Practical Processing of GPR Data

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Abstract

Digital processing of GPR data can be extremely beneficial in some cases and totally inappropriate in others. The general question the user must address is whether the processing is cost effective. While not normally addressed in research meetings, cost of processing plays a big part in determining what processing, if any, is applied in state-of-the-practice surveys.

Here we review the general processing steps which are needed in the analysis of GPR data. The basic steps include the initial data compilation and other spatial and general editing requirements of data. The next steps usually encompass that of assessing appropriate time gains for data sets and applying simple spatial and temporal filtering. The more advanced processing steps include multi-fold data processing, CDP semblance analysis, combined spatial and temporal filtering, (i.e., FK filtering, and migration).

The final steps in data processing involve transforming radar data into user usable images of the ground. Quite often this requires considerable simplification of the complex mass of GPR data. We conclude with a review of the need for a cost benefit to be inherent in any processing.

1. INTRODUCTION

Ground penetrating radar (GPR) is now used extensively for a variety of applications in many differing fields. The ubiquitous access to inexpensive computer facilities means that more and more computer processing of GPR data occurs. The objective of this paper is to provide a brief overview of GPR data processing. The very broad nature of the topic makes it impossible to provide a complete discussion. The focus, therefore, will be to indicate the steps which should be followed in data processing and to stress the need for the processor (the person not the computer) to remember that there must be a cost benefit at the end of the day.

Processors can exploit many of the developments of seismic data analysis which have been evolved to a very high level. Numerous commercial software packages are available which allow almost any imaginable data manipulation. For anyone contemplating use of seismic processing on GPR data, the excellent text by Yilmaz (1987) should be considered essential reading. While all seismic processing can not be applied to GPR data, the vast majority can be used directly as evidenced by Fisher et al. (1992a), Maijala (1992), and Rees & Glover (1992).

GPR data are most often treated as a scalar quantity while the electromagnetic fields which are the basis of the method are vector quantities. Extensive use of GPR where the vector nature of the field has been exploited are few but growing. For processors with a seismic background, GPR data are more analogous to shear wave than compressional wave data.

The processing flow for GPR data is depicted in Figure 1. The initial stage of operations is the acquisition of data and this is normally accompanied by real-time display. In many applications the real-time display is used for on-site interpretation and may indeed be the end point for the radar survey. Frequently data are now recorded and are available for post-acquisition processing and re-display.

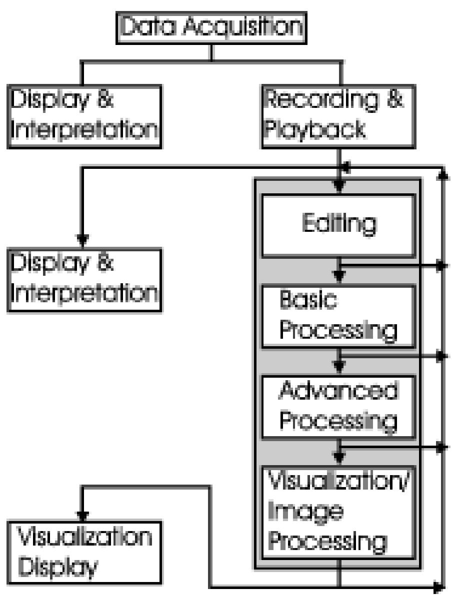

Figure 1: A general overview of GPR data flow.

The highlighted zone in Figure 1 is the topic of this paper. The areas of data processing have been grouped under the headings: data editing, basic processing, advanced processing, and visualization/ interpretation processing. Processing is usually an iterative activity. A data set will flow through the processing loop several times with the data changes visually monitored by the processor. Straight through batch processing may be applied on large data sets after iterative testing on selected data samples.

The data processing subdivisions indicated are meant to reflect that the data manipulation becomes more and more processor (the person) dependent and hence more subjective because a particular end result is sought. The following discussion is biased toward single fold, common offset, reflection profiling data processing owing to the fact that the majority of GPR data is of this type.

The issue of data display, hard copy and visualization while somewhat beyond the scope of data processing is an inherent factor in data processing. Raw information, which is normally an amplitude versus time signal with several decades of dynamic range, must be manipulated for the display devices which have about one decade of dynamic range. Since so many formats such as colour mapping, grey scale mapping and line graphs are available, it is difficult to totally divorce processing from presentation considerations.

2. Data Editing

Once data are recorded, the first step in processing is data editing. Field acquisition is seldom so routine that no errors, omissions or data redundancy occur. Data editing encompasses issues such as data re-organization, data file merging, data header or background information updates, repositioning and inclusion of elevation information with the data.

While this may sound like a trivial exercise, it is often the most time consuming one for a production survey. Large volumes of information have to be systematically maintained so that further processing can be done without having to constantly account for idiosyncrasies of acquisition. In many instances background information on acquisition is used in the processing stages. For instance, the centre frequency of the acquisition system antennas is a very important factor in processing. The temporal and spatial sampling interval are also important in most advanced processing steps. Data recorded on equal spatial and temporal time intervals are virtually mandatory for most of the advanced processing methods. As a result, data editing is essential before further processing in many situations.

