EKKO_Project
Processing Module

-

User's Guide

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s u b s u r f a c e   i m a g i n g   s o l u t i o n s

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1 Introduction

EKKO_Project was designed to simplify the display, editing, processing, and interpretation of Ground Penetrating Radar (GPR) data.

Processing is an optional module of the EKKO_Project software. It is used for processing GPR lines.

Processing features:

1. A semblance analysis routine for processing CMP/WARR surveys to extract velocity information. This routine is available as a processing routine and as part of a standard processing display.
2. Edit GPR lines with a variety of editing functions such as cropping data and repicking the first break.
3. Process GPR lines with a variety of processing routines such as temporal filters, spatial filters, two types of migrations, Instantaneous attributes etc.
4. Develop processing streams and save them as "recipes" to apply to other GPR projects or send to colleagues for them to use.

2 EKKO_Project User Interface

The Processing routines and the Standard Processing Plots (Average Trace Amplitude, Average Frequency Spectrum and Trace plots) are accessed a number of ways using the EKKO_Project user interface. The interface is described very briefly here but, if more information is required, refer to the EKKO_Project User's Guide.

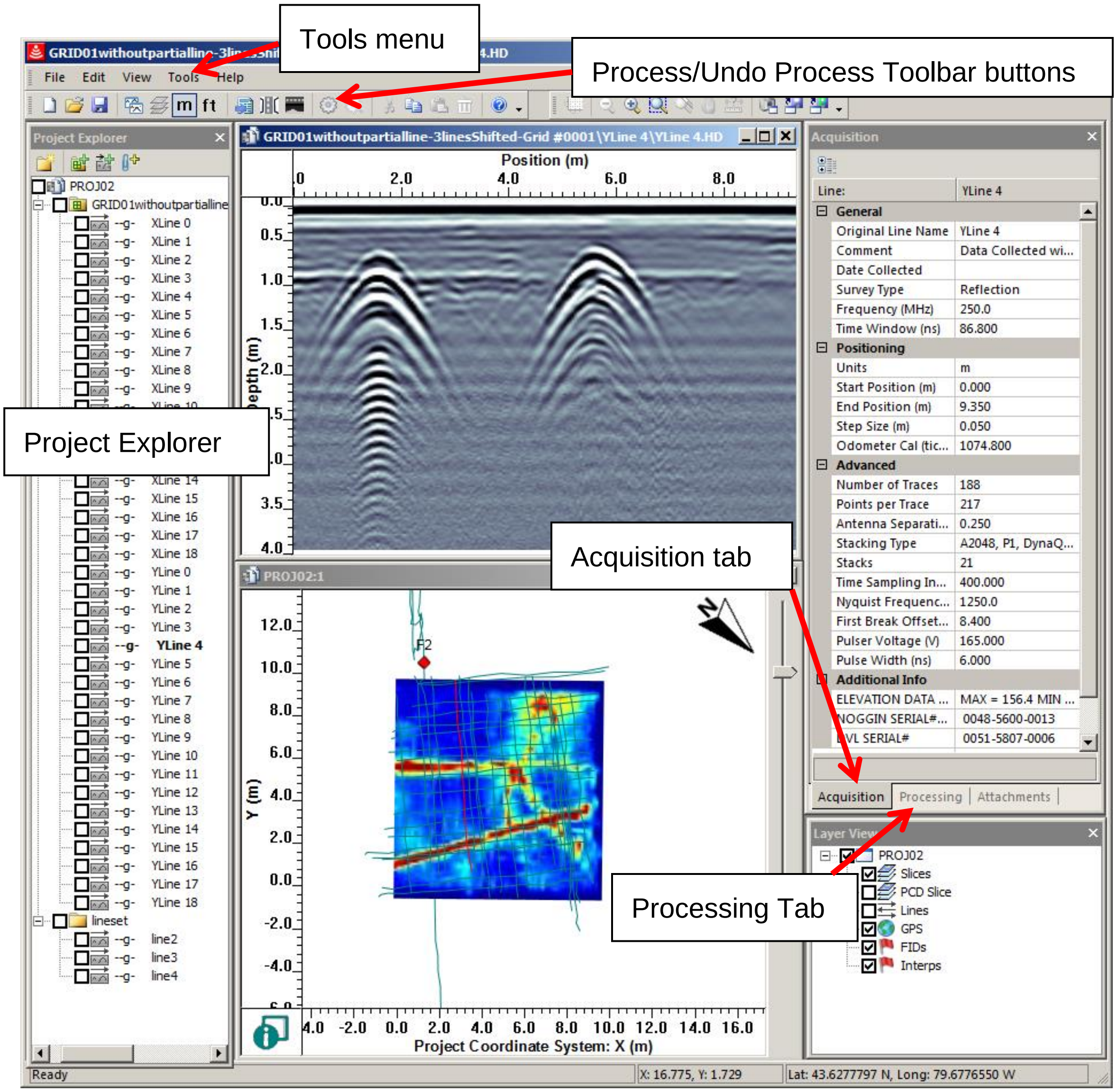


***Figure 1**: EKKO_Project user interface features used by the Processing module.*

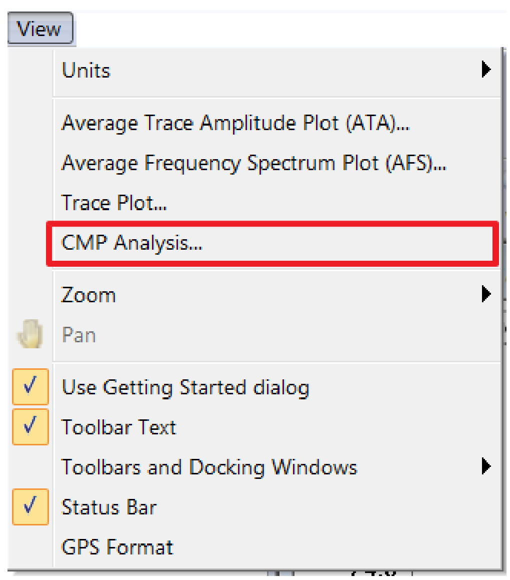
3 Standard Processing Plots

The Processing module offers several types of plots that follow a standard processing stream and output data that is of interest to advanced GPR users, typically with a familiarity with signal processing. These plots are described in this section.

3.1 CMP/WARR Analysis

An accurate radar velocity is critical for accurately determining the depth of a target. A CMP (Common Mid-Point) or WARR (Wide Angle Reflection and Refraction) surveys provide a way of measuring radar velocity in the ground or in a structure. The CMP Analysis routine processes a CMP file by semblance analysis; stacking the data traces at many different velocities. When traces are stacked at an incorrect velocity, they will tend to destructively interfere and produce low amplitudes. When traces are stacked at the correct velocity, they will constructively add together and produce high amplitudes. A plot of the stacked data allows the user to match the highest amplitudes with a velocity value. This velocity can then be used when plotting GPR lines.

To apply CMP Analysis to the currently selected CMP file in Project Explorer, select or check the file name and then click **View > CMP Analysis.**



The CMP Analysis dialog opens:

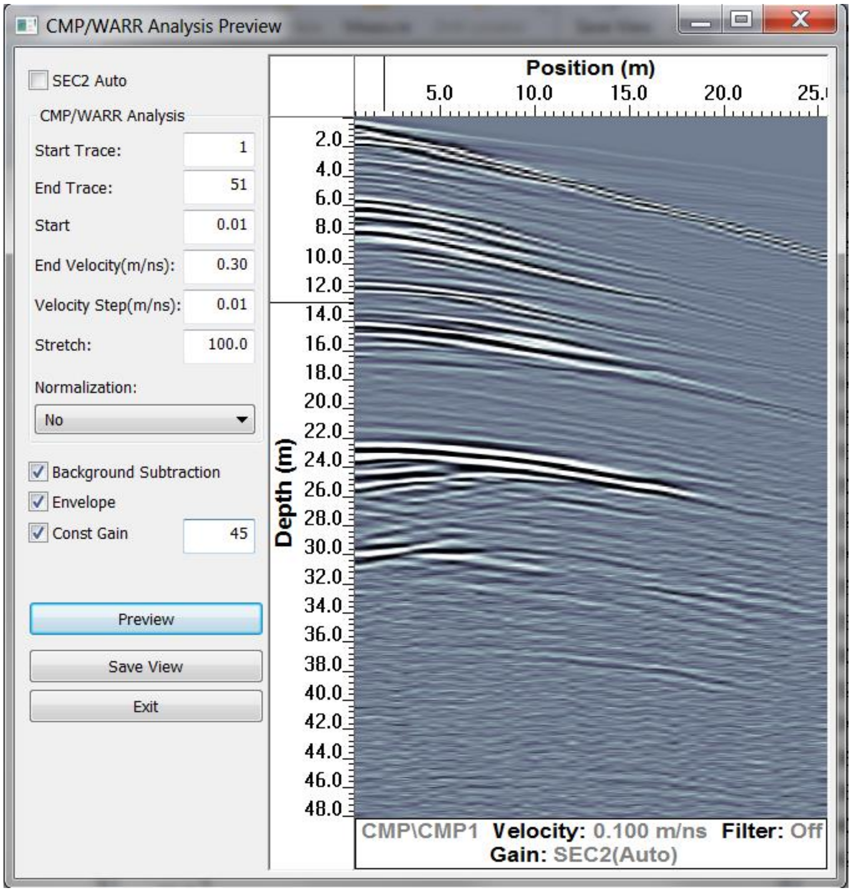


***Figure 2**: CMP Analysis dialog*

3.1.1 Parameters

SEC2 Auto

If SEC2 Auto is checked, an exponential (SEC) gain is applied to the input CMP/WARR data prior to stacking the traces in the CMP Analysis. Details of the SEC2 gain are described in SEC2. In CMP/WARR Analysis Preview, the SEC2 parameters are automatically calculated and not manually entered by the user.

Note that even if this gain function is applied, it may still be necessary to apply a small Constant (Const) gain when plotting the output velocity section using the EKKO_Project plotting programs (see below).

CMP/WARR Analysis

Details of the CMP/WARR Analysis and the parameters are described in CMP/WARR Analysis.

Background Subtraction

If Background Subtraction is checked, the average trace of all the traces generated by the CMP/WARR Analysis process is subtracted from each stacked trace in the CMP/WARR file. The details of this process are described in Background Average Subtraction.

This option is useful because, when viewing the velocity section generated by the CMP/WARR Analysis Preview, it is often difficult to determine exactly which stack velocity has enhanced the reflector the most. High velocities yield a constant stack result which is velocity independent; several different velocities may look similar, making the final determination difficult. Background Subtraction can help determine the best stack velocity.

Envelope

If Envelope is checked, the stacked traces generated by the CMP/WARR process are enveloped so, rather than displaying the GPR traces with both the positive and negative signal components, all signals are positive. The details of this process are described in Envelope.

In most cases, enveloping the data helps to determine the best stack velocity.

