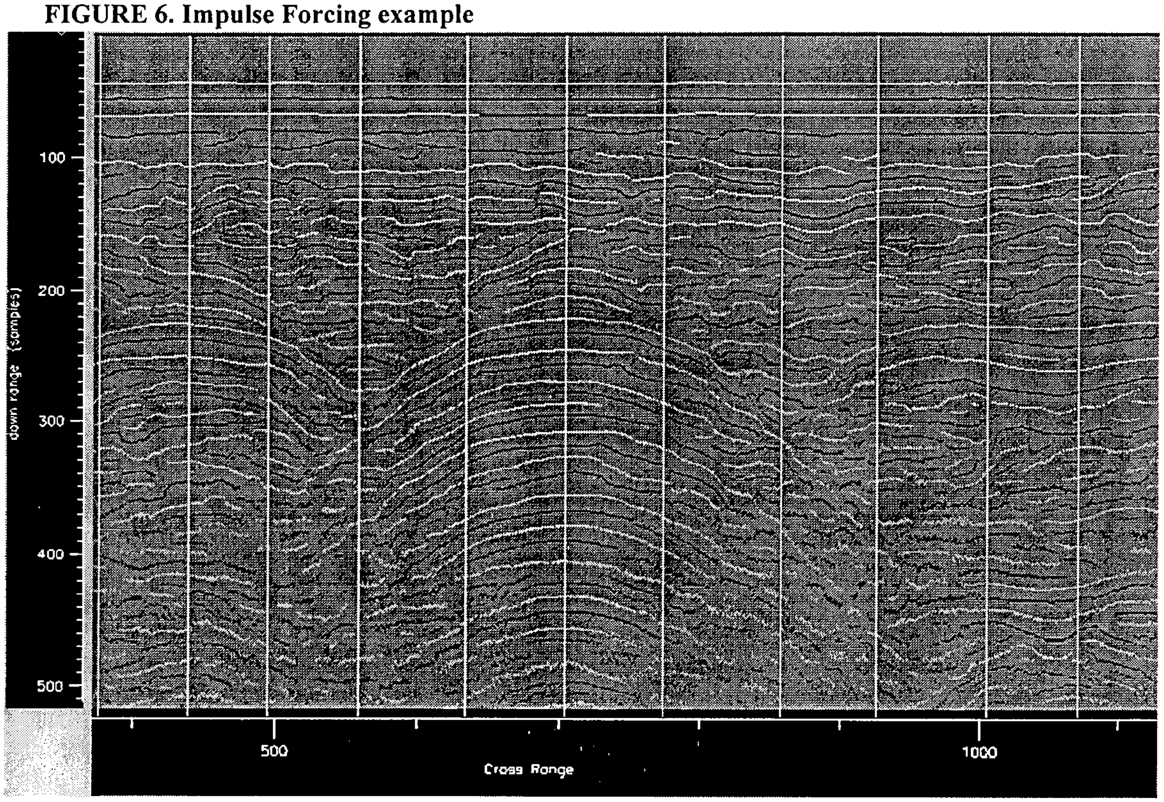
The filter gets closer and closer to being able to predict the next value until it is predicting as well as possible. At this point, the filter is said to have "converged" to an estimate of the model for the input signal. If the adaptive filter is now predicting the next value of the input, then the error between the predicted value and the actual value must be that which it cannot predict in the measured response: the noise-like response of the ground and the additive noise in the system. This error, therefore, is an estimate of the impulsive subsurface filter having high, narrow responses at each layer interface. Algorithms have been coded which implement this blind deconvolution scheme and return an estimated profile of the ground impulse filter. Many assumptions were made to produce the blind deconvolution algorithm. The results of the algorithm are only as good as the assumptions which are made. For this reason, it is easy to understand why an ideal ground response profile is not achieved. In fact, the assumptions in no way accounted for the hyperbolic integration problem mentioned previously. However, the assumptions are good enough to enable the blind deconvolution algorithm to benefit interpretation of GPR profiles. The algorithm is capable of collapsing some of the responses, which are widespread in the

down-range time-domain, into denser clusters of information. Recognition of true responses from objects is significantly improved in many profiles using the blind deconvolution algorithm.

3.2.9 Impulse Forcing

Profiles are easily cluttered by wide bands of color which exist in the display because of the wide crests and troughs of the electromagnetic source waveform, the wide beamwidth response pattern, and the interference between neighboring objects. An algorithm has been designed which often alleviates some of the visual overload associated with these many complex phenomena. The Impulse Forcing algorithm filters each trace in a profile and returns an impulse, weighted by the original sample value for every sample that meets the following criterion: 1. The sample must be the highest valued sample within a sliding window of a user specified width centered around the sample, and 2. The sample must be a certain percentage, determined by a user specified threshold, higher than the standard deviation of all the samples within the sliding window.

FIGURE 6. Impulse Forcing example



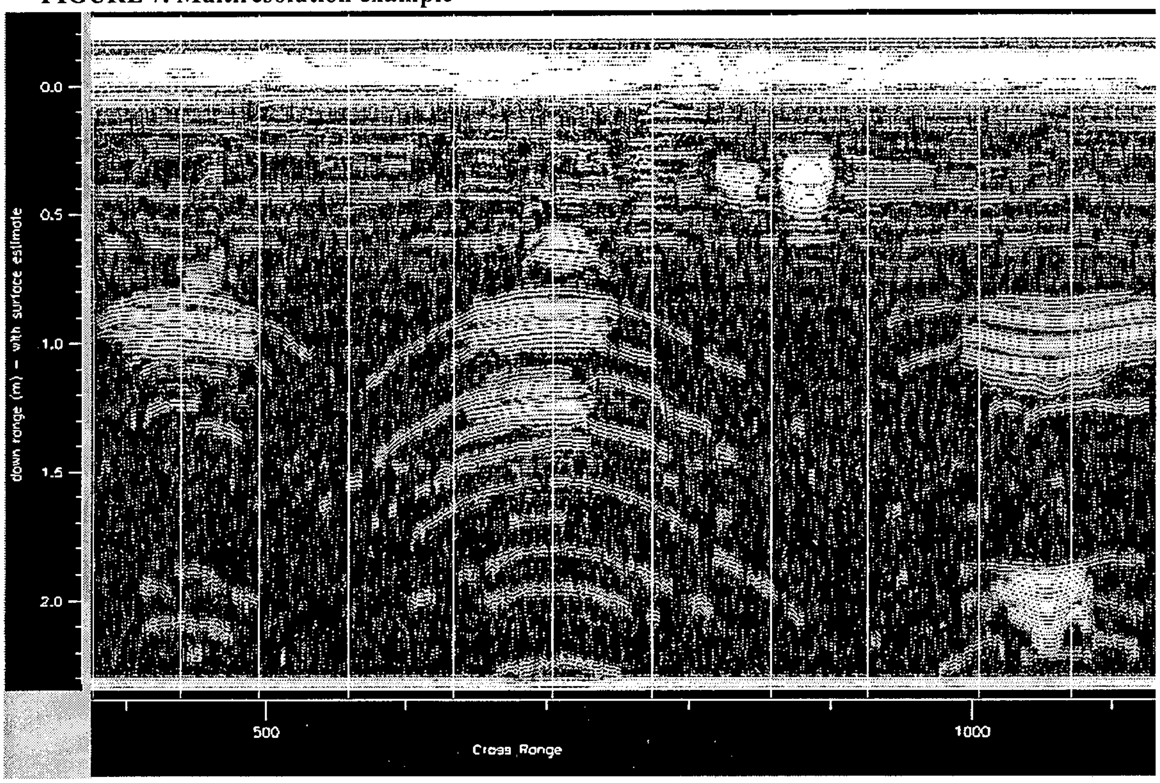
This algorithm attempts to replace broadly shaped returns with fine lines at the positive and negative peaks subject to a specified window size. It also attempts to ignore low amplitude peaks which are probably not from legitimate returns by comparing their value with the standard deviation within the sliding window. The peak must be of significant size compared to the surrounding data samples to register as an impulse. The Impulse Forcing procedure emphasizes the slopes and curvatures of responses within a profile and presents some insight into subsurface features. The algorithm may be used on the unprocessed profile and can also be informative when applied after the Blind

Deconvolution process. Typically, the results of this algorithm are best viewed in signed decibel mode without histogram equalization.

3.2.10 Multiresolution Analysis

GPR signals do not readily lend themselves to typical frequency analysis. The measured waveforms are not stationary and, therefore, have a frequency content that varies with time. Fourier analysis determines the frequency content of the entire signal, but fails to provide any time information content. This is the exact dual to the original measured time series providing only time information, but no frequency information content. One possible solution to many non-stationary signal processing applications involves a relatively new concept known as multiresolution analysis using the wavelet transform. The underlying principle in Fourier analysis is a comparison of the signal of interest with cosine functions of varying frequencies.

FIGURE 7. Multiresolution example



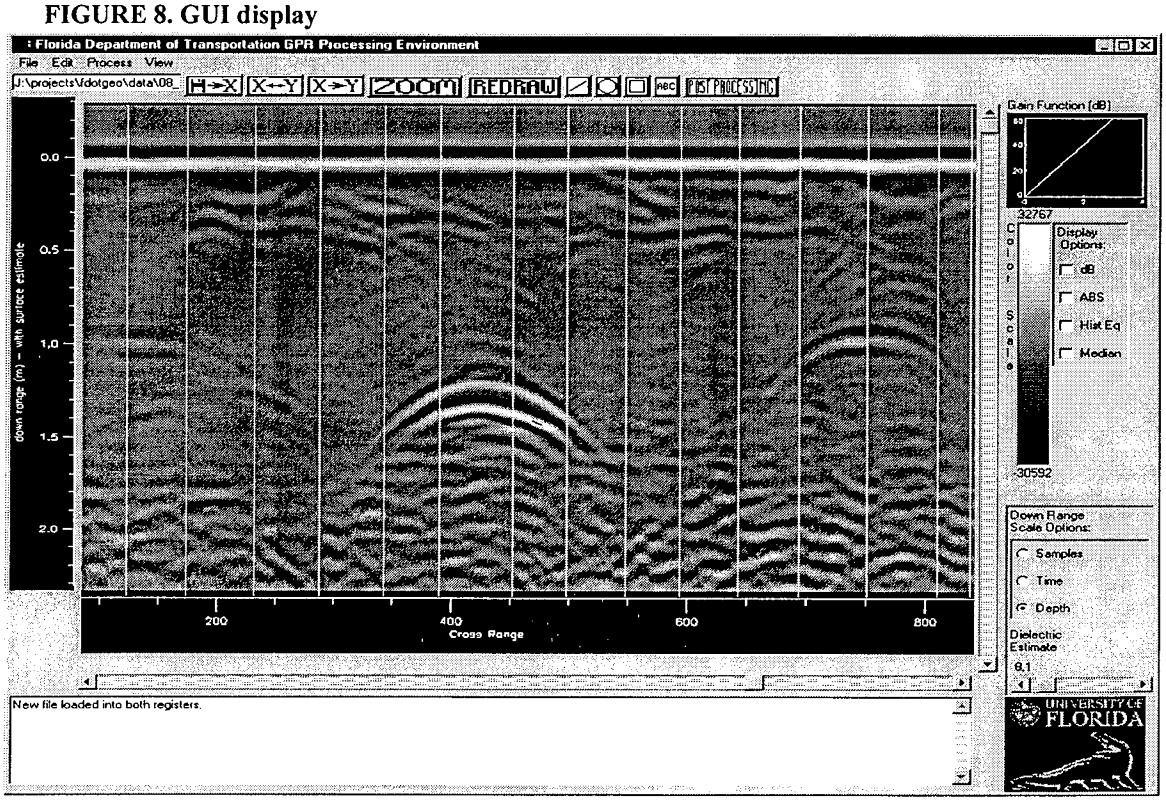
High correlation between the signal and a particular frequency indicates the presence of that frequency in the waveform. In this manner, a signal may be dissected into the frequency components, of which it is composed. Cosine functions are of infinite extent, causing time to be absent in the frequency decomposition. The wavelet transform uses basis functions other than cosines in the signal decomposition. These basis functions, called wavelets, are finite in extent and have a very narrow frequency content. In frequency analysis, the signal of interest is compared to cosines of varying frequency. In wavelet analysis, the signal is compared to wavelets of varying scales. The wavelet scale is a variable in the wavelet function which determines the frequency and extent of the waveform, just like frequency in the cosine function does to the cosine waveform. The

wavelet waveform changes, based upon its scale, from low frequency with long extent to high frequency with short extent. Therefore, because the wavelet basis functions have both frequency and finite extent, the final wavelet transform contains both time and frequency information. This time-frequency component is called resolution. A signal may be decomposed into its multiple resolutions by comparison with wavelets through a range of scales--hence the notion of "multiresolution analysis". Similar to frequency filtering, where only the important frequencies in a signal are kept; once a signal has been decomposed using the wavelet transform, the desirable resolutions may be kept while the unimportant are discarded. In this way, features in the signal may be selectively chosen based upon their resolution. Such processing may be applied to measured GPR returns and proves to be beneficial in enhancing the returns from artifacts while reducing clutter in the display of GPR profiles. Subsurface features are, therefore, more easily recognized, and interpretation is significantly improved. Algorithms providing such processing have been developed. They allow user selection of the most beneficial scale, as well as a choice of several wavelet basis functions which are provided. Multiresolution analysis provides excellent results in many situations and is quite fast due to the Fast Fourier Transform method used to compute the wavelet transform.