Figure 2 illustrates some of the many activities involved with data editing. The upper portion of the figure shows a typical file header which contains initial survey information including the number of traces in the file, the start and end position, the frequency of acquisition, as well as the processing history. The lower section shows a final raw data plot. In this case polarity, statics and topography corrections have been applied, three files have been merged and all this information is annotated properly for future reference. A basic time gain has been applied to make the display.

```
Barrow 1
Rathcroghan Mound Radar Survey, Co Roscommon.
Same Line from -37 at +.25M station interval.
20/05/93
NUMBER OF TRACES    = 499
NUMBER OF PTS/TRC   = 375
TIMEZERO AT POINT   = 47
TOTAL TIME WINDOW   = 300
STARTING POSITION   = -37.000000
FINAL POSITION      = 87.500000
STEP SIZE USED      = 0.250000
POSITION UNITS      = metres
NOMINAL FREQUENCY   = 50.000000
ANTENNA SEPARATION  = 1.000000
PULSER VOLTAGE (V)  = 400
NUMBER OF STACKS    = 128
SURVEY MODE         = Reflection
ELEVATION DATA ENTERED : MAX = 9.192000   MIN = 0.916750
SIGNAL SATURATION CORRECTION APPLIED
THIS FILE A MERGING OF \2 AND c:\gmaud\maeve4.
POLARITY FLIPPED FROM POSITION -37.000000 TO -0.500000
POLARITY FLIPPED FROM POSITION -37.000000 TO -0.500000
POLARITY FLIPPED FROM POSITION -37.000000 TO -0.500000
SOURCE DATA FILE    = c:\gmaud\mmaeve2
FIRST BREAK POINT CORRECTED. THRESHOLD = -10000
FIRST BREAK POINT CORRECTED. THRESHOLD = 5000

PROCESSING SELECTED:
   Trace Stacking     : 1
   Points Stacking    : 5
   Trace Differencing: N
   Gain Type   : SEC
     Velocity : 0.100 m/ns
     Attenuatn: 1.000 dB/m
     Amount    : 50% Maximum
   Selection   : Time = all
                 Trace = 50 to 450

PLOT LAYOUT PARAMETERS:
   Trace Spacing       : 0.013"
   Trace Width         : 0.050"
   Trace Position      : 1.000" to 3.500"
   Left/Right Margin : 0.000" / 0.000"
   Border Size         : 0.500"
   Page Length/Width : 10.000" / 7.500"
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Figure 2a: Example of data processing documentation.

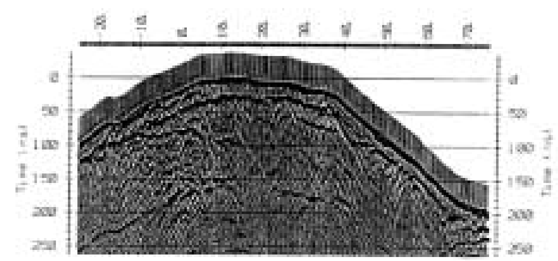

Figure 2b: Example data set from an archaeological investigation whose history is described in 2a. The data were assembled from three data sets and have had tomography, polarity and static correction applied. An SEC time gain is applied in the plotting.

To date, multifold GPR data acquisition is not done extensively. If it becomes more common, this step of processing is the one where re-organization and sorting of multifold coverage data would be handled. The steps are essentially the same as with multifold seismic data (Fisher et al, 1992a).

3. Basic Processing

The subject of basic data processing addresses some of the fundamental manipulations applied to data to make a more acceptable product for initial interpretation and data evaluation. In most instances this type of processing is already applied in real-time to generate the real-time display. The advantage of post survey processing is that the basic processing can be done more systematically and the use of non-causal operators to remove or enhance certain features can be applied.

The initial basic processing step is usually temporal filtering to remove very low frequency components from the data. This step is frequently referred to as 'de-wowing' the data. Very low frequency components of the data are associated with either inductive phenomena or possible instrumentation dynamic range limitations. This process has historically been done using analog filters in hardware but with the advent of true digital acquisition this has also become a data processing issue (Gerlitz et al, 1993).

