



Crustal Imaging and Characterization Team

GP Workbench Manual: Technical Manual, User's Guide, and Software Guide

By Charles P. Oden and Craig W. Moulton

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Introduction

GP Workbench is a general-purpose geophysical data processing program written primarily for ground penetrating radar (GPR) data, and also includes support for several USGS prototype electromagnetic instruments. The two main programs in the package are *GP Workbench* and *GP Wave Utilities*. *GP Workbench* provides the standard two-dimensional (section view) and three-dimensional (plan view) processing for GPR data, as well as some research features. *GP Workbench* can produce high-quality graphics for reports when *Surfer 8* or higher (Golden Software, Inc., Golden, CO, not included) is installed. *GP Wave Utilities* provides a wide range of processing algorithms for single waveforms. *GP Wave Utilities* is used primarily for calibrating radar systems and processing individual traces. Both programs are written to run on the Windows™ operating systems. This release of *GP Workbench* contains an install program called *InstallGPWorkbench1_7_1_11.exe*. Run this installation program to install *GP Workbench* and associated programs to a Windows operating system. The source code for the project can be found in the self-extracting zip-file *GPWorkbench1_7_1_11.exe*. See Appendix B for more information about compiling *GP Workbench*.

GP Workbench can import GPR data file formats used by major commercial instrument manufacturers including Sensors and Software, GSSI, and Mala. *GP Workbench* also supports data file

formats for some USGS systems such as the VETEM system (Wright and Chew, 2000), the ALLTEM system (Wright et al., 2006), and the RTDGPR system (Wright et al., 2005). The native file format is SU (Seismic Unix, Cohen and Stockwell, 2003). Files generated by *GP Workbench* can be read by SU as well as many other data processing packages.

The intent of releasing this software is not to duplicate the commercial GPR processing packages, but to provide a framework for researchers to test and implement new processing algorithms. These programs provide a toolbox that is applicable to a wide range of equipment and problems. By adding to the source code provided here, scientists can investigate new processing algorithms. Both *GP Workbench* and *GP Wave Utilities* were written with Microsoft Visual C++ 6.0. The source code files extracted from *GPWorkbench1_6_5_22.exe* are organized into two main project directories (one for each program) in the standard manner for Visual C++ projects. An easily distributable installation program is generated using the freely available Inno Setup Compiler (Russel, 2004). A few functions rely on programs and code that were written by others. A GPR forward modeling program (Powers, 1995) was modified and included. Some data structures and a program to summarize information in GPR file headers were adapted from Lucius and Powers (2002). The *prjpt.exe* program (Webring, 1998) facilitates conversions from latitude and longitude to northing and easting (or vice versa). Some wavelet transform functions were adapted from Press et al. (1992). The MatClass library (Birchenhall, 1993) is used for matrix calculations. *GP Workbench* uses a Windows™ automation interface to Golden Software's *Surfer 8* package (not included) to generate high-quality plan views of time-slice data. Finally, note that the structural organization of the software is not optimal, and that individual routines have not been optimized for speed. Although the software is object oriented, strict adherence to object-oriented programming methodologies has not been followed. The only conventions followed are to write in an active voice and to use 'Hungarian notation' in naming variables.

GP Workbench uses a right-handed Cartesian coordinate system. In the instrument reference frame, the x-axis is directed to the right of the survey line, the y-axis is directed along the survey line, and the z-axis is directed upwards. In the map reference frame, the x-axis is in the direction of easting, the y-axis is in the direction of northing, and the z-axis is directed upwards. When the bearing of the survey instrument is zero degrees, the instrument reference frame and the map reference frame are identical. Unless otherwise noted, frequencies are in megahertz (MHz), time is in nanoseconds (ns), and position is in meters (m).

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GP Workbench Views

An entire survey can be loaded and examined in section view or plan view. The section view provides hyperbola fitting for velocity analysis, zooming in time or position, and panning. Waveforms are displayed at mouse click position as well as time and depth to reflector. Figure 1 shows an example of the section view. The small vertical red lines at the top of the section indicate marked traces (i.e., traces with a known position). The cursor index values shown in the legend are the trace number and sample number at the current cross hair position.

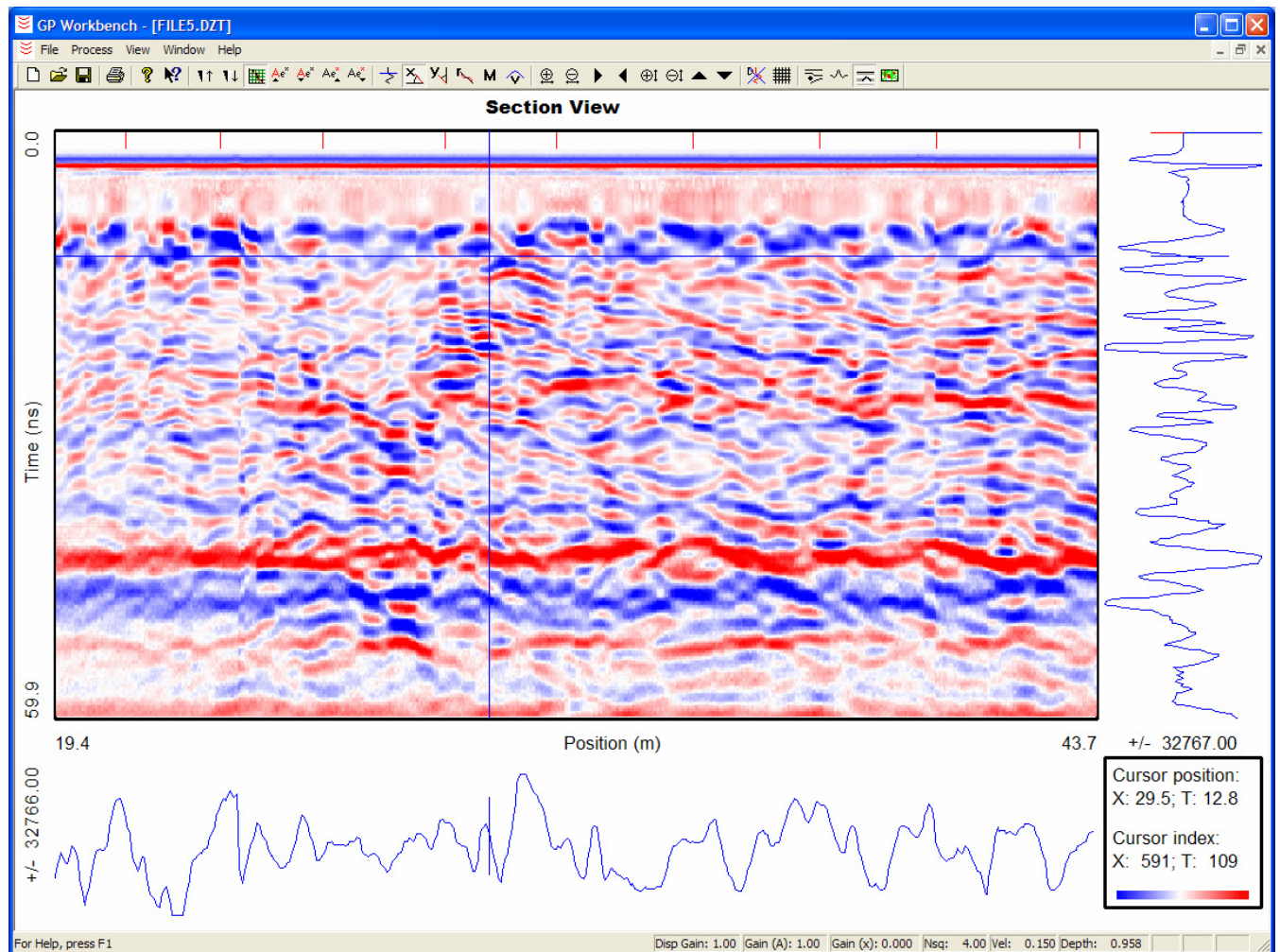


Figure 1. An example of the section view.

An example of the plan view is shown in figure 2. The legend shows the time of the current time slice and the position at the cross hairs. The cross hairs are placed by clicking on the image with the mouse. Several plan view imaging methods are available with varying quality and speed. The ungridded method is the fastest but provides a low-quality image. The gridded method displays an image that is the result of a conical filter applied to the data (see Grid Parameters in the Menu and Toolbar Functions Section). The final method uses Surfer (Golden Software) to produce a high quality image.

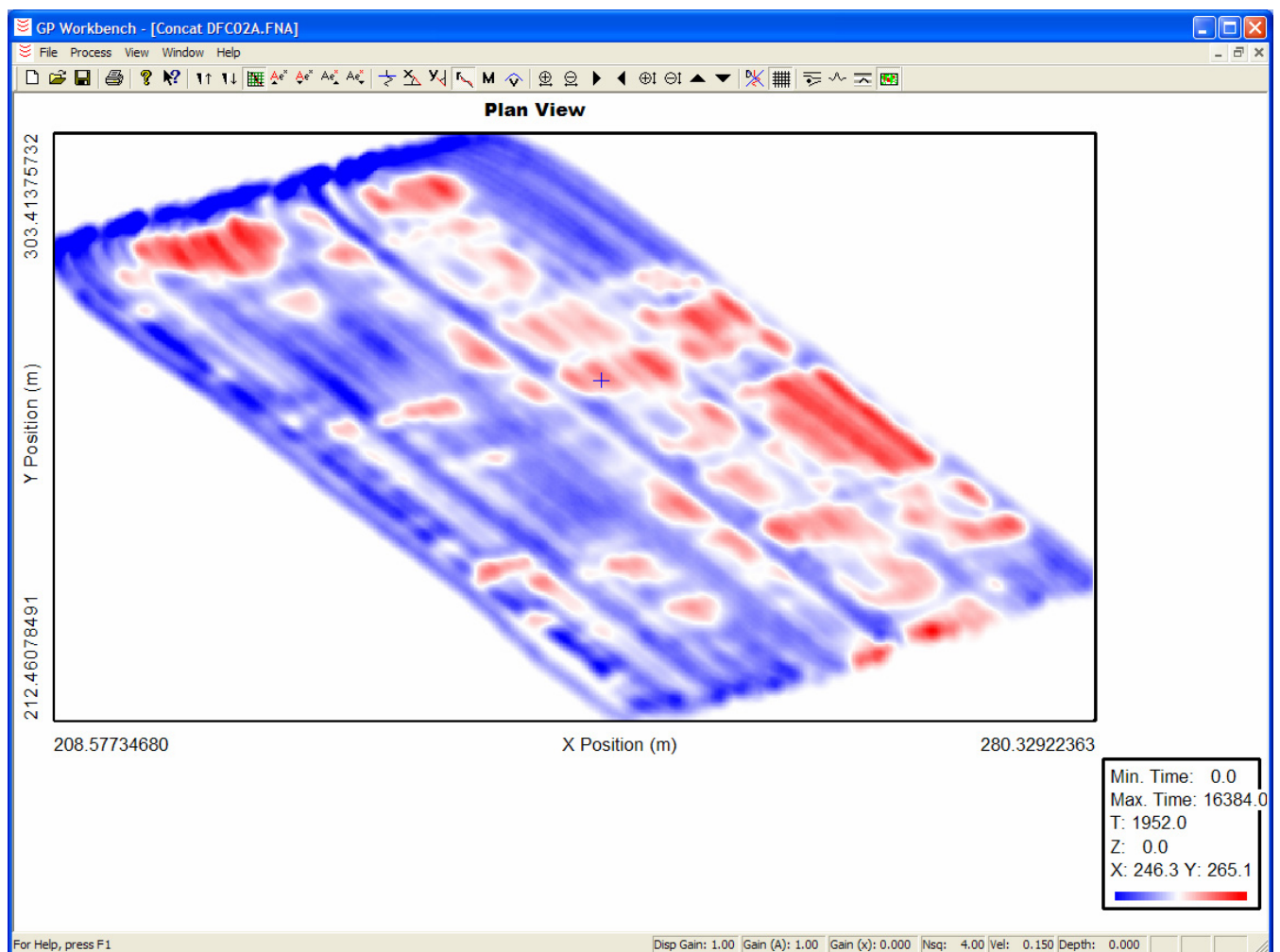


Figure 2. An example of section view.

Menu and Toolbar Functions

This section provides an overview of the *GP Workbench* menu commands and toolbar buttons. When the mouse pointer is placed over a menu command or a toolbar button, a help message appears in the status bar at the bottom of the screen that describes the function of the menu item or button. Additionally, a flying help message appears when the mouse pointer is placed over a toolbar button.

File Menu

The *File* menu contains the standard menu items offered by most Windows applications. A new document can be created or saved, and recent files can be opened. The page for printing can be set up, documents can be printed, and the printout can be previewed. Non-standard Windows menu items are described below.

Import

The Import and Export menu items offer additional functions. The *Import, Survey Line (section view)* and *Import, 3D Survey (plan view)* menu items allow the user to select and import data files with various formats as listed in table 1.

Table 1. A listing of file types that can be imported with *GP Workbench*.

| File Type (extension) | Format Description |
|----------------------------|----------------------|
| *.su, *.txt | Generic data formats |
| *.dzt | GSSI |
| *.dt1 | Sensors and Software |
| *.rd3 | Mala |
| *.fna | VETEM (USGS) |
| *.aq1, *.aq2 | RTDGPR (USGS) |
| *.uxa, *.uxb, *.h1m, *.zzm | ALLTEM (USGS) |

Data are saved in the *.SU format (see Seismic Unix, Cohen and Stockwell, 2003). Note that the trace identification code used in GP Workbench *.SU files ranges from 200 to 202, whereas most seismic programs use an identification code of 1. This difference may cause some difficulties when opening GP Workbench *.SU files with other programs. Also, note that *.SGY files, which are an industry standard in the seismic industry, have the same format as *.SU files with the exception of an added header at the beginning of the file. The *Survey Line (section view)* menu option imports data and displays it in section view, while the *3D Survey (plan view)* option imports and displays data in plan view. In plan view, a data value recorded at a given time is displayed for each trace as a function of lateral position. The display time of the view can be adjusted using the up and down arrow keys, so that the user can observe the data in plan view while moving forward or backward in time.

The position of each trace recorded by a prototype USGS instrument has an associated Global Positioning System (GPS) record. The GPS records contain the latitude and longitude of the instrument when each trace was recorded. The latitude and longitude of each trace is converted to northing and easting during the import process. When importing files containing GPS data, the import routines look for a file called Import.txt in the same directory as the data files being imported. This file contains information specifying how to convert from latitude and longitude to northing and easting. The specification of this conversion is location specific. If this file is not found, the assumed location is the Denver Federal Center in Lakewood, Colorado. A simple linear relation is used for the conversion. This linear relationship is usually sufficient when the lateral survey dimensions are less than a kilometer. The contents of the Import.txt file are shown below.

Listing 1. Import.txt.

```
GPRWorkbench Import File v. 1.0
LocationName=YPG
LatitudeReference=32.8531143
LongitudeReference=114.2466241
LatitudeFactor=108474.8000000
LongitudeFactor=-96491.387000
```

NorthingOffset=13.681
EastingOffset=15.363

The following relationships are used in the conversion:

$$\text{Northing} = (\text{Latitude} - \text{LatitudeReference}) \cdot \text{LatitudeFactor} - \text{NorthingOffset} \quad (1)$$

$$\text{Easting} = (\text{Longitude} - \text{LongitudeReference}) \cdot \text{LongitudeFactor} - \text{EastingOffset} \quad (2)$$

The program *prjpt.exe* (Webring, 1998) can be used to convert latitude and longitude to UTM (universal transverse mercator) coordinates.

Multiple files can be selected for importing. When selecting multiple files, note the order that the files are listed in the File Name edit box of the *Open* dialog box. The files will be imported and concatenated in the order they appear in this edit box. File concatenation is helpful for some data processing procedures, especially when combined with a filter operation (filters are described below). For example, the response to local geology that has been recorded in one file can be subtracted from the response of a target buried in similar geology that has been recorded in another file.

Export

The *Export, Section Data* menu item exports section view data to a *.csv text file that can be imported by other applications for further processing. The *Export, Time Slice XYZ* menu item exports data at the currently displayed time slice to a *.csv text file that can be imported by other applications for further processing.

ALLTEM Data

When working with ALLTEM data, some File Menu commands have enhanced functionality. Surveys with the ALLTEM system typically produce multiple data files with different combinations of coil polarizations. *GP Workbench* can open, close, save, and process these files simultaneously or

individually. Files with extensions *.h1m or *.zsm are considered master ALLTEM files, and the others are called associated ALLTEM files. To work with these files simultaneously, open, close, save, or process a master file; *GP Workbench* will ask if you want to make the same operation on the associated files. The files associated with a given ALLTEM master file are defined in the file ALLTEM.def that is located in the same directory as the master file. A sample listing of this file is given below. Note that ALLTEM.def is a standard Windows section file, and therefore comments can be included as long as the first character in a comment line is a semicolon.

Listing 2. ALLTEM.def.

```
[ALLTEM_System_Definition]
Number_of_polarization_combinations=7
Master_file_extension=h1m
StaticSample1=313
StaticSample2=868
PeakSample1=337
PeakSample2=892

[Combination_1]
File_extension=h1m
TX_polarity=z
RX_polarity=z
Cart_center_height=0.678
RX_midpoint_position_x=0.0
RX_midpoint_position_y=0.0
RX_midpoint_position_z=0.0
RX_offset_x=0.0
RX_offset_y=0.0
RX_offset_z=0.5

[Combination_2]
File_extension=hbl
TX_polarity=z
RX_polarity=z
Cart_center_height=0.678
RX_midpoint_position_x=-0.25
RX_midpoint_position_y=-0.25
RX_midpoint_position_z=0.0
RX_offset_x=0.0
RX_offset_y=0.0
RX_offset_z=0.5

[Combination_3]
File_extension=hbr
TX_polarity=z
```

RX_polarity=z
Cart_center_height=0.678
RX_midpoint_position_x=0.25
RX_midpoint_position_y=-0.25
RX_midpoint_position_z=0.0
RX_offset_x=0.0
RX_offset_y=0.0
RX_offset_z=0.5

[Combination_4]
File_extension=hfl
TX_polarity=z
RX_polarity=z
Cart_center_height=0.678
RX_midpoint_position_x=-0.25
RX_midpoint_position_y=0.25
RX_midpoint_position_z=0.0
RX_offset_x=0.0
RX_offset_y=0.0
RX_offset_z=0.5

[Combination_5]
File_extension=hfr
TX_polarity=z
RX_polarity=z
Cart_center_height=0.678
RX_midpoint_position_x=0.25
RX_midpoint_position_y=0.25
RX_midpoint_position_z=0.0
RX_offset_x=0.0
RX_offset_y=0.0
RX_offset_z=0.5

[Combination_6]
File_extension=vlr
TX_polarity=y
RX_polarity=y
Cart_center_height=0.678
RX_midpoint_position_x=0.0
RX_midpoint_position_y=0.0
RX_midpoint_position_z=0.28
RX_offset_x=0.0
RX_offset_y=0.5
RX_offset_z=0.0

[Combination_7]
File_extension=vfb
TX_polarity=x
RX_polarity=x
Cart_center_height=0.678
RX_midpoint_position_x=0.0
RX_midpoint_position_y=0.0
RX_midpoint_position_z=0.28
RX_offset_x=0.5
RX_offset_y=0.0
RX_offset_z=0.0

This listing also shows the default settings that are used when this file does not exist in the same directory as the master file. The definitions in this file are used to calculate the coil locations and polarizations that were used when recording data files with the indicated extension. The location of each coil is specified with respect to the X-Y location (easting and northing respectively) of the center of the ALLTEM cube (Z is positive up); the transmitter coils are 1-meter-square loops centered about the center of the cube with the indicated polarization (TX_polarity). The center of the differential receiver coil pairs are specified by the RX_midpoint_position entry, and the location of each individual coil is found by adding or subtracting the RX_offset value from the midpoint of the coil pair.

Process Menu

The *Process* menu contains a variety of commands, which are used to make calculations on existing data and to generate new data.

Grid Parameters

The first Process Menu item, *Grid Parameters*, controls the processing steps used in processing the position information associated with each trace. In many surveys, the position of the instrument is not measured for each trace that is recorded. Rather, the positions of a few traces are recorded, and the remaining trace positions are determined using one of the methods described in table 2. This process is referred to as gridding. The *Grid Parameters Dialog* box shown in figure 3 controls how the positions of all traces are calculated. This dialog box writes an *.xyz file (same file name as imported data file) that describes how the trace positions are to be calculated when the grid button (see toolbar) is pressed. The *.xyz file is a text file that typically contains the positions of each marked trace or of each trace. Since this file is a text file, it can be edited as needed. When viewing imported or un-gridded data, the measured locations (or marked positions) are displayed as red marks at the top of each section view.