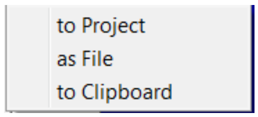
Const Gain

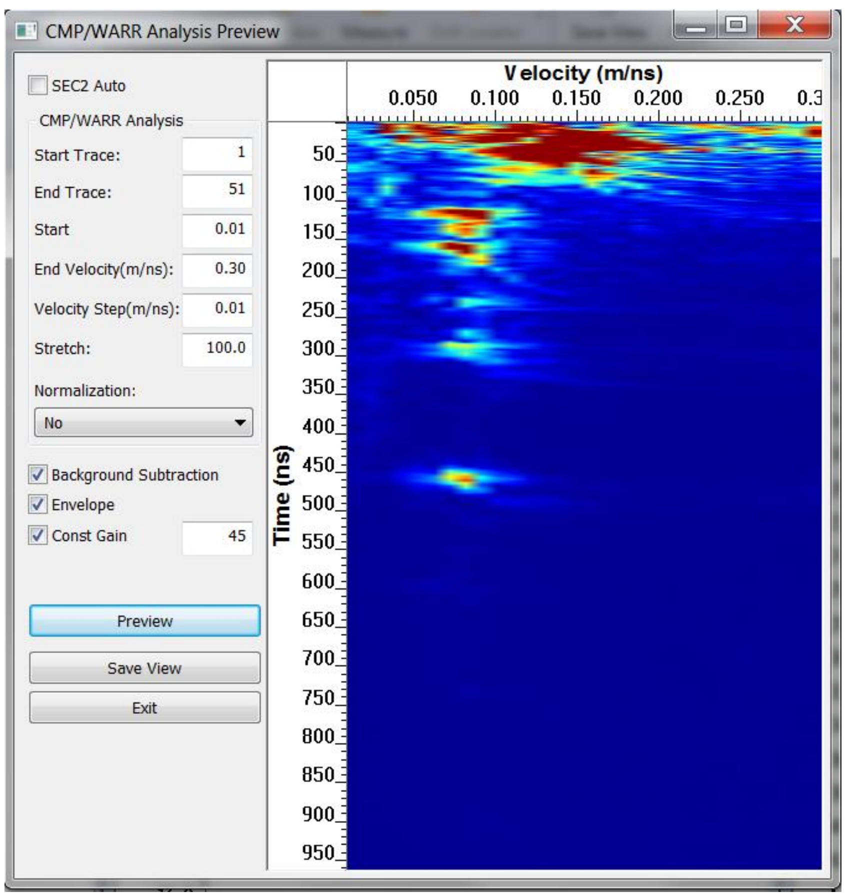
If Const Gain is checked, a constant gain is applied to the stacked traces generated by the CMP/WARR process. Details of the Constant gain are described in Constant Gain.

Applying a small (typically 2-50) constant gain is often necessary when plotting the output velocity section using the EKKO_Project plotting programs.

Use the following table as a guide to working with the CMP/WARR Analysis:

Item	Description
Preview	Pressing the **Preview** button applies the CMP/WARR Analysis as well as the checked pre and post processing to the CMP/WARR data and generates and displays the velocity section (see figure below). To change the processing applied, simply edit the processing checkboxes and parameters and press **Preview** again. It may take several iterations, adjusting the SEC2 Auto and the Constant gain level to optimize the velocity section so the best stacked velocities can be easily determined. The result of the CMP/WARR analysis is displayed on the right side of the window.

Item	Description
Save View	Click **Save View** *before* clicking the **Preview** button to save the CMP/WARR data plot as an image. Click **Save View** *after* clicking the **Preview** button to save the CMP/WARR Analysis Preview plot as an image. The save options are:  **To Project** will save the image and attach it to the project file. When the GPR Summary Report is selected, the user can select from the images attached to project to appear in the report. To learn more, see the GPR Summary Report in the EKKO_Project manual. **As File** will save the image to a graphics image file **To Clipboard** will save the image to the Clipboard so it can be pasted into documents.
Exit	Click **Exit** to exit the CMP/WARR Analysis Preview routine.



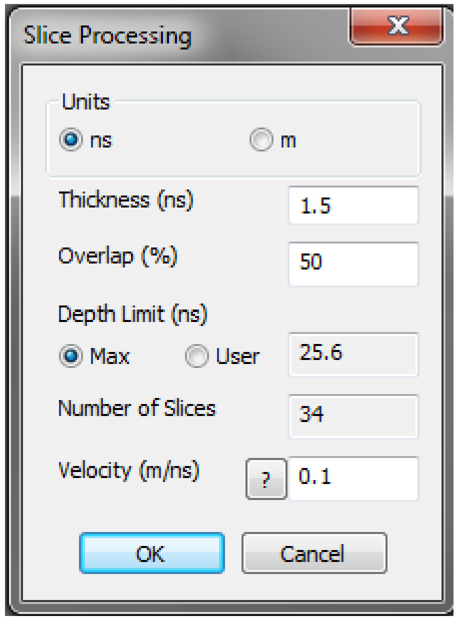
3.2 Slices

Use the Slices feature to export Average Trace Amplitudes for one or more intervals from all the traces in the selected lines to a comma separated (.csv) file. Slices are compatible with 2D plotting software applications such as Golden Software's Surfer.

This provides a means of generating depth slices from GPR data collected in a "random-walk" with GPS for positioning.

Figure 3*: Random walk GPR data using GPS for positioning.*

1. To export depth slice information from the project (gpz) file, click **File > Export > Slice**.



The **Slice Processing** dialog box is automatically populated with default data.

2. Use the following table as a guide to working with the Slice Processing dialog box:

Field	Description
Units	Select an option to generate slices based on time (ns) or depth (m or ft.).
Thickness	Enter the thickness for each slice, in terms of time (ns) or depth (m or ft.).
Overlap	Enter the overlap percentage between slices. Overlap represents the amount that each slice overlaps the previous slice as a percentage of the slice thickness.
Depth Limit **Max/User**	The maximum depth (or time) that slices will be generated: • Select **Max** to generate slices up to the maximum line depth • Select **User** to generate slices up to the user defined depth
Number of Slices	The number of slices in the slice export dialog is an estimate. For large antenna separations and low signal velocities the number of slices exported in depth mode may be fewer since the slicer uses individual depth for each line as shown in LineView depth axis at the selected velocity.
Velocity	Enter the signal velocity for generating depth slices. Click  to learn more about signal velocity

3. Click **OK**.
4. In the **Select folder to export to** dialog box, navigate to and then select the folder you want to save the slices to.

5. Click **Select Folder**.

   Windows Explorer opens to display where you saved the slices.

6. Double-click a .csv file to display the results:

X(m)	Y(m)	Longitude	Latitude	GPS-Easting (Z=33U)	GPS-Northing (Z=33U)	Amplitude (mV)	Elevation(m)
0	0	178.0216	48.40248	575612.5	5361540	10.68167	182.21
0.02	0	178.0216	48.40248	575612.5	5361540	11.02386	182.22
0.04	0	178.0216	48.40248	575612.5	5361540	11.57758	182.23
0.06	0	178.0216	48.40248	575612.5	5361540	10.57218	182.24
0.08	0	178.0216	48.40248	575612.5	5361540	10.83922	182.25
0.1	0	178.0216	48.40248	575612.5	5361540	10.10773	182.26
0.12	0	178.0216	48.40248	575612.5	5361540	9.425069	182.27
0.14	0	178.0216	48.40248	575612.5	5361540	9.862819	182.28
0.16	0	178.0216	48.40248	575612.5	5361540	10.61968	182.29

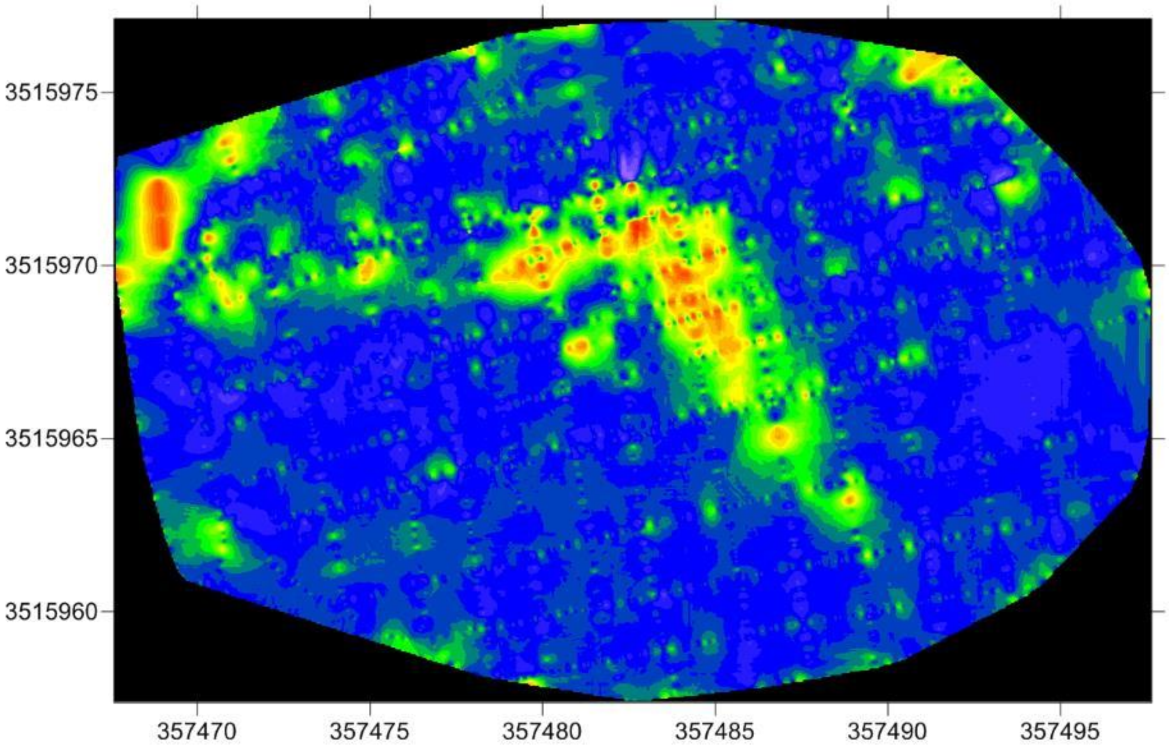
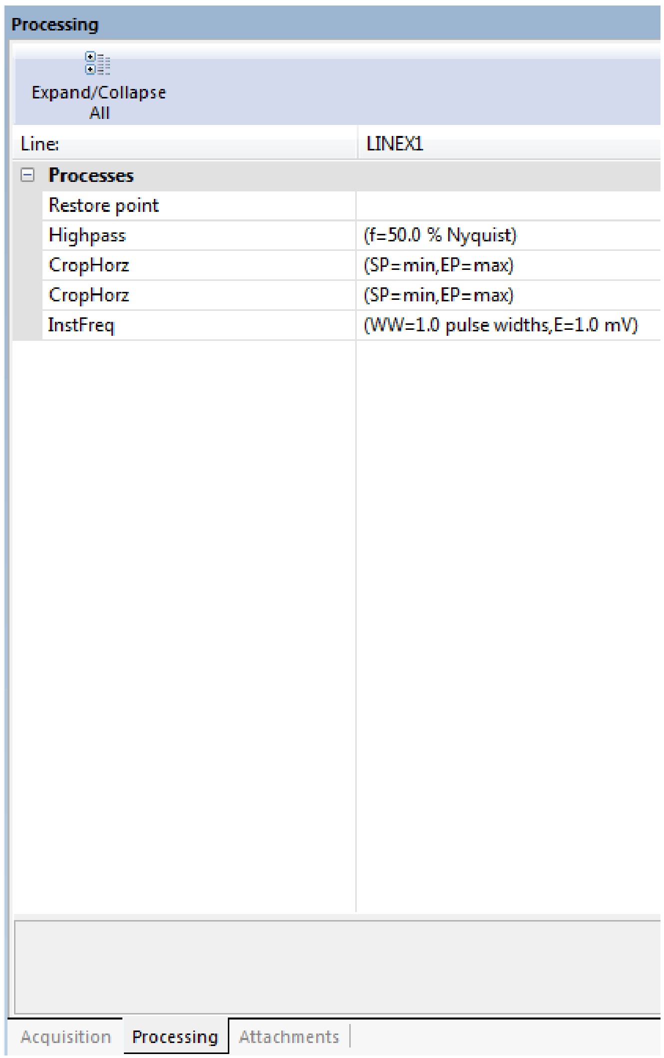


***Figure 4**: Depth slice from 1.0 to 1.1 meters depth from random walk data in previous figure. Plotted using Surfer 2D plotting software.*

4 Processing Tab

If GPR lines have been processed using the optional Process module, the processing details, including the name of the processes, the order the processes were applied, and the details of the process parameters are listed in the Processes tab.