The next step of basic processing is usually to select a time gain for the data set. Time gain has historically been very subjective and also very much display methodology dependent. The fact of the matter is that systematic ways of selecting gain are available. Generally the first step in selecting gain is to examine the amplitude versus time fall-off of the data. This can be done trace by trace or on a section basis. Generally, working on a section is the most useful way of approaching the problem but again there are degrees of variability in this. Figure 3 shows an average amplitude versus time plot for high pass (dewow) filtered but otherwise raw data set shown in Figure 2. The key point to note is that the radar signal amplitude falls off with time in a fairly systematic fashion. If one wants to display these data on a display device with a dynamic range of 20 dB (i.e., a factor of 10 between the smallest and largest signal) then the 60 dB dynamic range of the real signal has to compressed into a dynamic range of 20 dB of the display device. Figure 4 shows the average signal amplitude versus time after the time gain used for the plot in Figure 2 has been applied.

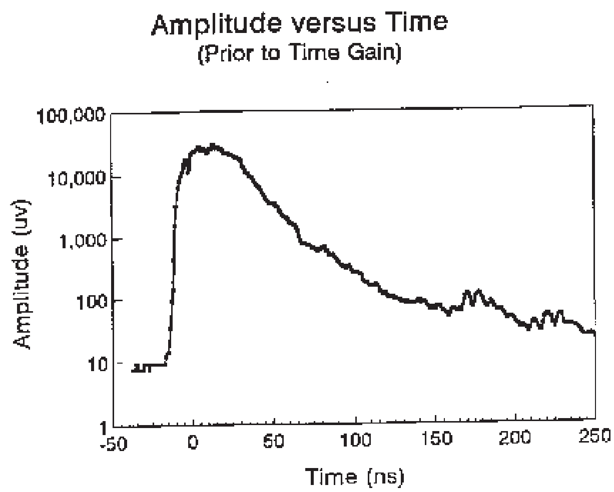

Figure 3: The average amplitude of the radar signal versus time for the data set presented in Figure 2b prior to time gain.

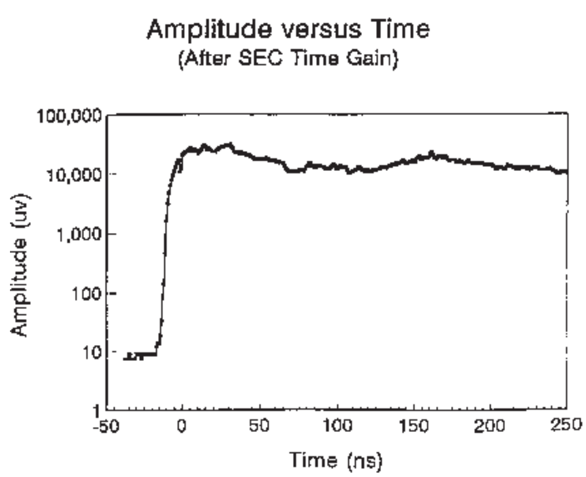

Figure 4: The average signal amplitude of the radar signal versus time for the data set presented in Figure 2b after the application of an SEC time gain.

There are a variety of ways of applying gain to radar data. The issue is whether or not one wants to maintain some sort of amplitude fidelity or whether one only wants to display all of the signals in the data. For stratigraphic horizon continuity sometimes showing all the information irrespective of amplitude fidelity is important. In this case a continuously adaptive gain such as AGC (automatic gain control) is used. With AGC gain, each data trace is processed such that the average signal is computed over a time window and then the data point at the centre of the window is amplified (or attenuated) by the ratio of the desired output value to the average signal amplitude.

Physical phenomenon based systematic gains, such as spherical and exponential compensation (SEC) gain, attempt to emulate the variation of signal amplitude as it propagates in the ground. The data displayed in Figure 2 have had an SEC gain applied and comparing Figures 3 & 4 shows the degree to which the time gain has compressed the signal dynamic range.

A variety of other gains can be applied. Gain should be selected based on some a priori physical model, not at the user whim. The objective should be to modify the data while retaining its full utility without introducing artifacts.

Temporal and spatial filtering are often the next stage of basic processing. Filtering can be applied before or after time gain as long as the effect of the gain is understood since time gain is a non-linear process. Temporal filtering means filtering along the time axis of the data set. A whole host of different types of temporal filtering may be applied from bandpass filtering using fast Fourier transforms (FFT) through to various types of linear and non-linear time domain convolution filter operators. Figure 5 shows the amplitude spectra for the data set shown in Figure 2 before and after an SEC gain function has been applied. In both cases the average amplitude spectrum for the whole section has been generated. From the spectra it can been seen that the majority of the energy is limited to a finite bandwidth and appropriate use of band limiting filtering may improve signal-to-noise without significantly altering the data. A low pass filter with an 50 MHz corner using an FFT approach generates the section shown in Figure 6a while 6b shows the result of a 80 to 120 MHz bandpass filter.