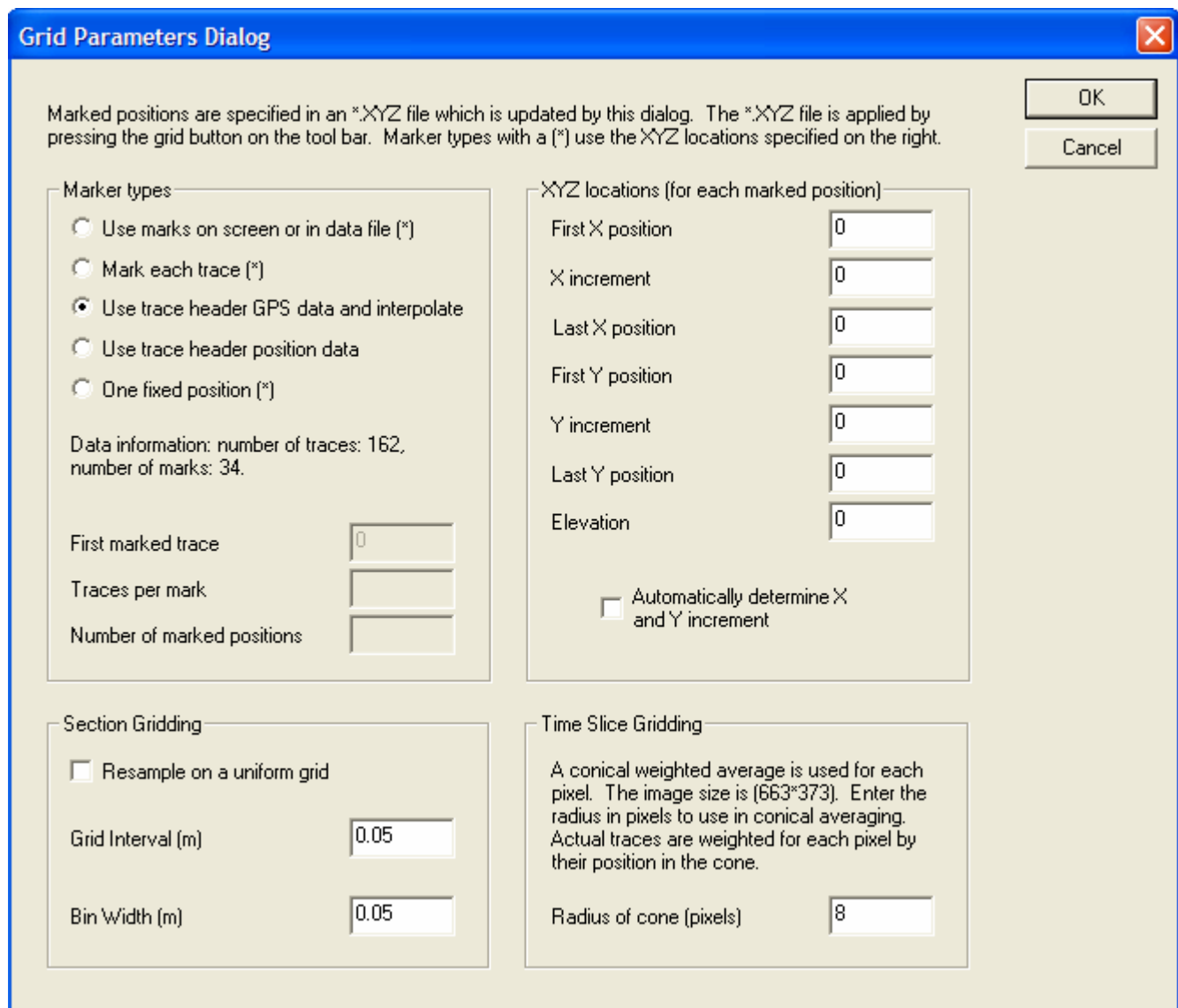


Figure 3. The *Grid Parameters Dialog* box.



After setting the gridding parameters with the above dialog box, press the grid button  on the toolbar to grid the document.

Table 2. Gridding methods.

| Method | Description |
|---|--|
| Use marks on screen or in data file | An entry in the *.xyz file is made corresponding to each mark in the data file (and on screen). The marked XYZ positions are specified by the XYZ locations part of the dialog. The location of unmarked traces is determined by linear interpolation between marked traces. |
| Mark each trace | An entry in the *.xyz file is made corresponding to each trace in the data file (and on screen). The marked XYZ positions are specified by the XYZ locations part of the dialog. |
| Use trace header GPS data and interpolate | The location of unmarked traces is determined by linear interpolation between traces with known GPS positions. |
| Use trace header position in data | The location of each mark or trace is determined by the information in each trace header. Some data file formats provide a position for each trace, or for marked traces. If unmarked traces exist, the location of unmarked traces is determined by linear interpolation between marked traces. |
| One fixed position | Use the same position for all traces in the data file. |

In many cases, geophysical data are not sampled on a uniform grid. Some processing algorithms such as fast Fourier transforms require data that are sampled on a uniform grid. Check the *resample on a uniform grid* box to resample the data on a uniform grid. After an XYZ position has been calculated for each trace using one of the methods described above, a new trace for each uniformly spaced grid point is calculated by interpolating between the recorded traces at their recorded positions. This is a simple amplitude interpolation made independently at each time sample. This method of resampling can cause distortion in the waveforms. Interpolating the waveforms in the frequency domain yields better results. The frequency-domain interpolation will be implemented in a future release. The grid interval specifies the interval (in meters) between adjacent resampled traces. The bin width specifies the width (in meters) of a moving window that is used to calculate the re-sampled trace. For each uniformly spaced grid point, the window is centered on the grid point, and all original traces in the window are averaged with equal weighting to obtain the resampled trace.

When gridding a master ALLTEM document (has an *.h1m or *.zzm extension), *GP Workbench* asks the user if the associated ALLTEM documents should also be gridded (see the File Menu Section for a description of associated ALLTEM documents). Note that a single grid file (*.xyz) is used for the master ALLTEM document and the associated documents. To use different gridding parameters with each ALLTEM document, each document must be gridded separately. In this case, select the document to be gridded (*Window* menu), make a grid file (*.xyz) for the current document (*Process, Grid Parameters*), and then press the grid button . Repeat for each document.

The grid files (*.xyz) are ASCII text files that can be edited with a standard text file editor such as *Notepad*. A typical grid file is shown below. The first line of the file must be exactly as shown.

Listing 3. Grid Parameters (*.xyz) file.

```
GPR Workbench Mark File v.1.0
G
  0.000      0.000      0.000
```

The second line describes the data to follow. Valid entries on the second line are described in the table 3. The lines following line two contain the X-Y-Z coordinates for each trace or marked trace.

When gridding a plan view of a time slice, the position of unmarked traces is determined by interpolating between the known positions of marked traces. The plan view gridded image is result of a conical filter applied to all of the data in screen pixel space. The radius of the conical filter is specified with the *Grid Parameters Dialog* box. This radius is specified in virtual screen pixels, where the image is plotted on an area of 663 by 373 virtual screen pixels. The value of each screen pixel is the weighted average of all traces at the current time-slice value that fall within the radius of the filter's conical window. The weighted value of each trace depends on where it lies under the conical window. The conical window has a maximum value of one at the center, and zero at the outside radius. Note that this conical filter is only used to display the data, and that no changes are made to the data with this gridding operation.

Table 3. Grid file (*.xyz) entries.

| Line Two Entry | Description |
|----------------|--|
| M | File contains the position of each marked trace. The position of each marked trace is listed on the following lines. |
| MR | As above, and the data will be resampled on a uniformly spaced grid. |
| T | File contains the positions for each trace. The position of each trace is listed on the following lines. |
| TR | As above, and the data will be resampled on a uniformly spaced grid. |
| G | Use the GPR positions in the data file for each marked trace. When importing data with GPR positions, a trace is marked when its position differs from that of the previous trace. Lines following line two are ignored. Note that the entries in the file Import.txt are used to convert from latitude and longitude to northing and easting. This option is used primarily for USGS prototype instruments. |
| GR | As above, and the data will be resampled on a uniformly spaced grid. |
| H | The position information in the file's trace header is used to determine the position of each trace. Lines following line two are ignored. |
| HR | As above, and the data will be resampled on a uniformly spaced grid. |
| F | Line three contains a position that will be used for all traces. |
| FH | As above, and the data will be resampled on a uniformly spaced grid. |

Position Shift

The *Process, Position Shift* menu item facilitates a positional shift of all traces in the current document. This operation is useful, for example, to account for an offset between the GPS position sensor and the instrument's measurement point. After selecting this menu item, the user is presented with a dialog box in which the shifts along the x-axis (easting) and y-axis (northing) can be entered. When applying a position shift to a master ALLTEM document (has an *.h1m or *.zzm extension), *GP Workbench* asks the user if the associated ALLTEM documents should also be shifted (see the File Menu Section for a description of associated ALLTEM documents).

Filter

The *Process, Filter* menu item opens the dialog box shown in figure 4. The *Filter Dialog* box can be used to filter section view documents or plan view documents. Seven filter types are offered –

three spatial filters, three temporal filters, and trace filtering. All filters operate on all traces in a document.

To remove the entire spatial background, GP Workbench calculates the background value of all traces in the document and subtracts the background trace from each trace. The background trace can be the average value of all traces, the median value of all traces, or the RMS value of all the traces. The average, median, or RMS values are calculated for each sample time included in the traces. Spatial filters are a function of the trace number. The trace number (beginning with zero) is assigned

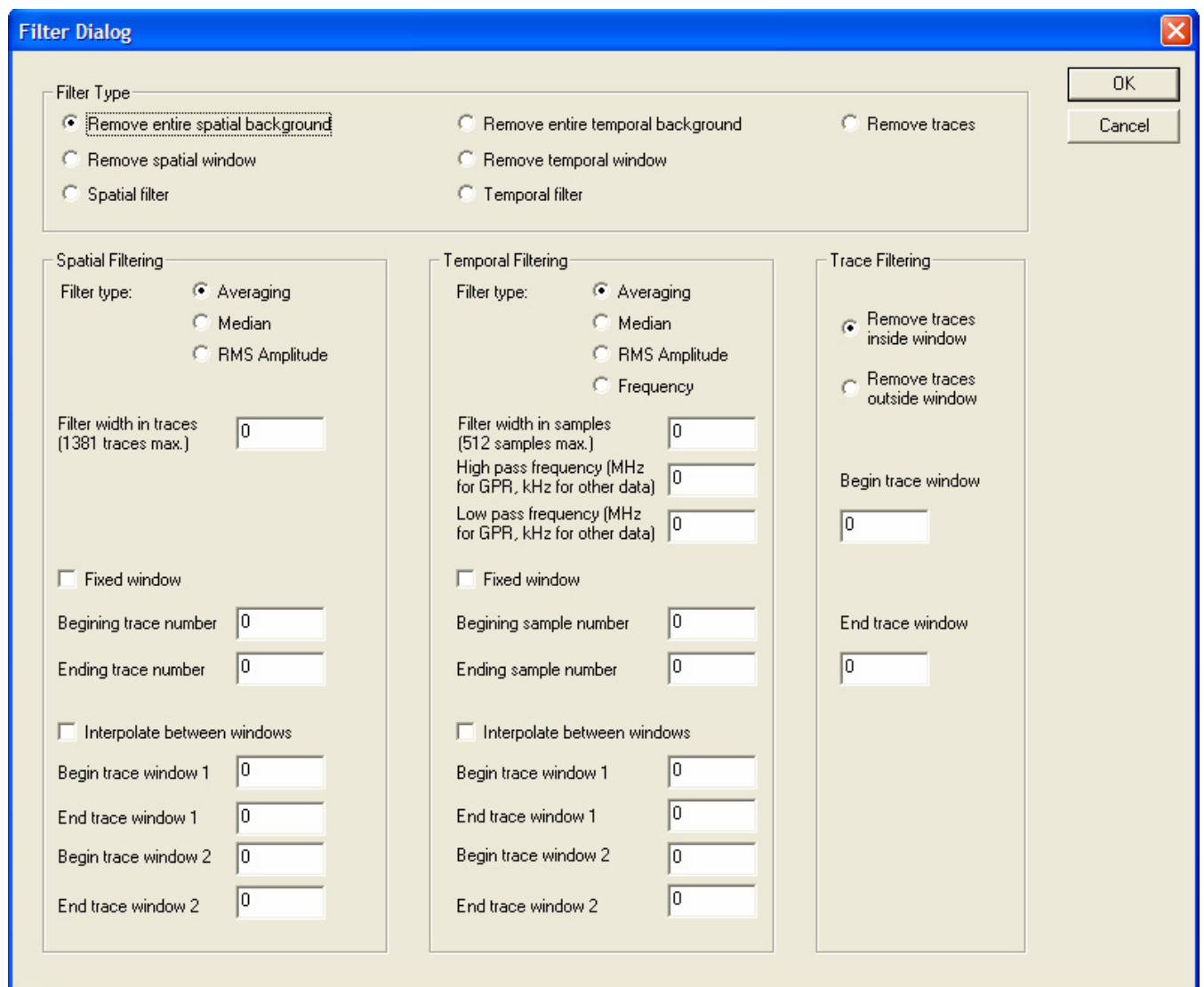


Figure 4. The *Filter Dialog* box.

sequentially to each trace when a data file is opened or imported. When *removing a spatial window*, a background trace is subtracted from each trace. The traces used to calculate the background trace can be taken from a moving window (specify *filter width in traces*) or a fixed window (check *fixed window* box and enter beginning and ending trace number). Alternatively, the trace number can be used to calculate an interpolated background trace between two fixed windows. The midpoint trace number of each fixed window is used as the endpoints in the interpolation.

A set of temporal filters is also available. Specification of these filters is analogous to the spatial filters, except that the temporal filters are functions of time or sample number. Additionally, frequency filters are available. The frequency filters are 100-point FIR (finite impulse response) filters. The high pass and low pass cutoff frequencies can be specified to realize high pass, low pass, or band pass filters. No high (low) pass filter operation is performed if the high (low) pass cutoff frequency is zero.

The final filter type can be used to remove traces from a document. This is useful, for instance, when isolating data containing the response to a single buried target to invert for target attributes. Specify the beginning and ending traces of a window, and delete the traces inside or outside this window.



Variogram

The next menu item, *Process, Variogram*, can be used to generate a horizontal semi-variogram image of the data. See Olhoeft (1994) for details on how the semi-variogram is calculated. The user will be prompted for the minimum and maximum range values to use in calculating the horizontal variogram. The document must be gridded to enable this menu item.

View Header

The *Process, View Header (GPR_RHDR)* command invokes the *GPR_RHDR.exe* utility (Lucius and Powers, 2002). This utility can be used to view the contents of GPR data files from most commercial manufacturers. File headers commonly have valuable information such as spatial sample interval, temporal sample interval, number of samples, and notes about the survey site. *GPR_RHDR.exe* does not return information about USGS prototype equipment.

GPR Forward Model

The *Process, GPR Forward Model* command invokes the 2.5 dimensional GPR modeling program called *2DRadar.exe* (Powers, 1995). After choosing a *.2DP input parameter file for *2DRadar*, a status screen displays progress as the program executes. The *.2DP file specifies the model geometry and material properties of the subsurface. The simulation generates a synthetic dataset that is displayed in section view. *2DRadar* can be used to simulate GPR data profiles for user-specified scenarios such as buried pipes in various media types, sand lenses, etc. After the simulation has completed, press the model view  and section view  buttons on the tool bar to change between views of the model used to generate the section data, and the section data. Consult Powers (1995) for more information on the *.2DP parameter files and the simulation method. Some example *.2DP files can be found in the directory where *GP Workbench* has been installed.

Migrate

The *Process, Migrate* command allows one of several frequency-domain migration techniques to be applied to the data. Note that the data must be gridded before migration is allowed. All of the migration techniques are based on the frequency-wavenumber method (Gazdag, 1978). The material properties of the background medium must be known for frequency-wavenumber migration. The

dielectric permittivity and magnetic permeability are frequency dependent quantities, and are specified in terms of the Cole-Cole distribution (Olhoeft, 1985). Four variations on the frequency-wavenumber method are available (see fig. 5). The first method uses fixed values for the dielectric permittivity and magnetic permeability. The fixed values are taken as the DC or zero frequency values from the Cole-Cole distribution. According to the Kramers-Kronig relations (Jackson, 1999), if a medium has a frequency-dependent propagation velocity, then it must also have frequency-dependent attenuation. The second migration method accounts for the frequency-dependent velocity, but not the frequency-dependent attenuation. The third migration method attempts to replace lost signal amplitude due to

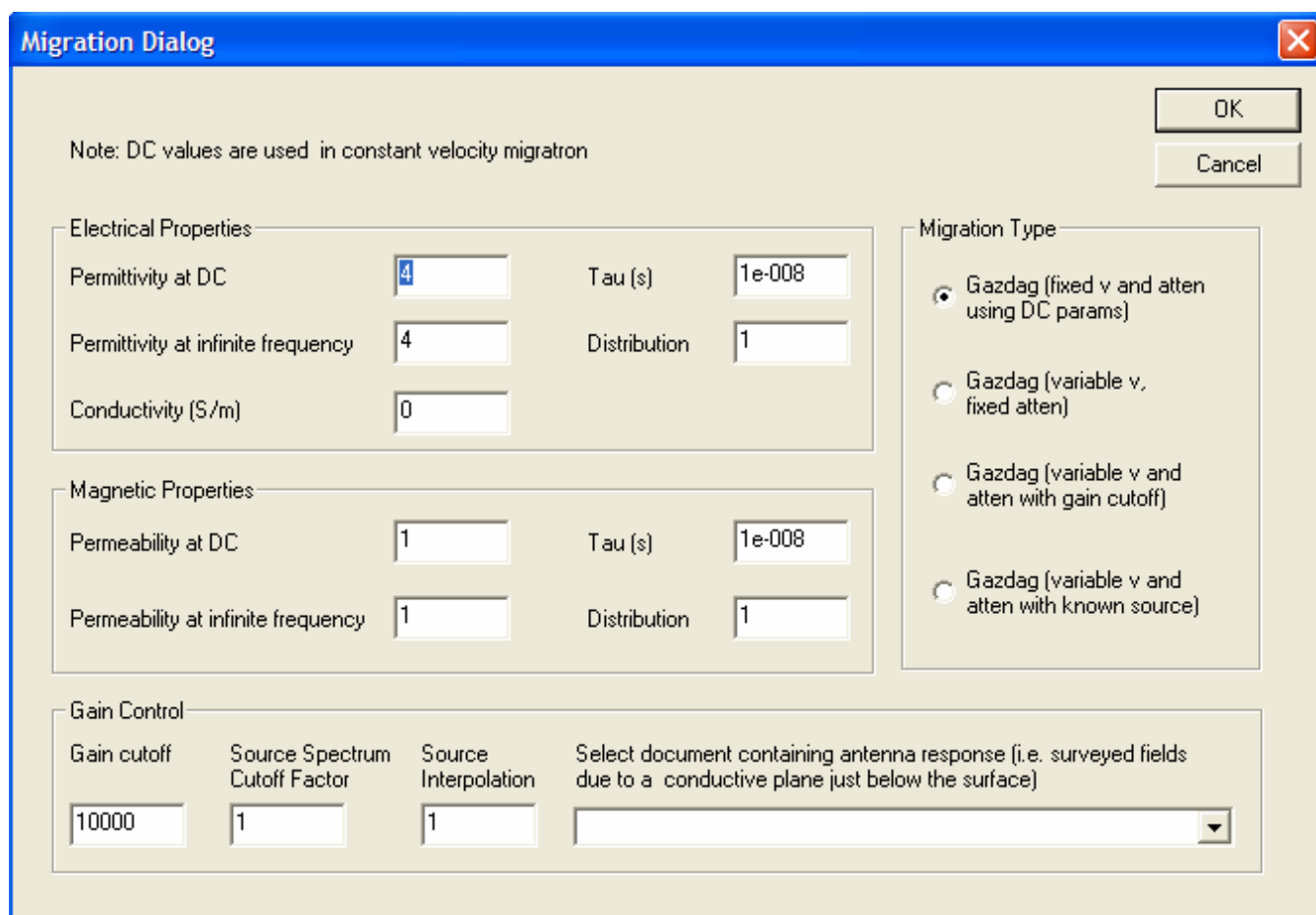


Figure 5. The *Migration Dialog* box.

propagation in lossy media (Powers and Oden, 2004). Reversing attenuation during migration is an unstable process, and a gain cutoff must be used to prevent over-amplification of noise. Entering a smaller number for the gain cutoff reduces the amount of reverse attenuation that is applied. Using a gain cutoff that is too small results in no reversal of attenuation, while using a cutoff value that is too large results in an image dominated by noise.