3.3 Design of GPR Graphical Environment

A major goal of this project is to improve the capacity of the FDOT in making meaningful interpretations of GPR profiles through enhanced signal processing techniques. With this goal in mind, methods of signal processing were studied and analyzed for applicability to GPR processing tasks.

FIGURE 8. GUI display



Procedures which were determined to provide suitable utility were coded for use in Visual Numerics' PV-Wave mathematical analysis software. These algorithms process the radar data; however, it was imperative that a graphical environment, or Graphical User Interface (GUI), be developed to facilitate the manipulation of GPR files and data, to provide intuitive access and operation of processing routines, and to display results in a visually beneficial format. Such an environment has been designed to fulfill these needs.

3.3.1 File Access

The file format of the GPR environment was designed to both load and save profile data in a manner which is compatible with software currently used by the FDOT. The FDOT uses a software package called RADAN to view and manipulate GPR profiles. Output from the GSSI SIR-10B radar system is saved to disk using RADAN's file format. The GPR software is capable of loading the RADAN file format and accessing the data and header information within. In an effort to increase utility of the GPR processing package for the FDOT, file output routines were written to save data and header information such that RADAN can access GPR environment processed profiles. This adds flexibility in FDOT analysis capabilities, allowing processing and visualization of data through any combination of the routines from either or both software packages.

3.3.2 Profile Editing

Functions were added to the ECL GPR processing environment which make editing of a GPR profile data file simple and efficient. All editing tools are easily accessed in menus of the GUI and provide for such functions as cropping out a section of interest for processing, deleting a section of unimportant data, automatically removing the gain function applied to the data by the radar, or modifying the gain by applying any gain function to the data set. The modify gain function has its own graphical tool for designing a gain function for use on the data. Editing of GPR profiles allows extremely large data files to be broken into smaller more manageable pieces. It also permits the user to extract only the data of interest for processing. This reduces the size of the data set and greatly increases the processing time required.

3.3.3 Data Processing

All of the GPR signal processing algorithms mentioned previously are integrated into the GUI and are readily available for use by the FDOT GPR specialists. Each processing routine has a graphical tool designed for efficient control of parameter selection and operation. The GUI makes use of all GPR algorithms easy, and all results are immediately displayed for user interpretation.

3.3.4 GUI Display

Processing of the data is not enough: intelligent data displays are required for meaningful visualization and an informed interpretation. The subsurface response is displayed in the main window of the GPR environment GUI. Perhaps the most influential elements of an effective display are the choice of colors and their allocation scheme. The main GPR display supplies freedom for the user to tailor these features of the profile display to best suit the visual information presented for each profile, before or after processing. A

selection of color tables has been provided for emphasizing various aspects of data, and a graphical tool has been designed to allow for the adjusting of these tables to maximize their utility. This capability greatly improves the visibility of significant qualities of the subsurface responses in the ECL GPR environment in comparison to previous GPR software packages used by the FDOT. The main profile display also supplies other display options, some of which were mentioned with the processing development section, including: decibel display, absolute value, histogram equalization, and median filtered display. The vertical axis of the display has several beneficial options. The axis may be displayed in sample number, sample time, or in depth estimate mode. Depth estimate mode requires user estimation of the dielectric constant for depth calculation. This dielectric estimate may be known from soil tests or it can be estimated using the mentioned migration estimate methods. It is also possible, if a target is buried at a known depth, to change the dielectric parameter until the display indicates the proper depth of the object. The dielectric constant associated with this correct depth indication may be used as an estimate of the medium dielectric. The GUI also contains a plot of the gain function currently applied to the data, and a command feedback display to provide information concerning the last procedure performed by the software.

3.3.5 Multiple Register Handling

The ECL GPR processing environment was designed with effort made to maximize efficiency and utility in the processing and analysis tasks required for typical FDOT GPR use. In an attempt to attain additional efficiency, data within the software is handled in two registers: X and Y. Upon loading a new profile, the profile data is entered in both registers. Only register X is displayed in the main display, and all processing within the environment is performed only on register X. At any point, the operator, using buttons on the GUI, may switch the contents of the X and Y registers. The contents of register X may also be copied into register Y at any time using a similar button. This system, with minimal practice, allows the user to keep two sets of the same profile data set at all times. Each one may be processed independently and compared to the other. The original file may be reloaded into register X by another button without disturbing the contents of register Y. The ability to compare and contrast features in the data, extracted by various forms of processing, greatly improves the GPR analysis system.

3.3.6 Final Results Editing

Once the processing has been completed and final results need to be documented, the processed profile image in the main display may be imported into a tool designed for annotating, printing, or exporting. The editor allows object oriented text, lines, ellipses, and boxes to be drawn in a variety of colors for annotation in the profile. The annotated product may be saved to disk for later modification as well. Additional features of the post-processing editor include zoom, statistical analysis of the pixel data, and multiple direction single slice plots. The tool is capable of printing to a file, so the image may be used in other desktop publishing software, as is often necessary for FDOT reports and papers. The post-processing editor completes the GPR signal processing environment, providing an enhanced signal processing system, tailored for the FDOT GPR processing application requirements.

4.0 Conclusion

This report completes documentation of work performed in the development of an improved GPR processing and analysis package for the Florida Department of Transportation. Methods of enhanced signal processing for GPR information extraction have been researched and developed. A graphical software environment tool has been produced making use of beneficial algorithms and providing direct application of new processing techniques. With FDOT GPR analysis capacity significantly improved by the development and installation of the new GPR processing software on the FDOT GPR analysis computer, the Electronic Communications Laboratory at the University of Florida concludes its research effort for the Florida Department of Transportation under HPR Study No. 860, WPI # 0510860, State Job 99700-3558-119, Contract No. BB-260, entitled "Ground Penetrating Radar (GPR) Signal Processing Enhancements for Geophysical Anomaly Identification."

4.1 Accomplishments

The following is a list of the accomplishments during the geophysical project:

1. Development of a graphical ground penetrating radar analysis environment was completed. This system provides a software tool that benefits the FDOT analysis personnel through an intuitive software interface, greatly improved subsurface visualization, enhanced subsurface profiles from modern processing techniques, simplified and efficient file/data management, and improved flexibility for results integration with commercial documentation software.

2. Progress was made in the field of GPR signal processing through the consideration and application of many modern signal processing algorithms to the enhancement of GPR data. Processing algorithms included in the provided software package improve visualization and the information present in representations of the subsurface profile.

3. Management of large GPR data sets was improved with the ability to section and modify extremely large data files into smaller sections of meaningful data. This allows for additional gains in processing speed by reduction of insignificant regions of collected data.

4. The main product of the FDOT often takes the form of reports documenting results found during area surveys using the GPR. Integration of such results was previously difficult. However, the ECL software package provides improved flexibility for simple transfer of processing results into commercial word processing and graphic design software packages. This simplifies the FDOT documentation practices and improves the efficiency of FDOT GPR analysis.

5. GPR data collection procedures were refined and improved throughout the course of this project as FDOT personnel became more informed of the scientific principles involved in GPR collection and analysis. The ECL has outlined goals and suggestions for improved collection techniques and has worked to improve FDOT personnel's understanding of pertinent GPR fundamentals. These efforts have resulted in better GPR data, better educated FDOT utilization of radar capabilities, and more informed FDOT analysis.

4.2 Recommendations for Further Improvements

This project has greatly improved the capacity of the FDOT for GPR analysis and documentation. However, there is room for future progress. The following items may be considered for continued development of GPR utility.

1. Processing of collected GPR data remains in an early stage of development. Enhancement and information processing of GPR images is a difficult task. Continued research of new algorithms and processing schemes may provide additional gains in analysis results.
2. The software environment currently allows vertical, two-dimensional display of only one traverse. Further improvements may investigate the possibility of combining multiple traverses in a grid-like fashion into a horizontal display of the survey area. This may provide additional information concerning the characteristics of subsurface objects.
3. Speed of processing algorithms may be addressed in future efforts. Although processing speed was a consideration during algorithm coding, additional work could be done to promote the processing efficiency of operation.
4. Future efforts could, perhaps, focus on the principles involved in data collection with the GPR system and investigate possible methods of increasing the information retrieved during data collection with changes to the collection system.

5.0 References

Several references have been identified as being very beneficial to the development of two-dimensional migration, reverse migration algorithms, adaptive deconvolution, and wavelet analysis. These references are listed below.

1. Clarebout, J. F., 1985, Imaging the Earth's Interior: Blackwell Scientific Publications.
2. Haykin, S,. 1996, Adaptive Filter Theory: Third Edition.
3. Stolt, R. H., 1978, Migration by Fourier Transform: Geophysics, v. 43, 23-48.
4. Torrence, C. and G. P. Compo, 1998: A Practical Guide to Wavelet Analysis: Bull. Amer. Meteor. Soc., 79, 61-78.

6.0 Appendix A:

The attached document, which follows, is the User's Manual for the ECL GPR environment software. The manual serves as an appendix to this final project report.

GPR ProcessingEnvironment User's Manual

Electronic Communications Laboratory
University of Florida
Gainesville, FL

for: Florida Department of Transportation

GPR ProcessingEnvironment User's Manual

Electronic Communications Laboratory
University of Florida
Gainesville, FL

for: Florida Department of Transportation

Contents

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CHAPTER 1

Basics

This chapter introduces basic operation tasks for use of the Ground Penetrating Radar Signal Processing Environment (GPRSPE) software. It covers the following:

- Overview
- Basic Procedures

Overview

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

Basic Procedures

This section covers the basic concepts involved with operation of the GPR processing software. These concepts involve:

- Software initialization
- System display features
- Menu operation
- Register management
- File handling
- Software exiting

Software Initialization

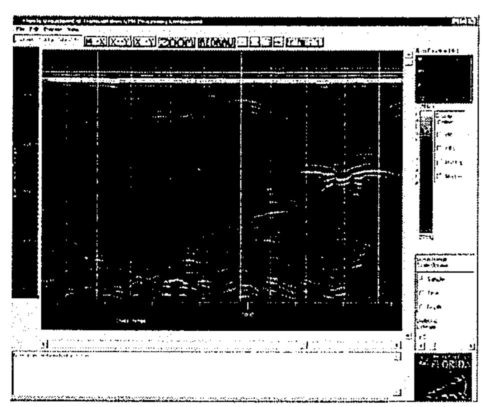
Software initialization is the procedure for starting the GPRSPE software. This task involves two simple steps.

1. Start Visual Numerics' PV-Wave software.
   From the Windows START menu, under the PV-Wave folder, begin a PV-Wave session.
2. At the wave prompt, type *@GoGPR*. Then press RETURN.

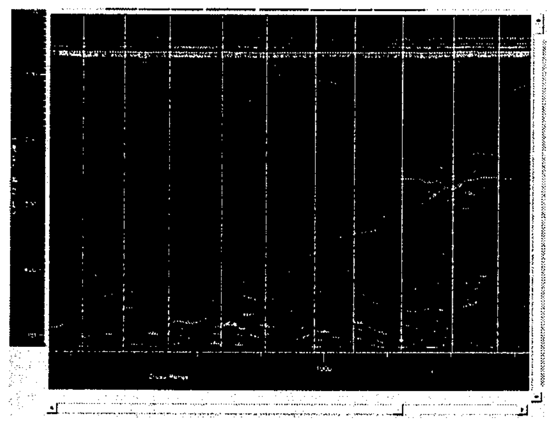
This should start the GPRSPE GUI which will open on the desktop.

System Display Features

The GPRSPE display contains multiple regions for profile display, system feedback and environment control. These regions serve to optimize the functionality of the GPR processing software.



1. Profile Display



The main display area is the where profile data is displayed.

> *def'n:* Profile - a GPR image of the subsurface consisting of a series of traces, which are recorded as the radar antenna is traversed along the surface.

The image displayed here represents the subsurface, with cross-range on the horizontal axis and down-range on the vertical axis. The cross-range scale, seen in the main window, shows the radar trace number.

> *def'n:* Trace - one measured pulse of the radar consisting of a series of samples/ measurements as electromagnetic wave propagates into the ground and returns from subsurface reflections.

Scroll bars below the main window allow sliding through profiles that are wider than the display. Markers placed in the data by the radar are displayed as white vertical lines.

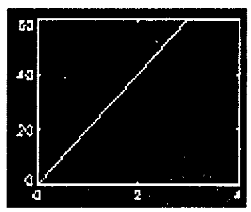
2. Vertical Axis

The down-range scale has its own window where it displays the vertical scale in either samples, time, or depth. The depth display is an estimate based on the travel time and dielectric constant of the medium, which is supplied by the operator.