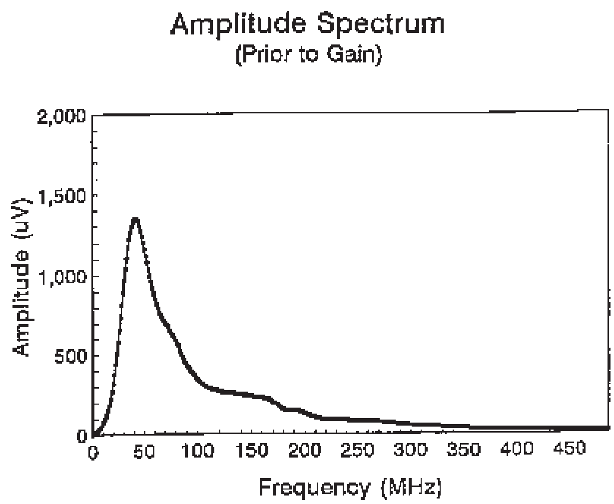

Figure 5a: Average time amplitude spectrum shown in figure 2b prior to time gain.

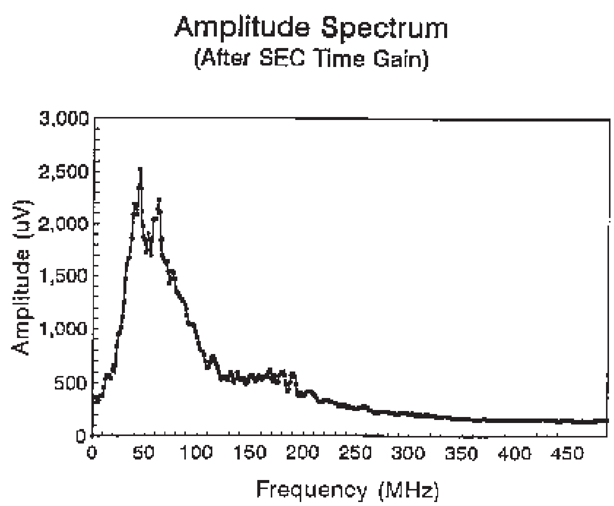

Figure 5b: Average amplitude spectrum for data shown in figure 2b after application of an SEC time gain.

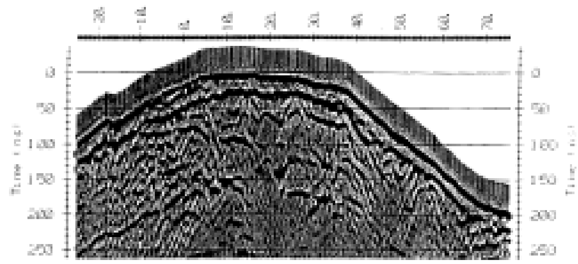

Figure 6a: *Data set shown in Figure 2b after low pass zero phase FFT filter with a cosine taper between 50 MHz and 100 MHz.*

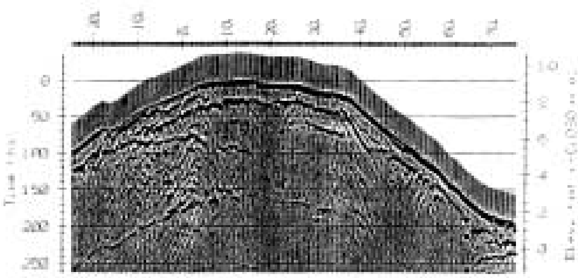

Figure 6b: *Data set shown in Figure 2b after 80 to 120 MHz bandpass zero phase FFT filter.*

Similar filtering operations can be applied in the spatial domain. The 3 radar sections shown in Figure 7 present the original radar section plus an example of high pass and low pass spatial filtering. The high pass spatial filter retains dipping events and suppresses flat lying events. The low pass filter has the opposite effect in that it enhances flat lying events and suppresses dipping responses.

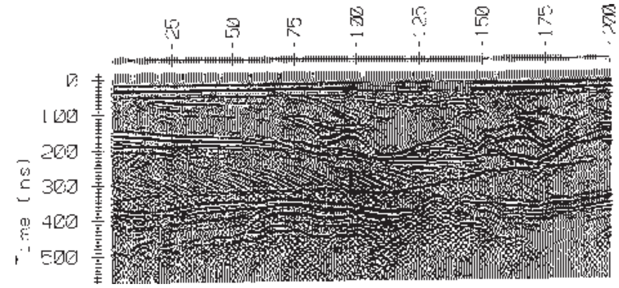

Figure 7a: *Example of time gained data in fluvial sand environment.*

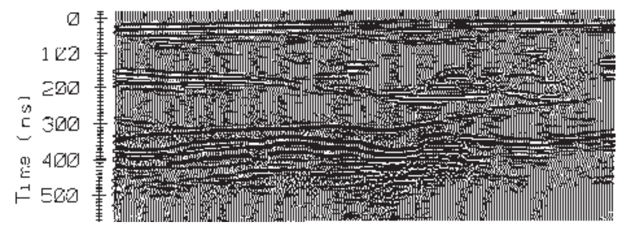

Figure 7b: *Illustration of spatial low pass filtering as applied to data shown in a. Note enhancement of flat lying reflectors.*

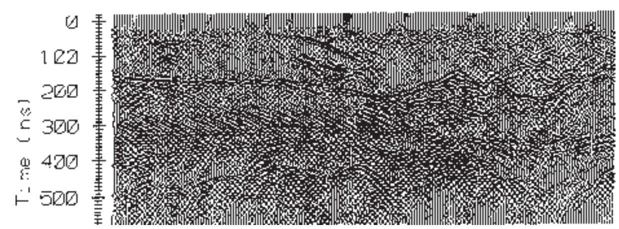

Figure 7c: *Illustration of high pass filter applied to data shown in b. Note enhancement of dipping events and diffraction details.*

Median and alpha mean trim filters offer powerful data "clean-up" filters for noise spikes. These filters can be applied in both the time or space domain. These filters may be applied before and after time gain but are usually most useful if applied before time gain and any type of data adaptive filtering.An example of spike removal from a data set using a 3-point temporal filter followed by trace spatial median filter is illustrated by the before and after sections in Figure 8.

The examples cited in this discussion are by no means exhaustive and a wide variety of simple data manipulations are available to enhance basic aspects of GPR data. As evident from the preceding, the order in which these processes are applied can also be varied producing different results because of the non-linear nature of some steps. As indicated earlier, the bias in this discussion is to single fold reflection data.

Basic data processing should leave the data sets reasonably intact. In other words, the processing should not be such that it radically distorts the information from that which was collected. Again the degree of distortion is subjective and obviously excessive bandpass filtering can drastically alter a data set as evidenced by the spatial high and low pass filtering shown in Figure 7. Normally minor changes to the overall data set occur if simple basic processing steps are applied intelligently.

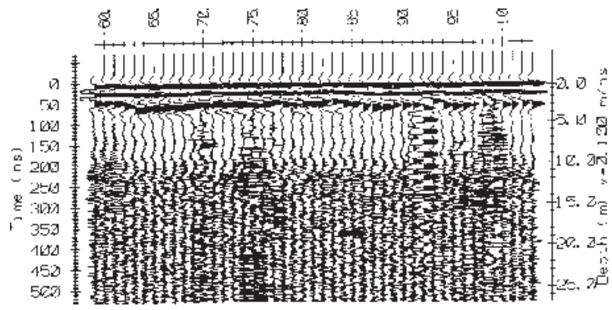

Figure 8a: An original data set with a large amount of spurious localized noise events.

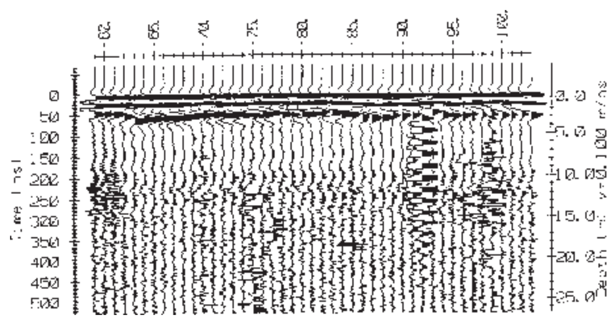

Figure 8b: The data set shown in a after a 3-point temporal median filter.

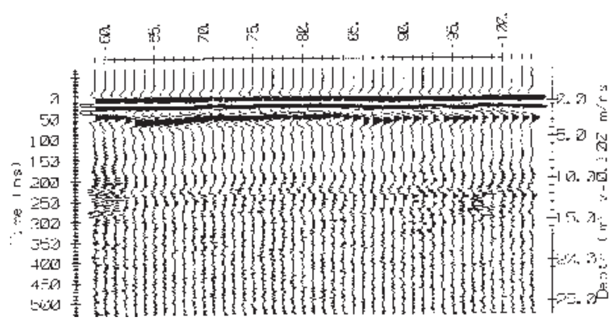

Figure 8c: The data set shown in Figure 8b after a 3-point spatial median filter.

4. Advanced Data Processing