Only processed GPR lines are identified by a small letter "p" in the Project Explorer will list processing information in the Processes tab. However, GPR Lines that have been processed and then copied into a lineset will be listed but will not be identified by the letter "p." To learn more, see Processing Functions.



Note: Distance units (m/ft.) listed in the processes tab are always displayed in the format the GPR line was collected in, even if the units have been changed in EKKO_Project.

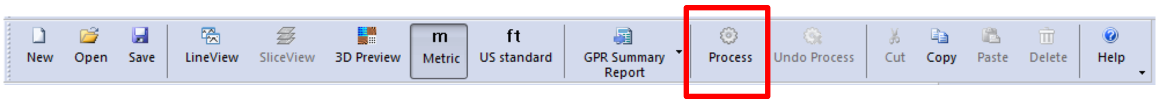
5 Process

Use the optional Processing module to edit and process GPR lines using various functions including repositioning, temporal and spatial filters, and migration.

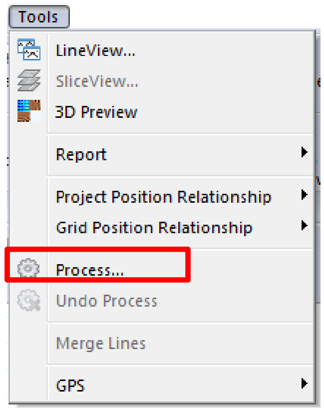
It is a best practice to make a copy of the GPR Lineset, grid or lines and then apply the processing to the copy of the GPR lines. While processing can always be undone, this is a good way to plot both the original data and the processed data to compare the effects of the processing.

5.1 Processing Multiple GPR Lines

1. If the **Process** button is selected from the Toolbar:



2. or from the **Tools > Process** menu:



all the GPR lines currently checked in Project Explorer are processed.

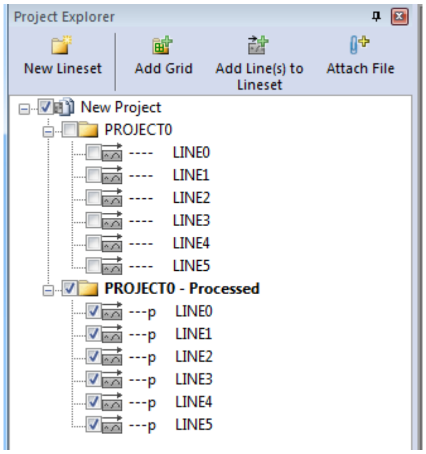
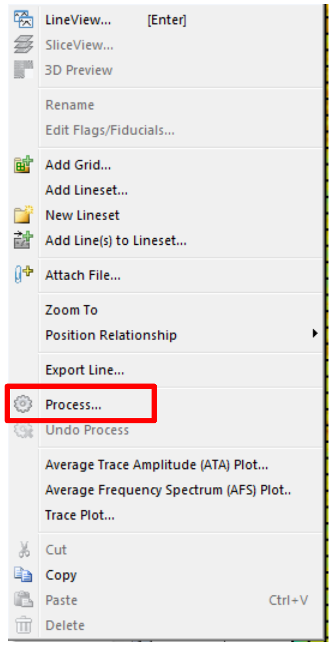


***Figure 5**: To process several GPR lines at once, check them in Project Explorer before selecting Process on the Toolbar or in the Tools menu.*

If no GPR lines are checked when Process is selected, processing is applied to the GPR line selected in Project Explorer.

5.2 Processing One GPR Line

If Process is selected from the Right-click menu in Project Explorer**:**



only the currently selected GPR line in Project Explorer is processed, regardless of whether any other GPR lines are checked.

5.3 Creating a Processing Stream

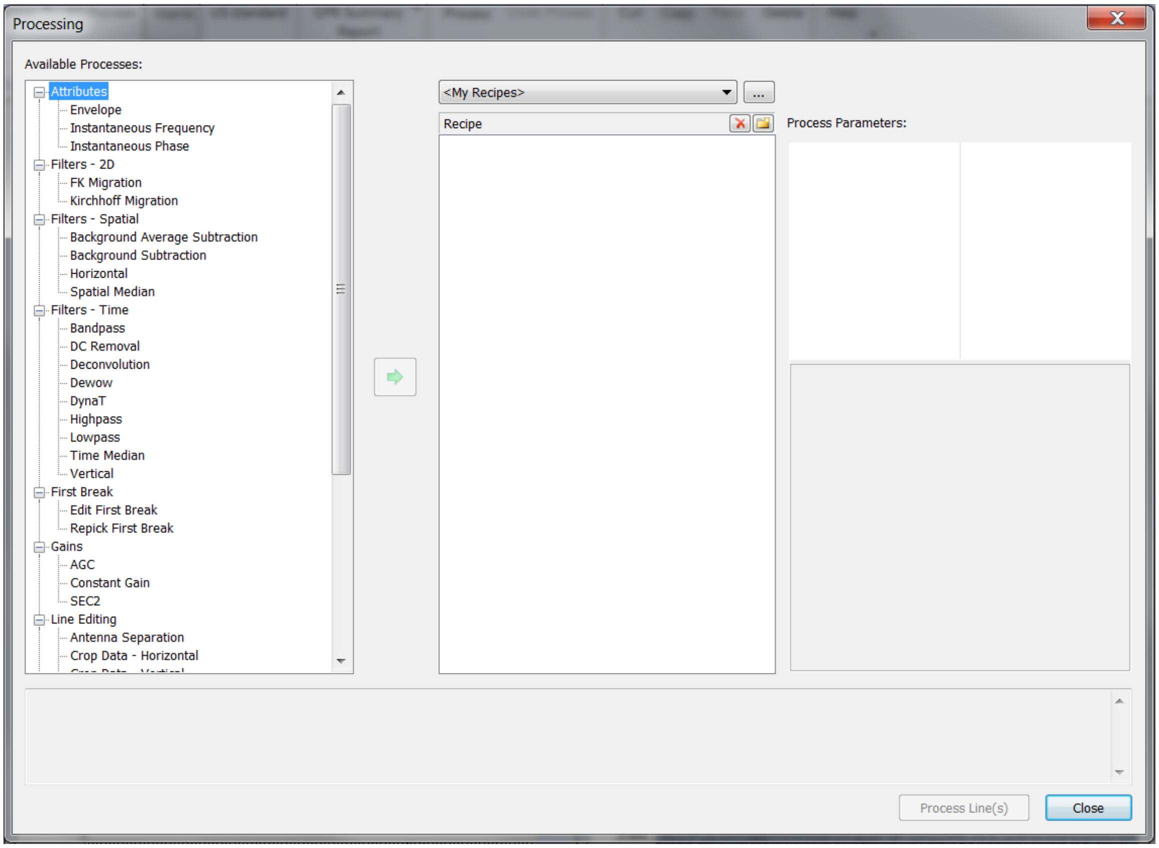
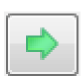


***Figure 6**: The Processing dialog lists available processing for GPR lines.*

The **Available Processes** pane lists all processes that you can add to your Recipe.

1. To add a process to your recipe, in the **Available Process** pane, select the process. To expand the processes list, click the **+** sign.
2. Click the selection arrow .

When a process is selected, a description is displayed on the bottom of the dialog. Detailed descriptions of every process are provided in Processing Functions.

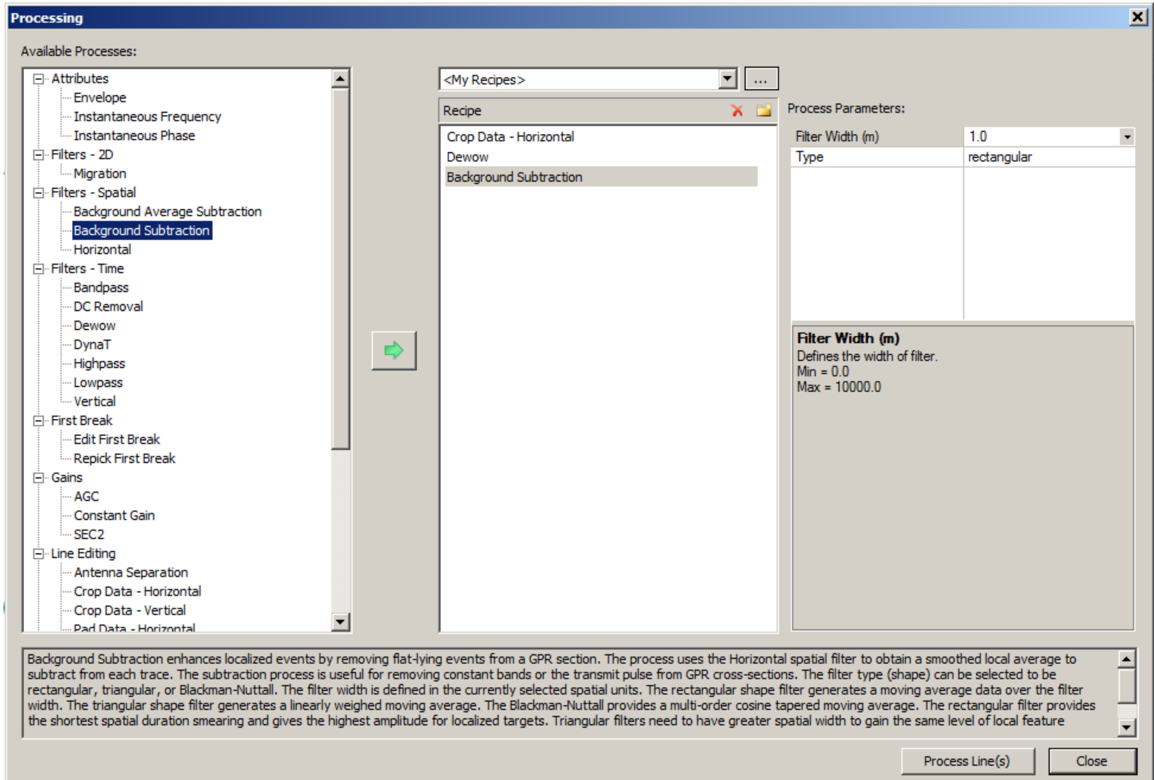


***Figure 7**: Processes added to the Recipes pane.*

3. Repeat step 3 until you have added all the processes you want to add to your recipe.

5.3.1 Input Parameters

Most processes require one or more input parameters. When a process is selected in the Recipe pane, the parameters are listed in the Process Parameters pane.

1. To modify a process value, click the drop-down arrow.
2. Click a value.

   For most numerical parameters, a new value can be entered by clicking the current value and then entering the new value.

5.3.2 Applying Processing

Once you have completed processing, click **Process Line(s)** to apply the processing to the selected GPR line(s).

The list of GPR lines is updated in Project Explorer to display the GPR lines that have been processed (indicated by a small letter "p" beside the file name – see **Figure 5**).