The final migration method uses knowledge of the source spectrum to limit the gain during the reverse attenuation operation (Oden, 2006; Oden et al., 2006). This gain-limiting scheme produces a higher resolution migrated image when working in lossy media. This scheme also prevents the over-amplification of noise that would otherwise degrade the migrated image quality. To use this migration scheme, a document must be open that contains the system response waveform. The system response waveform is defined as the response of the system to an infinite horizontal conductive sheet that is buried in the ground just deep enough that it does not affect the current distribution on the GPR antennas. The system response can be determined through calibration, simulations, or experimental measurements (see Oden, 2006, for more details). During migration, the gain is limited by a frequency-domain limiting spectrum. This limiting spectrum is usually the system response (when the *source interpolation* is one). Choosing a *source interpolation* value closer to zero adjusts the limiting spectrum to be more like the received spectrum (i.e., the recorded data). Choosing a *source spectrum cutoff factor* greater than one (one is the usual setting) allows more amplification before gain limiting begins. This limited-gain migration algorithm is described in more detail in Oden (2006).

UXO Forward Model

The *Process, UXO Forward Model* menu item generates an ALLTEM synthetic dataset for a UXO (unexploded ordinance) target. The induced magneto-static fields in the UXO target can be described by three orthogonal dipoles. Similarly, the magnetic fields at a given moment in time

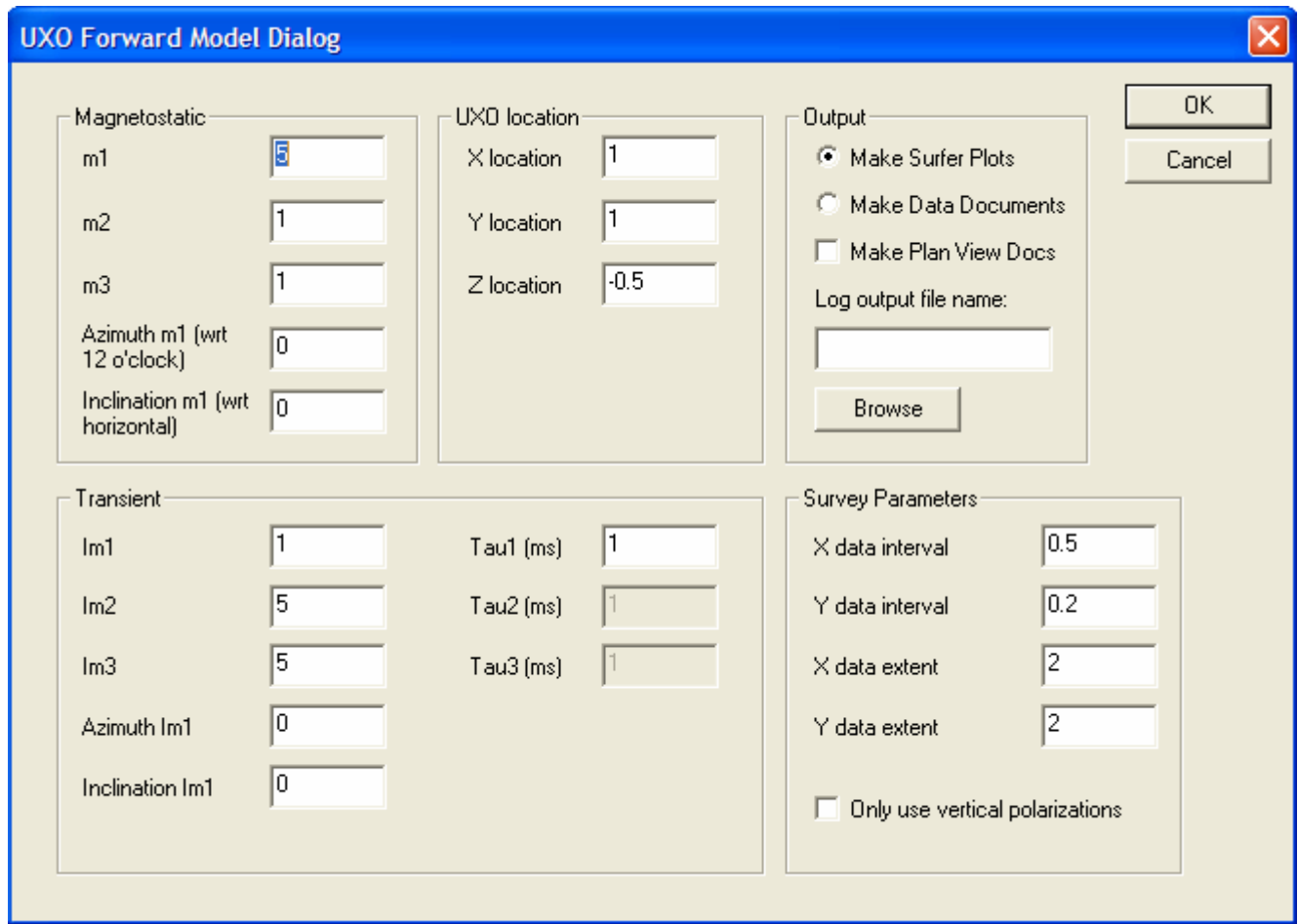


Figure 6. The *UXO Forward Model Dialog* box.

produced by the induced electro-dynamic response can be described by three orthogonal dipoles. The *UXO Forward Model Dialog* box is shown in figure 6. For the induced magneto-static response, the strengths of the three principal polarizability components are specified. The attitude of the first principal polarizability ($\hat{\mathbf{m}}_1$) is described in terms of azimuth and inclination from horizontal, the principal polarizability is horizontal ($\hat{\mathbf{m}}_2 = \hat{\mathbf{m}}_1 \times \hat{\mathbf{z}}$), and the attitude of the third principal polarizability is the cross product of the first two ($\hat{\mathbf{m}}_3 = \hat{\mathbf{m}}_1 \times \hat{\mathbf{m}}_2$). The location of the UXO can be specified, as well as the survey parameters. The survey parameters describe the spatial data density of the simulated data.

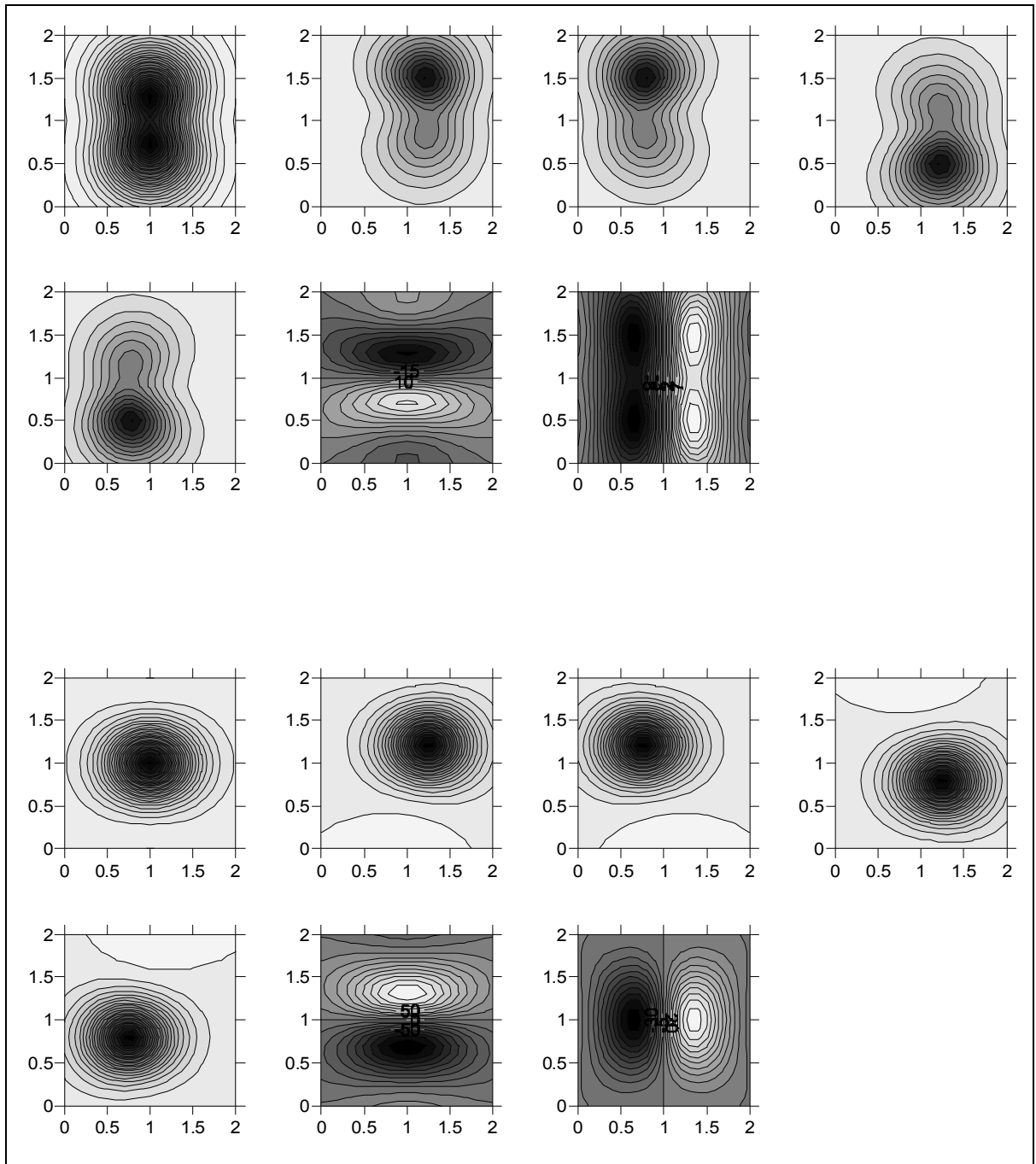


Figure 7. Simulated ALLTEM data for a horizontal rod-like UXO target. The first seven plots show the magneto-static response, and the last seven show the electro-dynamic response. These figures show the amplitude response of the ALLTEM induction system as a function of the X (horizontal axis) and Y (vertical axis) position of the ALLTEM system over a stationary target. Each of the seven images is the response for a different coil set (see text).

Typically, these parameters would be used to specify the line spacing and the distance between data points on a line. It is assumed that the survey starts at $(x, y) = (0.0, 0.0)$. Next, a log file must be specified. The simulation results will be written to the log file in text file format. Finally, an output format needs to be specified. Plots (see fig. 7) can be generated using Golden Software's Surfer graphing package (Surfer version 8.0 or greater must be installed). Alternatively, the user can generate *GP Workbench* documents in plan view or section view. Synthetic datasets can be generated in this manner for testing the UXO inversion algorithm (see the Estimate UXO Parameters section below). Since the ALLTEM system can collect data using many coil combinations, the forward operator looks for the file ALLTEM.def in the same directory as the log file. The ALLTEM.def file specifies which coil combinations to use in the simulations. A Surfer plot or a *GP Workbench* document is created for each coil combination listed in the ALLTEM.def file.

The ALLTEM UXO forward operator approximates the induced field response of a subsurface UXO. This operator describes the induced magnetic fields in the UXO in terms of three orthogonal principal polarizabilities. A set of principal polarizabilities is used to describe the induced magneto-static response, and another set is used to describe the induced electro-dynamic response. The forward operator A used in the inversion has the form

$$A([\mathbf{r}_{cart}, \mathbf{r}_{tx}, \mathbf{r}_{rx1}, \mathbf{r}_{rx2}, \mathbf{P}_{tx}, \mathbf{P}_{rx}, t], [\mathbf{r}_{s,uxo}, \phi_s, \theta_s, m_{s,1}, m_{s,2}, m_{s,3}, \mathbf{r}_{t,uxo}, \phi_t, \theta_t, m_{t,1}, m_{t,2}, m_{t,3}, \tau_1, \tau_2, \tau_3]) \quad (3)$$

$$= y([\mathbf{r}_{cart}, \mathbf{r}_{tx}, \mathbf{r}_{rx1}, \mathbf{r}_{rx2}, \mathbf{P}_{tx}, \mathbf{P}_{rx}, t])$$

where \mathbf{r}_{cart} is the location of the center of the ALLTEM cart, \mathbf{r}_{tx} , \mathbf{r}_{rx1} , and \mathbf{r}_{rx2} are the locations of the transmitting and receiving loops, \mathbf{P}_{tx} and \mathbf{P}_{rx} are the polarizations of the transmitter and receiver coils, t is time, and y are the simulated data. The UXO parameter set is listed in the second set of square brackets in the argument list of the forward operator, where $\mathbf{r}_{s,uxo}$ is the location of the UXO, $m_{s,1}$ through $m_{s,3}$ are the magnitude of the three orthogonal induced magneto-static principal polarizabilities, ϕ_s , and θ_s are the azimuth and inclination of the m_1 component, $\mathbf{r}_{t,uxo}$, $m_{t,1}$ through $m_{t,3}$,

ϕ_i and θ_i are the analogous parameters for the transient electro-dynamic response, and τ_1 through τ_3 are the late time decay constants for the transient dipole moments. A separate set of UXO parameters are used for the static and transient response to provide more information to better facilitate discrimination. This parameter set will be estimated by the inverse algorithm (see the Inversion Algorithm section below). The ALLTEM UXO forward operator is described in more detail in Appendix A.

ALLTEM Calibration

The *Process, ALLTEM Calibration* menu item provides a calibration routine for the ALLTEM system. After the data files containing the response to the calibration standard have been imported, and these data have been pre-processed, then the calibration routine can be used. Loading and pre-processing the data are described in the Data Processing Methods Section of this Manual. The pre-

UXO Inversion Calibration Dialog

This calibration is based on a spherical permeable conductive target. It uses the first trace in each document. Master document should be selected, and the documents contain the measured response to the calibration standard.

Target northing: 0

Target easting: 0

Target height: 1.6606

Cube northing (at reference point): 0

Cube easting (at reference point): 0

Cube height (at reference point): 0.678

Relative induced static dipole moment of target: 1

Relative induced transient dipole moment of target: 1

OK

Cancel

Figure 8. *UXO Inversion Calibration Dialog* box.

processed data contain the response to the calibration standard after removing the response of the system and of the geologic background. Make sure that the master ALLTEM document is selected (see the Window menu), bring up the calibration dialog box, then enter the location of the center of the calibration standard and the center of the ALLTEM coil cube. The default values are for the cube in the cart (center is 67.8 cm above the ground where $z = 0.0$), and a calibration standard positioned on the calibration standard holder located directly above the cart center. The calibration standard should be a ferrous, isotropic, conductive sphere. Enter the relative size of the induced magneto-static and electro-dynamic principal polarizabilities. The inversion algorithm will estimate the relative strengths of the induced dipole moments in the target with respect to the response of the calibration standard. The calibration routine will write a *.cal file with the same name and in the same directory as the master ALLTEM document. The *.cal file is a formatted text file that contains two matrices (column vectors) – one for the magnetic-static response, and another for the electro-dynamic response (see listing below).

Listing 4. A sample ALLTEM calibration (*.cal) file.

Kmu matrix: 7, 1

| Row | Col: | 1 |
|-----|------|----------|
| 1 | | -26.0269 |
| 2 | | -11.8141 |
| 3 | | -10.893 |
| 4 | | -11.7343 |
| 5 | | -10.0501 |
| 6 | | 0.0 |
| 7 | | 0.0 |

Ksig matrix: 7, 1

| Row | Col: | 1 |
|-----|------|---------|
| 1 | | 73.1902 |
| 2 | | 50.394 |
| 3 | | 53.4475 |
| 4 | | 46.9004 |
| 5 | | 54.6051 |
| 6 | | 0.0 |
| 7 | | 0.0 |

This file can be viewed or edited with a standard text file editor; however, one should only change the floating point numbers (numbers with a decimal point) and ensure these numbers remain right justified as shown in the listing. The numbers in each row are the calibration coefficient for the corresponding coil combination listed in the ALLTEM.def file.

Estimate UXO Parameters

The *Process, Estimate UXO Parameters* menu item inverts the UXO forward model (see Appendix A) to estimate the parameters of a UXO target from the ALLTEM data acquired over the target. The documents must contain a pre-processed data set for a single target that has had the background response of the system and of the ground removed. The master ALLTEM document must be selected (see the Window menu). The user must specify whether to use the magneto-static response, or the electro-dynamic response in the inversion (see fig. 9). Usually, an inversion will be run for both types of response. One or more initial models must be selected (see discussion below). Enter estimates of the noise level in the data, and the bearing of the survey lines. A calibration file for the current survey data must be selected. The inversion procedure will attempt to estimate the UXO parameters listed in Equation 3. During the inversion, the progress dialog box is shown (see fig. 10). When the inversion is complete, the text in the dialog can be selected with the mouse, copied to the clipboard, and pasted into another application such as a text editor where the results are being saved. The progress dialog box displays the parameter estimates and the normalized mean squared error at the current iteration. The number after the MSE label is the normalized mean squared error (i.e., the RMS difference between the predicted data and the actual data normalized by the RMS value of the data).

The forward operator generates a data set that can be compared with survey data to invert for UXO parameter estimates. For a given UXO target, a small data set containing the response to a single target is extracted from the field data set for use in the inversion. During a survey, the ALLTEM system

records the response of various transmitting and receiving loop combinations, at successive positions along a survey line. A survey generally consists of a collection of survey lines. A small data set for an individual target is made by extracting received waveforms with locations inside a window over the target as shown in figure 11. For each waveform, two data values are extracted. One value is extracted for the static response (the mean value of the waveform values at static sample numbers specified in the ALLTEM.def file, see Listing 2), and another value is extracted for the transient response (see fig. 12). To obtain the transient response, the static response of each half-cycle (using the samples specified in the ALLTEM.def file) is subtracted from the recorded waveform. The transient value is taken at the sample time where the transient response is 25% of the peak transient value (the sample numbers for the peak value are specified in the ALLTEM.def file) so that late time decays are measured. When

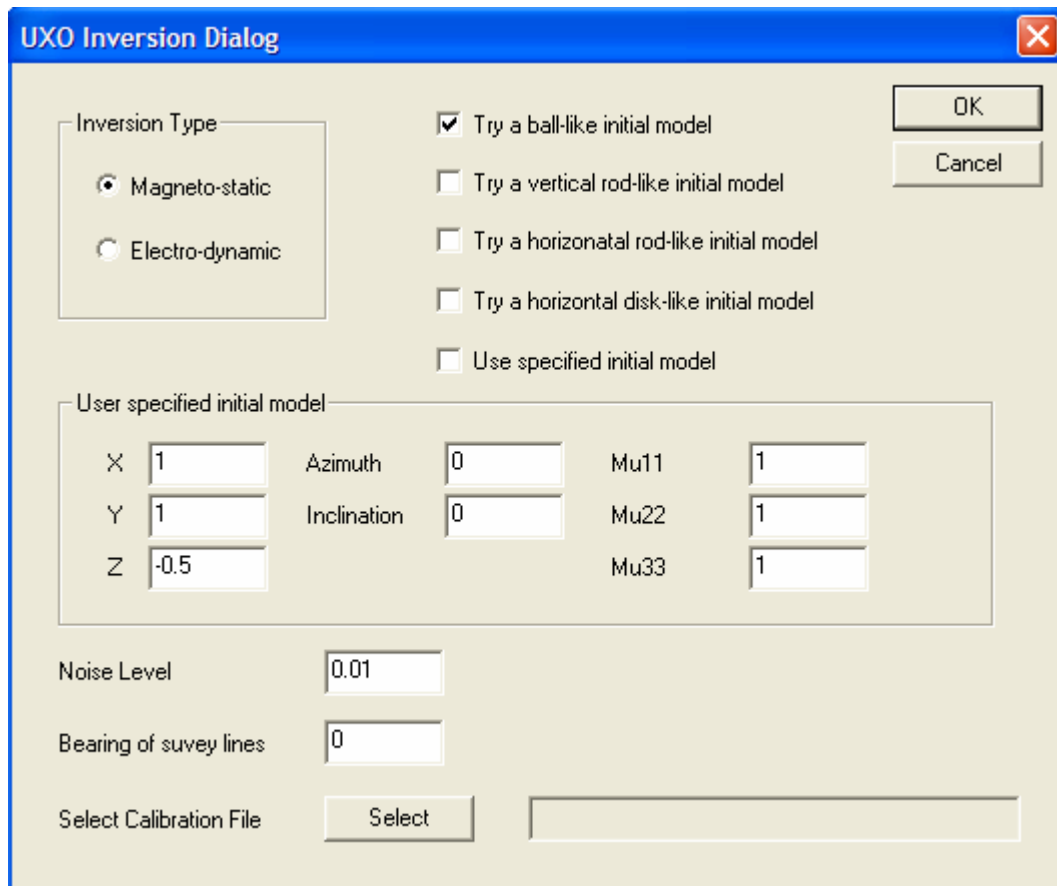


Figure 9. The *UXO Inversion Dialog* box.

processing data from multiple ALLTEM coil combinations, the transient values for each document are taken at the same sample time. To find this sample time, the RMS transient response of all documents is used. The transient sample time is when the RMS value of the waveforms in all documents is 25% of the RMS peak in all documents. The resulting data set for a given target is made up of the two waveform values extracted from waveforms recorded at various ALLTEM cart locations using various