Advanced data processing addresses the types of processing which require a certain amount of operator bias to be applied and which will result in data which are significantly different from the raw information which were input to the processing. Such processes include well-known seismic processing operations such as trace attribute analysis, FK filtering, selective muting, normal move out correction, dip filtering, deconvolution, and velocity semblance analysis as well as more GPR specific operations such as background removal, multiple frequency antenna mixing and polarization mixing (Tillard & Dubois, 1992).

Dealing with all these topics is impossible in the space available in this paper but two examples will be provided. One topic of interest is the use trace attribute analysis common in seismic processing (White, 1991). In this case a time series is decomposed using Hilbert transform and minimum phase assumptions into a real and imaginary time series from which the envelope and the frequency can be estimated at every point along the trace. Figure 9 shows the envelope of the data set originally shown in Figure 2. Figure 10 shows the instantaneous frequency computed for the same data set.

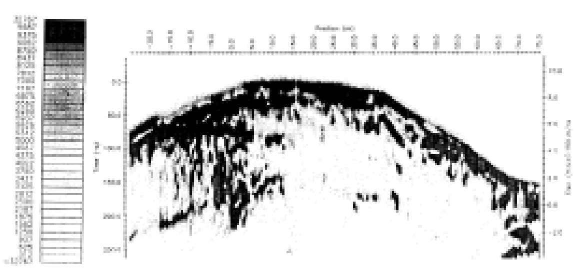

Figure 9: The amplitude envelope for data shown in Figure 2b. The envelope more accurately reflects the GPR resolution.

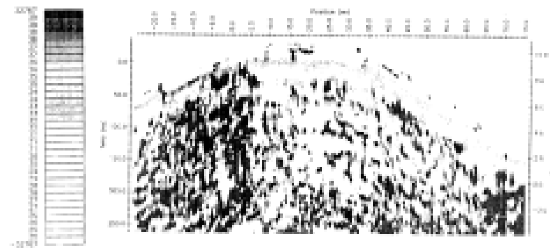

Figure 10: The instantaneous frequency for the data shown in Figure 2b. The instantaneous frequency tends to reflect the spatial scale of the radar targets.

The benefit of the envelope display is that it reflects the resolution of the data. One tends to get a false sense of resolution because of the oscillatory nature of the radar pulse. In fact the bandwidth or envelope of the pulse is what determines resolution not the time between zero crossings (which reflects the dominate frequency in the data). For this reason the envelope is extremely useful for generating more simple presentations which are representative of the data spatial resolution.

The instantaneous frequency can be a good indicator of certain types of features which selectively respond to the spectrum of the incident signal. An example of this is a thin layer in a stratigraphic sequence. If the layer is close to the thickness where the pulse spectrum is at the tuning frequency of the layer then an enhancement in the response of that particular frequency will occur. Instantaneous frequency gives a rough feel for the texture on spatial scale of the GPR signal scattering sources.

Examples of deconvolution and other types of filtering are given by Todoeschuck (1990) and Turner (1992) . It is important to note that deconvolution ("decon") of GPR data is not straight forward and has seldom yielded a great deal of benefit. Part of the reason for this is that the radar pulse is often as short and compressed as can be achieved for the given bandwidth and signal-to-noise conditions. Another important factor is that some of the more standard deconvolution procedures have underlying assumptions required for wavelet estimation such as minimum phase and stationarity which are not always appropriate for GPR data. The rapid decrease in GPR signal amplitude means that decon artifacts may mask weaker deeper events in time gain if not applied before decon and the non-linear nature of time gain may substantially alter wavelet character if gain is applied before decon. As a result decon can be both difficult to apply systematically and exhibit little enhancement in resolution. Instances where deconvolution has proven beneficial occurred when extraneous reverberation or possibly system reverberation have been involved. Deconvolution can then provide substantial pulse compression benefits.

One of the most common operations specifically applied to GPR data is the use of background removal. Most often this takes the form of a high pass filter or an average trace removal. More sophisticated approaches which yield similar results are orthogonal trace decomposition (Friere & Ulrych, 1988).