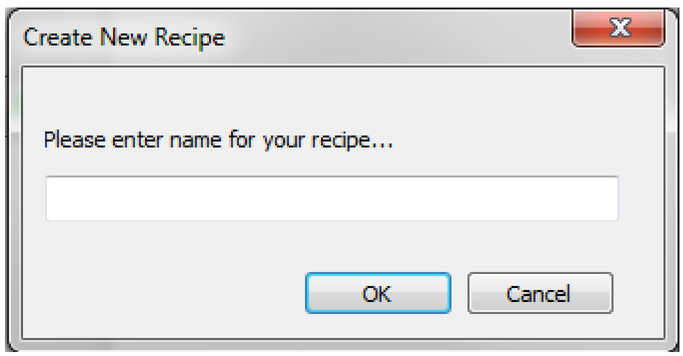
5.3.3 Deleting a Process

1. To delete a process, from the Recipes pane click the process you want to remove.
2. Click the **Delete**.

5.3.4 Save Recipe

A Recipe is a set of processing operations that can be saved and used again on other projects. Creating Recipes allows you to reuse common processes or compare different data sets using the same processing.

1. To save the selected processes to your Recipes, in the Recipes pane, click Add **Recipe to my Recipes** 
2. In the **Create New Recipe** dialog box, enter a name for the recipe.



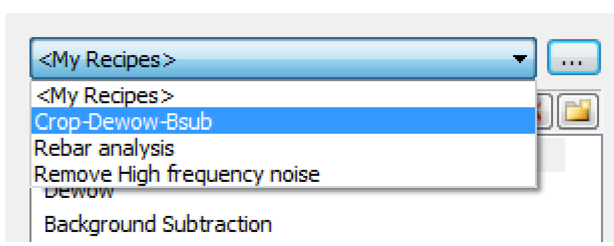
3. Click **OK**.

   Once saved, the recipe is available in the **My Recipes** drop-down.

Any recipe can be edited, saved, and renamed as another recipe.

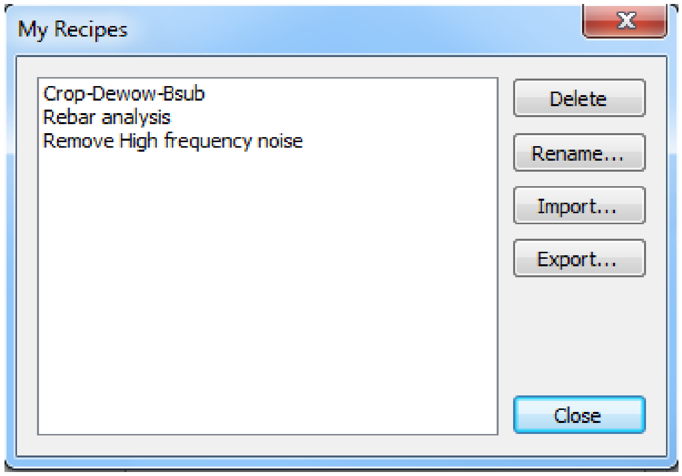
5.3.5 Load Recipe

Once a recipe has been saved, you can access it by clicking the My Recipes drop-down list above the Recipe pane.



5.3.6 My Recipe Management

1. To open your recipe list, in the Processing window, click the ellipsis icon  beside the My Recipes drop-down.



2. Use the following table as a guide to working with the My Recipes dialog box.

Field	Description
Delete	1 In the text area, select the recipe you want to remove. 2 Click **Delete**. 3 In the confirmation dialog box, click **Yes**.
Rename	1 To change the name of a recipe, click the recipe name. 2 Click **Rename.** 3 In the **Rename Recipe** dialog box, type the new recipe name. 4 Click **OK**.
Import	1 To bring a recipe file in to your recipe file, click Import. 2 In the Open dialog navigate to, and then select the file you want to import. 3 Click Open.
Export	1 To send a recipe to another EKKO_Project user, select the recipe. 2 Click **Export**. 3 In the **Save As** dialog box, save the file.

Note: Imported and exported recipes are saved as a .json files.

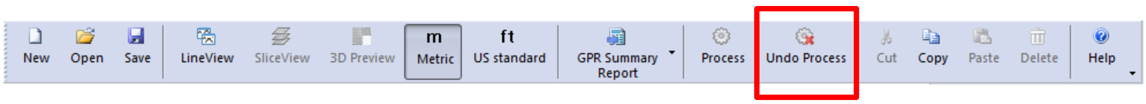
6 Undo Process

Undo Process resets processed GPR lines to their original state before processing was applied to them or to their processing state when they were copied.

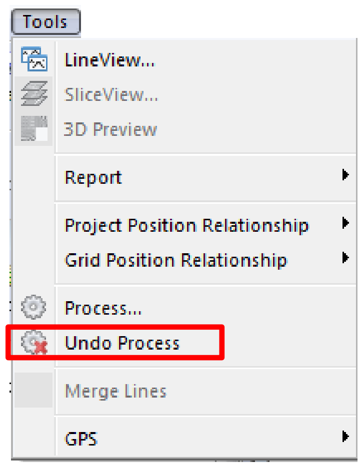
Note that when a line is copied, its current processing is permanent and cannot be undone.

6.1 Undo Processing on Multiple GPR Lines

1. If the **Undo Process** button is selected from the Toolbar:



2. or from the **Tools > Undo Process** menu:



all the GPR lines currently checked in Project Explorer have the processing removed.

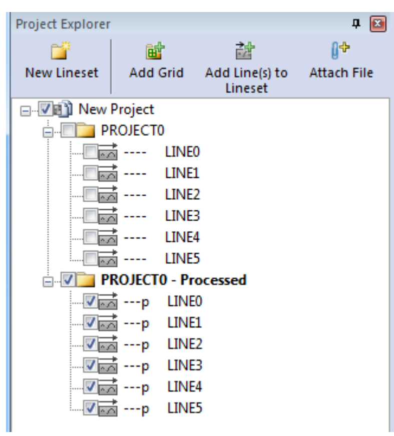
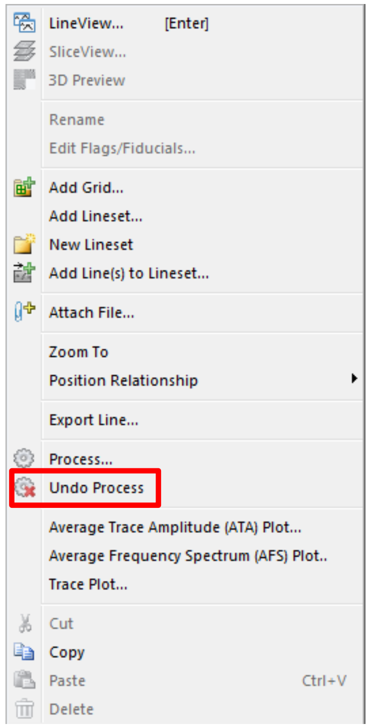


Figure 8*: To undo the processing on several GPR lines, check them in Project Explorer before selecting Undo Process on the Toolbar or in the Tools menu.*

If no GPR lines are checked when Undo Process is selected, the selected GPR line in Project Explorer has the processing undone.

6.2 Undo Processing on One GPR Line

If Undo Process is selected from the Right-click menu in Project Explorer:



only the currently selected GPR line in Project Explorer has the processing removed, regardless of whether any other GPR lines are checked.

7 Processing Functions

This section lists the details of the processing functions available in the optional Processing module.

7.1 Attributes

> **Note**: If you are unfamiliar with Attributes, you should refer to an outside reference as only a brief overview is given in this document. For example, Yilmaz, O., 1987, "Seismic Data Processing; Investigations in Geophysics No. 2: Society of Exploration Geophysicists."

While we normally only plot and interpret the real part of a complex-valued signal, the imaginary (or quadrature) component can be used to reveal some useful information about the signal. These attributes, usually called 'instantaneous attributes', include instantaneous amplitude (or trace envelope), instantaneous phase, and instantaneous frequency.

If a complex trace is given by:

$$z(t) = x(t) + iy(t)$$

where $x(t)$ is the real component of the trace

and $y(t)$ the imaginary component of the trace

Instantaneous Amplitude (or Trace Envelope) is given by:

$$e(t) = (x^2(t) + y^2(t))^{1/2}$$

Instantaneous Phase is given by:

$$\phi(t) = \operatorname{atan}\left(\frac{y(t)}{x(t)}\right)$$

Since Instantaneous Frequency is the derivative of Instantaneous Phase, it is given by:

$$\omega(t) = \left(\frac{1}{2\pi}\right)\frac{d\phi}{dt} = \left(\frac{1}{2\pi}\right) \cdot \frac{y'(t)x(t) - y(t)x'(t)}{x^2(t) + y^2(t) + \varepsilon}$$

where $x'(t)$ And $y'(t)$ are calculated using central differences:

$$x'(t) = \frac{x_i+1-x_i-1}{2\Delta t} \text{ and } x'(t) = \frac{y_i+1-y_i-1}{2\Delta t}$$

and ε is a constant value (defined as 1) to increase the stability of the function by preventing division by zero.

Since these attributes can only be calculated using the imaginary component of the complex trace, it is necessary that it be obtained before processing the data. This is done automatically in the Envelope, Instantaneous Phase, and Instantaneous Frequency routines using the Hilbert Transform

method. Basically, this method uses a time convolution approach to find the imaginary part of the trace.

7.1.1 Envelope

The basic idea behind enveloping a trace is to convert the trace from a wavelet with both positive and negative components to a monopulse wavelet with all positives. The process removes the oscillatory nature of the radar wavelet and shows the data in its true resolution. This process can also simplify the display of a radar section making it, perhaps, easier to interpret.

The mathematical definition of instantaneous amplitude is shown above. The instantaneous amplitude outlines the envelope of the trace. It is independent of phase, that is, it may have its maximum at points other than the peaks and troughs of the real trace, especially where an event is the composite of several reflections. While it is often referred to as reflection strength, some believe that this term places a dubious interpretational assumption on the true meaning of instantaneous amplitude. They suggest that the envelope of a trace is simply an interpretational tool that describes waveform shape. Interpretation is aided by comparing the constancy of reflection character.

Envelope Parameters

Window Width	Is the width of the filter in pulse widths. The default value is 1.0 pulse widths.

7.1.2 Instantaneous Frequency

The mathematical definition of instantaneous frequency is shown above; it is used as a correlation tool. The frequency character of an event will change as the lithology changes, the thickness changes or at interfaces such as gradational boundaries, pinch-outs and the water table.

Instantaneous Frequency Parameters

Window Width	The width of the filter in pulse widths. The default value is 1.0 pulse widths
Epsilon	Enhances the stability of the result for small signals The default value is 1.0 millivolt

7.1.3 Instantaneous Phase

The mathematical definition of instantaneous phase is shown above. It is used to emphasize the continuity of events. Since phase is independent of the trace envelope, it can often make weak coherent events more prominent, even events that interfere with one another. Instantaneous phase is always measured between -π and +π and therefore data tends to have a saw-tooth appearance.

The instantaneous phase is multiplied by amplitude/epsilon if amplitude <= epsilon. This drives the instantaneous phase towards zero for amplitudes smaller than epsilon.

If the amplitudes have a DC offset that place it near a zero imaginary component and a slightly negative real component, +/-pi phase cross over can occur and data will appear noisy. Removing DC bias using DEWOW is recommended to so that epsilon will remove this problem.