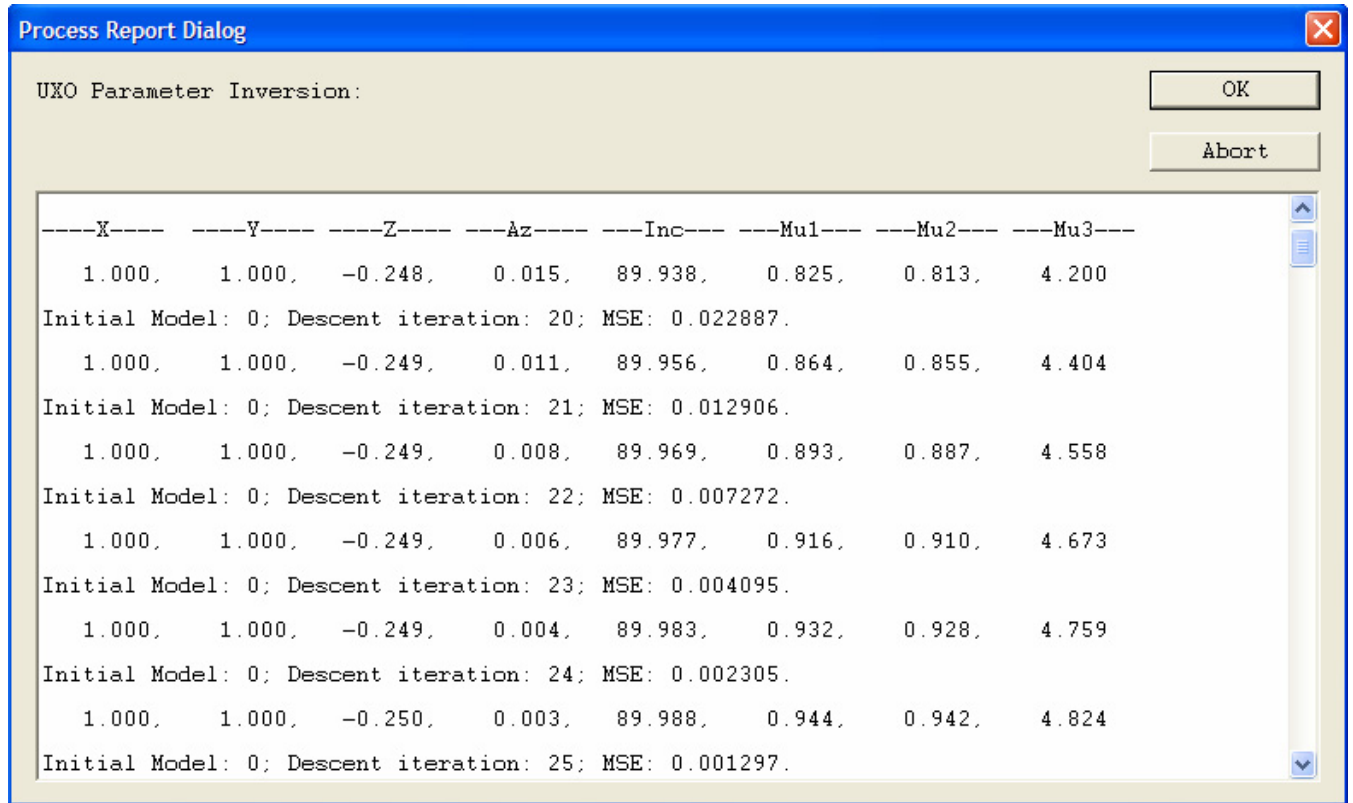


Figure 10. The progress dialog box shown during the UXO inversion process.

coil polarizations. For a standard survey, using a 50-cm line spacing, 20 cm between each record along each line, and seven different polarization combinations of the transmitting and receiving loops, there will be about 350 waveforms and 1,050 data points that can be used to estimate 19 parameters.

During the early-time transient response, the induced dipole moments are oriented parallel to the primary magnetic field. The induced eddy currents will attenuate quickly if the cross-sectional area of the currents in the target is small. Conversely, the induced currents will decay slowly if the cross

sectional area containing the currents is large. Therefore, the late-time transient data contain information about the orientation of the large area conductive planes in the target, and the targets aspect ratio (length to width ratio). For these reasons, late-time data are used in the forward model and inversion, and early-time data are not processed.

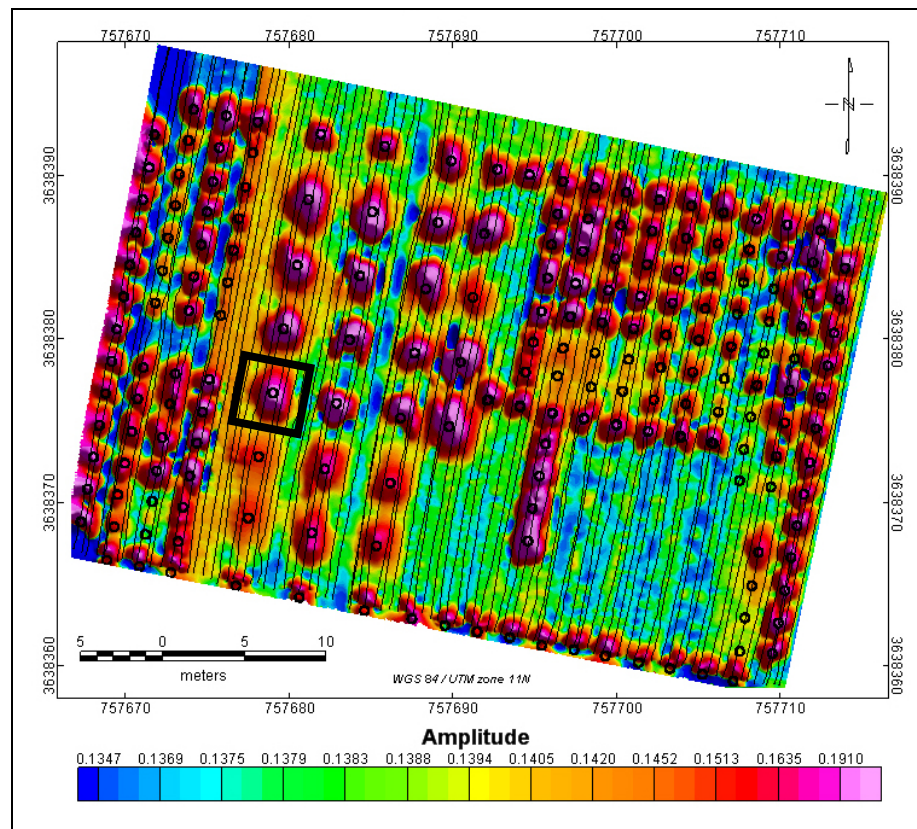


Figure 11. Survey data from the Yuma Proving Ground. Data are for 1 meter square vertically polarized transmitter and receiver coils. A data set for an individual target is made by extracting received waveforms with locations inside a window over the target as shown.

The inverse algorithm uses the Gauss-Newton method (Gill et al., 1986; Zhdanov, 2002) to reduce the RMS difference between the predicted data and the measured data. This RMS difference is referred to as the objective function. The predicted data are calculated using the forward operator with an initial set of UXO parameters, and the value of the objective function is calculated. The inversion

algorithm then chooses a new set of UXO parameters (i.e., a new model) by moving in the down-gradient direction of the objective function. The value of the objective function using the new parameter set will (usually) be less than the value using the initial parameter set. This process is repeated until the objective function is minimized. An acceptable solution (i.e., UXO parameter set) to

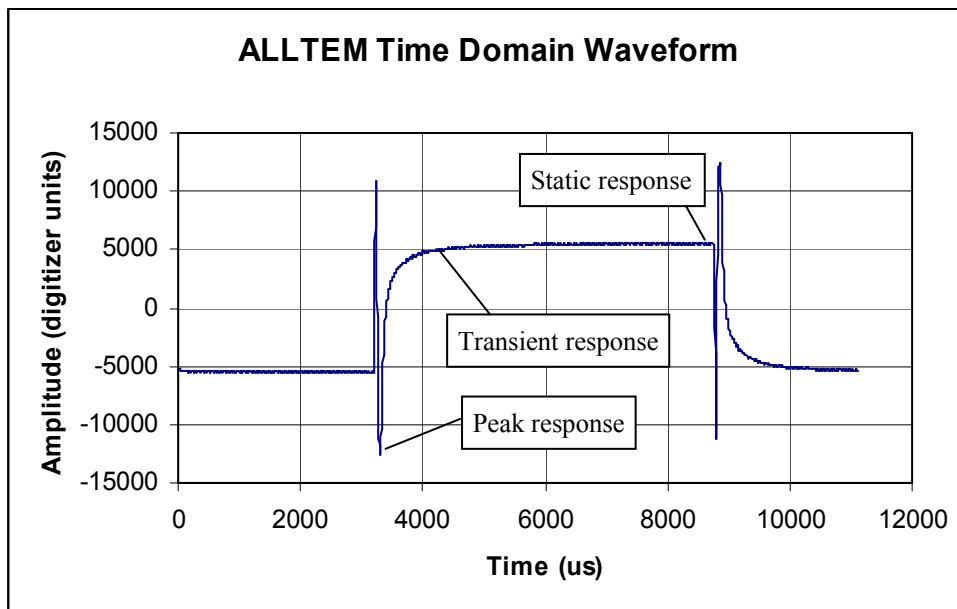


Figure 12. ALLTEM time domain waveform. One data point is extracted for the static response, and two data points are extracted for the transient response.

the inverse problem is reached when the RMS difference between the predicted data and the actual data is less than the RMS noise level in the data. Since this is a non-linear problem, it is possible that the UXO parameter set determined by the inversion algorithm is located at a local minimum of the objective function rather than a global minimum. The parameter set at a local minimum may not be an acceptable solution to the inverse problem, and may have markedly different values than the parameter set at the global minimum. To solve this problem, the inversion can be performed with up to five different initial models (see fig. 9). An attempt to solve the inverse problem is made with each initial model, and the process stops when an acceptable solution is found. For each initial model, the inversion

algorithm takes 100 steps (iterations) down gradient. If an acceptable solution is not found after 100 iterations, the next initial model is started. While stepping down gradient, a reasonable estimate of the location and depth of the target is usually found in the early iterations. Therefore, the target location and depth do not change with subsequent initial models. For the first initial model, the target location is at the center of the data set, and the depth is 1 meter ($z = -1$). A similar inversion scheme has been used successfully for other non-linear problems (Oden, 2006; Oden et al. 2006).

The noise level in the data can be estimated by dividing the amplitude of the signal variations measured over no target by the amplitude of the signal variations over the target. The RMS noise in the data has several components. They are system noise from the electronics and sensors, electromagnetic interference, the response from varying electromagnetic properties of the soil, the response to topography, and the response due to the changing attitude of the cart. The inversion procedure can more accurately estimate the UXO properties when the noise level is small. The uncertainty in a UXO parameter estimate can be calculated from the estimated value near the final solution according to

$$\sigma_p = \left| \frac{p_{n+1} - p_n}{\Sigma_{n+1} - \Sigma_n} \right| \cdot \frac{\sigma_{RMS}}{\sqrt{2}}, \quad (4)$$

where p_n is the parameter estimate at the n th iteration, Σ_n is the normalized mean square error between the actual data and the predicted data at the n th iteration (obtained from the inversion progress dialog), σ_{RMS} is the RMS noise level in the data, and σ_p is the uncertainty in the estimate of parameter p .

It should be noted that the inversion algorithm provides estimates of the UXO parameter set defined by the forward model. The inversion algorithm does not attempt to identify specific targets. A library should be compiled that maps specific UXO types to the UXO parameter set estimated by the inversion. The aspect ratio of the targets is determined from the three principal polarizabilities. If one component is significantly larger than the others, then the target is rod-like. If one component is significantly smaller than the others, then the target is disk-like. If all polarizabilities have similar

magnitudes, then the target is ball-like. A separate location and attitude of the principal polarizabilities are determined for the magneto-static response and for the electro-dynamic response. Therefore, it may be possible to compare these locations and attitudes to better discriminate and identify targets when *a priori* information about the targets is known.

View Menu

The view menu contains commands for turning the toolbar and the status bar on or off. The non-standard commands are described below.

VDL Colors

The *View, VDL Colors* menu item brings up the dialog shown in figure 13. This dialog can be used to edit the color map used to represent data values. The color map is defined by a collection of anchor color values. The colors that represent non-anchor values are determined by interpolating between anchor values. Anchor values can be added by typing in a new numerical value in the *value* list box and pressing the *add/edit* button to define a new color. Pressing the *add/edit* button invokes a color selection dialog box. The anchor value currently displayed by the list box can be deleted with the *delete*

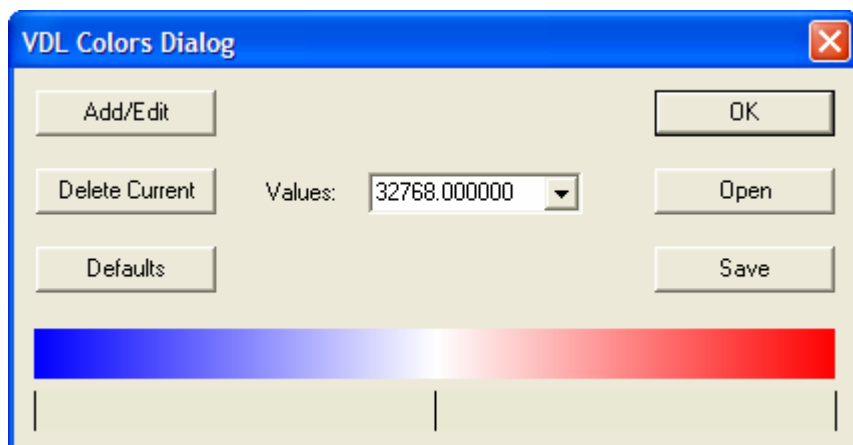


Figure 13. The *VDL Colors Dialog* box.

current button. A set of anchor color values can be saved to a color map file (*.clr), or read from a color map file.

Surfer

Use this menu item to generate a rendered surface of the current time slice using *Surfer* (Golden Software). If the file crop.bln is found in the current document's directory, then it is used to crop portions of the rendered surface. Usually, cropping is used to remove portions of the rendered surface that lie outside regions containing data. Consult the *Surfer* help file for more information on generating and using *.bln files. This menu item is only available in plan view.

Make JPGs

Use this menu item to generate a rendered surface for all time slices in the current document using *Surfer* (Golden software). Each rendered surface is saved in a *.jpg file. The entire set of *.jpg files can be used to make a movie, or viewed sequentially using a *.jpg viewer program (such as *Windows Explorer*). This menu item is only available in plan view.

GP Wave Utilities

If a trace is currently marked by the cross hairs in section view, then this menu item starts *GP Wave Utilities*, which opens with the currently marked trace. *GP Workbench* has many waveform utilities that may be helpful in processing and characterizing a given response. This menu item provides a method to open any data set that can be read by *GP Workbench* using *GP Wave Utilities*.

Window and Help Menus











The Window and Help menus contain standard windows menu items for selecting a view, arranging view windows, and obtaining information about *GP Workbench* and how to use it.

The Toolbar

The toolbar shown below provides many operations for viewing and processing data. Each button on the toolbar will be described in more detail below.



Figure 14. The *GP Workbench* toolbar.

-  The new document button generates a new empty document. A document must exist to be able to import data files.
-  The Open-File dialog can be used to open *GP Workbench* document files (*.SU files).
-  The save document saves the current document. If a file has not yet been associated with the document, the user is prompted for a file name.
-  The print button prints the current document using the default printer.
-  This button displays information about *GP Workbench* such as the version number.
-  This button opens the help file (GP Workbench.pdf) that describes the various operations of *GP Workbench*.
-  This button increases the display contrast. The current contrast setting is shown in the status bar (Disp Gain: 1.00).
-  This button decreases the display contrast. The current contrast setting is shown in the status bar (Disp Gain: 1.00).
-  This button turns the range gain used in the acquisition of the data on or off.
-  This button increases the data multiplier that is applied to the data before plotting. The current multiplier setting is shown in the status bar (Gain (A): 1.00).



This button decreases the data multiplier that is applied to the data before plotting. The current multiplier setting is shown in the status bar (Gain (A): 1.00).



This button increases the exponential gain that is applied to the data before plotting. The current gain setting is shown in the status bar (Gain (x): 1.00).



This button decreases the exponential gain that is applied to the data before plotting. The current gain setting is shown in the status bar (Gain (x): 1.00).



This button is used to set the zero time sample number. Many GPR systems begin recording GPR traces before the transmitter fires. On section view, click on the section image, then use the arrow keys to move the cross hairs to the desired zero time sample. Press this button when the cross hairs are at the desired time sample.



This button selects the x-coordinate (usually easting) of each trace position when plotting in section view.




This button selects the y-coordinate (usually northing) of each trace position when plotting in section view.







This button selects the radial position coordinate ($r = \sqrt{x^2 + y^2}$) of each trace position when plotting in section view.



This button toggles the mark indicator associated with each trace. It is assumed that the position of marked traces is known (see the *Process, Grid Parameters* menu item). Note that the screen resolution may not be sufficient to display all marks in sections with many traces that span a large distance. For these cases, the horizontal zoom ( button) should be used to select a horizontal plotting scale where individual marks are clearly visible. This prevents inadvertently toggling the marks of unintended traces.



This button is used to enter the velocity hyperbola mode. The diffraction hyperbola of point-like scatterers can be used to estimate the velocity of the overlying material. Velocity hyperbola mode is only available in section view mode with data that have been gridded (see the *Process, Grid Parameters* menu item and the  button). For valid results, the zero time must also be selected before using the velocity hyperbola mode (see  button). To estimate the velocity of the medium, place the cross hairs at the apex of a diffraction hyperbola. Then press the  button or 'v' key to enter the velocity hyperbola mode. Press the arrow keys until the model hyperbola fits the diffraction hyperbola in the data. Then press the  button or 'v' key to exit the velocity hyperbola mode. After fitting the velocity, click on the section or use the arrow keys to position the cross hairs at another position. The status bar displays the index of refraction squared (Nsq: 10.0), the velocity in m/ns (Vel: 0.1), and depth of the target (Depth: 6.3).



This button increases the horizontal zoom (section view only).



This button decreases the horizontal zoom (section view only).



This pans to the right (section view only).



This pans to the left (section view only).



This button increases the vertical zoom (section view only).



This button decreases the vertical zoom (section view only).



This pans up (section view only).



This pans down (section view only).



This can be used to delete a trace at the cross hairs in section view or plan view. Noisy traces can be deleted in section view. Traces with bad position records can be eliminated in plan view. If the current document is a master ALLTEM document (*.h1m or *.zxm files), the user will be prompted to delete the same trace number on the associated documents that are currently open.



This button toggles between gridded and ungridded data. See the *Process, Grid Parameters* menu item for more details on the gridding algorithm.



This button displays the model geometry used to generate synthetic GPR data. See the *Process, GPR Forward Model* menu item for more details on the forward model.



This button performs and displays the wavelet (Debauchies) decomposition of the waveform at the current crosshairs.



This button selects or indicates the section view.



This button selects or indicates the plan view.

GP Wave Utilities

The *GP Wave Utilities* program has many processing algorithms designed for a single waveform. It also contains routines for working with synthetic GPR data generated using FDTD simulation programs such as *GPRMax* (Giannopoulos, 2004) and *XFDTD* (Remcom, Inc., State College, PA). Although some of the processing algorithms are specific to the RTDGPR (USGS) radar system, they can be modified for use with other systems or for more general use.

The *GP Wave Utilities* View

Two data types can be viewed with *GP Wave Utilities*. These are one-dimensional waveform data and three-dimensional wave field data. Both of these data types can be viewed in the time or



Figure 15. The GP Wave Utilities view showing two waveforms.

frequency domains. Figure 15 shows a typical view where two waveforms are being compared. Figure 16 shows a typical view of wave field data. In any view, click on the plot to position the cross hairs. The time and amplitude at the cross hair is shown on the status bar at the bottom of the screen. The x-axis is time in seconds (samples), and the y-axis is amplitude (for waveform data) or position (for wave field data). Right click on the plot to bring up the *Plot Parameters Dialog* box (see fig. 17).