Average trace removal is a form of spatial filtering. In some situations where transmitter reverberation and time synchronous system artifacts appear it is very effective in allowing subtle weaker signals which are lost to become visible in a processed section. Figure 11 illustrates this concept with before and after sections where average trace removal has been applied. In this case, the target is shallow and the ground response is masked by the transmit pulse.

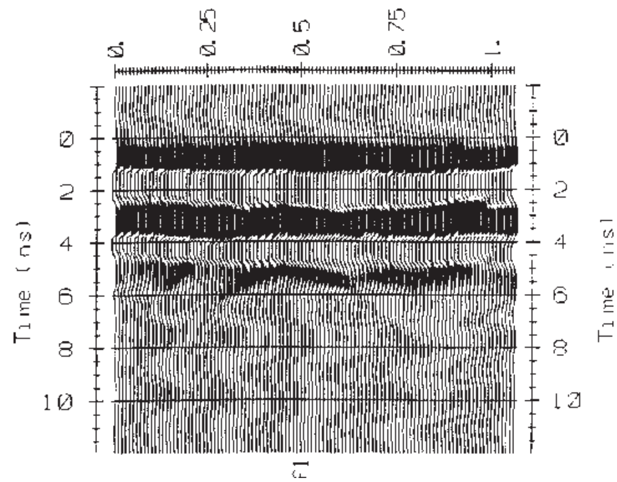

Figure 11a: Example of initial data set over a buried pipe.

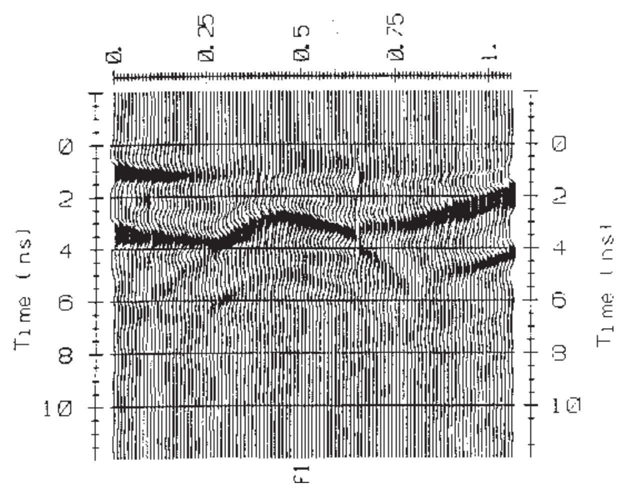

Figure 11b: Data set shown in a after the average trace for the whole section has been subtracted. The hyperbolic pipe response is clearly visible as are the gently sloping edges of the excavation.

The important feature of advanced processing is that it focuses on making weaker signals visible, enhances specific components of the data for an interpretation requirement, or derives quantitative information such as velocity and attenuation versus depth from the data. The advanced processing methods also have the potential of introducing artifacts in areas where there are no responses in the ground giving rise to specious interpretations. Considerable user insight is required when this type of processing is applied so that undue emphasis is not placed on artifacts induced in the response by the processing.

5. Visual/Interpretation Processing

Processing in this context is usually conducted when a good deal of information about a site is available and a need for the processing has been defined which achieves a final objective. Processing in this class will often result in data which are totally changed from the original data set. Furthermore the type of processing is usually subjective in the sense that there is some a priori bias in the processor's mind as to what end product is desired.

Processing in this class includes topics such as migration using various types of algorithm, event picking, subjective gain enhancement and amplitude analysis. All of these require completion of the previously mentioned processing steps and availability of corollary control information.

For example, migration is extremely useful and reconstructs the radar image in a form which is probably a better representation of the ground (Fisher et al, 1992b) Unfortunately migration requires a good knowledge of the velocity structure in the ground and a processor who is aware of the artifacts that migration introduces into the section. As a result it is dangerous in the hands of a novice but powerful in the hands of a processor who has acquired the ability to use it effectively and recognizes the limitations. Migration is often an interactive process as background velocity is adjusted to optimize the migrated result.

Figure 12 shows an example of data from a site before and after migration (Brewster, 1993). In this case the migration has been used to remove defractions from vertical sheet pile walls at the edge of the site. These metal sheets were driven down into the soil to act as a containment barrier. The reflections and scattering from these metal walls are visible across most of the cell and tend to mask some of the other features in the data set. Migration very conveniently removes the diffractions by placing these events back in the correct spatial location. While an enhancement is quite visible in the data, it is not easy to assess what distortion, if any, have been generated.

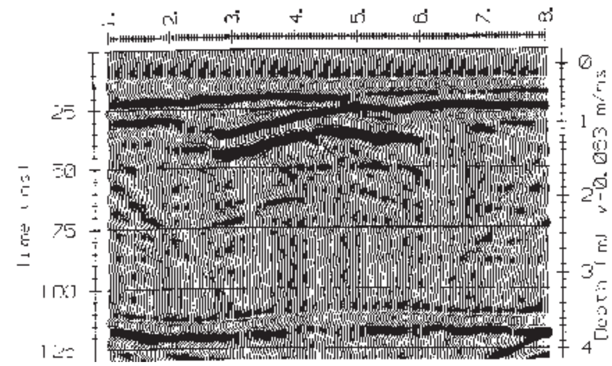

Figure 12a: Example of GPR data from a contaminated DNAPL spill. Note the dipping events which slope down from each end of the section associated with scattering from sheet pile containment walls driven into the ground.