3. Gain Function Display

A gain function may be applied to the data by the radar or by the GPRSPE software.

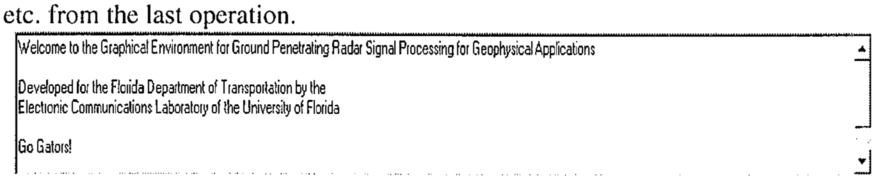
def'n: Gain Function - a function applied to each trace which amplifies the data according to its sample number. Typically, in GPR, early samples receive little amplification while late samples in a trace receive larger amplification. This helps account for the lower amplitude of the later samples due to attenuation caused by their deeper penetration.



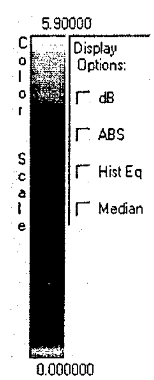
This gain is meant to amplify small signal returns from deep objects in order to make them visible. The current gain function affecting the profile data is displayed in the Gain Function Display window.

4. Command Feedback Display

As the GPRSPE is used, feedback from each procedure is displayed in a text box at the bottom of the environment display. This information provides the parameters, etc. from the last operation.



5. Display Parameters Box



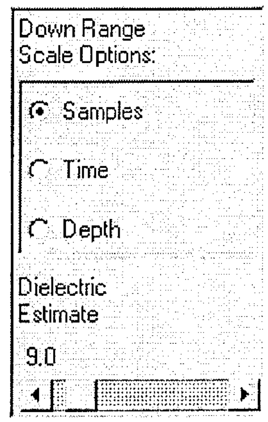
The current display options and the colorscale are displayed. The options buttons may be selected on or off to change the display.

def'n: Colorscale - the array of colors allotted for the display of data. Each color is assigned to represent a data value in the display according to some allocation scheme. Points in the data set are displayed using the color closest to their data value.

6. Filename Display

The current file name is displayed in its own text box. If the name is longer that the box width, the entire name will not be visible. If this is the case, clicking in the box and scrolling over will make the filename visible.

7. Down-range Scale Options Box



Several options are available for units of the vertical scale. These options are selected with the Scale Options buttons. Display of depth requires an estimate of the dielectric constant of the subsurface medium.

> *def'n:* Dielectric Constant - a parameter of any medium which determines the velocity of electromagnetic waves within that medium.

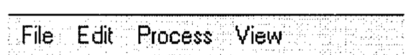
This parameter is set by the operator using the slider in the Down-range Scale Options box.

8. Button Bar

Many operations may be selected using the buttons on the GPRSPE display. The Button Bar functions will be discussed further in the following sections of this manual.

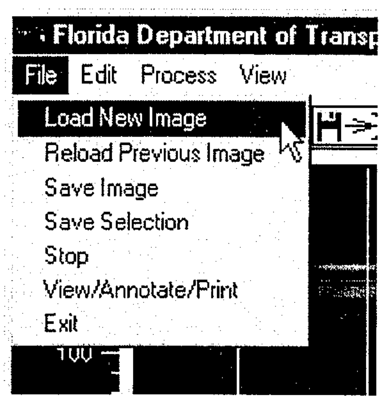
9. Menu Bar

The menu bar allows selection of a majority of the GPRSPE functions. Its use and the functions available will be discussed in the following sections of this manual.



Menu Operation

Most of the system operations are initiated through use of the GPRSPE menus found in the Menu Bar. The operations are divided into appropriate categories so that desired functions may be located intuitively.



To select a menu option, simply click on that option using the mouse pointer. One of three things will happen depending on the choice's function:

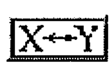
- A list of other choices will appear.
- A graphic tool will appear for additional function control.
- The chosen function will begin operation.

Register Management

The GPRSPE was designed with effort made to maximize efficiency and utility in the processing and analysis tasks required for typical FDOT GPR use. In an attempt to attain additional efficiency, data within the software is handled in two registers: X and Y. Upon loading a new profile, the profile data is entered in both registers. Only register X is displayed in the main display, and all processing within the environment is performed only on register X. At any point, the contents of X and Y may be switched. The contents of X may also be copied into register Y at any time. This system, with minimal practice, allows the user to keep two sets of the same profile data set at all times for independent processing and comparison using differing methods.

Register management is primarily handled using buttons on the Button Bar.

-- Reloads the previously loaded file into X only.



-- Switches the contents of X and Y.

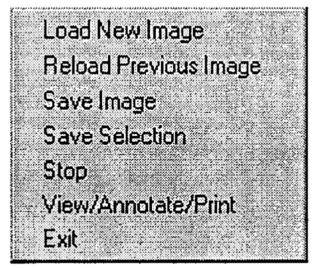
-- Copies the contents of X into Y.

Reloading the file into X may also be performed using the **Reload Previous Image** choice under the **File** menu. Switching the registers may be selected in the **Edit** menu with **Swap Disp Image**.

File Handling

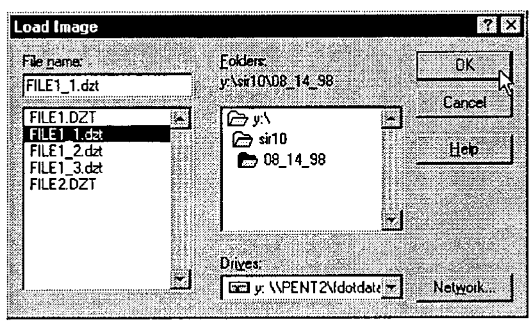
Before any processing can be done, GPR profile data must be loaded from disk into the software. The GPRSPE is designed to both load and save data in the RADAN format. This is the format used by the GSSI SIR-10B when saving raw radar data to disk. GPR profiles may be loaded, edited, and saved in this format allowing both software packages to exchange files.

To load profile data from a file:



Select **Load New Image** from the **File** menu in the Menu Bar. This will initiate the file selection tool.

The tool will allow selection of the appropriate drive, folder and filename. Select the desired file and then choose the **OK** button. GPR files typically have the extension "dzt." The GPR profile will load into both the X and Y registers. All data in both registers will be overwritten.

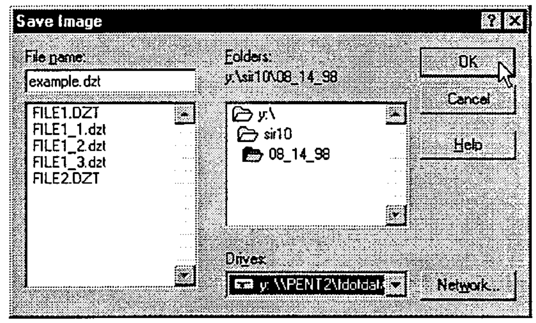


The display will be updated with the new subsurface profile, gain function, and vertical scale according to the current display parameters. Any of the processing algorithms may be used on the new data.

There are two ways to save profile data to disk. The entire profile may be saved, or a selected region may be saved as its own independent profile. Saving only a section allows very large files to be divided into smaller pieces for easier handling and faster processing. It also allows sections of interest to be filed away independently for more efficient organization

To save an entire profile to disk:

Select **Save Image** from the **File** menu in the Menu Bar. This will initiate the save image tool. Choose the desired drive, folder and filename. Then click **OK**.



To save only a selection of a profile to disk:

Select **Save Selection** from the **File** menu. A dialog box will prompt for selection of the first point. Press **OK**. Move the cursor to any point in the profile at the cross-range location at the start of the section being saved. Click the left mouse button. A dialog box will prompt for selection of the end point in the selection. Press **OK**. Select the end point in the same manner as the start point. The same save image tool will appear as shown above. Choose a filename and press **OK**.

Software Exiting

Exiting the GPRSPE is the same as nearly any Windows application. Data should be saved, as necessary, before exiting. All unsaved profile processing results will be lost if not saved.

To exit the GPRSPE:

Select **Exit** from the **File** menu or select the "X" button in the top right corner of the environment display.

CHAPTER 2

View Management

This chapter introduces properties of profile displays in the GPRSPE. Visualization of profile data requires intelligent display formats to maximize the information presented. Display options and parameters are explained in the following sections:

- Profile Navigation
- Image Filters
- Color Selection
- Scale Format
- Zoom
- Redraw

Profile Navigation

Many profiles may be longer in cross-range than can be displayed at one time within the main profile display window. When large profiles are loaded into the GPRSPE, only a window length of the data is shown at any instance. However, the entire profile may be viewed by scrolling through the data.

To navigate the profile view:

To move through a profile in cross-range, simply use the scroll bar at the bottom of the main profile display window. Click and drag the navigation bar on the scroll bar, click on either side of the navigation bar, or use the arrow buttons on either side of the scroll bar. Moving through the profile in no way affects the data. Processing performed on the profile is performed on the entire profile, not just that which is currently visible in the main display window.

Image Filters

Communication of information in a profile to the software operator takes place primarily through one channel: the profile image. It is essential that this image present the profile data effectively such that important features and qualities of the subsurface returns may be distinguishable. To further this task, several image processing routines are available to control display characteristics. Theses options include:

- Signed decibel
- Absolute value
- Histogram equalization
- Median filter

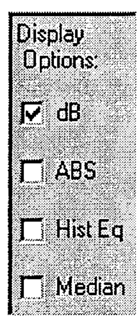
The display options were not designed to be used alone. They may be used in any combination to achieve the best results. Access to the routines is efficient, allowing various combinations to be quickly tried in each situation.

Signed Decibel

Data collected by the GPR may typically range in amplitude over several orders of magnitude due to the exponential attenuation of the electromagnetic signal during propagation through the subsurface. This makes visualization of many profiles difficult, if not impossible, using a linear scale, which distributes the allocated colors evenly between the lowest and highest values in a data set. Very high values often cause small values to be indistinguishable when the data is displayed. One way to often improve the display of such large dynamic ranges is to display the data in decibels.

To display in decibel, twenty times the LOG_{10} of the data is calculated. The displayed dynamic range is, therefore, compressed allowing both high and low amplitude returns to be seen. The only problem is that the LOG_{10} of negative values does not exist, so the absolute value of the data is typically taken first. Unfortunately, this removes any information present in the sign of the signal amplitude. In GPR this may represent significant information to the operator, due do the alternating sign of the peaks in an electromagnetic waveform. Hence, discarding the sign of GPR data is not an ideal solution. A better solution is included in the GPRSPE. The decibel values are calculated as usual; then the points are given the sign of the corresponding point in the original data. In this way, the dynamic range is compressed, but sign is preserved.

Signed decibel display mode should be used when all that can be seen in the profile is the strong response from very shallow objects. In this case, little to nothing may be seen in most of the profile. Signed decibel mode may make deeper objects visible. The function may be turned on and off to compare results. Then the most informative display may be chosen.



To turn Signed dB mode on and off:

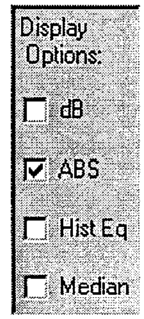
The Signed dB mode may be selected and deselected using the **dB** button in the **Display Options** parameters box. Simply click the mouse on the **dB** button. The mode may also be toggled using the **dB Display** selection in the **View** menu.

Absolute Value

At times, before or after processing, the magnitude of returns may prove to be interesting without regard to sign. In such instances, the GPRSPE provides for absolute value display.

Absolute value display removes the sign of the data before its display. This flips both negative and positive peaks of the electromagnetic wave returns to the same side. The colorscale is then adjusted to scale from zero to the maximum magnitude of the data values, rather than from the minimum data value to the max. At times, this will demonstrate some significant features in the return. However, the display mode is often more useful after various processing methods to see a magnitude response.

To turn Absolute Value mode on and off:



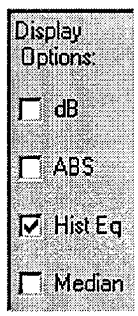
The Absolute Value mode may be selected and deselected using the **ABS** button in the **Display Options** parameters box. Simply click the mouse on the **ABS** button. The mode may also be toggled using the **ABS Display** selection in the **View** menu.

Histogram Equalization

When colors are allocated for the display of data, they are most often distributed in a linear manner. This means that the colors are ranked in some order according to some predefined colorscale. The top color value is assigned to the highest sample value in the data while the bottom color value is assigned to the lowest sample value in the data. All the colors between the top and bottom are allotted data values which are evenly distributed between the highest and the lowest values. The colors are, therefore, allocated without regard for where the data values are most prevalent within the determined range. In many situations, a better method will allocate the available colors only in the ranges where data values exist within the set. Histogram equalization provides such a method.