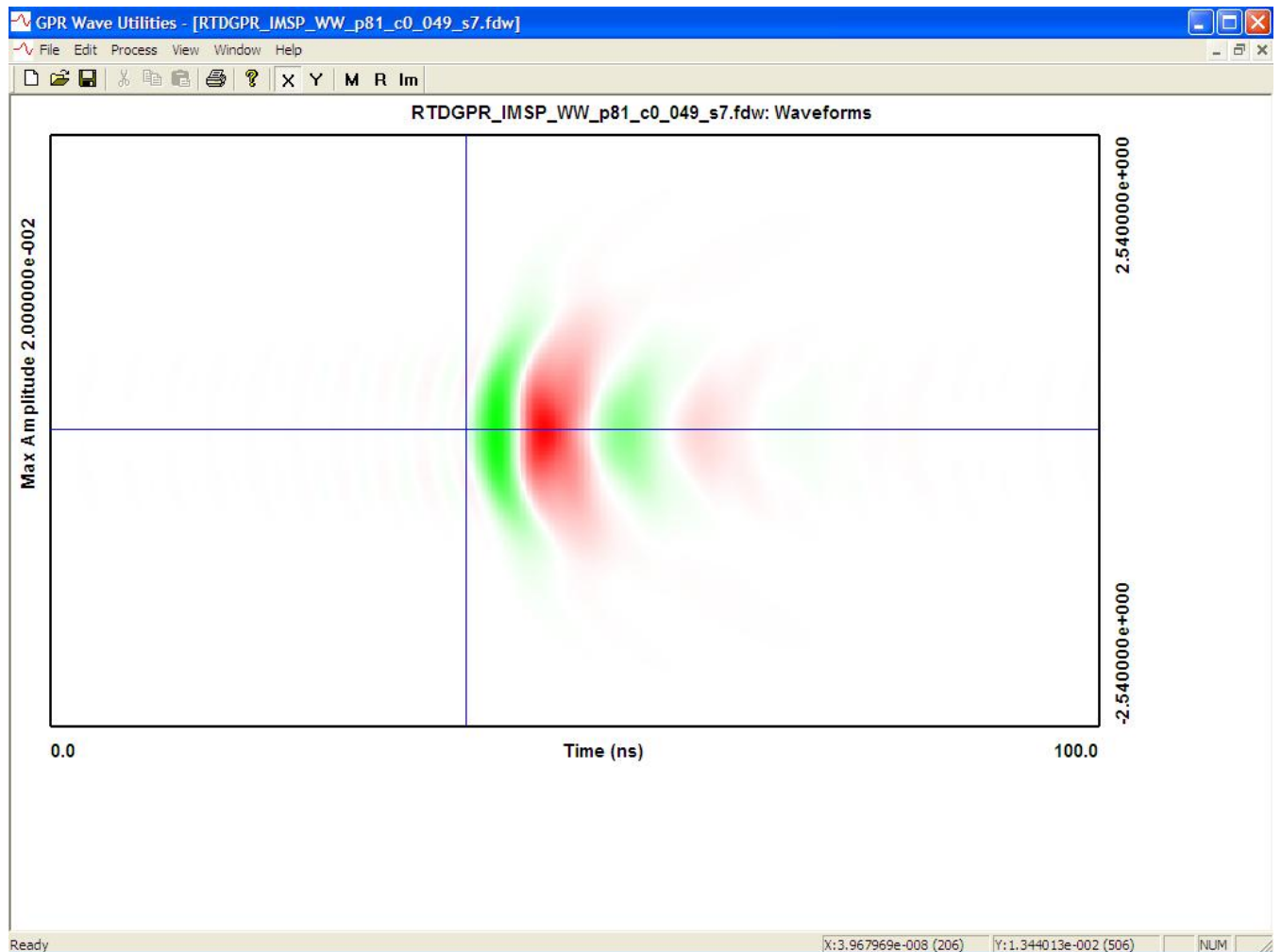


Figure 16. GP Wave Utilities view of wave field data. The vertical axis is position in meters (position scales are on right side of plot)

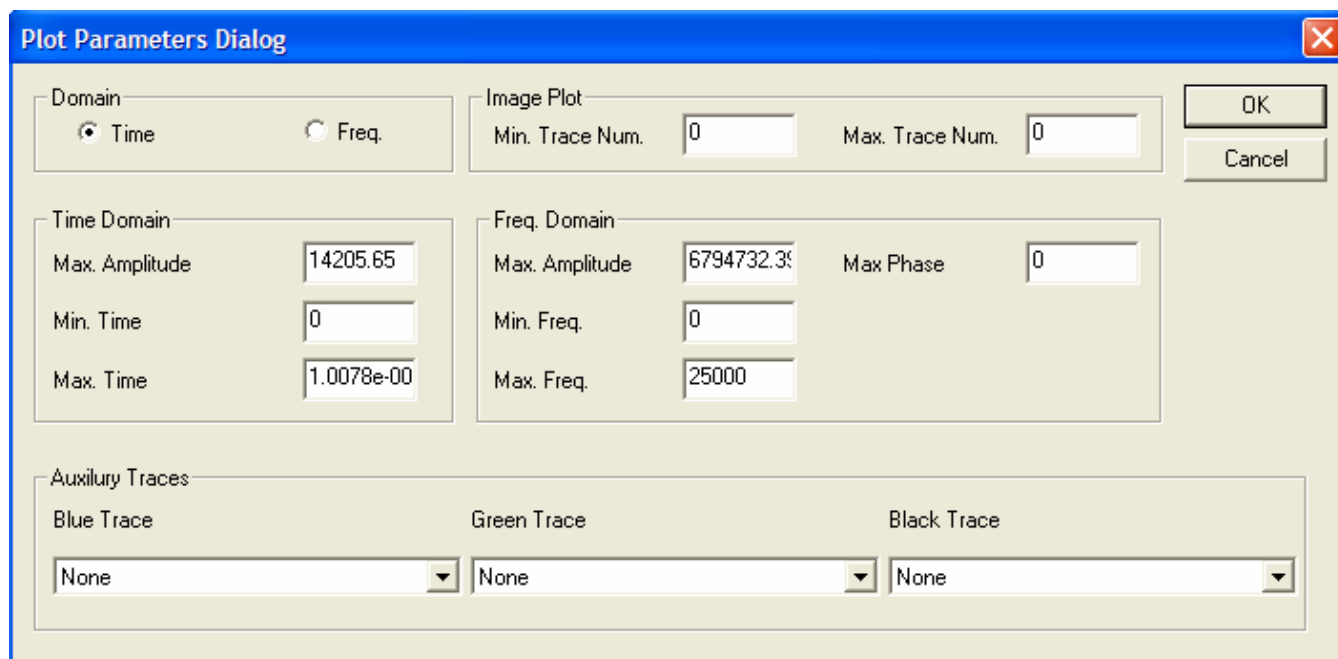


Figure 17. The *Plot Parameters Dialog* box.

The *Plot Parameters Dialog* box is used to change the view between the time-domain or frequency-domain views. The plotting scales and limits can be set for both time and frequency domains. Multiple waveforms can be plotted on the same graph by selecting auxiliary traces from other documents that are open in *GP Wave Utilities*. When plotting three-dimensional wave field data, the image plot consists of multiple traces (i.e., like raster lines on a television screen). The extents of a wave field image plot can be adjusted by selecting the range of traces to display and the minimum and maximum plotting time (or frequency).

Menu and Toolbar Functions

This section provides an overview of the *GP Wave Utilities* menu commands and toolbar buttons. When the mouse pointer is placed over a menu command or a toolbar button, a help message appears in the status bar at the bottom of the screen that describes the function of the menu item or

button. Additionally, a flying help message appears when the mouse pointer is placed over a toolbar button.

File Menu

The *File* menu contains the standard menu items offered by most Windows applications. A new document can be created or saved, and recent files can be opened. The page for printing can be set up, documents can be printed, and the printout can be previewed. Non-standard Windows menu items are described below.

Import and Export

The Import and Export menu items offer additional functions. The *Import* menu items allow the user to select and import data files with various formats as listed below.

Table 4. File types imported by GP Wave Utilities.

| File Type (extension) | Format Description |
|--|--|
| *.txt | ASCII Text file |
| *.aq1 | RTDGPR (USGS) |
| *.out | GPRMax Field files (fields, current, etc.) |
| *.src; *.txt | GPRMax Source files |
| *.g0 | XFDTD Wave files |
| *.fss | XFDTD Field files |
| *.src | XFDTD Source files |
| *.ao | XFDTD Impedance files |
| Any file imported by <i>GP Workbench</i> (see table 1) | <i>GP Workbench</i> (see <i>GP Workbench, View, GP Wave Utilities</i> command) |

When importing text files, the dialog shown in Figure 18 is displayed. This dialog displays the first few lines of the text file. Text files containing data often have a few descriptive lines before the

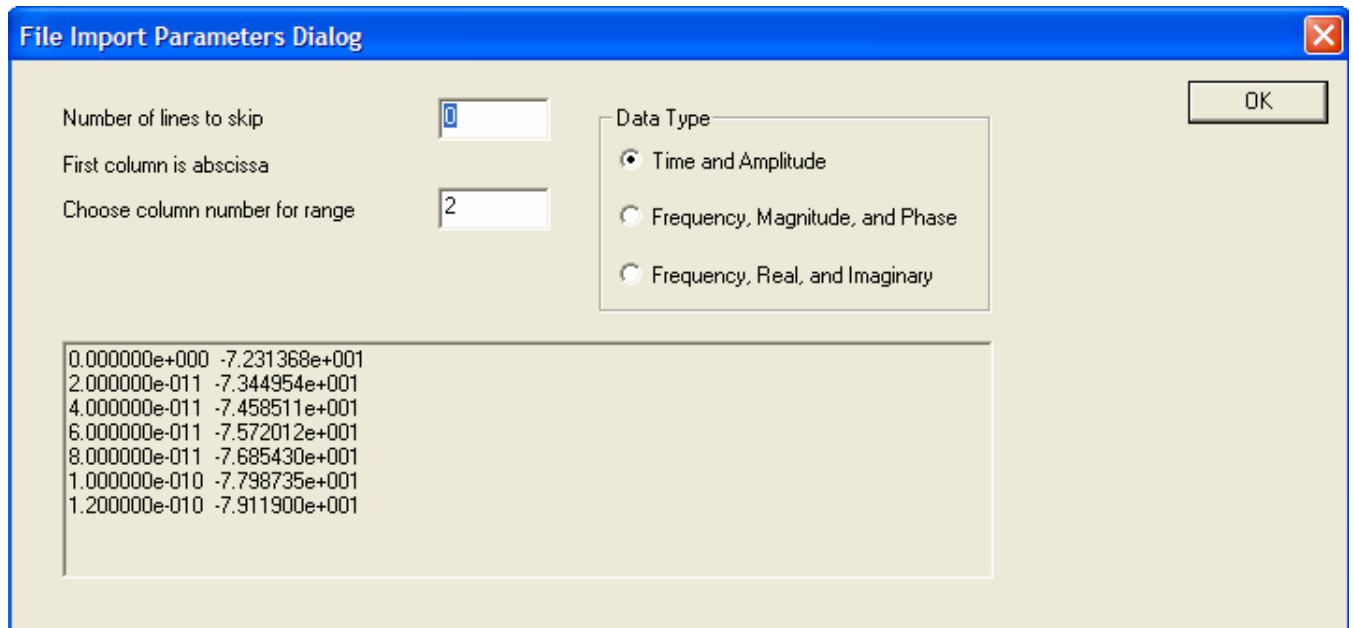


Figure 18. Text *File Import Parameters Dialog* box.

data begins. These must be ignored. The first column of numbers must be the abscissa (time or frequency). The user can specify which column to begin importing the range data (amplitude, magnitude and phase, or real and imaginary). Data can be imported in the time-domain or the frequency-domain. The fast Fourier transform (FFT) is an integral part of the *GP Wave Utilities* program. Therefore, a few data samples with the final sample value are concatenated to the imported data so that the proper number of data points are available for FFT operation. This usually involves adding a small number of samples (~10) because the prime factor FFT is used. Data are saved in the *GP Wave Utilities *.fdw* format.

When exporting data, an ASCII text file is written. The contents of this file depend on whether a time-domain or frequency-domain plot is currently displayed. For time-domain data, two columns of data are written: time and amplitude. For frequency-domain data, five columns of data are written: frequency, real component, imaginary component, amplitude, and phase.

Process

The menu items in the *Process* menu section are where most of the GP Wave Utilities functions can be found.

Wave Plot, Filters and Operators

This menu item brings up the dialog box shown in figure 19. Select one of the operations on the left side of the dialog and enter the corresponding parameters in the relevant subsections. Two frequency filters are available – a finite impulse response (FIR) filter and a fast Fourier transform (FFT) based filter. The FIR filter convolves a 100-point filter function with the time domain waveform. The FFT filter applies the filter in the frequency-domain. Note that since FFTs require a circularly continuous function, if the first and last samples have a significantly different level, then a step is

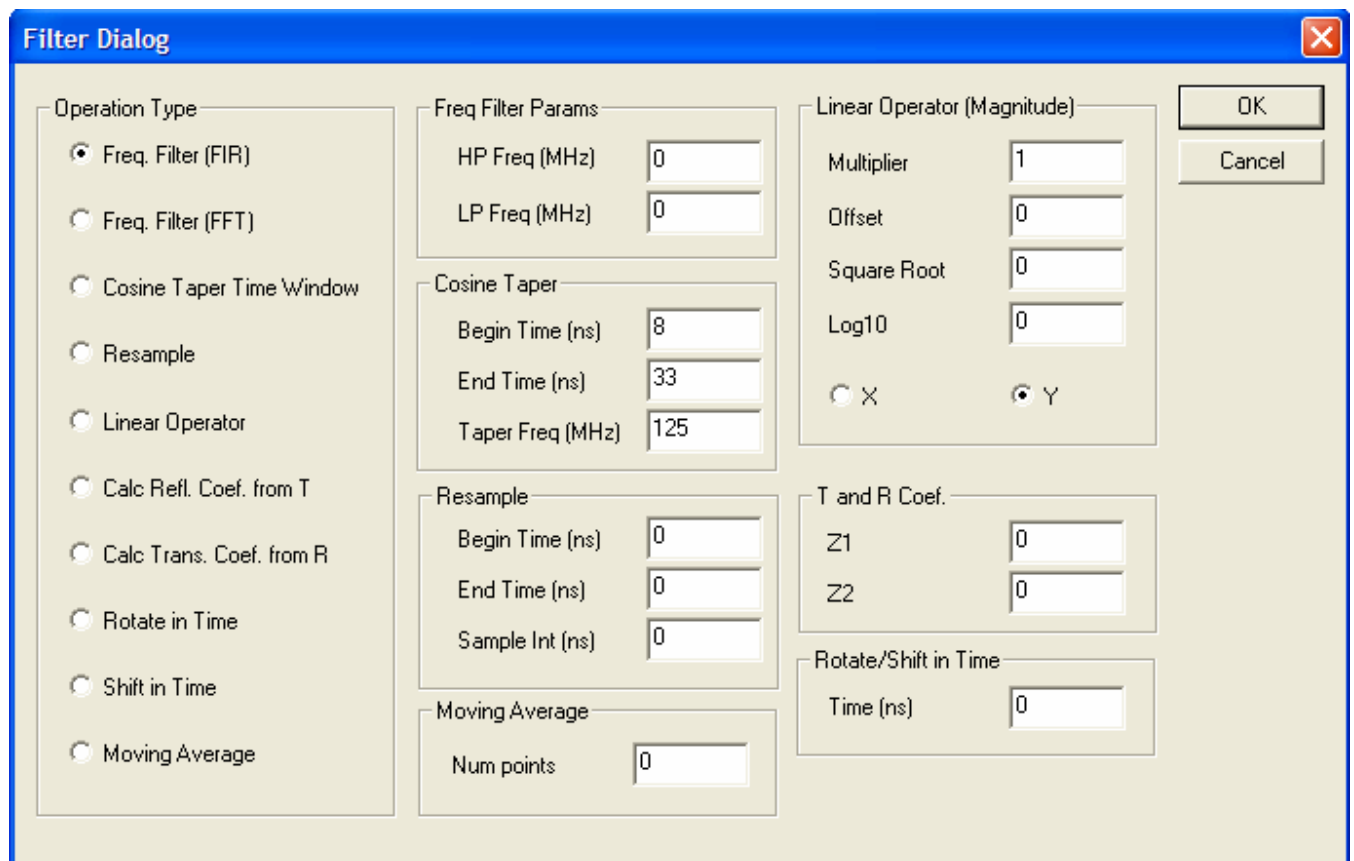


Figure 19. The *Filter Dialog* box.

present in the data. If this is the case, the frequency-domain representation data will have energy across the band because a step function contains all frequencies. To avoid this effect, use the *Process, Wave Plot, Subtract Ramp* menu item. If any FFT operations are anticipated for the data in the document, then FFT filters should be used rather than the FIR filters. The cosine-taper time window weights the data with a cosine taper in time. This window has a zero value at times before the begin time and after the end time. The value is one at times between the begin time and end time. The taper frequency is used to specify the cosine-taper frequency and thus specifies the rise and fall time of the window. The resample operation resamples the data over the specified time window and sample rate. If the time window extends beyond the range of the current data, then the data are padded using the nearest existing data point. Data are removed if the time window is smaller than the data extent. New resampled data points are determined by interpolating between existing data points. The linear operator operates on the x-axis values (e.g., time or frequency) or the y-axis values (e.g., amplitude). The operation is given in equation 5,

$$newx = (multiplier \cdot x) + offset + (squareroot \cdot \sqrt{x}) + (log10 \cdot \log10(x)). \quad (5)$$

Equation 5 is applied to every data point in the document. Note that the *newy* and *y* are used in place of *newx* and *x* in equation 5 when operating on the y-axis values. The frequency-dependent transmission coefficient (T) can be calculated from the frequency-dependent reflection coefficient (R) that is loaded into the current document. The intrinsic impedance *Z* of layers one (contains incident and reflected waves) and two (contains transmitted wave) must be specified. The transmission and reflection coefficient calculations are for waves normally incident on a planar interface. Alternatively, the frequency-dependent reflection coefficient (R) can be calculated from the frequency-dependent transmission coefficient (T) loaded into the current document. A waveform can also be rotated or shifted in time. When rotating a waveform, the last part of the waveform is rotated to the beginning part

of the waveform (or vice-versa depending on the direction of rotation – positive or negative). When shifting a waveform, the waveform is padded on one side using the nearest sample value, and truncated on the other side. The final operation in this dialog box, the moving average, convolves the waveform with a boxcar filter function having the specified number of points. In all cases, the current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Subtract Ramp

Use this menu item to subtract a ramp from the waveform so that the first and last sample both have the same value. If these samples have the same value, the broadly distributed frequency components of a step function will be added to the frequency-domain spectrum of the waveform, which may cause problems with some waveform processing operations. This happens because an FFT assumes that a waveform is periodic. Ramp subtraction is a routine part of processing many waveforms. The current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Subtract Waveform

Use this menu option to subtract a waveform (sample by sample) in another document from the waveform in the current document. Both waveforms must have the same sample interval and the same number of samples. If necessary, use the re-sample function (*Process, Wave Plot, Filters and Operators* menu item) to re-sample the waveforms so that they have the same sample interval and the same number of samples. The user will be asked to select a currently opened document containing the waveform to subtract from the current waveform. This is a time-domain operation. The current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Remove DC

The menu item subtracts the average or DC value from the current waveform. This is a time-domain operation. The current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Deconvolve

Select this menu item to deconvolve (in the time-domain) the specified waveform from the current waveform. The user will be asked to select a currently opened document containing the waveform to deconvolve from the current waveform. Deconvolution can be an unstable procedure when parts of the frequency-domain spectrum of the waveform to deconvolve have low amplitudes in comparison to the other frequency-domain components. Dhaene et al. (1994) describe an adaptive filter to reduce many of the problems associated with frequency-domain deconvolution of time-domain data.

The realization of their filter used in this work is given by

$$F(\omega, \gamma, \lambda) = \frac{|x(\omega)|^2}{|x(\omega)|^2 + \gamma\omega^2 + \lambda}, \quad (6)$$

where λ is a pre-whitening or peak reduction parameter, and γ is a low pass filter or smoothing parameter. In the resulting deconvolution,

$$h(\omega) = F(\omega, \gamma, \lambda) \frac{y(\omega)}{x(\omega)}, \quad (7)$$

the peak reduction parameter reduces the effect of noise at frequencies where $x(\omega)$ is small, and the smoothing parameter reduces the effect at high frequencies where most of the power in $x(\omega)$ is noise. In this work, the parameters λ and γ are selected to maximize the power in the resulting deconvolution at frequencies below 200 MHz, and minimize the power above 400 MHz. The assumption is that the most power in $x(\omega)$ and $y(\omega)$ is distributed over the lower frequencies, and that the power at higher

frequencies is mostly noise. This assumption is based on the fact that most time-domain electromagnetic equipment produces a negligible amount of energy above a certain frequency (about 250 MHz for the RTDGPR built by the USGS). The code can be easily modified to use other frequencies or to ask the user to provide these frequencies. The current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Convolve

Use this menu item to convolve two traces in the time-domain. The user will be asked to select a currently opened document containing the waveform to convolve with the current waveform. The current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Correlate

Use this menu item to correlate two traces in the time-domain. The user will be asked to select a currently opened document containing the waveform to correlate with the current waveform. The current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Envelope

This menu item is used to calculate the envelope of the current waveform. Two methods are available. The first method, the *peak* method, simply calculates the average value of the absolute value of the waveform using a moving boxcar window of the user-specified length. For the second method, the *Hilbert envelope* method, the waveform in the current document and its Hilbert transform are combined in quadrature in the frequency domain. This method generally produces a more compact envelope than the *peak* method. The current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Hilbert transform

Use this menu item to calculate the Hilbert transform of the waveform in the current document.