Instantaneous Phase Parameters

Window Width	The width of the filter in pulse widths. The default value is 1.0 pulse widths
Epsilon	Enhances the stability of the result for small signals The default value is 1.0 millivolt

7.2 Filters – 2D

7.2.1 Migration

The process of concentrating the energy back to its source location and presenting it in graphical form is called migration. The purpose of migration is to process GPR data such that the received energy is located at the point in space point that represents the source of the energy. The method has been widely used in the petroleum seismic industry and has many advanced approaches.

With GPR we have a limited set of information, as only a single transmitter and receiver is used; hence, many of the more advanced processes are not accessible. Background on migration can be found in the textbook by Yilmaz (Seismic Data Analysis, SEG, 2001).

In the Processing module, two methods are available for migration. In principle they should yield the same result, but the mathematical approaches are different, so the results are never exactly the same because of the inherent approximations required. The two methods are referred to as F–K migration and Kirchhoff migration.

There are many variables in the processes which have been optimized in the routines in the Processing module, so there are few user inputs.

Migration requires a velocity for the host material. Beyond that, both migrations have some choice of normalization of the output. In general, both approaches attempt to maintain the RMS signal amplitude. The main difference lies in the data used in the process. The F-K Migration uses the whole data set, even though only a portion of the data are needed at any one location. The Kirchhoff Migration uses a finite region of data around the energy source point and has the option for the user to define the operational width.

The F-K Migration has an inherent assumption that the GPR data have zero (or very small) transmitter-receiver separation. Kirchhoff Migration can accept finite offset data and, as part of the migration process, automatically translates the data into zero offset data.

In both cases, only a constant velocity migration is implemented. More complex variable velocity schemes are possible but GPR seldom if ever has enough information available to develop a velocity model. Trial-and-error using a range of velocities is the most common approach for addressing this topic at present.

7.2.1.1 F-K Migration

The F–K migration applies a synthetic aperture image reconstruction process to the GPR line. The GPR data are Fourier-transformed into plane waves at a monochromatic frequency. The waves are then processed individually to superimpose the energy at source point. This transformation was devise by R.H. Stolt (Geophysics, Vol 43 1978, p 23-48) and is often called Stolt migration.

The process collapses GPR hyperbolic responses from point-like targets back into a point. Hyperbolic shape is dictated by the ground velocity, so migration requires the input velocity to be as accurate as possible. If the velocity is too low, the data will be under-migrated with the hyperbola not fully collapsed.

If the velocity is too high, the data will be over-migrated with hyperbolas inverted into smile shapes. The optimal velocity can be determined by experimentation or measured using the Hyperbola Velocity Calibration tool in LineView.

Migration Parameters

Velocity Radar velocity to use in the synthetic aperture process.

Must be 0.01 to 0.30 meters/nanosecond or 0.03 to 0.98 feet/nanosecond.

Typical velocities of ground materials are 0.06 to 0.15 m/ns (0.20 to 0.49 ft/ns).

The default value is 0.1 m/ns (0.328 ft/ns).

The migration process will fail if the First Break Offset time is negative (to learn more, see the Acquisition tab).

7.2.1.2 Kirchhoff Migration

The Kirchhoff migration processes the data in its original space and travel time form and is more intuitive. The Kirchhoff migration sums along a hyperbolic trajectory for a given velocity and places that energy at the apex of the hyperbola. This concept is readily understood from examining GPR records with localized point targets. The point target response results in energy lying on hyperbolic trajectory in space-time cross sections. The Kirchhoff summation approach essentially takes all the energy along a given hyperbola, sums it up and places it at the apex of the hyperbola which is the location of the source.

Hyperbolic shape is dictated by the ground velocity, so migration requires the input velocity to be as accurate as possible. If the velocity is too low, the data will be under-migrated with the hyperbola not fully collapsed.

If the velocity is too high, the data will be over-migrated with hyperbolas inverted into "smile" shapes. The optimal velocity can be determined by experimentation or measured using the Hyperbola Velocity Calibration tool in LineView.

Some ancillary parameters are available for the user to select an appropriate gain function, if desired.

Migration Parameters

Velocity Radar velocity to use in the migration process.

Must be 0.01 to 0.30 meters/nanosecond or 0.03 to 0.98 feet/nanosecond.

Typical velocities of ground materials are 0.06 to 0.15 m/ns (0.20 to 0.49 ft/ns).

The default value is 0.1 m/ns (0.328 ft/ns).

Width Width of the window used for summing along the hyperbolic trajectory.

Default value is calculated based on the GPR line parameters and used during processing.

If not using the default, the value must be in meters.

Target Type of target being imaged to optimize the gain for amplitude normalization.

The options are: 0=All Targets, 1=Point Targets, 2=Rod/Cylinder-targets, and 3=Planar Targets.

The default is 0=All Targets.

7.3 Filters – Spatial

Spatial filters act on radar data in the spatial (or position) direction. These filters use adjacent traces during the filtering procedure. They alter the shape of the trace through various mathematical manipulations designed to enhance or eliminate certain features.

7.3.1 Background Average Subtraction

Background Average Subtraction is used to subtract the average trace of the entire GPR line from every trace in the line.

This process has the effect of enhancing dipping events (like hyperbolas from point targets) and removing horizontal responses common to all traces in the line. It is commonly used to remove the direct air and direct ground waves (also known as the transmit pulse) visible at the top of the line. It will also remove horizontal bands in the data present throughout the length of the line.

The average trace is calculated by adding all the traces in the line together and dividing by the total number of traces. This average trace is then subtracted from each trace in the line.

Background Average Subtraction is similar to the Background Subtraction routine below, but, because it averages over the full width of the GPR line, rather than a shorter length typically used with that routine, it tends to be less severe in its removal of horizontal events. The more traces used in the Background Subtraction Filter Width parameter, the more localized horizontal features remain in the data.

Background Average Subtraction Parameters

There are no input parameters necessary to run this process.

7.3.2 Background Subtraction

Background Subtraction is used to apply a running-average background subtraction to the data set.

This process has the effect of enhancing dipping events (like hyperbolas from point targets) and suppressing or completely removing horizontal responses. This can be very useful for removing localized flat-lying events.

A window of traces with a width defined by the **Filter Width** parameter is averaged with a weighted average (see below) and the result is subtracted from the trace in the center of the window. The window moves along one trace and the process is repeated.

To illustrate the processing, consider the case of a GPR line collected with a step size of 0.1 meters. If a Filter Width of 0.5 meters is chosen, the operation works on a window of 5 traces at a time. When the routine processes trace number 9, it reads traces 7, 8, 9, 10, and 11, finds the average of the five traces, subtracts that average trace from the original trace 9 and saves the resultant in place of trace 9. It then moves over one trace to trace 10, averages traces 8, 9, 10, 11 and 12, subtracts the average trace from the original trace 10 and saves the resultant as trace 10, and so on.

The more traces used in the background subtraction process, the more flat-lying reflections will remain in the data. For example, setting the Filter Width to 2 meters removes any local flat-lying reflections 2 meters long or longer. Flat-lying reflectors less than 2 meters long will remain in the data line, although their amplitudes may be reduced.

To remove all flat-lying events from data, set the Filter Width to a distance equal to two times the step size.

Choosing a Filter Width as large as or larger than the line will remove the average trace. Signal from line data, similar to the Background Average Subtraction process described

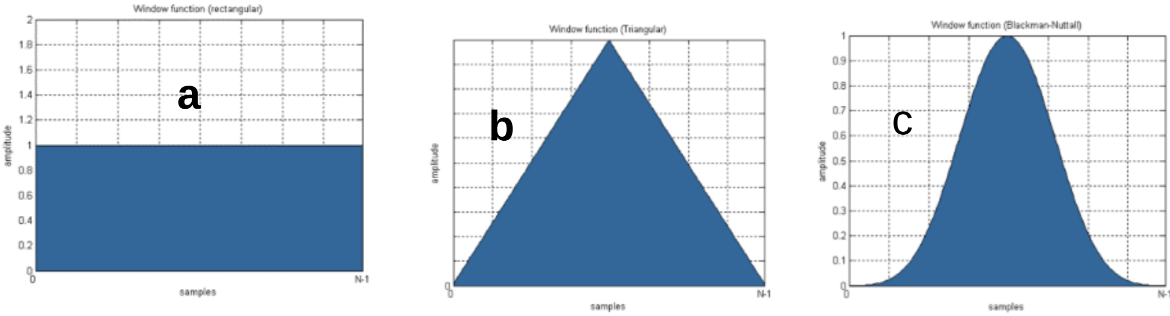


***Figure 9**: Filter types for the Background Subtraction Filter. (a) Rectangular, (b) Triangular (c) Blackman-Nuttall*

The **Filter Type** dictates the weighting the traces on the edges of the Filter Width have on the calculation of the average trace.

- **Rectangular** filter type uses equal weighting to all traces
- **Triangular** filter type applies more weight to the trace in the center of the window and linearly less to the traces moving out from the center to the edges of the window
- **Blackman-Nuttall** filter type applies more weight to the trace in the center of the window and less to the traces on the edges of the window but uses a shape similar to a Gaussian curve (Figure 9)

Background Subtraction Parameters

Filter Width	The width of the running-average window added together in the spatial trace-differencing filter. If the filter width is greater than the length of the GPR line, a filter width equal to the length of the line is used. The default value is 1 meter.
Type	The shape of the filter used to calculate the running-average trace. Options are Rectangular, Triangular or Blackman-Nuttall. The default is rectangular.

7.3.3 Horizontal

Horizontal applies a running average filter horizontally along a GPR line. It replaces each trace with an average trace produced by averaging adjacent traces together. Its primary purpose is to emphasize flat-lying or slowly dipping reflectors while suppressing rapidly changing ones (i.e. hyperbolic tails or random noise).

A window of traces with a width defined by the **Filter Width** parameter is averaged and the resultant replaces the trace in the center of the window. The window moves along one trace and the process is repeated.

To illustrate the processing, consider the case of a GPR line collected with a step size of 0.1 meters. If a Filter Width of 0.3 meters is chosen, the operation works on window of 3 traces at a time. When the routine processes trace number 5, it reads traces 4, 5, and 6, finds the average of the three traces and uses the average trace in place of trace 5. It then does the same thing with trace 6, and so on. If the number of traces to average is even, then the extra trace is taken from the 'left' side, i.e. from the lower trace number.

7.3.4 Spatial Median

Spatial Median is used to apply an alpha-mean trim filter spatially (horizontally or trace-to-trace) along a GPR line.

The GPR signal is filtered by replacing the data amplitude at a given point by the median value of points from adjacent traces in a window centered about that point. Its primary purpose is to filter out single "bad" traces from the data. Bad traces can occur for a variety of reasons including collecting data too close to a highly conductive object i.e. a manhole cover or fence. In this case the trace is 'ringy' with a single frequency dominating the trace and obscuring the desired signal. Bad traces make a section difficult to interpret so the spatial median filter is designed to eliminate these traces.

The input parameters are the Filter Width (in traces) and Mean (in traces).

To illustrate the process, if the Filter Width is 3 traces and the Mean is 1 trace (the defaults), the program calculates point #5 in trace #12 by using the median value of point #5 in traces 11, 12, and 13. For example, if point #5 in trace #11 has a value of -23431, point #5 in trace #12 is 168 and point #5 in trace #13 is -1248, the filter arranges the values in ascending order (in this case -23431, -1248 and 168) and uses the middle value (in this case -1248). In this way extreme values (like -23431 above) are eliminated from the data.