Linear color allocation is perfectly acceptable in many instances. In fact, it works very well, and it provides a linear association between the data value and the position of the color within the color range. Generally, this linear color association is more natural or intuitive. However, there are many situations when this method provides little to no color separation between features of interest within a data set. For example, suppose there are both a few very high data values and a few very low data values within a given data set. In this set consider also that a majority of the data values are within a much smaller range somewhere in the middle of the set, with no values of data points in the substantial regions between this central group of points and either the small, high group or the small, low group. In the linear allocation scheme, colors will be assigned evenly between the highest group and the lowest group. Many colors will be wasted in the display of the data because they will be assigned to data values which do not exist in the data set: values between the middle group and the high or low groups. There will be few of the limited number of colors available to display the very large middle group of points. These few colors will be distributed evenly over the important middle set of points, and each point will be displayed using the color representing a value which is closest to the actual data value. Small differences in the actual data values, which may represent significant features in the data, may not be visible because they are mapped to the same color as a result of the insufficient number of colors available for their display.

Histogram equalization will allocate the available colors only in the ranges where data values exist within the set. In this way, all colors will be used to visualize the data without wasting colors. Before determining where colors should be distributed, histogram equalization maps out the number of occurrences of each data value within a given set. It then chooses to assign the colors such that each color is used an equal number of times in displaying the data. Narrow congregations of data with many representative points, having small differences between them, now receive a sufficient number of colors for the mapping of small differences in value to different colors. The important features may now be visible, whereas before they might not have been.



Histogram equalization works very well in many instances. Sometimes, however, it applies too many colors and makes interpretation difficult. In these cases, normal color assignment is preferable. Histogram equalization complements the standard linear allocation very well, and with viewer discretion succeeds in significantly improving the visibility, and therefore interpretation, of GPR profiles.

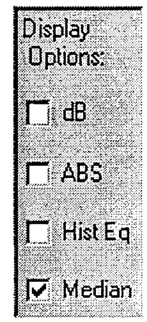
<u>To turn Histogram Equalization mode on and off:</u>

The Histogram Equalization mode may be selected and deselected using the **Hist Eq** button in the **Display Options** parameters box. Simply click the mouse on the **Hist Eq** button. The mode may also be toggled using the **Equalize Display** selection in the **View** menu.

Median Filter

On occasion, profile displays contain a significant amount of what is called "salt and pepper" noise before or after processing. The phenomenon exerts itself as high valued, outlying points in an image. These points seldom truly represent meaningful points in a data set and often cloud the image with a grainy appearance and/or an inappropriate color scaling. One solution to this problem is a median filter.

Median filters are often used in many image processing applications. They take all the points within an area around a pixel and return the median of the points as the pixel's new value. This effectively removes any outlying points and produces a less corrupted display.



The median filter should be used when the image has a grainy appearance resulting from "salt and pepper" noise or when it is suspected that a few outlying points are disrupting the color allocation scheme.

To turn Median Filter mode on and off:

The Absolute Value mode may be selected and deselected using the **Median** button in the **Display Options** parameters box. Simply click the mouse on the **Median** button. The mode may also be toggled using the **Median Filter** selection in the **View** menu.

Color Selection

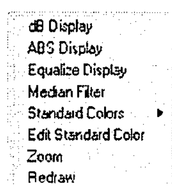
A very important feature of the GPRSPE is the ability to easily choose and modify the colortable used to display the profile data. Much greater color depth is available compared to previously used software. Color schemes have also been designed to emphasize various characteristics of data. Intelligent use of color greatly affects the visibility of features in GPR data.

The GPRSPE allows selection of a variety of predefined colortables. Each colortable may cause different features or characteristics of the subsurface to be more visible. Color selection is quick and easy such that, in each situation, different colors may be efficiently compared to produce the most beneficial results.

One consideration when choosing a colortable is whether the table is one-sided or two-side. One-sided tables typically have one color at one extreme and another at the other extreme. For example, a one-sided colortable may have a linear gradient between black on one side and white on the other side.

One-sided colortables often represent absolute-valued data very well. Zero maps to one color while high values map toward the other. Two-sided maps better represent data having positive and negative values. Such maps typically have a color, often black, in the middle with gradients to different colors toward each end.

Positive and negative peaks of the electromagnetic waveform, for example, are mapped to different colors with a two-sided colortable. Often in GPR processing, several colortables should be utilized when viewing results. The current colortable is always displayed with a colorbar in the **Display Options** control box.



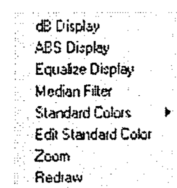
To select a colortable:

Colortables may be chosen under the **View** menu. Selecting **Standard Colors** will open a list of the available colortables. Simply click on the desired table to switch the display to the new table. Switching colortables is also possible using the **Color Table Tool**.

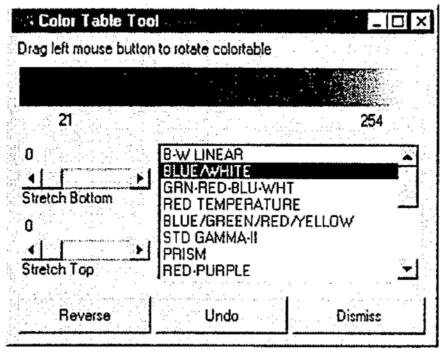
Color Table Tool

Colortables may be selected and customized using the **Color Table Tool**. The tool allows improved flexibility in the display of profile data giving the operator the ability to control how data is visualized. Improved feature recognition can result in a better interpretation.

To start the **Color Table Tool**:



Select **Edit Standard Color** from the **View** menu. A tool will appear on the desktop which allows selection and modification of the available colortables.



To select a colortable:

Simply click the mouse on a colortable name to choose it. The name will highlight, and the new table will be displayed in the colorbar. The scroll bar on the right of the list will display more options.

To modify the current colortable:

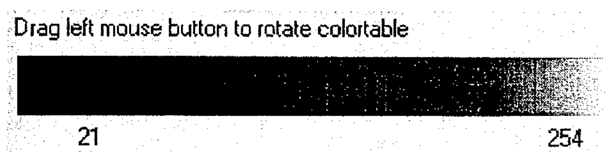
There are five modifications which can be made to the current colortable:

1. Reversing the colortable

To reverse the colortable, simply select the **Reverse** button at the bottom left of the **Color Table Tool**. This will completely flip the colortable. Results will be shown in the colorbar.

2. Rotating the colortable

To rotate the colortable, move the mouse pointer on top of the colorbar on the **Color Table Tool**. The pointer will change shape.



Click and hold the left mouse button, and then drag the mouse to the right or left. The colors of the colormap will rotate in the direction of mouse movement. When satisfied with the results, simply release the mouse button.

3. Stretching the top of the colortable

To stretch the top of the colortable, use the **Stretch Top** slider on the **Color Table Tool**. Click and drag the slider bar or use the arrow at each end of the slider to adjust the stretching value. The colorbar will change to show modifications as the colortable is stretched.

4. Stretching the bottom of the colortable

This procedure is identical to stretching the top, except that the **Stretch Bottom** slider on the **Color Table Tool** should be used.

5. Undoing the changes

The colortable may be reverted back to its original form using the **Undo** button at the bottom center of the **Color Table Tool** or by reloading the original table by selecting it in the color table list.

To exit the **Color Table Tool**:

To exit the tool, simply click on the **Dismiss** button at the bottom right of the **Color Table Tool**.

Scale Format

The vertical scale of the profile display may assume several units: sample number, time, or depth estimate. Each of these formats serve to present operators with information they may need from a GPR survey.

To change the down-range scale:

Changing the down-range scale requires simply clicking on the appropriate button of choice in the **Down Range Scale Options** box on the GUI. The scale displayed in the vertical axis window will change to the appropriate format.

Depth estimation is based upon a user supplied estimate of the average dielectric constant of the subsurface medium. The dielectric estimate must be set by the operator using the **Dielectric Estimate** slider in the **Down Range Scale Options** control box.

To change the dielectric estimate for depth calculation:

To change the dielectric estimate click and drag the slider bar on the **Dielectric Estimate** slider, or click on the arrows on either side of the slider. The depth scale will change with each modification of the dielectric constant estimate.

Zoom

The **Zoom** function may be used for a closer look at a region of the profile.

To use the **Zoom** function:

To zoom in on a region of a profile, click on ZOOM. A dialog box will prompt for a zoom center point. Select **OK** and then click in the profile display at the location of interest. A new zoom window will appear with a close up display of the selected region. **Zoom** may be used multiple times; each time a new zoom window is created.

To destroy zoom windows:

To destroy zoom windows, click the **X** button in the upper right corner of the windows, as is the procedure for closing most window applications.

Redraw

On occasion it may be desirable to refresh the profile display. This is accomplished using the **Redraw** function. **Redraw** re-displays the GPR data in the main display. This will effectively remove temporary annotations placed in the display using the annotation buttons. This does not apply to the **Post Processing Editor** display or any annotation applied therein.

To redraw the display:

To redraw the display, simply click on REDRAW in the Button Bar.

CHAPTER 3

Profile Editing

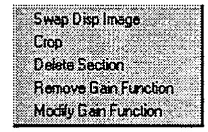
This chapter introduces profile editing concepts pertinent to use of the GPRSPE. Profile editing helps with data management tasks, speeds processing of data, and prepares profile data for processing techniques. Editing methods discussed in the following sections include:

- Cropping Data
- Deleting Data
- Removing Gain
- Modifying Gain
- Sketching Objects

Cropping Data

Processing time is directly related to the amount of data to process. Less data means quicker processing. For this reason, efficiency of GPR analysis may be improved by processing only important sections of GPR data sets. Cropping out only the section of interest is one method of reducing the amount of data to process.

To crop out a section of data:



To crop out a region of data, select **Crop** from the **Edit** menu. A dialog box will appear prompting for the first cross-range location of the region to crop. Click the **OK** button and then click in the profile display at any vertical point, having the desired cross-range value, in the profile for the starting point of the region. A second dialog box will then appear prompting for selection of the second cross-range value. Once again, click **OK**. The scroll bar may be used to move through the profile. Click in the profile display to select the second cross-range value, for the end of the desired region. The display will update to show only the cropped section of the profile. At times the scroll bar may need to be moved for it to reset, so the profile can be seen.

Deleting Data

Deleting unimportant sections of GPR data is another way to reduce the amount of data to process. Once again, this is very important for reduction of processing time and the subsequent improved efficiency of GPR analysis.

To delete a section of data:

Deleting a section of data is very similar to the procedure for cropping out a section. Select **Delete Section** from the **Edit** menu. A dialog box will appear prompting for the first cross-range location of the range to delete. Click the **OK** button in the profile display at the start of the range. A second dialog box will prompt for selection of the end of the range. Click **OK**. The scroll bar may be used to move through the data, and then select the end of the range to delete. The display will update to reflect the profile with the undesired range removed. At times the scroll bar may need to be moved for it to reset and show the profile correctly.

Removing Gain

Many times the gain function applied to the GPR data by the radar is not desired for processing. Algorithms often process based upon the natural characteristics of the returned waveform or the subsurface features. An arbitrary gain function is in no way correlated to either of these qualities, and is therefore undesirable. The gain function often magnifies system noise to an unsatisfactory level as well. The GPRSPE will easily remove the gain function that was applied to the data by the radar. The necessary information to perform this task is retrieved from the header information written in the data file by the radar system.

To remove the gain function:

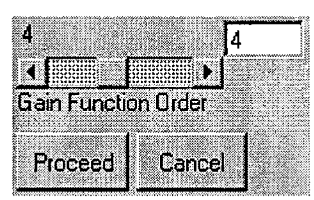
To remove the gain function, simply select **Remove Gain Function** from the **Edit** menu. The gain function will be removed. The profile display and the gain function display will be updated to demonstrate the modified data and gain function.

Modifying Gain

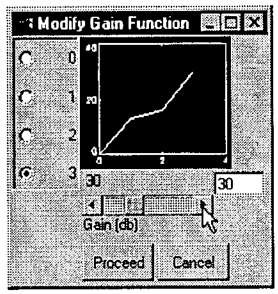
Sometimes applying a gain function to profile data will make deeper objects visible. As long as the function does not disturb other processing, a gain function will often amplify small returns from subsurface features which have been attenuated by long travel distances in the ground. Careful use allows gain functions to increase visibility and benefit GPR analysis.

Modifying the gain function in the GPRSPE utilizes a graphical tool specifically designed to be compatible with gain functions used in the radar system. This allows compatibility between the GPRSPE and formerly used GSSI software. The gain function may contain up to eight points. The value of the gain is linearly interpolated between the gain values at the points. Gain values at each point are set using the graphical tool. The new gain function is stored in the data file header when the profile is saved.

To modify the gain function:



To initiate the **Modify Gain Function** tool, select **Modify Gain Function** from the **Edit** menu. This will begin the graphical tool which appears on the desktop. The tool will set the number of gain points in the gain function. As many as eight points may be used. Set the number of points by dragging the slider bar, by using the arrow buttons on either side of the slider, or by clicking in the edit box and typing the desired number from the keyboard. Once the number of points has been set, select the **Proceed** button at the bottom left of the tool.



The tool will be replaced by a second graphical tool which will allow the gain values at each gain point to be set. A control box on the left of the tool contains buttons for each gain point. The number of buttons will reflect the number of gain points selected previously. The tool slider sets the value of the currently selected gain point while the graphic display shows the entire gain function.