The current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Path Length

Use this menu item to calculate the RMS path length of the waveform. This is done by summing the quadrature path lengths of all line segments making up the waveform. The quadrature path length is found by combining the vertical and horizontal lengths of a line segment in quadrature. The current waveform in the current document will be replaced by the resulting waveform.

Wave Plot, Amplitude Response

Use this menu item to build a non-linear function that maps one waveform (e.g., an input waveform to an amplifier) to another (e.g., the waveform output from the amplifier). This function can be used to build a non-linear amplitude response function for a signal-processing module such as a logarithmic amplifier. The currently selected document must contain the output of the signal-processing module. The user is prompted to select another opened document containing the input to the signal-processing module. The time scale and sample interval must be the same in both waveforms. The sample times of the output waveform should be adjusted so that the waveform value at a given time represents the signal-processing module output for the input at the same time. By comparing the input amplitude to the output amplitude at each sample, an amplitude response function is built. After calculating the amplitude response function, the response function is displayed. In the response function plot, the input amplitude is plotted on the vertical axis, and the output amplitude is plotted on the horizontal axis. The resulting response function can be used to linearize the non-linear response of a signal-processing module (see the *Process, Wave Plot, Amplitude Linearization* menu item). For

example, after calculating the amplitude response of a logarithmic amplifier, the logarithmic compression imposed by the amplifier can be removed from the signal. Figure 20 shows the input and output waveforms for a signal-processing module, and the calculated amplitude response function.

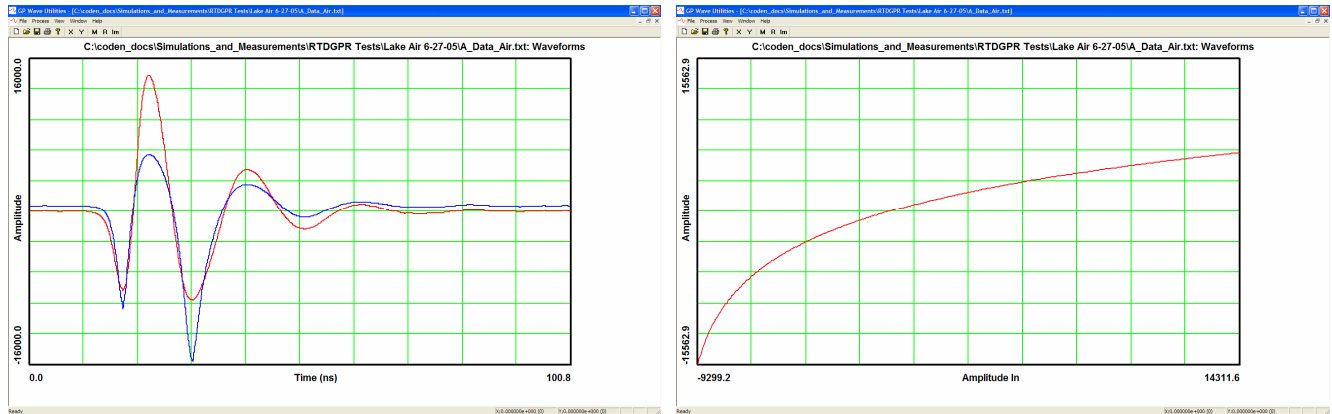


Figure 20. The left panel shows an input waveform (red) and an output waveform (blue). The right panel shows the calculated response function for the signal-processing module.

Wave Plot, Amplitude Linearization

Use this menu item to calculate the input to a non-linear signal-processing module (e.g., a logarithmic amplifier) given the module's output waveform and the non-linear response function. The output waveform should be loaded in the current document. Then the user will be prompted to select the opened document containing the non-linear response function that was calculated using the *Process, Wave Plot, Amplitude Response* menu item, as shown in the right side of figure 20.

Wave Plot, Packet Time and Amplitude

Use this menu item to calculate the RMS value of the waveform, and the temporal centroid of the RMS value (i.e., the time in which half of the contribution to the total RMS value is due to earlier parts of the waveform). These calculated values can be used in subsequent data processing, where, for instance, waveforms need to be compared or arrival times are needed.

Wave Plot, Compare Waves

This menu item was designed to compare various early time waveforms produced by the RTDGPR (USGS). The user will be prompted to select an opened document containing a waveform to compare with the waveform in the current document. This menu item makes a temporary copy of each waveform, and temporally aligns them at their largest positive peak. Then waveform data after 40 ns are set to zero by a 125 MHz cosine filter. Next, the selected waveform is scaled so that it has the same RMS value as the waveform in the current document. Finally, the procedure reports the following values: the time shift needed to align the first positive peak of each waveform, the RMS difference between the waveforms, and the scaling factor used. This menu item only makes a comparison between the waveforms. No data are modified.

Image Plot, Extract Trace

Use this menu item to extract a trace from an image plot (a.k.a. wave field plot; see fig. 16), so that it can be viewed and manipulated like a waveform (see fig. 15). An image is comprised of many horizontal traces that are vertically adjacent to each other. The user is prompted for the trace number to extract. The trace numbering begins at the bottom of the screen. The currently displayed trace numbers can be selected using the *Plot Parameters Dialog* box (see fig. 17). The plot parameters dialog box is invoked by right-clicking on the plot.

Image Plot, 3D Depth Shift

Use this menu item to mathematically propagate a digital representation of an electromagnetic wave field through a user-specified medium. The current document must contain wave field data (see the *Process, Calc TE and TM Spectrum* menu item). Depending on the size of the wave field, this depth shift operation may require a PC with 1 GB or more of RAM so that efficient calculations can be made

(approximately 20 seconds on a 3 GHz Pentium). The calculation may be exceedingly lengthy if insufficient RAM is available. The required RAM is a function of the spatial and temporal sample density of the wave field. It is assumed that the wave field in the current document represents an electromagnetic wave field on a horizontal scan plane as shown in figure 21. The scan plane is an X-Y plane for a constant Z (or depth) value. It is further assumed that the waves are propagating downward. The user will be presented with the *Depth Shift Dialog* box shown in figure 22. Enter the Cole-Cole material properties of the medium, and depth shift value to use. A new wave field will be calculated for the horizontal plane whose depth is the depth of the original scan plan plus the depth shift.

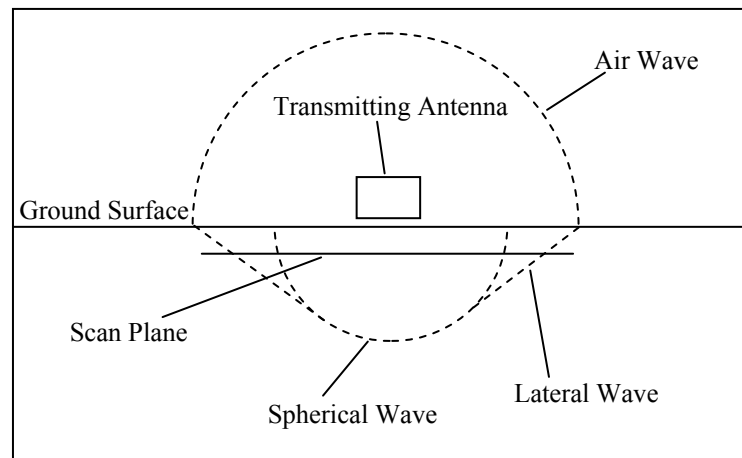


Figure 21. Section view illustrating subsurface wave fronts and scan plane beneath a GPR antenna (adapted from Oden, 2006).

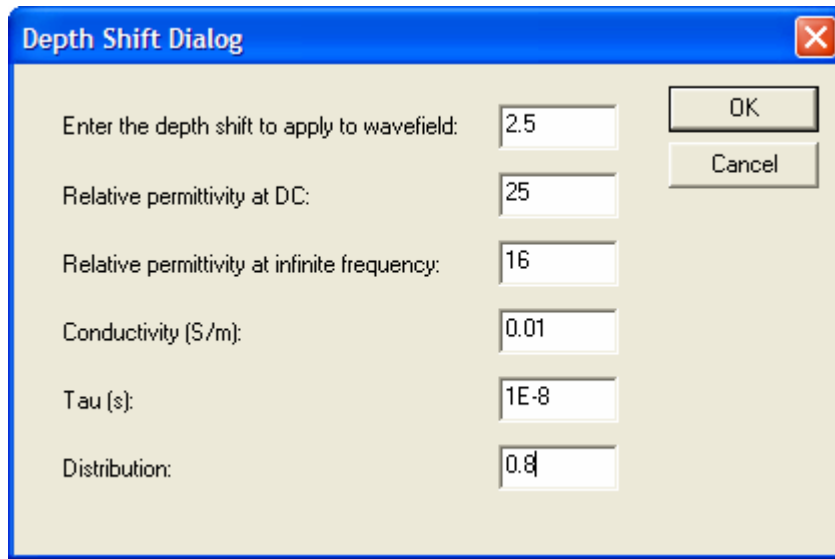


Figure 22. The *Depth Shift Dialog* box.

Image Plot, 2D Depth Shift

This menu item is essentially identical to the *Process, Image Plot, 3D Depth Shift* menu item, except that the calculations are made in two dimensions – X and Z. Wave spreading and attenuation are not accounted for in the Y direction. This calculation is faster than the three-dimensional calculations, but they are not accurate. Despite this, the two-dimensional calculations can provide useful information. The two-dimensional results are especially inaccurate when the scan plan or the depth-shifted plane are in the near field zone of the antenna (see fig. 21). See Oden (2006) for a discussion on the near field regions of GPR antennas.

Image Plot, System Response $a(w)T(k,w)R(k,w)$

This menu item can be used to calculate the frequency-domain system response of a GPR system due to a perfect planar reflector at an arbitrary depth as shown in figure 23. Here, the system response is defined as the received waveform produced by a given GPR system over a perfect planar reflector at a specified depth, and for specified soil properties. This response includes the signal sent to the

transmitting antenna $a(\omega)$, the transmitting antenna response function $T(k, \omega)$, and the receiving antenna response function $R(k, \omega)$, where ω is radian frequency, and k is spatial frequency. Spatial frequency is accounted for in the X and Y directions, but is shown as k here for simplicity. The product $a(\omega)T(k, \omega)$ is the frequency-domain wave field at the reflector. The product $a(\omega)T(k, \omega)R(k, \omega)$, the system response, is the frequency-domain waveform at the receiving antenna. To be concise, these response functions and their relations are written symbolically and many mathematical and physical details have been omitted. Consult Oden (2006) for a more detailed treatment. The system response for a given GPR system over a perfect planar reflector at a specified depth, and for specified soil properties can be calculated using the following steps.

- 1) Build a scan plane wave field (see figure 21 and the *Process, TE and TM Spectrum* menu item).
This scan plane wave field is the product $a(\omega)T(k, \omega)$ for the waves at the scan plane.
- 2) Use the *Process, Image Plot, 3D Depth Shift* menu item to shift the wave field to the desired depth. The wave field now represents the product $a(\omega)T(k, \omega)$ for the waves at the reflecting plane.
- 3) Use the *Process, Image Plot, System Response $a(\omega)T(k, \omega)R(k, \omega)$* menu item to calculate the product $a(\omega)T(k, \omega)a(\omega)R(k, \omega)/Z_0$, where Z_0 is the characteristic impedance of the transmission line connected to the receiver antenna terminals (usually 200 ohms for GPR antennas using banana jack style connectors). It is assumed that the receiving antenna is identical to the transmitting antenna.
- 4) Deconvolve $a(\omega)$ and multiply by Z_0 to obtain the received waveform $a(\omega)T(k, \omega)R(k, \omega)$.
- 5) If needed, convolve by the response of the receiver electronics $b(\omega)$ to obtain $a(\omega)T(k, \omega)R(k, \omega)b(\omega)$.

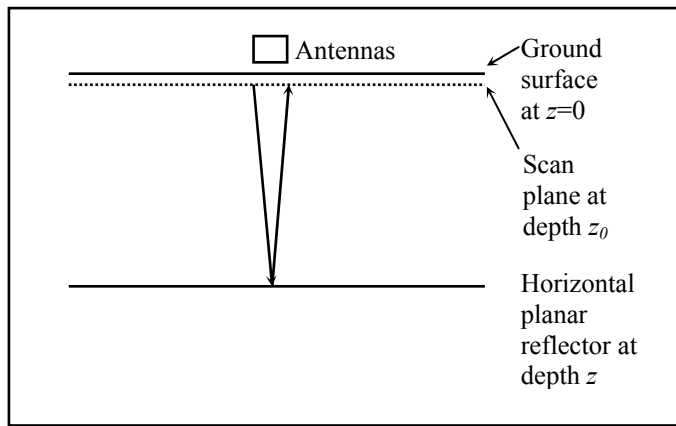


Figure 23. Diagram of a GPR system response over a perfect horizontal planar reflector.

This procedure can be used to deconvolve for the electrical properties of a horizontal reflector. This deconvolution procedure is outlined in figure 24. For this procedure, the fields on the scan plane are determined by numerical simulations of the GPR antennas system, and laboratory measurements of the signal sent to the transmitting antenna.

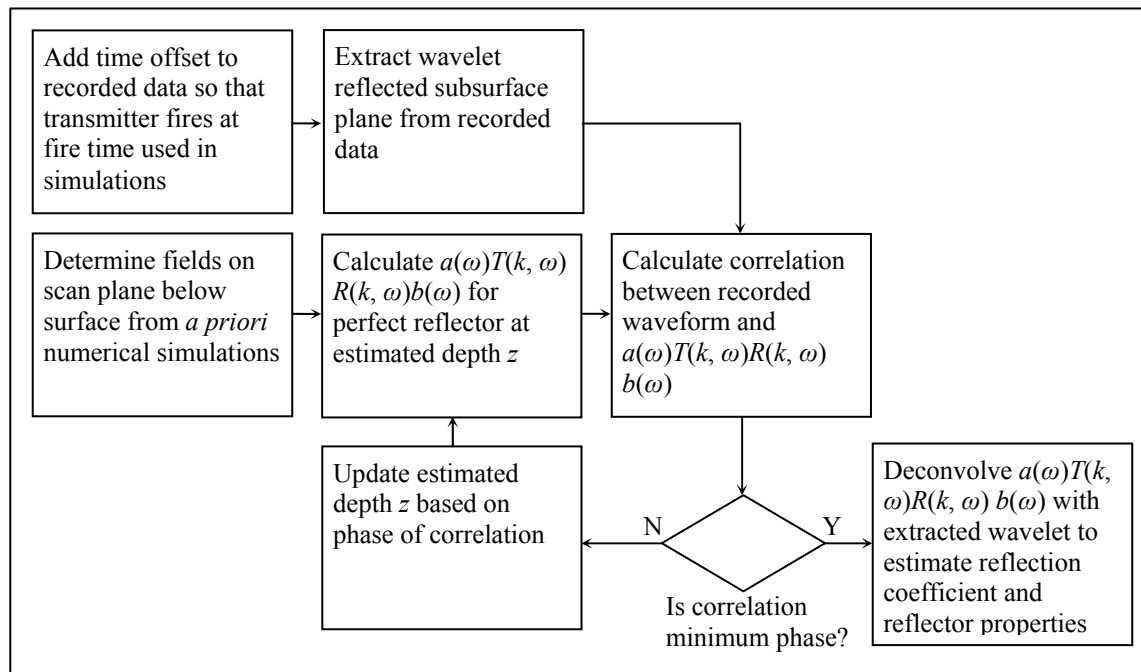


Figure 24. Flow chart for deconvolving for reflector properties.

Radiation Pattern

This menu item invokes an experimental routine to estimate a two-dimensional radiation pattern from a GPR antenna. Note that this routine is experimental, and the results have not been carefully verified. The routine reads a simulated wave field that has been recorded on a scan plane below a GPR antenna (see fig. 21). Accurate simulations of actual GPR antennas can be made using the finite-difference time-domain methods (Oden, 2006; Giannopoulos, 2004). The routine imports a two-dimensional wave field (X versus time) from data files recorded during the simulation. The imported wave field is converted to the frequency-domain representation. The frequency-domain wave field is comprised of a collection of plane waves, each with a certain frequency and traveling in a certain direction. The routine adds up the amplitude of all plane waves traveling in each direction to obtain the radiation pattern.

The *GPRMax* simulations must be set up to record the fields on the scan plane using snapshot files (*.snp). The simulations calculate the wave field at a series of time steps (e.g., 0 to 100 ns in 20 ps intervals). The wave field values on the scan plane for each time step are recorded in a snapshot file. A different file is written for each time step with the name *_nnnn.snp, where nnnn is the index of the time step. If 1,000 time steps are used in the simulation, the first file will be named *_0000.snp and the last *_0999.snp. The scan plane, as defined by the field values recorded in the snapshot files, must be centered beneath the transmitting antenna, and have the same spatial extent in the X and Y directions. To begin the calculation, select the *_0000.snp file. The process may require about an hour to run depending on the number of time steps in the simulation, the size of the scan plane, and the spatial sample interval. After calculating the radiation pattern, the pattern is displayed as a waveform. A radiation pattern with poor resolution will result from using a scan plane that is too small.

Ground Properties

Use this menu item to estimate the shallow soil properties under ground-coupled GPR antennas using the early-arriving portions of the received waveform. This procedure requires an existing ground properties model that specifies the response of the antennas as a function of the soil properties (see the *Process, Ground Properties Model* menu item). The user will be presented with the *Invert for Ground Properties Dialog* box shown in figure 25. The first step is to specify the waveform(s) to use in estimating the soil properties. The waveform in the currently loaded document can be used. Alternatively, the waveforms from a number of *GPRMax* (Giannopoulos, 2004) simulations (*.out files)

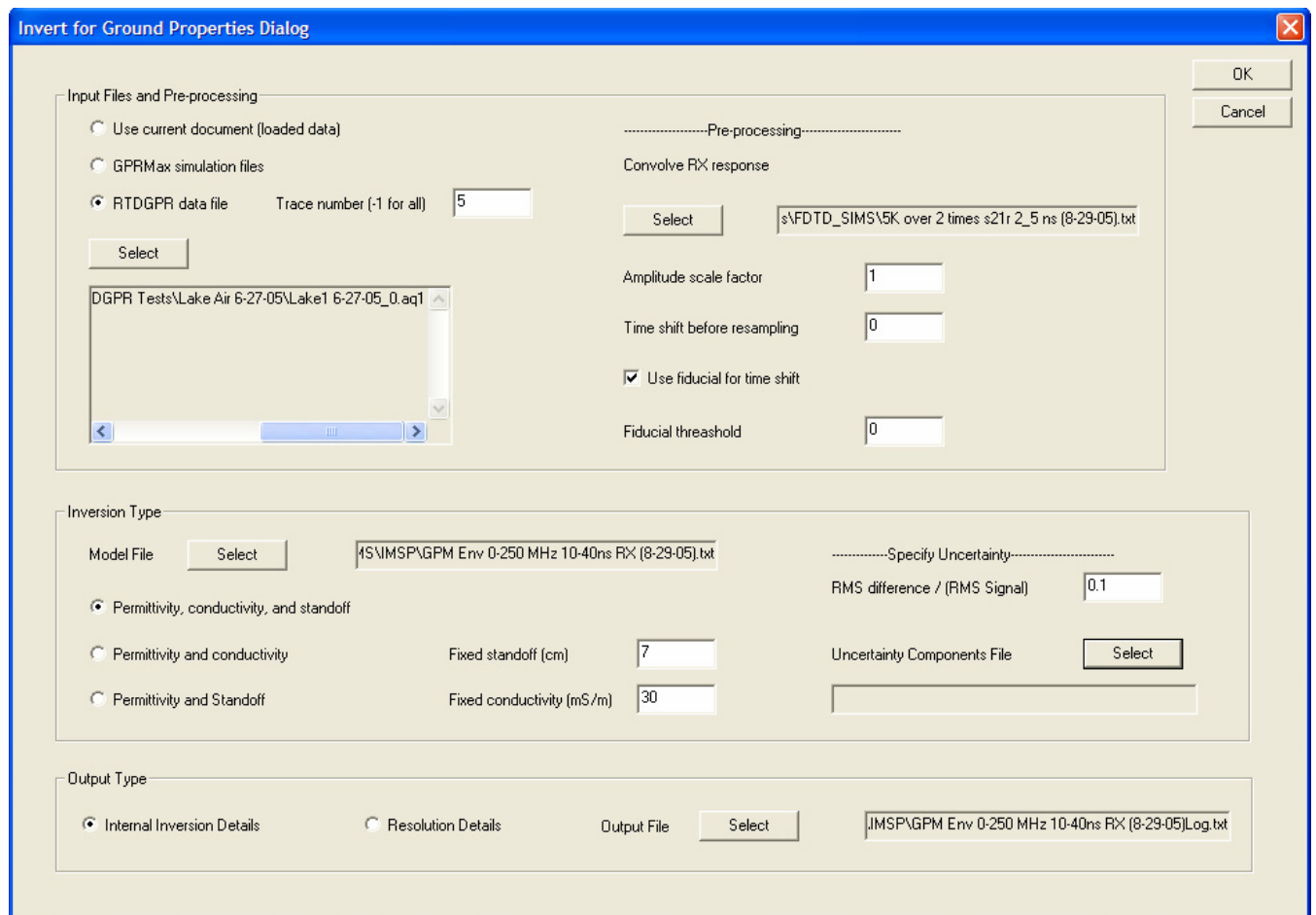


Figure 25. The *Invert for Ground Properties Dialog* box.

can be used. The first waveform listed in each selected *.out file will be used. Multiple *.out files can be selected. Finally, the waveform(s) in a RTDGPR (USGS) data file can also be used. The user can either specify a single trace number, or specify that all of the waveforms in the file should be used. When multiple waveforms have been specified, a set of soil property estimates will be made for each waveform.