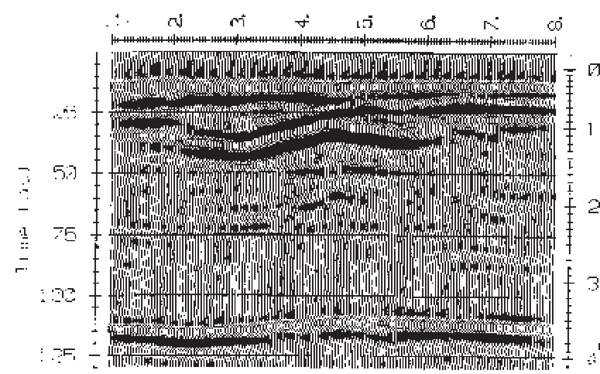

Figure 12b: Data in a after F-K migration. Note that the wall events have been migrated out of this section. The strong reflection between 2 and 6 m position at times of 25 to 40 ns is the return from a DNAPL pool.

The key to success in the migration process rests in having a good knowledge of the velocity section and quite often with single fold GPR data this information is not available. Migration is then very much at the discretion of the processor rather than controlled by the site conditions. Iterative migration by varying velocity structure to make the most acceptable (to the processor) result is common.

Another way of manipulating data is to pick events and display the reduced event data set. This is a very useful thing because it simplifies the data set and pulls out only those features which are deemed important. The important point to note is the very subjective and application dependent nature of the processing. Figure 13 shows the result of picking both amplitudes and arrival time data from a 2D grid of which Figure 12 shows one section to create a target depth versus position plot over an area. This information was subsequently used to estimate the volume of a DNAPL contaminant in the ground.

Pool 1 Topography, at 36 hours

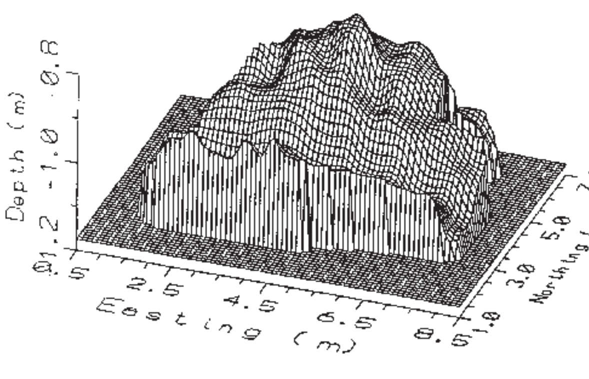

Figure 13: Depth to top of the DNAPL pool shown in Figure 12 based on an event picking grid of survey lines. Figure 12 shows the radar cross section at 5 east.

Visual/interpretation processing are most useful when one wants to move to 3D visualization of data versus space and time. For example, Figure 14 from Brewster (1993) shows a 3D view of DNAPL contamination pools for which data shown in Figure 12 and 13 were prior stages of processing. While raw data can be displayed this way, most often the essential information is enhanced and the rest of the information suppressed. Frequently the end product is the most easy to present to non-technical users. This is perhaps the most dangerous area of data processing in that the visualization may over simplify the problem and give a false impression of real conditions.

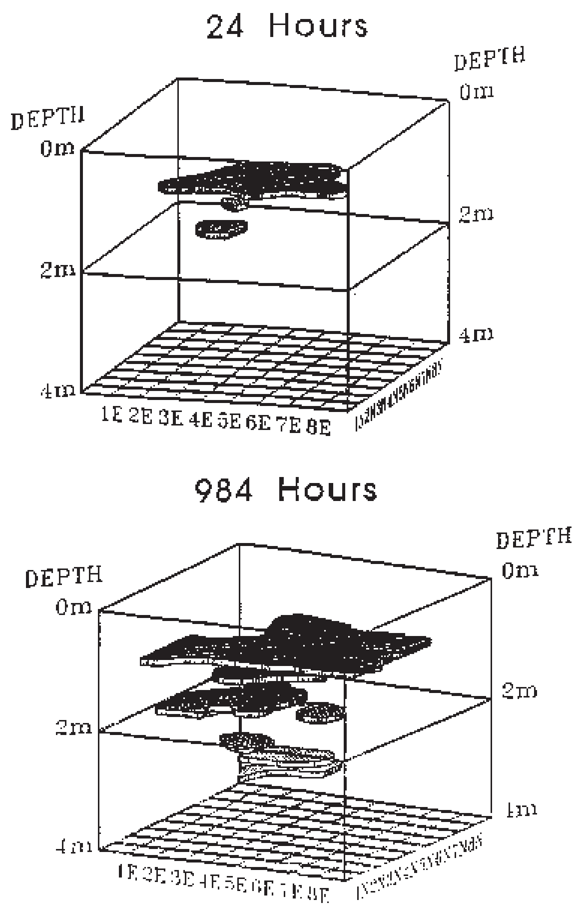

Figure 14: Simplified time and 3D spatial visualization of DNAPL pools based on procedures as illustrated by Figures 12 and 13.

6. Discussion

The preceding has provided a brief overview of the steps of data processing which are entailed in GPR analysis. As has been previously stated, the amount of processing can vary from none through to quite sophisticated analysis and manipulation.

As some of the simple processing steps presented here have vividly illustrated, processing can markedly alter the appearance of a data set. As a result it is very important that a processing trail be maintained for audit purposes. Since survey results in engineering and environmental projects may be used as evidence in legal proceedings, it is imperative that the means of creating a processed data set be reproducible. Figure 2 a) illustrates how the historical genesis of a processed data set is maintained in a commercial software package.

All of the processing methods discussed and display methods illustrated can be carried out on readily available personal computers with relatively low cost commercial software. Anyone who wishes to process GPR data can do so with a modest capital outlay.