To set the gain function:

Setting the gain function involves setting the gain value for each of the gain points. The values between gain points will be linearly interpolated. Select a gain point to modify by clicking on a gain point button in the upper left control box of the tool. The buttons are numbered according to the gain point number. Once a point has been selected, its current value will be shown by the slider control. Use the slider to set the gain point value by dragging the slider bar, by using the arrow buttons on either side of the slider, or by clicking in the edit box and typing the value using the keyboard. The graph of the gain function will change to illustrate the gain point modification. Notice that the scale must often adjust. Repeat the procedure, setting each gain point. Once the desired gain function is created, select the **Proceed** button at the bottom left of the tool. The previous gain function will first be removed from the data, and then the new gain function will be applied. The display will be updated to show the modified profile data, and the gain function display will show the new gain function.

> NOTE: Each time the gain function is modified, it is not applied on top of the previous gain function. The previous gain function is removed first, such that the new function is applied to the unamplified data.

Sketching Objects

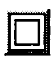
Functions have been added to the GPRSPE to allow temporary sketching of objects in the profile display. These objects include: text, lines, boxes, and circles. The objects in no way affect the data and are simply meant to serve as temporary markings in the profile display. Such functions may be useful during profile analysis. The markings are removed anytime the display is redrawn. However, they will be permanently present in the Post-Processing Editor if they were visible in the display when the editor was initiated.

To sketch objects in the profile display:

The sketching functions may be selected using buttons on the Button Bar. The functions operate in a similar fashion to most graphic design applications and Windows programs.

-Text layout tool. Click the button. A window will appear and prompt for the location of the text. Press **OK**. Select text location in the profile display. A text input window will appear. Enter text in input box. Press **OK**.


-Line tool. Click the button. A window will appear and prompt for the starting point of the line. Press **OK**. Click the left mouse button at the starting point of the desired line. A second window will appear and prompt for the ending point of the line. Press **OK**. Move the mouse to the endpoint of the line, and then click the mouse button.


-Rectangle tool. Click the button. A window will appear and prompt for the starting corner of the box. Press **OK**. Click the left mouse button at the starting point of the desired box. A second window will appear and prompt for the ending corner of the box. Press **OK**. Move the mouse to the end corner of the box, and click the mouse button.


-Circle tool. Click the button. A window will appear and prompt for the center of the circle. Press **OK**. Click the left mouse button at the starting point of the desired circle. A second window will appear and prompt for a point on the circle. Press **OK**. Move the mouse to a point on the desired circle and click the mouse button.

To clear the sketched objects from the profile display:

Simply press 

or select **Redraw** from the **View** menu. This will redraw the main profile display window. Any time the profile display is redrawn the sketched objects are removed. Most processing routines redraw the display to show results and, therefore, erase any sketched objects.

CHAPTER 4

Processing

This chapter introduces the GPR processing capacity of the GPRSPE. Processing concepts are discussed, and algorithm use is illustrated. GPRSPE functions to be covered include:

- Migration
- Thresholding
- Background Removal
- Adaptive Inversion
- Impulse Forcing
- Multiresolution Analysis

Migration

Migration is the process of focusing the hyperbolic responses of point targets in GPR profiles to points with the goal of providing a more meaningful representation of the subsurface for interpretation. Fixing the problem, however, is not a simple task. Several difficulties arise. First, not all responses are from point targets and do not, therefore, have a nice hyperbolic shape. Few prior assumptions can be made about the subsurface to remedy this problem. Second, the inconsistent cross-range sample interval corrupts the shape of the responses, so matching hyperbolas to the responses can sometimes prove difficult. Third, the hyperbolic shape depends on the velocity of the electromagnetic wave in the medium, which is not constant for most situations. So, the responses may be distorted by gradients in the dielectric constant, which cannot be determined to a sufficient extent to correct the problem. Finally, interference from multiple nearby targets creates a much more complex response. With all this said, the possibility of migration of GPR returns sounds nearly impossible; but, in many situations, it may in fact be helpful. Typical use of the radar often involves locating utilities such as buried pipes and cables, or rebar--all of which respond as point targets in a perpendicular cross-section. The dielectric may vary a significant amount between targets located in different sections of a profile, but it will often be constant enough in the immediate area around a specific target. If the data is carefully collected such that the cross-range sample rate maintains a relatively constant sample interval, then migration can be of use for improving the interpretation and cross-range localization of the object of interest, particularly of point targets.

> *def'n:* Migration - focusing the hyperbolic responses of point targets to more point-like response for improved recognition and localization.

> *def'n:* Interference - distorted response due to overlap between responses from multiple targets which have added together making the return from each individual object less recognizable.

Two migration methods have been found to be beneficial and have been coded for use in the processing software:

- Simple Migration
- FFT Migration

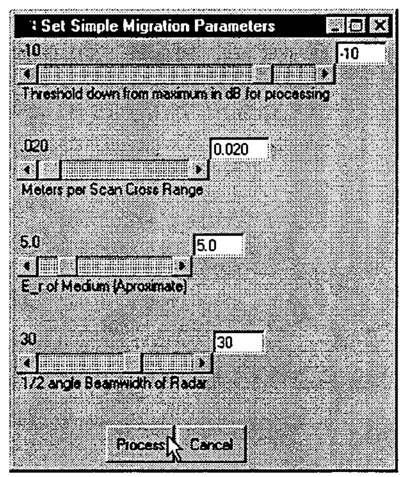
Simple Migration

It can be shown that the hyperbolic shape for a point target will be a specific shape for a given target depth, medium dielectric constant, and radar antenna beamwidth. The simple migration algorithm uses the physical geometry of the radar system and the resulting hyperbola associated with an un-migrated point target in a GPR profile image to migrate GPR data.

The algorithm uses the assumption that the target is a point object with sufficient returned energy to be discernible from the profile background, where no significant level returns were detected. With this assumption the algorithm thresholds the amplitude data from the GPR and only processes significantly high responses which are considered to be likely candidates for point targets. If the GPR image pixel is above the threshold, the hyperbolic shape is calculated for the specified GPR beamwidth, medium dielectric, and depth of the target. The energy contained along the hyperbola is then integrated or summed to create the new value for the pixel at the hyperbola's apex. This effectively collapses the hyperbolic shape to a more point-like object, as is more appropriate for interpretation. The process is repeated for each pixel in the profile which meets the threshold requirement. Focusing the point targets also narrows the extent of the target response in cross-range, providing a more precise location of the object.

To migrate a profile using simple migration:

To migrate a profile select **Simple Migration** from the **Process** menu. A graphical parameter selection tool will appear on the desktop. This tool sets all the parameters required for using the Simple Migration algorithm.



Four parameters must be set for operation of the algorithm. Each parameter is controlled using a slider on the graphical tool. Set each parameter to the desired value by clicking and dragging the slider bar, by using the arrow buttons on either side of the slider, or by clicking in the edit box and typing the value from the keyboard. The four parameters which must be set are:

1. Threshold down from maximum

This threshold determines the cutoff in dB below the maximum sample value for processing. The algorithm will ignore all points with lower amplitude than this threshold. It is assumed that significant returns have a relatively high amplitude. For this reason, the routine throws out all points considered too low to be a true return, based upon the set threshold. A lower threshold includes more points and, therefore, takes longer to process. Conversely, a higher threshold takes a shorter time to process.

2. Meters per scan in cross-range

This parameter is the cross-range sample interval of the radar. The radar is sampling as the antenna is traversed across an area. The average distance between each sample is the sample interval. To calculate the sample interval, markers must be placed in the data at regular intervals. These markers appear in the profile display and allow the operator to estimate distance in cross-range. The horizontal axis of the profile display shows the cross-range sample, or trace, number. To calculate the cross-range sample interval, simply divide the number of meters between markers in cross-range by the number of samples between the same markers. For a more accurate estimate the distance and samples over several marker lengths should be used. Using multiple marker lengths for the calculation is highly recommended.

3. E_r of Medium

This parameter is the average dielectric constant of the subsurface medium. The dielectric constant may be known from additional material analysis. It may also be estimated based upon operator experience and material characteristics. The profile may also be reprocessed through a range of dielectrics if the constant is not accurately known. The parameter value which produces the best results provides an estimate of the subsurface medium dielectric constant.

4. 1/2 angle beamwidth

The half-angle beamwidth specifies in degrees how far out from directly below the radar antenna can see. It is one-half of the beamwidth of the antenna. This parameter is used in the calculation of the hyperbolic shape for matching with the profile data. A larger beamwidth means the radar could see a target sooner; the response would, therefore, be larger. This requires a longer computation time. Smaller beamwidths calculate faster. The half-angle beamwidth should typically be set in the 30-50 degree range.

Once the parameters have been set, processing may be initiated by selecting the **Process** button at the bottom left of the tool.

<u>To estimate the dielectric constant using simple migration:</u>

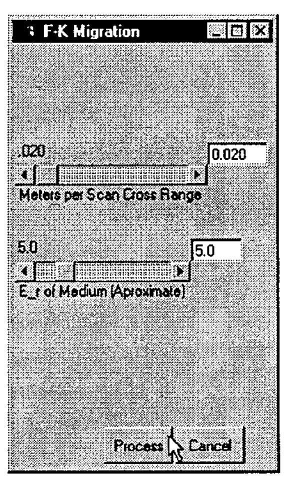
An estimate of the dielectric constant may be found by migrating a known point target response in a profile using a range of values for the dielectric parameter required by the Simple Migration algorithm. The parameter value which produces the best results may be considered an estimate of the dielectric constant of the subsurface medium surrounding the point target.

FFT Migration

"FFT" is an acronym for Fast Fourier Transform, which is a very fast algorithm that transforms a signal from the time domain to the frequency domain. FFT Migration is, therefore, a migration method using the Fast Fourier Transform. This method of profile migration was originally developed for seismic data processing. It has also been used for Synthetic Aperture Radar (SAR) applications, which are similar in nature to the geophysical GPR application. The algorithm takes advantage of relationships between traveling wavefronts in the frequency domain.

FFT Migration processing transforms the time-domain profile into the 2-D frequency domain. It is able to use the Fast Fourier Transform for this conversion, which results in a remarkably efficient algorithm and extremely fast operation. Once in the frequency domain, a spatial transformation is executed to perform the required focusing, and then the Inverse Fast Fourier Transform is performed to return the migrated GPR profile.

To migrate a profile using FFT migration:



To migrate a profile select **FFT Migration** from the **Process** menu. A graphical parameter selection tool will appear on the desktop. This tool sets all the parameters required for using the FFT Migration algorithm.

Two parameters must be set for operation of the algorithm. Each parameter is controlled using a slider on the graphical tool. Set each parameter to the desired value by clicking and dragging the slider bar, by using the arrow buttons on either side of the slider, or by clicking in the edit box and typing the value from the keyboard. The two parameters which must be set are:

1. Meters per scan in cross-range

This parameter is the cross-range sample interval of the radar. The radar is sampling as the antenna is traversed across an area. The average distance between each sample is the sample interval. To calculate the sample interval, markers must be placed in the data at regular intervals. These markers appear in the profile display and allow the operator to estimate distance in cross-range. The horizontal axis of the profile display shows the cross-range sample, or trace, number. To calculate the cross-range sample interval, simply divide the number of meters between markers in cross-range by the number of samples between the same markers. For a more accurate estimate the distance and samples over several marker lengths should be used. Using multiple marker lengths for the calculation is highly recommended.

2. E_r of Medium

This parameter is the average dielectric constant of the subsurface medium. The dielectric constant may be known from additional material analysis. It may also be estimated based upon operator experience and material characteristics. The profile may also be reprocessed through a range of dielectrics if the constant is not accurately known. The parameter value which produces the best results provides an estimate of the subsurface medium dielectric constant.

Once the parameters have been set, processing may be initiated by selecting the **Process** button at the bottom left of the tool.

To estimate the dielectric constant using FFT migration:

An estimate of the dielectric constant may be found by migrating a known point target response in a profile using a range of values for the dielectric parameter required by the FFT Migration algorithm. The parameter value which produces the best results may be considered an estimate of the dielectric constant of the subsurface medium surrounding the point target.

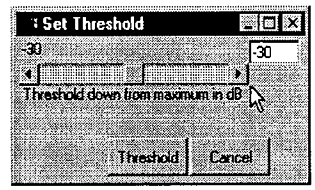
Thresholding

Electromagnetic returns from subsurface objects are often of significantly higher magnitude than the magnitude of background noise, particularly for near-surface objects. Many times interpretation of GPR profiles benefits from simply zeroing out data values below some threshold, effectively removing unwanted clutter from background noise.

def'n: Background Noise - unwanted signal received and measured by the radar which often clutters a profile display. Often a result of random thermal noise within the radar system or receive electromagnetic radiation from other electro-magnetic sources.

To threshold GPR data:

To threshold a profile select **Threshold** from the **Process** menu. A graphical parameter selection tool will appear on the desktop. This tool sets the parameter required for using the Threshold algorithm.