If the Filter Width is 7 traces and the Mean is 3 traces, then the program calculates the new value of point #10 in trace #37 by using the comparing the values of points 10 in traces 34, 35, 36, 37, 38, 39 and 40. Again, the filter arranges the values in ascending order and this time uses the average value of the middle 3 points.

Spatial Median Parameters

Filter Width Number of traces in the spatial alpha-mean trim (median) filter.

Must be an odd value greater than 1.

The default value is 3.

Mean Number of traces in the middle of the Filter Width to use in the calculation of the mean.

Must be an odd value.

The default value is 1.

7.4 Filters - Time

7.4.1 Bandpass Filter

Bandpass filtering is used when the GPR signal is contained in a defined band of frequencies and there is "noise" energy in the remainder of the spectrum. By bandpass filtering, the desired signals can be enhanced at the expense of the out-of-band noise. Bandpass is designed around the use of Fourier transform filtering concepts.

The use of Fourier transform-based filtering is quite common in the geophysical realm and many texts and papers describe the concepts very well. The following briefly outlines the processing, how it is implemented, and the side effects that improper application of the filter may induce.

Each GPR trace is a time series which can be viewed as being composed of a superposition of sinusoidal signals. With a Fourier transform based filter, a GPR trace is decomposed into its spectral (sinusoidal) components through a Fourier transformation algorithm, the spectral amplitudes multiplied by the filter transfer function, and the resultant spectrum is inverse Fourier transformed to create the filtered GPR trace.

Filtering is restricted to zero phase bandpass filtering. To describe the transfer function of a bandpass filter one has to define its lower and upper cut-off frequencies. In addition, the sharpness of the cut-off at either end of the pass band must be quantified.

The transfer function of the filter is characterized by four frequencies, fc1, fp1, fp2, and fc2. The filter has zero amplitude at all frequencies below fc1 and above fc2. In the pass band between frequencies fp1 and fp2, the filter has unit amplitude. Between fc1 and fp1 and fp2 and fc2, the transition from zero amplitude to unit amplitude is a cosine curve that gives a smooth transition.

The most efficient way of Fourier transformation is to exploit the Fast Fourier Transform (commonly referred to as the FFT) algorithm. The FFT algorithm is based on the assumption that the times series being processed is one cycle of an infinitely recurring signal. While this is not strictly true, by extending a finite time series with zeros and tacitly assuming periodicity, one can use the FFT algorithm with impunity to carry out a periodic convolution operation. Bandpass uses this approach.

Bandpass Filter Parameters

The parameters needed for this application are:

fc1 Lower cut-off frequency.

Frequencies below this value are completely removed from the GPR line.

fp1 Lower pass band frequency.

Frequencies below this value taper to zero at the fc1 frequency. Frequencies above this value to the fp2 value are retained in the GPR line.

fp2 Upper pass band frequency.

Frequencies below this value to the fp1 value are retained in the GPR line.

Frequencies above this value taper to zero at the fc2 frequency.

fc2 Upper cut-off frequency.

Frequencies above this value are completely removed from the GPR line.

- Frequencies must be ascending order and it is suggested that the slope of the high frequency side be less steep than the slope of the low frequency side to minimize filter artifacts on the data.
- All frequencies are entered as a percentage of the antenna center frequency.
- Default frequencies are 40%, 80%, 120% and 160% of the antenna center frequency.

Average Frequency Spectrum plots can be used to help determine filter parameters.

7.4.2 DC Removal

While the Dewow process below automatically removes any low frequency "wow" from the data, sometimes it may be desirable to perform a DC removal on the data in addition to, or instead of DEWOW. For example, tests have shown that a DC removal applied to high frequency radar data (> 200 MHz) rather than a Dewow correction may be more effective in reducing correction artifacts.

DC Removal is used to remove a DC level from all the traces in the GPR data line(s). The DC level to be removed can be manually input by the user or automatically calculated by the program.

With an input DC level, the value is subtracted from all the points in all the traces in the data set.

If DC_SHIFT calculates the DC level to be removed, it calculates a new DC level for each trace in the GPR line. This is done by taking all points in each trace and calculating a DC level for that trace. This value is then subtracted from each point in the trace. This process is repeated for each trace in the data set. Typically, traces will have approximately the same DC shift in a given GPR line.

7.4.3 Deconvolution

The predictive deconvolution algorithm follows most of the standard seismic processing concepts (for an overview, see *Yilmaz, O., 1987, Seismic Data Processing; Investigations in Geophysics No. 2: Society of Exploration Geophysicists*.).

Deconvolution attempts to convert a radar wavelet into a spike.

Unlike seismic signals, GPR wavelet signals are more like zero-phase than minimum phase wavelets. In addition, estimation of the GPR wavelet based on the seismic approach that the autocorrelation of the data trace yields a reliable estimate of the excitation wavelet is just not a reliable approach. Therefore, Deconvolution uses the GPR center frequency to constrain the wavelet estimation process.

The program uses the following logic for deconvolution:

1. The GPR signal is assumed to be an idealized dipole wavelet with 1 -2 1 basis.

2. The desired output is a triangular pulse.

3. The deconvolution filter is created using the Weiner least squares approach traditional in the seismic literature. The process requires the computation of the GPR wavelet autocorrelation and the cross correlation of the GPR wavelet and the desired triangular waveform. The least squares solution generates a Toeplitz matrix which is iteratively solved to estimate the deconvolution filter.

4. The wavelet is zero-phase so the deconvolution requires a finite lag to achieve proper pulse shaping. The lag must be at least as much as the half length of the GPR wavelet. Experience has shown somewhat larger lags may improve the spiking performance.

5. The GPR data traces are then convolved with the deconvolution filter to provide the filtered deconvolved GPR line.

6. This program applies the process described and uses the *Numerical Recipes* canned code for Toeplitz matrix inversion.

Deconvolution Parameters

The parameters needed for this application are:

Frequency	The center frequency of the GPR signal. If set to **Auto**, the center frequency of antennas is used.
Filter Width	The width of the deconvolution filter in nanoseconds. If set to **Auto**, the default value is 3 pulse widths at the center frequency.
Delay	The amount of time lag (in nanoseconds) between input signal and the output spike. Should be equal to 0.5*Filter Width. If set to **Auto**, the default value is 1.5 pulse widths at the center frequency. For good results, Filter Width > Delay + Spike Width
Spike Width	The width of the output triangular spike in nanoseconds. If set to **Auto**, the default value is 0.3 pulse widths at center frequency.
Whiten	Factor from 0.0-1.0 to stabilize the deconvolution filter estimation. The default is 0.1.

7.4.4 Dewow

In most cases when processing GPR data, it is recommended that Dewow be applied to the GPR line before any other processing steps.

Depending on the proximity of the GPR transmitter and receiver as well as the electrical properties of the ground, the transmit signal may induce a slowly decaying low frequency "wow" on the trace which is superimposed on the high frequency reflections.

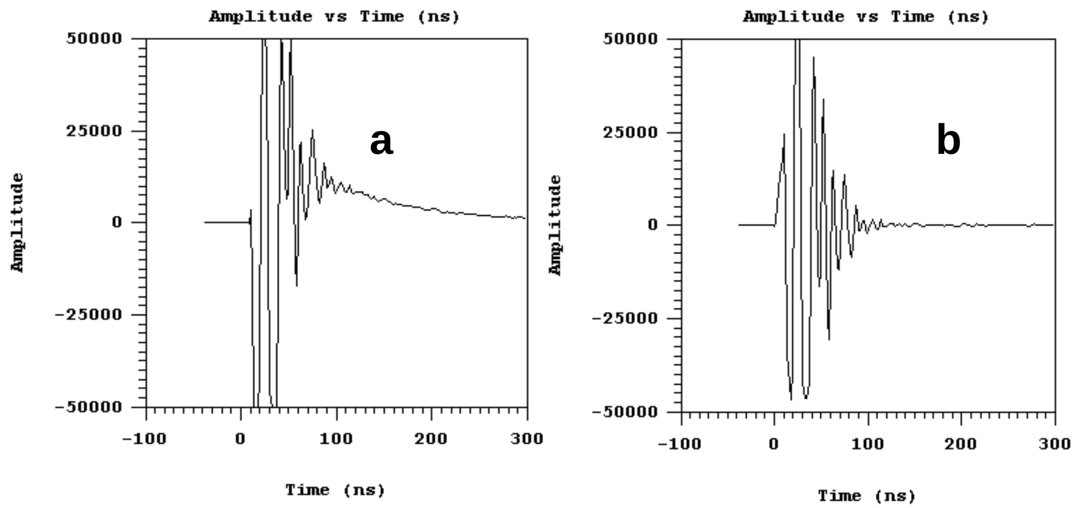


Figure 10*: (a) Raw GPR trace with WOW. (b) GPR Trace with WOW removed using DEWOW.*

All GPR data contains a low frequency component. The magnitude of the low frequency component and how it manifests itself in the data depends on the ground conditions around the antennas and the distance between the transmitter and receiver. In general, the low frequency component of the GPR signal does not propagate but diffuses into the ground. In other words, the lower end of the spectrum sees an inductive (eddy current) type response as opposed to a propagating (displacement current) type response.

The result is that the large transmit pulse emitted by the radar can be followed by a slowly decaying transient, commonly called "wow".

With this wow usually present, it is common practice that GPR data be high pass (Dewow) filtered. In fact, LineView and other GPR line display software automatically applies Dewow before plotting the data. Users are often unaware of the wow or low frequency component in the data. The raw data, however, always retains this information.

Dewow is designed to remove this unwanted low frequency while preserving the high frequency signal. The removal of this wow in the data is also called the "signal saturation correction".

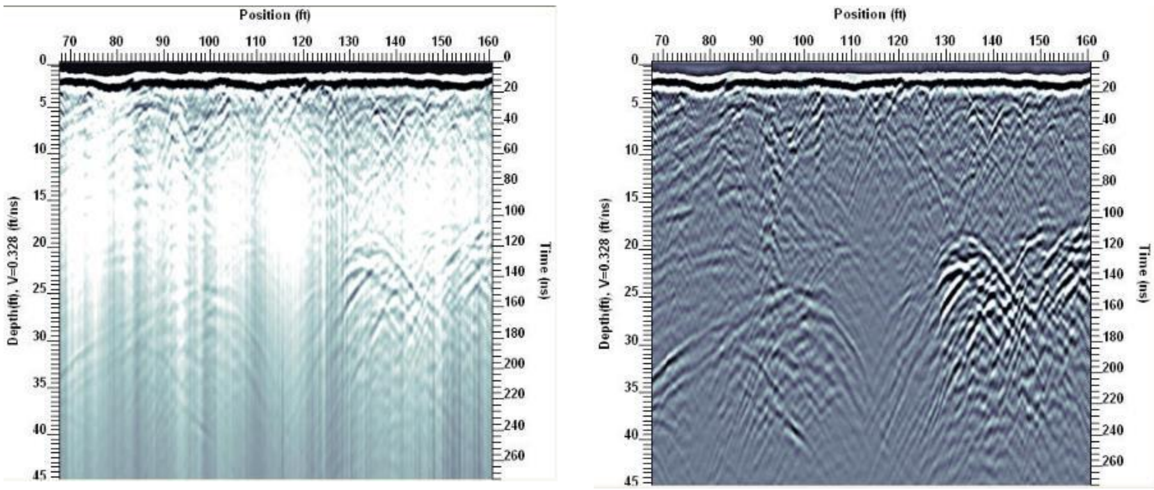


***Figure 11**: (Left) Raw GPR line with WOW. (Right) GPR line with WOW removed using DEWOW.*

The wow is removed from the data by applying a running average filter down each trace. A window with a width of 1.33 pulse widths at the nominal frequency is set on the trace. The average value of all the points in this window is calculated and subtracted from the central point. The window is then moved along the trace by one point and the process is repeated.