Perhaps the most important fact that should be kept in mind is that there must be an end objective. For any GPR survey, a value of some sort is always attached to the survey objective. (Otherwise why do it in the first place??) However this value is defined, one must remember that processing entails time, resources and money. While people do not always recognize it, the biggest single cost is the human time entailed in data manipulation, data organization and thought. Usually this requires a reasonably well trained person whose time is not inexpensive. While computer costs must be considered, man power costs frequently exceed equipment costs.

Figure 15 shows a simplified chart of the above concepts. The vertical axis shows a value or a financial cost implication. The horizontal axis shows a measure of time elapsed during processing. As the degree of processing increases, the amount of time and hence costs increase.

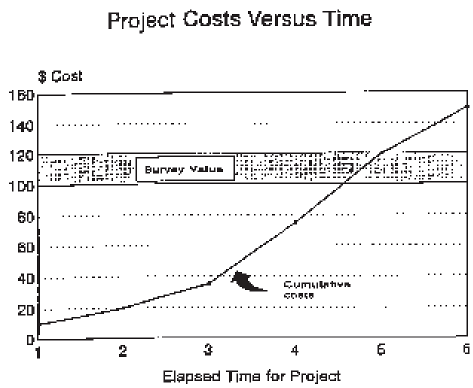

Figure 15: Illustration of how the value of a GPR survey is fixed while costs climb as time passes as will ensure if iterative and uncontrolled data processing occur.

It is important that this type of analysis be carried out before one does extensive GPR processing. By taking the survey value and dividing it by cost, one obtains a benefit-to-cost ratio and processing should not be carried on beyond the point where the benefit-to-cost ratio is one as indicated in Figure 16.

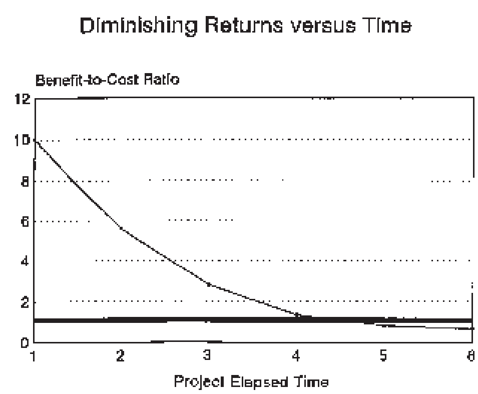

Figure 16: As time and processing increase, the benefit-to-cost ratio decreases. When the ratio approaches unity, the benefit of further processing and analysis becomes dubious.

Unlike some applications of geophysical methods such as petroleum or mineral exploration where quite large financial rewards exist at the end of the successful project, there are smaller and quite often much more poorly defined rewards at the end of engineering and environmental geophysics projects. Since this is the area where GPR finds its use most often, the benefit-to-cost ratio is one which has to be kept in mind and frequently approaches unity early in the data processing scheme.

While research institutions and government agencies with unconstrained man-power and resource availability can carry out much more advanced processing, many commercial applications often have benefit-to-cost ratios such that the processing is terminated at the field acquisition step. In other words, no processing is done!!

7. Conclusions

The preceding has been an attempt to provide an overview of the current state-of-practice of ground penetrating radar data processing. While less than an exhaustive treatise, the important points that should be noted are the following:

a) GPR data processing is within the financial and technical reach of anyone who wishes to process data, not just the few who have extensive high power computing facilities and software development resources.
b) Many of the vast array of reflection seismic processing techniques can used directly on GPR data.
c) GPR data are not totally identical to seismic data and there are GPR specific processing techniques.
d) An audit trail should be an integral part of any data processing program.
e) Data processing has to have a cost benefit and, for many GPR projects, processing is cost limited rather than technology or methodology limited.

The processing of GPR data is still truly in its infancy. The flood gates are opening to GPR world wide and there is an explosive growth in GPR awareness. These factors will feed a growth in GPR processing because more and better GPR results will be obtained, advances in processing and presentation will occur, processing costs will decrease and a higher value will be placed on GPR results. The cost benefits of processing will become easier to establish and hence processing will be more readily justifiable and more frequently used.

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