Only one parameter must be set for operation of the algorithm. The parameter is controlled using a slider on the graphical tool. Set the parameter to the desired value by clicking and dragging the slider bar, by using the arrow buttons on either side of the slider, or by clicking in the edit box and typing the value from the keyboard. The only parameter which must be set is the desired threshold. The threshold is specified in decibels below the maximum data value. All data points whose magnitude is less than the threshold will be set equal to zero.

Once the threshold has been set, processing may be initiated by selecting the **Process** button at the bottom left of the tool.

Background Removal

Horizontal bands frequently obscure more important information in a GPR profile. These bands sometimes result from ringing of the antenna, ground coupling effects, or the response from some artifact maintaining a constant distance from a poorly shielded antenna. Routines have been written which remove banding in a response profile. The algorithms assume that any response which is constant for the entire profile, or for a user selected range, is useless information. The algorithms, therefore, average the traces over the given cross-range and subtract the result from each trace in the profile. This procedure effectively removes the banding and quite often reveals pertinent data. The routine must be used with caution due the possibility of removing responses from anomalies with significant horizontal extent.

To automatically remove background clutter:

To remove the background automatically, select **Remove Background Auto** from the **Process** menu. The algorithm will process the data and the display will be updated to show the modified profile without additional input or parameter selection.

To remove background clutter using a selected range:

To remove the background with a manually selected range, select **Remove Background Manual** from the **Process** menu. A dialog box will appear prompting for the start of the range. Select **OK** and then click the mouse pointer in the profile display at any point with the desired cross-range value for the starting point. A second dialog box will appear prompting for input of the range ending point. Click **OK** and then select the range endpoint by clicking the mouse in the profile display at the appropriate cross-range. Processing will then begin averaging the traces within the selected range and subtracting the average values from every trace in the profile.

Adaptive Inversion

One way of considering the GPR subsurface imaging problem is to interpret the ground as a filter. The source waveform from the radar would be the input to the filter, and the received signal would be the output from the filter. This filter could be generalized as a series of impulses, having an impulse at each interface between layers of differing dielectrics. It would be easier to interpret a profile if the profile were more like this original subsurface filter, having narrow peaks at each layer interface.

What is seen as the output in a GPR profile is the result of the source waveform being filtered by, or convolved with, the ground response.

> *def'n:* Convolution - the mathematical process of filtering a time series or signal with another signal/filter.

This response appears similar to a "mexican hat" waveform at each interface. The "mexican hat" has a high main lobe and two smaller, negative sidelobes. One reason GPR profiles are difficult to interpret is that each interface returns a waveform with multiple lobes of alternating sign. Ideally, it would be easier to interpret a profile if the profile were more like the original subsurface response, which consists of one high amplitude, narrow peak at each interface. The desired profile, the impulse response of the ground, can be attained by separating, or mathematically speaking, deconvolving the source waveform from the returned response.

> *def'n:* Deconvolution - the mathematical process of separating one signal/filter from the output signal given the other signal/filter.

However, this filtering cannot be done when a ground coupled radar is used because the input signal is a function of the ground coupling and, therefore, is not accurately known or measurable. Resolving this problem calls for more creative methods. One such method is known as adaptive inversion, or blind deconvolution.

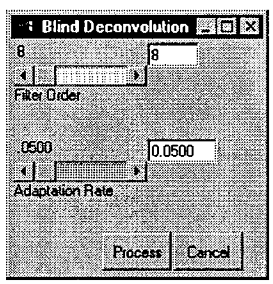
> *def'n:* Blind Deconvolution - Separating two signals given only the combined signal. Assumptions must be made about the characteristics of the two signals which will allow separation.

The deconvolution procedure is considered "blind" because it must separate both signals without knowing either one of them. In order to do this, one of the signals is modeled as a white noise process, while the other is modeled as linearly predictable. Both the additive noise and the subsurface impulse response may be modeled as a white noise process due to their random nature; no combination of previous values of the samples tells anything about the next samples. The input signal, however, may be approximately modeled as the impulse response of an all-pole, minimum-phase filter. This means that each sample value is a linear combination of previous samples, and the next sample may be effectively predicted from the current sample and previous ones. In summary, the input signal may be predicted, with an appropriate filter, from current and previous samples while the ground response and additive noise may not. This assumption is very beneficial and allows for an estimated deconvolution of the two signals. To perform this blind deconvolution, an adaptive filter is utilized.

> *def'n:* Adaptive Filter - a filter which is designed to change itself over time to minimize the error between its output and some desired response.

The filter is designed to predict the next value of each sample in a trace as it filters the trace. After each prediction, the error between the predicted value of the trace and the actual value is used to modify the values of the filter such that it is more capable of predicting the next value. Hence, the filter adapts to minimize the error between what it predicts as the next sample in a trace and the measured sample. The filter gets closer and closer to being able to predict the next value until it is predicting as well as possible. At this point, the filter is said to have "converged" to an estimate of the model for the input signal. If the adaptive filter is now predicting the next value of the input, then the error between the predicted value and the actual value must be that which it cannot predict in the measured response: the noise-like response of the ground and the additive noise in the system. This error, therefore, is an estimate of the impulsive subsurface filter having high, narrow responses at each layer interface. Many assumptions were made to produce the blind deconvolution algorithm. The results of the algorithm are only as good as the assumptions which are made. For this reason, it is easy to understand why an ideal ground response profile is not achieved. In fact, the assumptions in no way accounted for the hyperbolic integration problem mentioned previously. However, the assumptions are good enough to enable the blind deconvolution algorithm to benefit interpretation of GPR profiles. The algorithm is capable of collapsing some of the responses, which are widespread in the down-range time-domain, into denser clusters of information. Recognition of true responses from objects is significantly improved in many profiles using the blind deconvolution algorithm.

To inverse the GPR profile:



For adaptive inversion of the profile, select **Inverse - Adaptive** from the **Process** menu. A graphical parameter selection tool will appear on the desktop. This tool sets all the parameters required for using the Adaptive Inversion algorithm.

Two parameters must be set for operation of the algorithm. Each parameter is controlled using a slider on the graphical tool. Set each parameter to the desired value by clicking and dragging the slider bar, by using the arrow buttons on either side of the slider, or by clicking in the edit box and typing the value from the keyboard. The two parameters which must be set are:

1. Filter Order

The filter order is the number of previous samples used by the adaptive filter to predict the next sample. For every additional sample used in the prediction, the order of the system increases. This increases the computation required for the prediction; but, more importantly, it greatly increases the computation required to adapt the filter. The speed of the algorithm is inversely proportional to the filter order.

2. Adaptation Rate

This parameter determines how fast the adaptive filter changes itself to minimize the prediction error. If the adaptation rate is set too low, the filter will not reach an acceptable model of the input electromagnetic waveform fast enough to perform the blind deconvolution appropriately. If the parameter is set too high, the filter may change too quickly and become unstable.

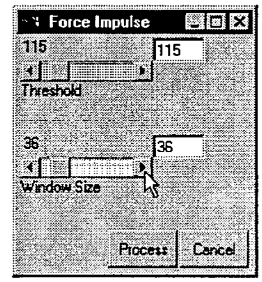
Once the parameters have been set, processing may be initiated by selecting the **Process** button at the bottom left of the tool.

Impulse Forcing

Profiles are easily cluttered by wide bands of color which exist in the display because of the wide crests and troughs of the electromagnetic source waveform, the wide beamwidth response pattern, and the interference between neighboring objects. The Impulse Forcing algorithm has been designed to alleviate some of the visual overload associated with these many complex phenomena.

The Impulse Forcing algorithm filters each trace in a profile and returns an impulse, weighted by the original sample value for every sample that meets the following criterion: 1. The sample must be the highest valued sample within a sliding window of a user specified width centered around the sample, and 2. The sample must be a certain percentage, determined by a user specified threshold, higher than the standard deviation of all the samples within the sliding window. This algorithm attempts to replace broadly shaped returns with fine lines at the positive and negative peaks subject to a specified window size. It also attempts to ignore low amplitude peaks which are probably not from legitimate returns by comparing their value with the standard deviation within the sliding window. The peak must be of significant size compared to the surrounding data samples to register as an impulse. The Impulse Forcing procedure emphasizes the slopes and curvatures of responses within a profile and presents some insight into subsurface features. The algorithm may be used on the unprocessed profile and can also be informative when applied after the Blind Deconvolution process. Typically, the results of this algorithm are best viewed in signed decibel mode without histogram equalization.

To force impulse returns in a GPR profile:



To run the Force Impulse algorithm, select **Force Impulse** from the **Process** menu. A graphical parameter selection tool will appear on the desktop. This tool sets all the parameters required for using the Force Impulse algorithm.

Two parameters must be set for operation of the algorithm. Each parameter is controlled using a slider on the graphical tool. Set each parameter to the desired value by clicking and dragging the slider bar, by using the arrow buttons on either side of the slider, or by clicking in the edit box and typing the value from the keyboard. The two parameters which must be set are:

1. Threshold

The threshold parameter determines what percentage of the standard deviation the sample value must be above to be considered for an impulse point.

2. Window Size

This parameter sets the width of the window for the algorithm. Impulses will not be placed in the data any closer than one window width. The window width should not be set smaller than the minimum desired resolution.

Once the parameters have been set, processing may be initiated by selecting the **Process** button at the bottom left of the tool.

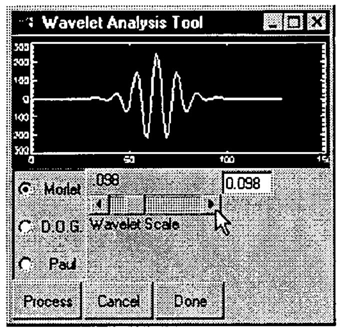
Multiresolution Analysis

GPR signals do not readily lend themselves to typical frequency analysis. The measured waveforms are not stationary and, therefore, have a frequency content that varies with time. Fourier analysis determines the frequency content of the entire signal, but fails to provide any time information content. This is the exact dual to the original measured time series providing only time information, but no frequency information content. One possible solution to many non-stationary signal processing applications involves a relatively new concept known as multiresolution analysis using the wavelet transform.

> *def'n:* Multiresolution Analysis - study of a signal by decomposition of its time series into a range of resolutions using the Wavelet Transform.
>
> *def'n:* Wavelet Transform - maps the correlation between a signal and a wavelet function verses scale/resolution and time.

The underlying principle in Fourier analysis is a comparison of the signal of interest with cosine functions of varying frequencies. High correlation between the signal and a particular frequency indicates the presence of that frequency in the waveform. In this manner, a signal may be dissected into the frequency components, of which it is composed. Cosine functions are of infinite extent, causing time to be absent in the frequency decomposition. The wavelet transform uses basis functions other than cosines in the signal decomposition. These basis functions, called wavelets, are finite in extent and have a very narrow frequency content. In frequency analysis, the signal of interest is compared to cosines of varying frequency. In wavelet analysis, the signal is compared to wavelets of varying scales. The wavelet scale is a variable in the wavelet function which determines the frequency and extent of the waveform, just like frequency in the cosine function does to the cosine waveform. The wavelet waveform changes, based upon its scale, from low frequency with long extent to high frequency with short extent. Therefore, because the wavelet basis functions have both frequency and finite extent, the final wavelet transform contains both time and frequency information. This time-frequency component is called resolution. A signal may be decomposed into its multiple resolutions by comparison with wavelets through a range of scales--hence the notion of "multiresolution analysis". Similar to frequency filtering, where only the important frequencies in a signal are kept; once a signal has been decomposed using the wavelet transform, the desirable resolutions may be kept while the unimportant are discarded. In this way, features in the signal may be selectively chosen based upon their resolution. Such processing may be applied to measured GPR returns and proves to be beneficial in enhancing the returns from artifacts while reducing clutter in the display of GPR profiles. Subsurface features are, therefore, more easily recognized, and interpretation is significantly improved.

The Multiresolution Analysis algorithm provides such wavelet based processing and a graphical tool that allows user selection of the most beneficial scale, as well as a choice of several wavelet basis functions which are provided. Multiresolution analysis provides excellent results in many situations and is quite fast due to the Fast Fourier Transform method used to compute the wavelet transform.



To use multiresolution analysis:

To start the **Wavelet Analysis Tool**, select **Multiresolution** from the **Process** menu. The graphical parameter selection tool will appear on the desktop. This tool sets all the parameters required for using multiresolution analysis.

Two parameters must be set for operation of the algorithm. The two parameters which must be set are:

1. Wavelet Function

The first parameter is simply selection of which wavelet function will be used for the analysis. Three options are available: Morlet, Derivative Of Gaussian (D.O.G.), and Paul. The wavelet function is selected using the buttons in the control box at the left side of the graphical tool. Simply click the mouse on the button by the function of choice. The waveform display will update to show the appropriate function.

2. Wavelet Scale

The second parameter which must be set is the scale of the selected wavelet function. This parameter is controlled using a slider on the graphical tool. Set the scale to the desired value by clicking and dragging the slider bar, by using the arrow buttons on either side of the slider, or by clicking in the edit box and typing the value from the keyboard. As the scale is changed, the waveform display update to show modifications.