Next, the preprocessing parameters must be specified. Preprocessing may be needed to make the waveforms in the specified input files represent the same situations as the processed waveforms that were used to generate the ground properties model. For instance, if the input file is the simulated response of the antenna system, then it may be necessary to convolve the simulated waveform with the response of the receiver electronics. An amplitude scale factor can also be specified. Actual data may need to be time shifted before they can be used with the selected ground properties model. For the case of the RTDGPR (USGS), a fiducial marker is placed on the recorded waveform to indicate when the transmitter fired. An amplitude threshold must be specified so that the fiducial can be found. The fiducial is interpreted to occur at the time of the first peak that is higher than the specified amplitude threshold.

Next, a ground properties model file must be selected. The ground properties model files contain information specifying the waveform attributes to extract, and how these attributes vary with changing soil permittivity, conductivity, and antenna height above the ground. The parameters to find in the inversion must be specified. Sometimes, one of the parameters (soil permittivity, conductivity, and antenna height above the ground) is already known (perhaps through independent measurement). This helps to constrain the inversion. The uncertainty between the measured waveform attributes and the predicted waveform attributes must be specified. This uncertainty includes noise in the data, the difference between the *GPRMax* simulated attributes and the actual attributes, and the discretization

error in the forward operator (i.e., the ground properties model). Specifying each of these uncertainty components as an RMS difference, and adding them in quadrature leads to the RMS difference between the predicted waveform attributes and the recorded waveform attributes. Normalizing this RMS difference by the RMS attribute amplitude of the recorded waveform gives the normalized uncertainty to enter in the dialog box. When the normalized uncertainty value is unknown, a value of 0.1 (10%) can be used. A provision for selecting an uncertainty components file has been provided for future development. For a more detailed discussion about uncertainty and the process of inverting for soil property estimates, consult Oden (2006). Finally, specify the information to record in the output file (output type) and press OK to begin the inversion. If *Internal inversion details* is selected, then the output file will contain the convergence information at each iteration of the inversion process. If *Resolution details* is selected, then the output file will contain the parameter estimates for each input waveform. If only one input waveform is selected, then the results will be presented on screen.

Ground Properties Model

Use this menu item to calculate a response model that can be used to estimate the soil properties just beneath a pair of ground-coupled transmitting and receiving GPR antennas. A suite of simulations must have been run using *GPRMax* (Giannopoulos, 2004) to model the antenna pair response to a variety of soil properties. Each *GPRMax* simulation models the response of a transmitting-receiving antenna pair, and the results of each simulation are written to a *.out file. The *.out files can contain electromagnetic field values for many spatial locations in the simulation grid. When using these simulation files to calculate ground response, the first waveform in each *.out file must be the electric field waveform at the receiving antenna feed port. A suite of simulations are needed that model the antenna response for various ground properties (permittivity and conductivity), and the antenna height above the ground. Figure 26 graphically depicts the range over which the ground properties and the

antenna standoff (i.e., antenna height above the ground) can vary for a given ground properties model. This is known as the model space grid. For the soil properties and antenna standoff represented at each grid corner, a simulation has been run and the antenna response is known. This collection of simulations is used to create a response model that can be used to estimate ground properties beneath GPR antennas in actual surveys. Once the shallow soil properties are known beneath GPR antennas in a given location, the antenna response can be calculated. This in turn enables other data processing techniques such as deterministic deconvolution for subsurface reflector properties. Consult Oden (2006) for a detailed discussion on estimating shallow soil properties beneath ground-coupled GPR antennas, determining the antenna response at a given location, and the data processing techniques that these steps enable.

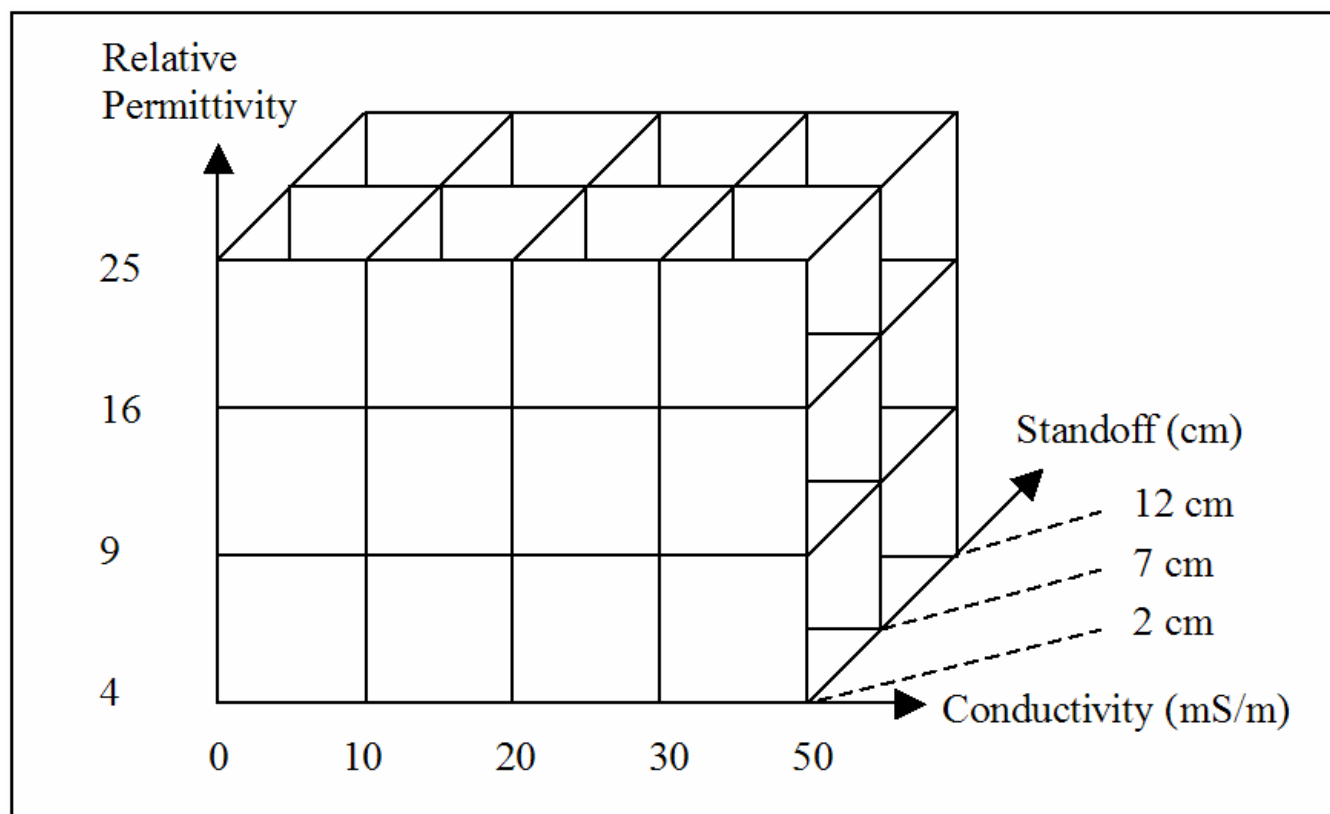


Figure 26. The model space grid. The simulated response is known at the corners of each grid cell.

The *Process, Ground Properties Model* menu item invokes the *Model Ground Properties Dialog* box shown in figure 27. The first step is to choose a suite of simulations files. The simulation files should cover a uniform model space such as the one shown in figure 26. The file names containing *GPRMax* simulation results that will be used to create the ground properties model must follow a prescribed naming convention. *GP Wave Utilities* requires the soil properties and antenna standoff used

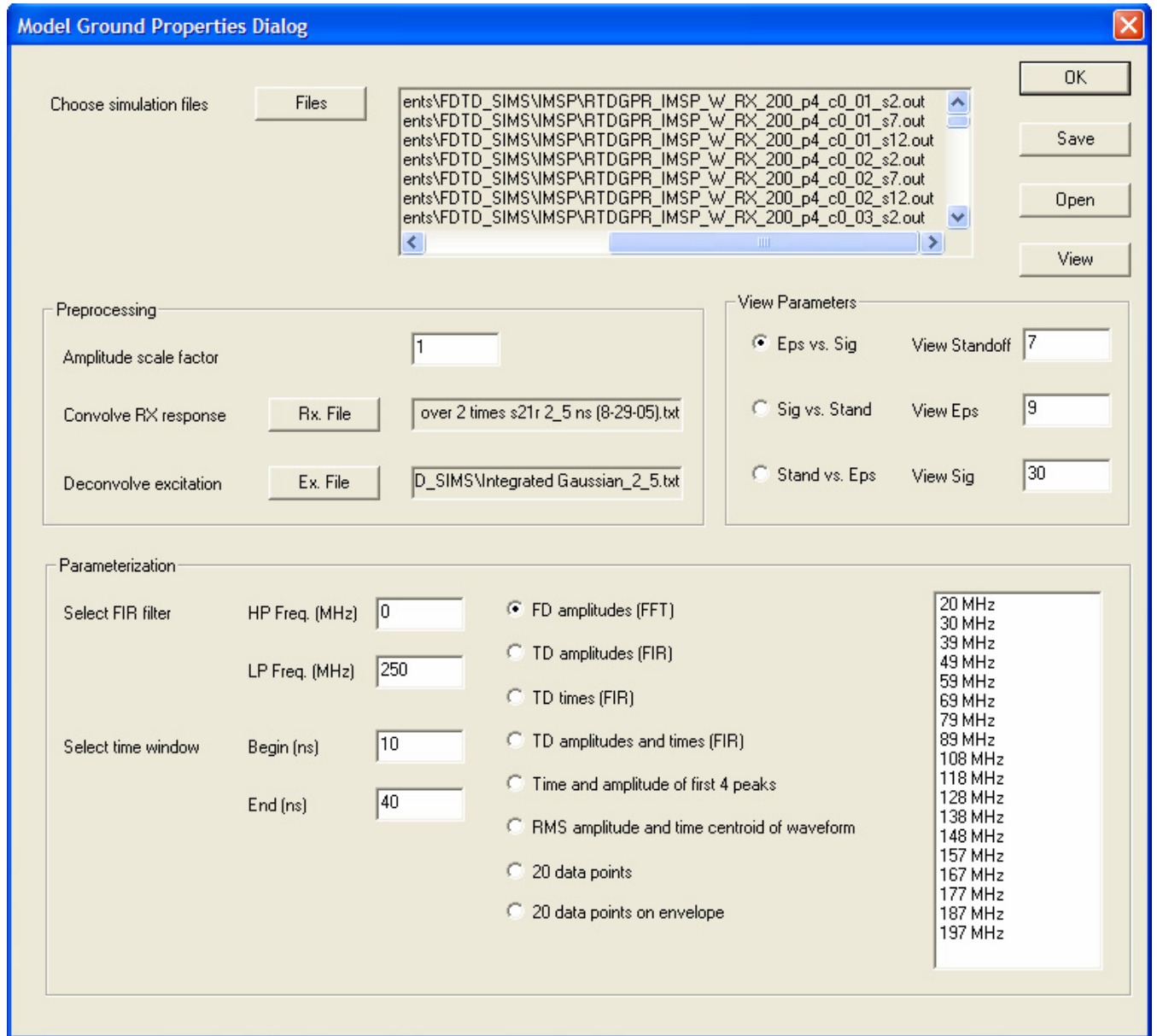


Figure 27. The *Model Ground Properties Dialog* box.

in the simulation to be encoded in the file name. The beginning of the file name can be anything, but the end must be written as follows

*_p9_c0_02_s7.out,

where the number following the p is the RDP, the number following the c is the conductivity (in mS/m), and the number following the s is standoff (in cm). An underscore is used in place of the decimal point in the conductivity value, and to separate fields. The file extension must be *.out. Next, a variety of processing steps are needed to convert the simulated antenna response to the response of the entire GPR system. An amplitude scaling factor can be set. A response waveform can be convolved with the simulated response. For example, the response of the receiver electronics and/or the signal presented at the transmitting antenna feed port can be convolved with the simulated antenna response. A signal can also be deconvolved. This may be necessary when the transmitting antenna excitation used in the simulation is different than the actual excitation (i.e., the transmitting antenna feed port signal). Next, a user-specified finite-impulse-response band-pass filter can be applied to the simulated waveforms. Finally, a 125 MHz cosine taper window can be used to eliminate energy outside of the specified time window. For example, one may eliminate energy at late times when it is undesirable to use the late time energy to predict ground properties. After pre-processing the simulated waveforms, attributes of the waveforms will be extracted for the ground properties model. The ground properties model specifies the waveform attributes as a function of the soil properties and antenna standoff. This ground properties model can be inverted to estimate the soil properties under GPR antennas from survey data (see the *Process, Ground Properties* menu item). A ground properties model can be made using different attributes sets (i.e., attributes of a given type) of the simulated waveforms. Table 5 lists the various methods for extracting waveform attributes. The *FD amplitudes* and the *20 data points on envelope* methods provide the best results.

After specifying the input files and processing parameters, press the save button to calculate a ground properties model and save the model to disk. A file save dialog box will be presented so that the user can specify the file name (a *.txt file) in which to store the model. Pressing the open button allows an existing ground properties model to be opened. A two-dimensional contour map of each waveform attribute can be made using the view button. This button uses *Surfer* (Golden Software) to generate the contour maps. Each waveform attribute varies as a function of soil permittivity, conductivity, and antenna standoff (i.e., three dimensions). A contour map of the attributes can be made as a function of any two of these parameters by adjusting the view parameters. For example, selecting *Eps vs Sig* plots and specifying a *view standoff* of 7 would generate a contour plot of each attribute where the horizontal axes of the graph are soil permittivity (epsilon) and conductivity, and the standoff is held to a constant value of 7. By changing the view parameters, the character of the changing attributes can be viewed on

Table 5. Methods of extracting waveform attribute sets.

| Attribute Set | Description | Results |
|--|---|----------|
| <i>FD amplitudes</i> | FFT spectral amplitudes from 10-200 MHz. If the waveform is 100 ns long, an amplitude value will be available at 10 MHz intervals. | Good |
| <i>TD amplitudes</i> | Peak amplitudes of waveform after applying a band pass filter bank. The filter bandwidths were 10 MHz and centered at frequencies between 10-200 MHz at approximately 10 MHz intervals. | Marginal |
| <i>TD times</i> | Time of energy peak of waveform after applying a band pass filter bank. The filter bandwidths were 10 MHz and centered at frequencies between 10-200 MHz at approximately 10 MHz intervals. | Poor |
| <i>TD amplitudes and times</i> | All parameters from the previous two methods | Poor |
| <i>Time and amplitude of first 4 peaks</i> | Time and amplitude of first four peaks. | Poor |
| <i>RMS amplitude and time centroid</i> | RMS amplitude and time of energy peak of waveform. | Poor |
| <i>20 data points</i> | 20 samples evenly spaced throughout the selected time window. | Poor |
| <i>20 data points on envelope</i> | 20 samples of the Hilbert envelope of the waveform evenly spaced throughout selected time window. | Good |

any plane (as long as one parameter remains fixed) that cuts through the model space shown in figure 26. This is useful for investigating the topography of a ground properties model (i.e., a forward model), and assessing how an inversion based on this forward model would perform.

Compare Waveforms

Use this menu item to compare waveforms measured in the field or laboratory with simulated waveforms. This is useful, for instance, when testing several GPR antenna models to find the one that produces simulation results similar to the actual GPR antenna response. This menu item produces the *Compare Waveforms Dialog* box (see fig. 28). This is a modeless dialog box, meaning that it does not have to be dismissed to access the other menu items or toolbar buttons. Click and drag on the blue header at the top of the dialog box to move the dialog box as needed. The dialog box will compare a single waveform from a field or laboratory test with a number of simulated waveforms. Use the corresponding *select* buttons to invoke the file selection dialogs. After selecting the files to be compared, check the invert boxes as necessary (the polarity of the simulated waveform may be different than that of the recorded waveform). The only supported file format for the field or laboratory data is the *.aq1 file recorded by the RTDGPR (USGS). The only simulation files supported at this time are *.out files created by *GPRMax*. The *.out files contain waveform data for the electromagnetic fields at many locations in the simulated model space. Enter the grid indices of the simulation grid corresponding to the physical location for the electric field waveform of interest (e.g., the receiving antenna port). Further operations to the simulated data may be needed before they can be compared with the recorded data. For example, the simulated data may only account for the antenna response, and the response of the receiving electronics must be included before a proper comparison to the recorded data can be made. Specify *.txt files containing waveforms to deconvolve and convolve if necessary. These waveforms should be written as ASCII text files where the first column contains the time values,

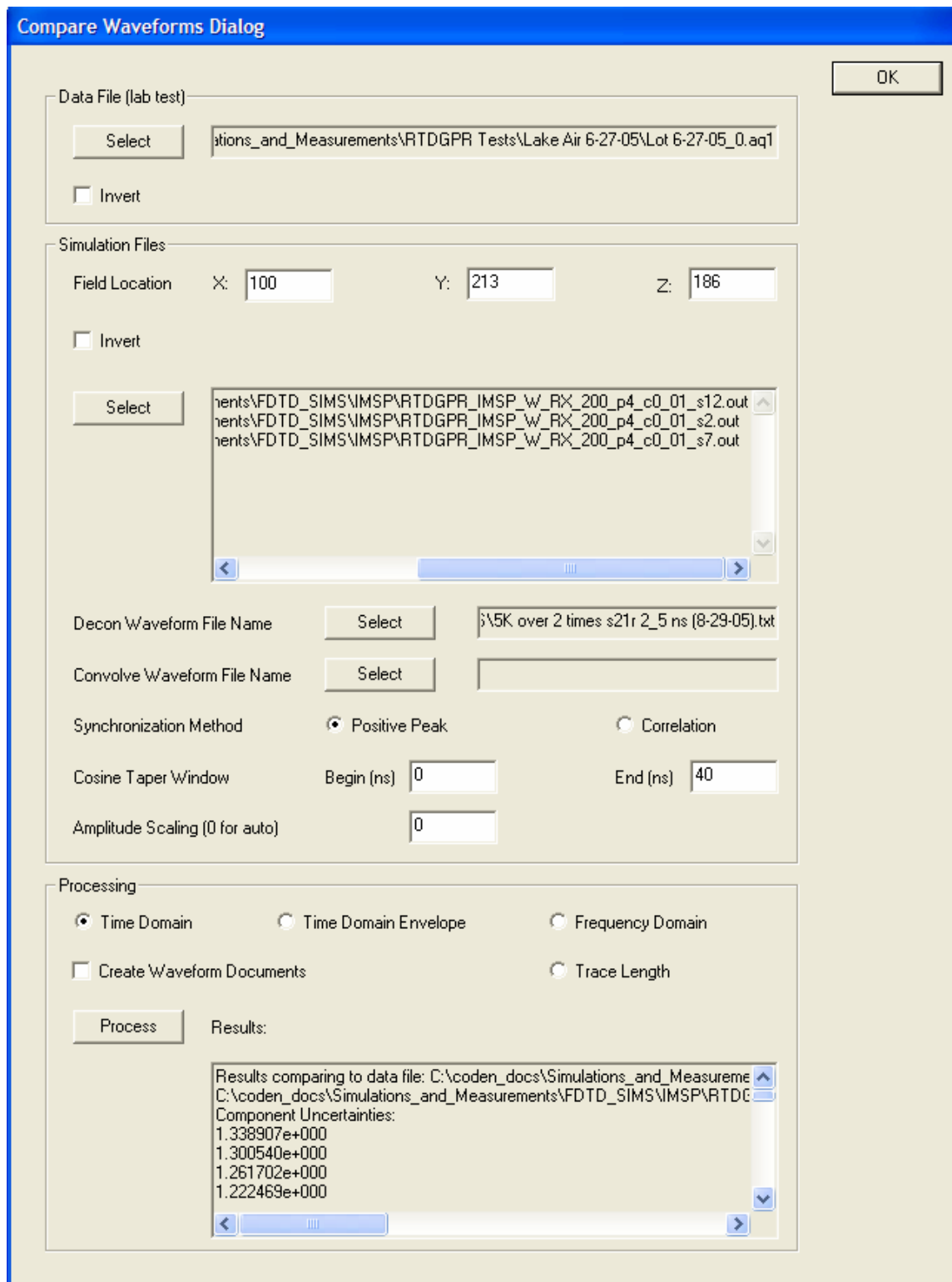


Figure 28. The *Compare Waveforms Dialog* box.

and the second column contains the data values. Note that any waveform that has been imported or created by *GP Workbench* can be exported in the ASCII text file format (see the *File, Export* menu item). The next step is to synchronize the waveforms using either the positive peak method or by correlation. The positive peak method adds a time shift to the simulated data so that the largest positive peak in the simulated waveform is aligned with the largest positive peak in the recorded data. The correlation method adds a time shift to the simulated data until a zero lag correlation is obtained between the simulated and recorded data. Next, a cosine taper can be applied to remove portions of the waveforms that should not be compared. For instance, a cosine taper could be used to remove a late time reflection from the recorded waveform that is not present in the simulated data. Finally, the simulated data can be amplitude scaled before being compared with the recorded data. If a value of zero is entered, an amplitude scaling factor will be calculated that causes the simulated data to most closely match the recorded data.