7.4.4.1 Dewow Artifacts

While any filter produces unwanted artifacts in the data to which it is applied, Dewow is a good compromise filter.

The Dewow filter can induce two types of artifacts into the plotted data sections. The first is a pre-cursor to the onset of a pulse (**Figure 12**: DEWOW artifacts: signal pre-cursor.). When the original data are high pass filtered the wavelet is stretched in time with additional oscillations occurring before and after the original pulse. This is what gives rise to a pre-cursor in the data before the first break on plotted GPR lines.

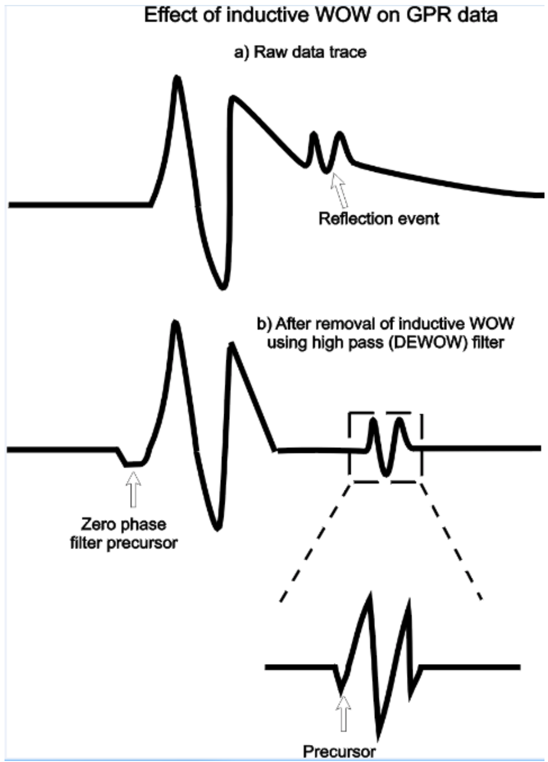


Figure 12*: DEWOW artifacts: signal pre-cursor.*

The second artifact is caused by electronic clipping. The basic concept is depicted in Figure 13.

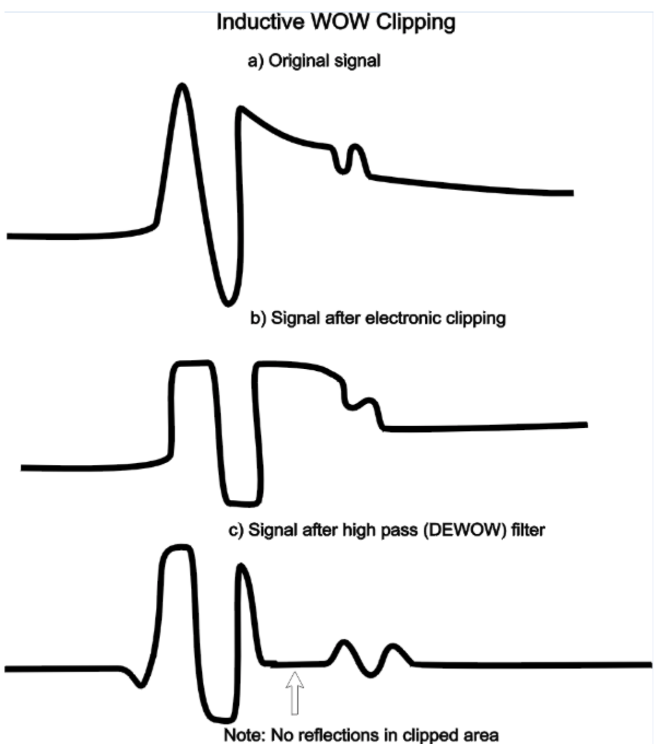


Figure 13*: DEWOW artifacts: electronic clipping*

The original signal which is acquired by the antenna and presented to the receiver electronics looks like that sketched in Figure 13 a. The radar electronics clip any signals above the 50 millivolt level. Figure 13 b shows the type of result that will be measured if clipping occurs in the signal pre-conditioning circuitry. When these data are finally high pass filtered, a blank zone in the area where the original signal had a large wow above the clipping level of the electronics can appear. This results in a blank section on the record with no reflections visible (Figure 13 c). The user must be aware that this can occur in some geologic settings and the antenna spacing should be increased to reduce the wow signal amplitude below the clipping level of the receiver electronics.

Dewow Parameter

Window Width	is the width of the filter in pulse widths The default value is 1.33 pulse widths.

7.4.5 DynaT

Dynamic Target enhancement (DynaT) allows users to preferentially enhance the response from targets of different sizes – small, medium and large. GPR users usually use signal amplitude to discern targets and small targets can be difficult to see in GPR data because they always produce smaller amplitude responses than larger targets.

The DynaT process exploits the fact that the frequency content of the returned signal varies with target size. The rate of change of signal amplitude with size varies especially strongly for small targets. Using the ultra-wideband frequency content inherent in the GPR signals generated by Sensors & Software GPR systems, DynaT differentiates the frequency-dependent GPR target responses to enhance the amplitude of targets based on relative size.

DynaT Parameter

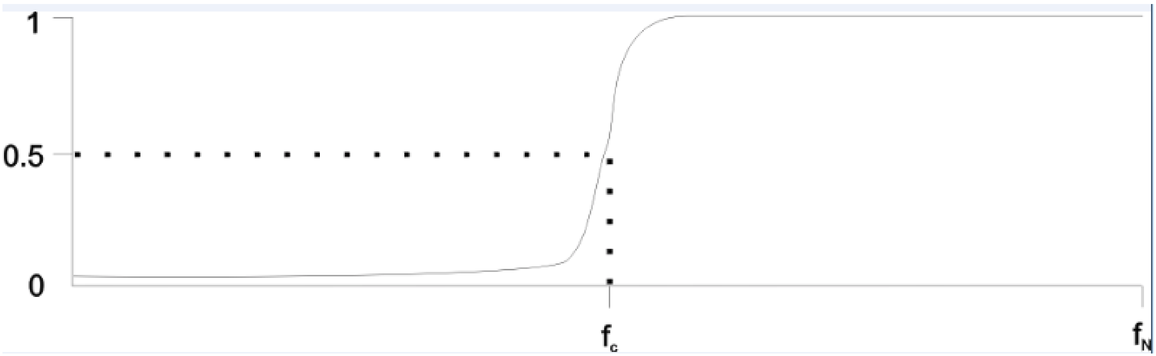
Target Size	The relative size of the target to enhance – Small, Medium or Large The default value is Medium.

7.4.6 Highpass

The highpass temporal filter removes frequencies below a cut-off frequency. It is useful for removing low frequency content in the GPR data; it is sometimes used instead of the Dewow filter.

High Pass is a recursive filter designed for filtering of a GPR line in the time domain. It is an infinite impulse response zero phase filter.

The typical frequency domain characteristics of the filter are as shown below.



The filter requires the input of the cut off frequency. Frequencies between 10% and 90% in 10% increments of the Nyquist frequency can be input.

The **Nyquist frequency** is determined from the **Time Sampling Interval** for the GPR line; these values are listed in the **Advanced** category of the Acquisition tab.

FNyquist = 1/(2 * time sampling Interval X 10^{-6})
Where:

the Nyquist frequency is in MHz and
The time sampling interval is in picoseconds (ps)

If the default temporal sampling intervals are used when collecting data, the Nyquist frequencies for each antenna frequency are listed in the following table:

Antenna Frequency (MHz)	Temporal Sampling Interval (ns)	Nyquist Frequency (MHz)
12.5	6400	78
25	3200	156
50	1600	313
100	800	625
200	400	1250
250	400	1250
500	200	2500
1000	100	5000

Highpass Parameter

Cut-off Frequency Percent The cutoff frequency is a percentage of the Nyquist frequency in 10% increments from 10%-90%.

Frequency above which data is preserved and below which data is removed.

For example, if the Nyquist frequency is 625 MHz, the possible cutoff frequencies are:

10% = 62.5 MHz
20% = 125 MHz
30% = 187.5 MHz
40% = 250 MHz
50% = 312.5 MHz
60% = 375 MHz
70% = 437.5 MHz
80% = 500 MHz
90% = 562.5 MHz

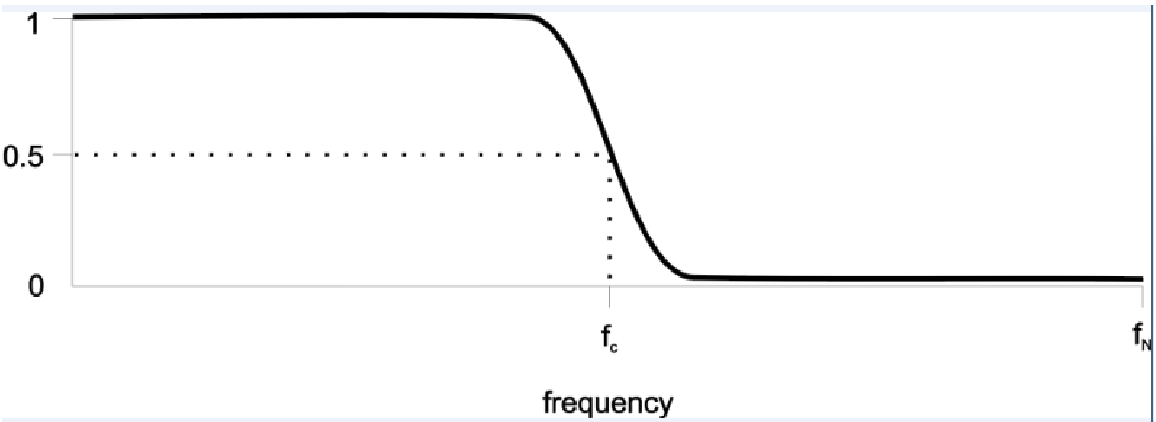
Note: The Average Frequency Spectrum plot extends from 0MHz up to the Nyquist frequency.

7.4.7 Lowpass

The low pass filter removes frequencies above a cut-off frequency. It is useful for removing high frequency noise in the GPR data.

Low pass is a recursive filter designed for filtering of a GPR line in the time domain. It is an infinite impulse response zero phase filter.

The typical frequency domain characteristics of the filter are as shown below.



The filter requires the input of the cut off frequency. Frequencies between 10% and 90% in 10% increments of the Nyquist frequency can be input.

The **Nyquist frequency** is determined from the **Time Sampling Interval** for the GPR line; these values are listed in the **Advanced** category of the Acquisition tab.

FNyquist = 1/(2 * time sampling Interval X 10^{-6})
Where:

the Nyquist frequency is in MHz and
The time sampling interval is in picoseconds (ps)

If the default temporal sampling intervals are used when collecting data, the Nyquist frequencies for each antenna frequency are listed in the following table:

Antenna Frequency (MHz)	Temporal Sampling Interval (ns)	Nyquist Frequency (MHz)
12.5	6400	78
25	3200	156
50	1600	313
100	800	625
200	400	1250
250	400	1250
500	200	2500
1000	100	5000

Low Pass Parameters

Cut-off Frequency Percent	The cutoff frequency is a percentage of the Nyquist frequency in 10% increments from 10%-90%. Frequency above which data is preserved and below which data is removed.