Once the parameters have been set, processing may be initiated by selecting the **Process** button at the bottom left of the tool. The main profile display will update to show the processed profile, which is actually the magnitude of the unprocessed image at the selected scale. Notice that the Wavelet Analysis Tool will not disappear. Many times, several wavelet scales may need to be tried before the most beneficial scale is found. For this reason, the tool does not close. The parameters may be adjusted, and **Process** may be selected again to re-process the original image. After some number of iterations provide an acceptable result, select the **Done** button at the bottom right of the tool. This will close the Wavelet Analysis Tool and leave the processed profile data as the current data set in Register X. Or, if no results were found to be acceptable, revert back to the original unprocessed profile by selecting the **Cancel** button at the bottom of the tool. This will close the

Wavelet Analysis Tool and return the original unprocessed profile to the display and the current data set in Register X.

CHAPTER 5

Post Processing

This chapter discusses the GPRSPE Post-Processing Tool. The Post-Processing Tool is used when GPR profile processing has been completed to annotate results, save annotated images, export images for use in graphic design software, and for additional viewing features. Topic to be covered include:

- Basics
- View Management
- Annotation
- Input/Output

Basics

The GPRSPE Post-Processing Tool is designed to handle many common after-processing tasks. Concepts covered in this section include:

- Tool initialization
- Tool display features
- Menu operation
- Tool exiting

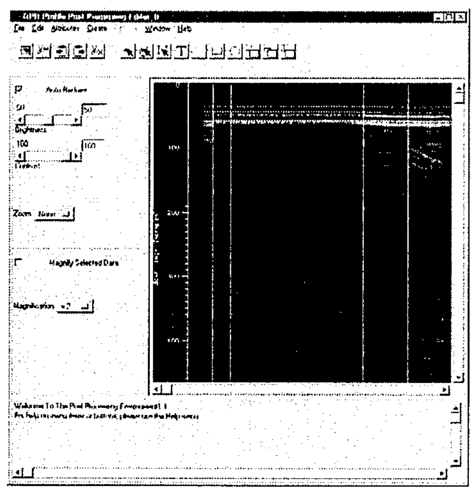
Tool Initialization

Starting Post-Processing Tool may be accomplished in two ways:

1. Select **View/Annotate/Print** from the **File** menu.

2. Select the POST PROCESSING button on the Button Bar.

Starting the tool will import the current profile display window image and the vertical scale, as they are currently seen, into the Post-Processing Tool. Only the width of the profile display window will be imported, larger profiles will be cropped by the profile window width and location. The tool may be started multiple times. Each time a new multiple of the tool will appear.



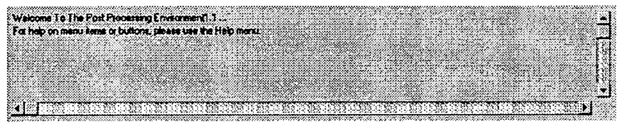
Tool Display Features

The tool display contains multiple regions for image display, system feedback and environment control.

1. Image Display

The image display window is the large main window where the profile image is displayed. Scroll bars on the right and bottom sides allow navigation through the image, which is often larger than the size of the display window.

2. Command Feedback Display



The tool provides feedback and instructions for each procedure in a text box at the bottom of the tool.

3. Display Properties Control

A control box for display properties allows several parameters to be set including: automatic redraw, brightness, and contrast.

4. Zoom Control

A control box on the left side of the tool allows the zoom factor to be modified.

5. Selected Data Display Control

A selected range of data may be viewed in a zoom window. Control of this feature, including the zoom factor, has its own control box at the left of the tool.

6. Button Bar

The tool has a Button Bar for control of many of the tool functions.

7. Menu Bar

The tool has a standard menu bar, like all Windows applications, for control over most of the tool features and functions.

Menu Operation

Most of the tool operations may be initiated through use of the menus found in the Menu Bar. The operations are divided into appropriate categories so that desired functions may be located intuitively. Operation of the menus is identical to that of the main GPRSPE environment.

Tool Exiting

Exiting the Post-Processing Tool is the same as nearly any Windows application. Data should be saved, necessary, before exiting. All unsaved profile processing results will be lost if not saved.

To exit the Post-Processing Tool:

Select **Exit** from the **File** menu or select the "X" button in the top right corner of the environment display. Since multiple tools may be open at any one time, make sure this procedure is only performed on the individual tools which need to be closed.

View Management

This section discusses properties and options of the tool image display including:

- Image Navigation
- Display Parameters
- Zoom Options
- Profile/Slice Display

Image Navigation

Many images in the tool may be larger than can be displayed at one time within the display window. However, the entire image may be viewed by scrolling through the data.

To navigate the image view:

To move through an image, simply use the scroll bar at the bottom or right side of the image display window. Click and drag the navigation bar on the scroll bar, click on either side of the navigation bar, or use the arrow buttons on either side of the scroll bar. The image in the display will move as the scroll bars are modified.

Display Parameters

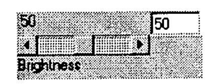
Several features of the display may be modified using a control box on the tool.

1. Auto redraw

This option controls whether the display redraws itself when changes are made. Simply click on the button to toggle this feature on and off.

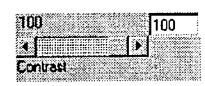
2. Brightness

The brightness of the image display may be modified in the tool. Adjust the slider value till the displayed image is satisfactory.



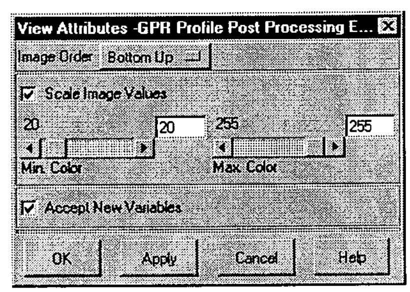
3. Contrast

The contrast of the image display may also be changed. Once again, simply adjust the slider till the displayed results are acceptable.



4. View Attributes

Several view attributes may be modified by selecting **View Attributes...** from the **Attributes** menu.

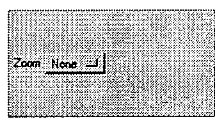


- Image Order - sets whether the image is flipped vertically. To change, click on the current setting box, and a list will drop down. Select the desired option.
- Scale Image Values - determines whether the pixel values are scaled to a modified range of colors. In the Post-Processing Tool, twenty colors in the color scale are set to special plotting colors and reserve at the bottom of the scale. So, the colorscale is squeezed from 0-255 to 20-255. This makes little noticeable difference in the display. When **Scale Image Values** is set, the pixel values are scale to fit the modified colorscale. This makes the image look the same as it does in the main environment. This scaling may, however, be turned off or set to scale to a different range. The range may be changed using the sliders. Typically, this option should not be modified.

- Accept New Variables - used for additional functions not required for this application.

Zoom Options

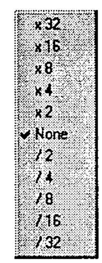
Two different control boxes on the tool control zoom mechanisms. The zoom factor may be set for the both typical image display and for a separate display window for a selected range of data.



To change the main display zoom factor:

In the zoom control box, click the mouse on the current zoom setting box.

A list will drop down. Select the new zoom factor. The display will update.



To change the selected data zoom factor:

In the selected data zoom control box, turn on the zoom by selecting the **Magnify Selected Data** button. A new window will appear for displaying the magnified data region. Then click the mouse on the current zoom setting box. A list will drop down. Select the new zoom factor. The magnified data will be displayed in the new window.

To select a data range:

There are two types of data ranges that can be selected: a typical rectangular range, and an irregularly shaped range. Buttons on the Button Bar start these two operations.

 - starts the regular, rectangular region selection. Click the button to begin, and then click and hold the left mouse button in the image display. Drag the mouse to define a region. Release the mouse button. The selected region will be highlighted. To deselect the region hold down the SHIFT key and press the left mouse button. Statistical data is provided in the **Command Feedback Display** for the selected rectangular region.

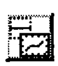
 - starts the irregular shaped region selection. Click the button to begin. Click and hold the left mouse button in the image display. Drag the mouse to encompass the desired region, and then release the mouse button. The region will be highlighted. To deselect the region hold down the SHIFT key and press the left mouse button. Statistical data is not provided for irregularly shaped regions.

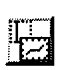
Both regular and irregular selection modes may also be initiated using the **Data Select** and **Irregular Data Select** options respectively in the **Edit** menu.

Profile/Slice Display

The GPR image pixel values in the Post-Processing Tool may be viewed along any line using three similar functions. The functions display a plot of a slice of the image in a separate window. Buttons in the Button Bar initiate the three slice display functions.

 -starts the Endpoint Profile Slice display. Click the button to begin. A new slice display window will appear on the desktop. Move the mouse to the image display. Click and hold the left mouse button at a starting point, and then drag the mouse. A line will be shown in the display from the starting point to the current mouse position. In the slice display window, a plot of the image amplitude along the line will be displayed. When finished, release the mouse button. To remove the slice display window, click the **Dismiss** button in the window.

 - starts the Row Profile Slice Display. Click the button to begin. A new slice display window will appear on the desktop. Move the mouse to the image display. Click in the image at a starting point. In the slice display window, a plot of the image amplitude along the row of the starting point will be displayed. Dragging the mouse in the image will cause a dynamic display of each row as the mouse is moved. When finished, release the mouse button. To remove the slice display window, click the **Dismiss** button in the window.

 - starts the Column Profile Slice Display. Click the button to begin. A new slice display window will appear on the desktop. Move the mouse to the image display. Click in the image at a starting point. In the slice display window, a plot of the image amplitude along the column of the starting point will be displayed. Dragging the mouse in the image will cause a dynamic display of each column as

the mouse is moved. When finished, release the mouse button. To remove the slice display window, click the **Dismiss** button in the window.

The three slice functions may also be started in the **Edit** menu by selecting the **Endpoint Profile, Row Profile,** and **Column Profile** selections.

Annotation

The main purpose of the Post-Processing Tool is to allow object-oriented annotation of processed GPR images. Text, lines, boxes, and ellipses may be added to images. They are object-oriented in the sense that each is considered its own entity, capable of being selected, deleted, copied, pasted, etc. The Post-Processing Tool provides an excellent system for preparing documentation of GPR analysis results.

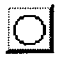
Tool Use

The annotation functions may be selected using buttons on the Button Bar or through selections in the **Create** menu. The functions operate in a similar fashion to most graphic design applications and Windows programs. Control for each tool is described in the Command Feedback Display when the function is selected.

 -Text layout tool. Click the button. Select text location in image. A text attribute selection window will appear. Enter text in input box. Set any desired attributes such as color, line width, font, fill color, angle, etc. Press **OK**.

 -Line tool. Click the button. Click and hold the left mouse button at the starting point of the desired line. Drag the mouse to the endpoint of the line, and then release the mouse button. Holding the CONTROL key forces the line to be either vertical or horizontal.

 -Rectangle tool. Click the button. Click and hold the left mouse button at the starting point of the desired box. Drag the mouse to the end corner of the box, and release the mouse button. Holding the CONTROL key forces the box to be square.

 -Ellipse tool. Click the button. Click and hold the left mouse button at the starting point of the desired ellipse. Drag the mouse to the end point of the ellipse and release the mouse button. Holding the CONTROL key forces the ellipse to be a circle.

 -Object selection tool. Click the button. Click on a drawn object or drag a box around the object. The object will be selected. Click on the object and drag it to move the object. Click and drag the control points to change the object shape. Double clicking on an object brings up an attributes control window for the object. Multiple objects may be selected or deselected by holding the SHIFT key. Once an object is selected it may be deleted, copied and pasted, or its attributes may be changed by selecting **Selected Object...** in the **Attributes** menu. Objects may be deselected by re-selecting them with the SHIFT key held down. All objects may by deselected at once by choosing **Deselect All** from the **Edit** menu.

 -Redraw. Click the button. The display will be redrawn.

 -Cut. Select an object. Click the button. The object will be cut to the clipboard for pasting.

 -Copy. Select an object. Click the button. The object will be copied to the clipboard for pasting.

 -Paste. Click the button. Select a location in the image for the object.

 -Delete. Select an object. Click the button. The object will be removed.

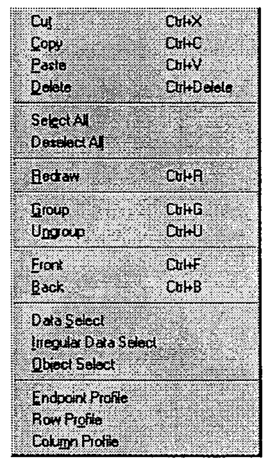
Object properties

Each object has several attributes including: color, line width, fill color, etc. The default attributes for each type of object may be set by selecting the object type from under **Defaults** in the **Attributes** menu. Once the defaults have been set, each new object will have the attributes of the default settings for that object type. To change the attributes of a previously drawn object, select the object using the Object Selection Tool. The either double click on the object or choose the **Selected Object...** option in the **Attributes** menu.