After processing the data sets, the comparison can be made. Four methods of comparing the waveforms are available. The time-domain method simply calculates the RMS amplitude difference between the waveforms on a sample-by-sample basis. The time-domain envelope method calculates the Hilbert envelope of each trace before calculating the RMS amplitude difference. The frequency-domain method takes the fast Fourier transform of each trace, and then calculates the RMS amplitude difference on a frequency-by-frequency basis. Finally, the trace length method determines the trace length (i.e., the sum of the length of each line segment making up the waveform) of each waveform, and compares these lengths. When all of the parameters for processing the waveforms and making the comparisons are set, press the *process* button to make the comparison. The amplitude-scaling factor and the difference between the simulated data and the recorded data will be displayed in the results pane. If the create waveform documents box is checked, then a *GP Workbench* document will be created for the

recorded data file and each simulated data file specified in the dialog box. The waveforms will be processed according to the parameters in the *Compare Waveforms Dialog* box before a document is created. A visual comparison between waveforms can be made by creating waveform documents, and then plotting multiple waveforms on the same graph (see the *Plot Parameters Dialog* box in Figure 17).

TM and TE Spectrum

Use this menu item to import a scan plane wave field (see fig. 21) from a set of numerical simulations. The simulations are needed to model the electromagnetic fields on a scan plane beneath the transmitting antenna of a GPR system. Accurate simulations of actual GPR antennas can be made using the finite-difference time-domain methods (Oden, 2006; Giannopoulos, 2004). These simulations can only directly calculate the fields near the antenna. If the fields further from the antenna are desired, then a field propagator can be used (see the *Process, Image Plot 3D Depth Shift* menu item). To import a scan plane wave field, *GP Wave Utilities* reads in the time- and space-domain wave field values from the files produced in the simulation. During import, these time-domain and space-domain wave field values are converted to frequency-domain field values. An electromagnetic wave field can be efficiently described in terms of the transverse magnetic (TM) spectrum, and the transverse electric (TE) spectrum. The TM and TE spectra are a subset of the frequency-domain wave field values. The salient point is that this import process converts the wave field into a more compact and readily usable format, which in turn facilitates wave field calculations such as those made with the *Process, Image Plot, 3D Depth Shift* menu item.

The *GPRMax* simulations must be set up to record the fields on the scan plane using snapshot files (*.snp). The simulations calculate the wave field at a series of times steps (e.g., 0 to 100 ns in 20 ps intervals). The wave field values on the scan plane for each time step are recorded in a snapshot file. A different file is written for each time step with the name *_nnnn.snp, where nnnn is the index of the

snapshot. If 1000 time steps are used in the simulation, the first file will be named *_0000.snp and the last *_0999.snp. The scan plane, as defined by the locations of the field values recorded in the snapshot files, must be centered beneath the transmitting antenna and have the same spatial extent in the X and Y directions. To begin the import process, select the *_0000.snp file. The import process may require a few hours to run depending on the number of time steps in the simulation, the size of the scan plane, and the spatial sample interval. After importing the wave field, it can be saved as a *GP Wave Utilities* file (*.fdw) for storage to disk and much quicker retrieval. For a detailed description of this process, refer to Oden (2006).

View, Window, and Help Menus

These menus contain the standard items for a Windows application.

The Toolbar

The toolbar shown below provides many operations for viewing and processing data. Each button on the toolbar will be described in more detail below.

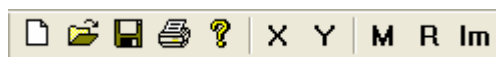


Figure 29. The GP Wave Utilities toolbar.



The new document button generates a new empty document. A document must exist in which to import data files.



The Open-File dialog can be used to open *GP Wave Utilities* document files (*.fdw files).



The save document saves the current document. If a file has not yet been associated with the document, the user is prompted for a file name.



The print button prints the current document using the default printer.



This button displays information about *GP Wave Utilities* such as the version number.



This button shows the wave field in the x-plane in either the time domain (x, t) of the frequency domain (k_x, ω). This button only functions with the wave field data.



This button shows the wave field in the y-plane in either the time domain (y, t) of the frequency domain (k_y, ω). This button only functions with the wave field data.



This button shows the magnitude of the wave field in the frequency domain. This button only functions with the wave field data.



This button shows the real part of the wave field in the frequency domain. This button only functions with the wave field data.



This button shows the imaginary part of the wave field in the frequency domain. This button only functions with the wave field data.

Data Processing Methods

The processing steps used to process each geophysical data set are different. There are, however, some basic processing outlines that are broadly applicable to many data sets. In this section, processing overviews are given for GPR and ALLTEM datasets.

GP Workbench GPR Data Processing Procedures

The goals of data processing vary. Even so, there are basic processing steps that are commonly followed when processing GPR data. An outline for section view processing and for plan view processing are presented below.

GPR Section View Processing

The following list provides a good start for processing a single file in section view.

- 1) Import the data file in section view.
- 2) After importing the data, it needs to be gridded. The exact procedure will vary depending on the type of data and the gridding algorithm used. If marked positions are used, the user should make sure that all marks are present, and no extra marked positions are included. See the toggle marks button on the toolbar section. Specify the grid parameters using the *Grid Parameters Dialog* box (see fig. 3). Then press the grid button on the toolbar.
- 3) Click on the plot and use the up and down arrow keys to position the cross hairs at time zero (when the transmitter fired). Press the zero time button on the toolbar.
- 4) Filter the image to improve the contrast of reflections with background and to remove noise. Use the *Process, Filter* menu item. Commonly applied filters include background removal and frequency filters.
- 5) Perform a velocity analysis. Locate a reflector on the section that exhibits hyperbolic move out. Click on the plot and use the arrow keys to position the cross hairs on the apex of the hyperbola. Next, click the velocity hyperbola button. Use the arrow keys to adjust the shape of the fitting hyperbola to match the diffraction hyperbola pattern. The velocity and index of refraction will be displayed in the status bar on the bottom of the main window. Click the velocity hyperbola button to exit the hyperbola fitting mode. Now, click on any point on the cross section and read the depth of the cross hairs from the status bar.

GPR Plan View Processing

The following steps outline a basic procedure for processing plan view GPR data.

- 1) Import the data files in plan view. If specific positional processing must be applied to each file, then each file should be opened in section view, gridded, and saved. These processed files can then be imported together in plan view.
- 2) After importing the data, it may need to be gridded. Usually, plan view data are not re-sampled on a uniform grid. It is important to have interpolated positions calculated between marked traces before continuing. This can be done on a line-by-line basis in section view before importing the files in plan view, or it can be done in plan view. Specify the grid parameters using the *Grid Parameters Dialog* box (see fig. 3). Then press the grid button on the toolbar.
- 3) Filter the image to improve the contrast of reflections with background and to remove noise. Use the *Process, Filter* menu item. Commonly applied filters include background removal and frequency filters.
- 4) Use the up and down arrows to select the time-slice of interest, then select the *View, Surfer* menu item. This will generate a high quality *Surfer* (Golden Software) image. See the *View, Surfer* menu item for more details.

GP Workbench ALLTEM Data Processing Procedures

The *GP Workbench* program defines a UXO target in terms of three orthogonal principal polarizabilities. When specifying these dipole moments, the attitude of the first (largest) principal polarizability is specified. The direction of second dipole is determined from the cross product of the first polarizability with the vertical axis. The direction of third polarizability is the cross product of the first two polarizabilities. Only one time constant is used to simulate the transient response. This is the effective time constant at given late time, and the dipole moments are the magnitude of the response at this time. When inverting actual data, data for the transient response for all polarizations are extracted

at the same moment in late-time. This moment is when the RMS amplitude of all channels is equal to 25% of the RMS peak value of all the channels.

The data processing procedures outlined below require that calibration data be recorded using the steel ball after the system has warmed up and the response has stabilized.

Calibration Procedure

1. Import data files recorded at a fixed location to obtain the system response. Import *.h1m and associated documents. Run a 5-point boxcar spatial filter. Select a trace to use in the calibration and run a fixed window spatial filter using this trace (i.e., replace all traces with selected trace). Remove all traces except the first 10 (use the *Filter Dialog* box). Use *Save As* to save files as *.h1m.SU.
2. Import data files recorded at a fixed location (same location that the system response was measured) where the response of the steel reference ball was measured. Import *.h1m and associated documents. Run a 5-point boxcar spatial filter. Select a trace to use in the calibration and run a fixed window spatial filter using this trace (i.e., replace all traces with selected trace). Remove all traces except the first 10 (use the *Filter Dialog* box). Use *Save As* to save files as *.h1m.SU.
3. Concatenate system response and steel shot response files by importing the *.h1m.SU files saved in steps 1 and 2 above. The files will be concatenated in the order they appear in the import file select list. Make sure that system response file is the first in the list.
4. Subtract background response. Use the *Filter Dialog* box, *remove spatial window, fixed window* 2-3. Process associated files concurrently.
5. Remove all records in each file except the last 5 (use the *Filter Dialog* box).

6. Select *Process, ALLTEM Calibration* from the menu. This will write the calibration file Cal.h1m.cal.

UXO Target Inversion Procedure

1. Import data files in section view. Remove noisy traces (using toolbar button). Process associated files concurrently. Use *Save As* to save as (*.h1m.SU, and associated files).
2. Import data files in plan view. Remove traces with bad GPR readings (using toolbar button). Process associated files concurrently. Use *Save As* to save as (*.h1m.SU, and associated files).
3. Make an import.txt file for the directory containing the data. This file contains the coefficients defining the linear mapping of latitude and longitude to northing and easting.
4. Pick a target to process. Identify the lines containing the response from this target. For each line, do steps 3-4. It is assumed that each line has leading and trailing data with no targets from which the system response and the soil response can be determined.
5. Subtract background response. Determine trace numbers for leading data and trailing data using viewer. Use the *Filter Dialog* box, *remove spatial window*, interpolate between windows 2-3 and 101-102, where the numbers are the trace numbers determined above. Process associated files concurrently.
6. Grid the data without resampling on a uniform grid.
7. Remove all records in each file except those containing the response from the target (use the *Filter Dialog* box). Use *Save As* to save files as TargetX.h1m.SU (or similar) and associated files.
8. With TargetX.h1m.SU and associated files opened in plan view (this interpolates between GPS marks without resampling), select *Process, Estimate UXO Parameters*

from the menu. Several initial models may need to be run to obtain a valid solution.

After inversion, text listing UXO parameter estimates can be copied from the progress dialog box.

GP Wave Utilities Data Processing Procedures

The various procedures offered by *GP Wave Utilities* can be combined in many ways to solve a myriad of signal processing problems. Two examples are given here. For the first, the transfer function of a signal processing electronics module is determined. For the second, simulated data and measured data are synchronized and compared.

Determining the Transfer Function

In this processing example, the transfer function of an amplifying analog to digital (A-D) converter module is determined.

1. Inject a signal from a signal generator to the input terminals of the A-D module. Record the signal at the input terminals with a digitizing oscilloscope. Most oscilloscopes record data in a text file format. Also, record the digital output of the module.
2. Import the data recorded with the oscilloscope using the *File, Import, ASCII* menu item. Create a new document (*File, New*) and import the digitized output of the module.
3. Switch to the oscilloscope data, and resample the data at the sample rate and time interval used when recording the module output.
4. Switch to the module data, then use the *Process, Wave Plot, Deconvolve* menu item to deconvolve the oscilloscope data from the module output data. Next, right click on the resulting plot and select the frequency-domain representation. The plot now shows the frequency-domain transfer function of the amplifier/A-D module.

Synchronize and Compare Experimental Data with Simulated Data

1. Import the simulated data. For example, use the *File, Import, GPRMax, Fields* menu item.
Import the experimental data (e.g., that from an oscilloscope) using the *File, Import, ASCII* menu item.
2. Switch to the oscilloscope data, and resample the data at the sample rate and time interval used when creating the simulated data.
3. Use the *Process, Wave Plot, Compare Waves* menu item to determine the time shift to apply to the oscilloscope data to synchronize it with the simulated data.
4. Use the *Process, Wave Plot, Filters and Operators* menu item to shift the oscilloscope data by the amount of time determined from the previous step.
5. Now the data are synchronized and can be visually compared. Right click on the plot and select the simulated data as an auxiliary trace. Now both traces will be plotted on the same graph. Use the *Process, Wave Plot, Compare Waves* menu item to determine the RMS error between the waveforms and the amplitude scale factor between them.

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Appendix A

The ALLTEM UXO forward operator approximates the induced field response of a subsurface UXO. The forward model includes both the induced magneto-static response, and the electro-dynamic response from induced transient eddy currents at a fixed instant in time. The magneto-static UXO response is modeled as three orthogonal magnetic dipoles, and the electro-dynamic response is modeled as three orthogonal exponentially-decaying magnetic dipoles. It is assumed that the target and the ALLTEM cart are in a non-magnetic, non-conducting whole space. The modeled magneto-static induction (T) at a receiver coil $\mathbf{B}_s(\mathbf{r})$ is calculated using

$$\mathbf{B}_s(\mathbf{r}) = \vec{\mathbf{k}} \cdot \left[\frac{3\hat{\mathbf{R}}(\mathbf{m}_s \cdot \hat{\mathbf{R}}) - \mathbf{m}_s}{R^3} \right] \quad (\text{A1})$$

where $\vec{\mathbf{k}}$ is a calibration matrix, \mathbf{r} is the location of the receiver, \mathbf{r}' is the UXO location, $\mathbf{R} = \mathbf{r} - \mathbf{r}'$, $R = |\mathbf{R}|$, $\hat{\mathbf{R}} = \mathbf{R} / R$, and \mathbf{m}_s is the static induced dipole moment (A-m²). The static induced dipole moment is given by

$$\mathbf{m}_s = \begin{bmatrix} \mathbf{m}_{s,1}\hat{\mathbf{m}}_{s,1} & \mathbf{m}_{s,1}\hat{\mathbf{m}}_{s,2} & \mathbf{m}_{s,1}\hat{\mathbf{m}}_{s,3} \\ \mathbf{m}_{s,2}\hat{\mathbf{m}}_{s,1} & \mathbf{m}_{s,2}\hat{\mathbf{m}}_{s,2} & \mathbf{m}_{s,2}\hat{\mathbf{m}}_{s,3} \\ \mathbf{m}_{s,3}\hat{\mathbf{m}}_{s,1} & \mathbf{m}_{s,3}\hat{\mathbf{m}}_{s,2} & \mathbf{m}_{s,3}\hat{\mathbf{m}}_{s,3} \end{bmatrix} \cdot \mathbf{H}_p(\mathbf{r}') \quad (\text{A2})$$

where $\mathbf{H}_p(\mathbf{r}')$ is the primary magnetic field (A/m), and the matrix is the polarizability tensor (m³) and the three induced magnetic moments are related by

$$\hat{\mathbf{m}}_2 = \hat{\mathbf{m}}_1 \times \hat{\mathbf{z}} \quad \text{and} \quad \hat{\mathbf{m}}_3 = \hat{\mathbf{m}}_1 \times \hat{\mathbf{m}}_2. \quad (\text{A3})$$

The primary field $\mathbf{H}_p(\mathbf{r}')$ at the UXO location is calculated using the Biot-Savart Law (Jackson, 1999) for the 1-meter-square loop transmitting coils. Similar relationships are used to model the electro-dynamic induction at a receiver coil,

$$\mathbf{B}_t(\mathbf{r}) = \vec{\mathbf{k}} \cdot \left[\frac{3\hat{\mathbf{R}}(\mathbf{m}_t(t) \cdot \hat{\mathbf{R}}) - \mathbf{m}_t(t)}{R^3} \right], \quad (\text{A4})$$

$$\mathbf{m}_t(t) = \begin{bmatrix} \mathbf{m}_{t,1}\hat{\mathbf{m}}_{t,1}e^{-t/\tau_1} & \mathbf{m}_{t,1}\hat{\mathbf{m}}_{t,2}e^{-t/\tau_1} & \mathbf{m}_{t,1}\hat{\mathbf{m}}_{t,3}e^{-t/\tau_1} \\ \mathbf{m}_{t,2}\hat{\mathbf{m}}_{t,1}e^{-t/\tau_2} & \mathbf{m}_{t,2}\hat{\mathbf{m}}_{t,2}e^{-t/\tau_2} & \mathbf{m}_{t,2}\hat{\mathbf{m}}_{t,3}e^{-t/\tau_2} \\ \mathbf{m}_{t,3}\hat{\mathbf{m}}_{t,1}e^{-t/\tau_3} & \mathbf{m}_{t,3}\hat{\mathbf{m}}_{t,2}e^{-t/\tau_3} & \mathbf{m}_{t,3}\hat{\mathbf{m}}_{t,3}e^{-t/\tau_3} \end{bmatrix} \cdot \mathbf{H}_p(\mathbf{r}'), \quad (\text{A5})$$

where τ_1 - τ_3 are the late time decay constants. In practice, the decay constant are ignored, and the electro-dynamic response is calculated for a given instant in time.

To calculate the ALLTEM response to a UXO target using a given loop polarization, the primary field $\mathbf{H}_p(\mathbf{r}')$ is calculated at the UXO location for the relevant transmitting loop, and the B fields at the relevant receiver loop locations are calculated. Each transmitter coil is modeled as a one-meter-square loop. For a given measurement, the ALLTEM uses two receiver coils to make a differential measurement. The B fields at each coil location are subtracted to model the differential measurement. Each receiver coil is approximated as an ideal small dipole located at the center of the actual coil. The error introduced by this approximation increases as the distance between a receiver coil and the UXO decreases, and as the area of the receiver coil increases.

Appendix B

This Appendix describes the steps for setting up the *GP Workbench* development project so that changes can be made to the code as needed, and new executables can be compiled. *GP Workbench* was written using *Microsoft Visual C++ v. 6*. This development system or a compatible development system must be installed to make changes and recompile *GP Workbench*.

1. Make a directory for the *GP Workbench* code. Extract the contents of the self-extracting zip-file *GPWorkbench1_7_1_11.exe* to this directory.
2. Open the *GP Wave Utils* directory, and then open the *MatClass* directory. Double click on the *MatClass.dsw* file to bring up the *MatClass* project. Select *Build, Set Active Configuration* from the menu. Select the debug configuration. Select *Build, Rebuild All* to build a debug version of the project. Repeat for the release version of the project. Copy the file *\FDTDProc – MatClass\MatClass\Release\MatClass.lib* to the *\FDTDProc – MatClass\Release* directory and to the *\GP Workbench\Release* directory. Copy the file *\FDTDProc – MatClass\MatClass\Debug\MatClass.lib* to the *\FDTDProc – MatClass\Debug* directory and to the *\GP Workbench\Debug* directory.
3. Open the *GP Wave Utils* directory, and then open the *FDTDProc - MatClass* directory. Double click on the *FDTDProc.dsw* file to bring up the *GP Wave Utilities* project. Select *Build, Set Active Configuration* from the menu. Select the debug configuration. Select *Build, Rebuild All* to build a debug version of the project. Repeat for the release version of the project. Look for a new *FDTDProc.exe* in the debug and release directories. Copy the release version of the executable to the program files directory where *GP Workbench* was installed (typically *C:\Program Files\GP Workbench*).

4. Open the *GP Workbench* directory. Double click on the *Radar.dsw* file to bring up the *GP Workbench* project. Select *Build, Set Active Configuration* from the menu. Select the debug configuration. Select *Build, Rebuild All* to build a debug version of the project. Repeat for the release version of the project. Look for a new *GPWorkbench.exe* in the debug and release directories. Copy the release version of the executable to the program files directory where *GP Workbench* was installed (typically *C:\Program Files\GP Workbench*). Note that when running *GP Workbench* from the *\GP Workbench\Release* or the *\GP Workbench\Debug* directories, some *GP Workbench* functions may not operate correctly because the program may need certain files that exist in the *C:\Program Files\GP Workbench* directory but not in the development directories.
5. The Inno Setup Compiler (Russel, 2004) can be used to make a single file install program for *GP Workbench*. Make the necessary changes to the file *GP Workbench\GPWorkbenchInstaller.iss* to make the install program. Consult the documentation for the Inno Setup Compiler for more information.