Grouping Objects

Multiple annotation objects may be grouped together. Once grouped, the objects are treated as one entity when cutting, copying, pasting, etc. A group of objects may be ungrouped at any time.

To group multiple objects:



Select the object selection tool using the Button Bar or **Object Select** from the **Edit** menu. Click in the display window and drag a box around the objects that need to be grouped. All objects in the box will be selected. Multiple objects may also be selected one by one using the mouse to select them if the SHIFT key is held down. All objects in the image may be selected at once using the **Select All** option in the **Edit** menu. Once the desired objects have been selected, choose **Group** from the **Edit** menu. The objects will be grouped and considered as one entity.

To ungroup objects:

Using the object selection tool, select the group of objects to be ungrouped. Choose **Ungroup** from the **Edit** menu. The group will be separated and each object will be treated as its own entity.

Changing Object Order

Objects are stacked on top of each other when displayed in the image window. Objects on top cover and hide objects below them. The order is determined by the order in which the objects were drawn. The last object drawn always covers the previously drawn objects. The order of the objects may, however, be forced to a desired order.

To change an object order in the display stack:

Use the object selection tool to choose an object. The selected object may be moved to the front or back of the display stack by choosing **Front** or **Back** respectively from the **Edit** menu. By selecting the objects one by one in the desired stacking order and shifting then in the same direction, back or front, the desired order may be achieved.

Input/Output

The Post-Processing Tool serves to provide a method for annotating GPR analysis results for FDOT documentation. The tool allows annotated results to be printed on paper for a hardcopy or to file for importing in word processing or graphic design software. Annotated images may also be saved to disk for later access and changes.

- Save/Restore
- Export Graphics
- Print

Save/Restore

Annotated images may be saved and restored. The objects are preserved as separate entities to allow modification at a later time.

To save an annotated image:

An annotated image may be saved using the **Save** or **Save As...** choices in the **File** menu. **Save As...** will start a file selection tool to allow the file name to be chosen. **Save** will save the image to file using the name previously selected. All objects will be saved as their own entities. This allows the annotations to be changed later.

To restore an annotated image:

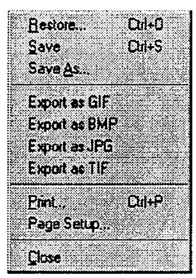
Restore an annotated image by selecting **Restore...** from the **File** menu. A file selection tool will appear for selection of the desired file. The file will be loaded. Annotations may then be changed or added.

Export Graphics

The annotated image may be exported as a graphic file for use in most popular word processing and graphic design applications. Several file formats are available to ensure compatibility: GIF, BMP, JPG, and TIF.

To export an annotated profile to a graphic file:

Export to a graphic file by selecting one of the export options from the **File** menu:



Export as GIF - Compuserve Graphics Interchange Format

Export as BMP - Window or OS/2 Bitmap

Export as JPG - Joint Photographic Experts Group format

Export as TIF - Tagged Image File format

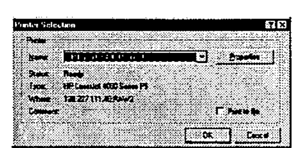
Once a file format has been selected, a file selection tool will appear. Select the desired file name and then press **OK**. The annotated image will be exported to the desired file using the appropriate file format. Most word processing and graphic design software is capable of importing at least one of the file formats available.

Print

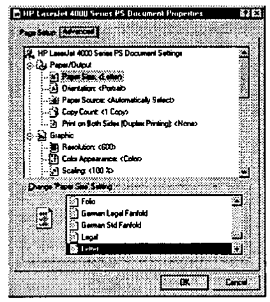
The annotated profile may be printed to the installed printers using the Post-Processing Tool.

To print an annotated profile:

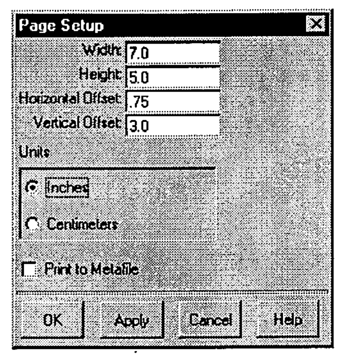
To print an image select **Print...** from the **File** menu. A print tool will appear. The tool allows selection of the desired printer and configuration of printer parameters. The printer features are controlled by



software from the printer manufacturer and Windows. After the parameters are set, select **OK** to print the image.



To change the page setup:



Selecting **Page Setup...** from the **File** menu will start a page setup tool. The tool allows page parameters to be set including: page height, page width, offsets, etc. There is also a button to select Window Metafile output. If this button is selected, the **Print...** command in the **File** menu will ask for a file name and print to a file in Windows Metafile format. This format may be imported in some graphic design applications. The format preserves objects as their own entities so that the annotation may be changed within other software. This format may not be 100% compatible with other software.

To print to a Window Metafile:

Choose **Page Setup...** from the **File** menu to start the page setup tool. Select the Window Metafile option. Close the tool and then select **Print...** from the **File** menu. A tool will appear for input of a file name. Type the desired filename and press **OK**. The annotated image will be printed to file using the Windows Metafile format. This format may be imported in some graphic design applications. The format preserves objects as their own entities so that the annotation may be changed within other software. This format may not be 100% compatible with other software.

CHAPTER 6

GPR Techniques

The chapter serves to emphasize some basic GPR data collection and analysis principles which can aid in producing quality analysis results. It covers the following:

- Overview
- Collection Techniques
- Analysis Techniques

Overview

Ground penetrating radar collection and analysis are not an exact science, meaning there are no well-defined, specific procedures or routines which always guarantee excellent results. At least for the time being, GPR will continue to rely on experience gained through use over time. However, through careful methods and powerful, intelligent processing techniques subsurface analysis efficiency and confidence can be improved. Experienced operators will benefit from reduced analysis time requirements and new operators will gain appreciable experience quicker due to effective collection methods, increased processing speed, and more informative subsurface profiles generated by powerful algorithms.

Collection Techniques

Taking a scientific approach to GPR data collection benefits analysis and GPR processing algorithms. Rigorous attention to detail and well-defined collection techniques produce higher quality data sets and result in more informative data.

Appropriate Radar Configuration

The radar, being the sole data collection device, must be configured properly for effective subsurface imaging.

1. Antenna center frequency

The antenna frequency determines the penetration depth and the achievable resolution of objects in the return. Penetration depth and resolution are proportional. Higher frequency antennas provide finer, better resolution but reduced penetration depth. Lower frequency antennas penetrate deeper but provide worse resolution. For this reason, the highest frequency antenna able to achieve the desired depth should be used to provide the best resolution. Multiple data collections might even be considered using a higher frequency antenna to image close objects at a better resolution and utilizing a lower frequency antenna for deeper objects.

2. Time range

The time length measured for each pulse determines the maximum depth to which an object may be imaged, subject to the dielectric constant of the surrounding medium. This range should be set such that it may "see" deep enough for objects of interest. However, it should not be set significantly deeper than required, or the cross-range sample resolution will have to be reduced by the radar. It is also useless to attempt to record returns from objects which are deeper (longer travel time) than may be seen due to the attenuation of the electromagnetic signal in the subsurface.

3. Sample rate

The radar is usually run for geophysical applications in continuous sample mode. The sample rate should typically be set as fast as the radar can achieve (limited by the required time range), to give the best results. This produces better cross-range resolution or, at the sacrifice of resolution, allows reduction of noise by stacking methods.

4. Samples per scan

The number of samples per scan should be set as high as the radar can achieve for the best resolution in the data. Size of individual traverses in typical geophysical applications do not create a data storage problem at maximum rates.

5. Filters

Care should be taken in setting the filters in the radar system. It is essential that the center frequency not be filtered out of the received signal. A significant bandwidth should be allowed to pass surrounding the center frequency to ensure quality results and resolution. It is best to filter out very little of the received signal. Perhaps very high and very low frequencies may be filtered out to reduce noise.

6. Gain function

The gain function should also be set very carefully. Extremely high gain functions amplify noise significantly and may cause clipping. The gain should not be set to produce a large response when there is nothing to reflect the signal underneath the antenna in the subsurface. When an actual object is passed a legitimate response will be received. This response, will then be greatly amplified and signal clipping will most likely result. If nothing is below the antenna, no response should be seen by the radar. This is a normal occurrence.

Survey Area Preparation

Collection from a well prepared area produces more precise results.

1. Clear area

Any materials on the surface which may encounter the antenna or produce a response should be removed. This is especially true for metallic objects. The antenna should be pulled evenly over as smooth of a surface as possible.

2. Grid area

The survey site should be sectioned into a grid system. Such a system allows the operator to collect data along more precise traverses. It also allows markers to be placed in the data at more precise locations for a better cross-range sample interval estimate.

Data Collection

1. Traverse rate

The GPR system samples at a constant rate, which causes the cross-range sample interval to depend on the traverse rate. To provide an consistent sample interval the antenna must be pulled at a perfectly even rate. However, the antenna is pulled manually by an operator who is walking. A walking traverse rate is never consistent so neither is the sample interval. Fluctuating sample intervals distort the shapes of returns from objects in the subsurface and, thus, inhibit some methods of processing such returns. For this reason, great care should be taken to traverse at as even a rate as possible. Often clearing the survey area helps keep the antenna from catching and jerking on surface articles which prevent a constant rate.

2. File storage

It is important to limit the size of files during data collection. Small files are more manageable and reduce processing time. If files are too large they may not even be capable of being loaded into processing software. A good way of keeping files manageable is to file data from each traverse along a gridline of the collection area in a separate file. This may be done automatically by the radar system using Stop/Start mode of data collection.

Analysis Techniques

It is important to realize that no one method of analysis is correct. Often several procedures must be used to produce desired results. The GPRSPE presents many options for processing, easy access and control of algorithms, and efficient comparison and visualization of GPR profiles. The system provides an excellent tool to extract as much information from GPR returns as possible for an informed interpretation. No one process solves every problem, however there are some guidelines that often serve to make analysis more effective.

1. Process small data sets

Processing speeds are directly related to the amount of data being processed. As speed is important for efficient analysis, small profile regions of interest should be processed at any one time rather than processing long traces of data at once. This reduces the memory required by the system to process the data in addition to reducing the amount of data to process. Both of these aspects result in much shorter processing times. Cropping of profiles using the GPRSPE allows selection of a region of interest, and deleting allows unnecessary sections to be removed.

2. Gain function removal

Many times the gain function makes deeper objects visible. However, this is not always beneficial for the processing routines, like Adaptive Inversion, for example. The gain function should often be removed prior to processing to prevent adverse affects on the algorithms. Display filters, such as dB display and histogram equalization, often make up for the lack of an added gain function.

3. Point objects

When the application specifically involves the location of buried point targets, such as pipes, cables, or rebar, migration may often provide a beneficial method of increasing the cross-range resolution by focusing hyperbolic returns. For objects with extent, migration is not typically as helpful.

4. Typical unknown profiles

For profiles where little is known about the subsurface, adaptive inversion and multiresolution analysis often provide the best results. These algorithms tend to resolve some of the features of returns from objects and features of the subsurface and produce a more informative display. They will also often bring out returns which were previously not visible or features which were too cluttered to be noticeable.

Impulse forcing may also provide useful results by emphasizing contours and features of the data that were not directly recognizable. This method of processing is helpful in a cluttered response for illustrating correlated returns from neighboring traces.

Glossary

Adaptive Filter - a filter which is designed to change itself over time to minimize the error between its output and some desired response. 43

Background Noise - unwanted signal received and measured by the radar which often clutters a profile display. Often a result of random thermal noise within the radar system or receive electromagnetic radiation from other electromagnetic sources. 41

Blind Deconvolution - Separating two signals given only the combined signal. Assumptions must be made about the characteristics of the two signals which will allow separation. 43

Colorscale - the array of colors allotted for the display of data. Each color is assigned to represent a data value in the display according to some allocation scheme. Points in the data set are displayed using the color closest to their data value. 14

Convolution - the mathematical process of filtering a time series or signal with another signal/filter. 42

Deconvolution - the mathematical process of separating one signal/filter from the output signal given the other signal/filter. 43

Dielectric Constant - a parameter of any medium which determines the velocity of electromagnetic waves within that medium. 15

Gain Function - a function applied to each trace which amplifies the data according to its sample number. Typically, in GPR, early samples receive little amplification while late samples in a trace receive larger amplification. This helps account for the 14

Interference - distorted response due to overlap between responses from multiple targets which have added together making the return from each individual object less recognizable. 36

Migration - focusing the hyperbolic responses of point targets to more point-like response for improved recognition and localization. 36

Multiresolution Analysis - study of a signal by decomposition of its time series into a range of resolutions using the Wavelet Transform. 47

Profile - a GPR image of the subsurface consisting of a series of traces, which are recorded as the radar antenna is traversed along the surface. 13

Trace - one measured pulse of the radar consisting of a series of samples/measurements as electromagnetic wave propagates into the ground and returns from subsurface reflections. 13

Wavelet Transform - maps the correlation between a signal and a wavelet function verses scale/ resolution and time. 47

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