For example, if the Nyquist frequency is 625 MHz, the possible cutoff frequencies are:

10% = 62.5 MHz
20% = 125 MHz
30% = 187.5 MHz
40% = 250 MHz
50% = 312.5 MHz
60% = 375 MHz
70% = 437.5 MHz
80% = 500 MHz
90% = 562.5 MHz

7.4.8 Time Median

Median is used to apply an alpha-mean trim filter temporally (vertically or down-the-trace) to a GPR line.

The signal is filtered by replacing the amplitude value at a given point by the median value over a window centered about that point. Its primary purpose is to eliminate high frequency noise spikes which sometimes occur in GPR data.

The input parameters are Filterer Width (in points) and Mean (in points).

To illustrate the process, if the Filter Width is 3 points and the Mean is 1 point (the default values), the routine calculates the new value of point #10 by using the amplitudes of points 9, 10 and 11.

For example, if point #9 has an amplitude of 2850, point #10 is 29067 and point #11 is -123, the filter arranges the values in ascending order (in this case -123, 2850 and 29067) and uses the middle value (in this case 2850). In this way, single point noise spikes (like 29067 above) are eliminated from the data. The number of points in the Filter Width can be any odd number greater than 1 but in practice 3 points is sufficient for most purposes.

If the Filter Width is 7 points and the Mean is 3 points, then the routine calculates the new value of point #10 by using the amplitude values of points 7, 8, 9, 10, 11, 12 and 13. Again, the filter arranges the values in ascending order and this time uses the average value of the middle 3 points.

Time Median Parameters

Filter Width Number of traces in the time alpha-mean trim (median) filter.

Must be an odd value greater than 1.

The default value is 3.

Mean Number of points in the middle of the Filter Width to use in the calculation of the mean.

Must be an odd value.

The default value is 1.

7.4.9 Vertical

The Vertical Filter is used to apply a running average filter vertically (down the trace) on a GPR line. The signal is averaged by replacing the data value at a given point by the average data value over a window centered about that point. Its primary purpose is to reduce random or high frequency noise by acting as a low pass temporal filter.

A window of pulse widths defined by the **Filter Width** parameter is averaged and the resultant replaces the trace in the center of the window. The window moves along one trace and the process is repeated.

To illustrate the processing, consider the case of a GPR line collected with an antenna frequency of 100 MHz and a time sampling interval of 800 picoseconds:

Pulse width = 1500 / (frequency * (time sampling interval/1000))

= 18 points.

If a Filter Width of 0.2 pulse widths is chosen, the operation works on a window of 3 sample points at a time. When the routine processes point number 5, it reads points 4, 5, and 6, finds the average of the three points and uses the average value in place of point 5. It then does the same thing with point 6, and so on. If the number of points to average is even, then the extra trace is taken from the left' side, i.e. from the lower trace number.

The more pulse widths (points) used in the Vertical filter, the more high-frequency data will be removed from the data. Typical values for the number of pulse widths in the filter are 0.1 to 1.

Antenna Frequency (MHz)	Temporal Sampling Interval (ns)	Pulse width (pts)
12.5	6400	18
25	3200	18
50	1600	18
100	800	18

200	400	18
250	400	15
500	200	15
1000	100	15

The following example calculates how to determine how many pulse widths to use in the averaging window.

To filter high frequency noise that's affecting your data:

1. Estimate the length (in nanoseconds) of the noise from a plot of the GPR line (Trace Plot and Average Trace Amplitude Plots can be helpful in determining this; see the EKKO_Project User’s Guide for more details).
2. Select a typical noise cycle from the section and then measure the peak-to-peak or trough-to-trough time length.
3. Divide this number by the time sampling interval in nanoseconds.

   The Time Sampling Interval for the GPR line is listed in picoseconds in the Acquisition tab’s **Advanced** category.

4. Divide by 1000 to calculate it in nanoseconds.

   The result is the length of the noise cycle in points (round up to the nearest whole number if necessary).

5. Divide the number of points in the noise by the number of points in the pulse width for the antenna frequency you are using (see table above).
6. To filter out this noise, use a Filter Width equal to or greater than this number.

Vertical Parameters

Filter Width

The width of the running-average window added together in the spatial trace-differencing filter.

If the filter width is greater than the length of the GPR line, a filter width equal to the length of the line is used.

The default value is 1 meter.

Type

The shape of the filter used to calculate the running-average trace.

Options are Rectangular, Triangular or Blackman-Nuttall.

The default is rectangular.

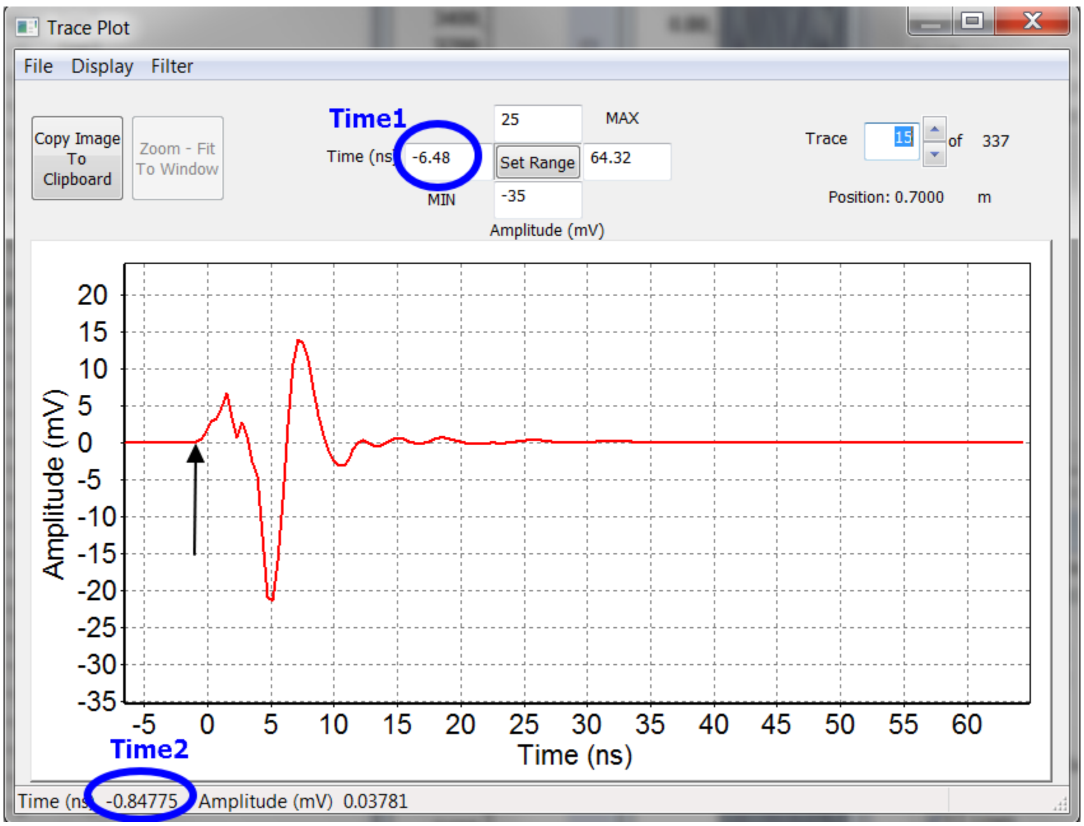
7.5 First Break

7.5.1 Edit First Break

Rather than using Repick First Break to determine the **First Break Offset** (listed in the **Advanced** category of the GPR line Acquisition tab (see **Figure 1**), it is sometimes desirable to calculate or estimate the first break manually and edit the GPR line. This is what the Edit First Break routine is for.

The first break is edited in a time value in nanoseconds.

One way to calculate the first break time is to plot the GPR Line in Trace Plot (see the EKKO_Project User's Guide) with the Filter > Dewow off and the Display > Custom Zoom on.



Set the mouse cursor at the first large deflection in the GPR signal, positive or negative, and subtract the Start Time in the Custom Zoom (Time1) from the time on the status bar (Time2). In this example:

First Break Time = Time2 – Time1

= -0.85 – (-6.48)

= 5.63 ns

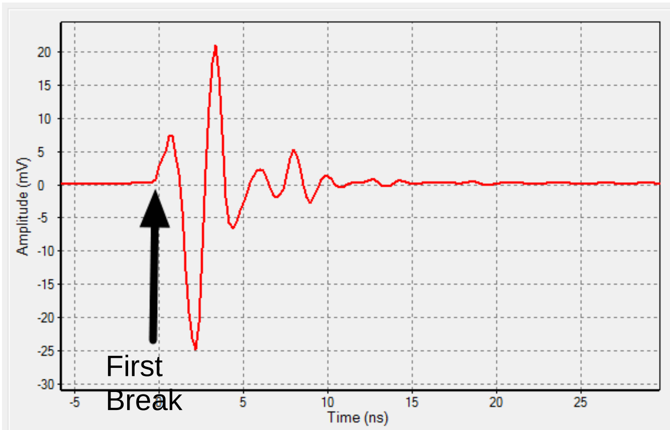
Edit First Break Parameters

First Break Offset The time of the first break on the trace.

7.5.2 Repick First Break

Repick First Break is used to re-pick the first break offset for the GPR line (listed in the **Advanced** category of the GPR line Acquisition tab (see **Figure 1**)).

When data are collected, the first trace collected is searched to find the first break. This is the first large deflection (either a positive peak or a negative trough) in the trace and indicates the arrival of the direct air wave to the receiver.



Sometimes the automatic first break search fails, and the first break is set to the wrong value. The Repick First Break routine uses a relative or absolute threshold value to re-pick the first break for the GPR line.

The relative threshold value is a percentage (0.0 to 100%) of the peak amplitude value in the trace.

The absolute threshold is a signal amplitude value in millivolts from -50 to +50.

The first point in the trace to exceed the threshold value is the first break offset time. This time value can be a decimal number between two points with values on either side of the threshold.

The default value is 5% or 5 mV. Typical percentages required to get a good first break are 5% to 10% or 5 to 10 mV, but if the data are particularly noisy, a higher threshold may be required.

It is recommended that Repick First break be applied to GPR lines that have not been Dewowed because the Dewow process introduces a pre-cursor to the data that can affect the Re-pick process.

Transition defines the first break: a positive deflection, a negative deflection or the first deflection either **positive** or **negative**. The default is **both** which means the first positive or negative deflection that exceeds the threshold is the first break.

When determining a threshold value to input, it is a good idea to plot the data in LineView or View > Trace Plot (see EKKO_Project User's Guide) and see whether the first major deflection is positive or negative. If the first deflection is positive, use a positive transition. If the first deflection is negative, use a negative transition. Repick First Break searches the input traces and records the first point to exceed the threshold value.

Shift Traces determines if the traces are physically shifted to align with one another. If

Shift Traces is set to No, Repick First Break calculates the first break offset time for each trace and sets the first break offset to the median value.

If Shift Traces is Yes, each trace is shifted up or down in time to align with the trace with the smallest first break offset.

Repick First Break may not always give a good pick for the first break. To check the pick, plot the traces in LineView or View > Trace Plot (see EKKO_Project User's Guide) and see where the first break is placed on the GPR line. If not, try another threshold value and see if the pick can be improved. The threshold needs to be large enough so that the transmit pulse (which should be a higher amplitude than anything before it) is the point that gets picked.

Usually the first break point on each trace lines up horizontally. However, if data are collected before the radar system has warmed up properly or if the fiber optic cables (on some Sensors & Software GPR systems) are damaged, the first break point may drift up and down from trace to trace. When this problem is visible in the data, the Shift Traces option can be used to horizontally align all the traces at the threshold value.

It is especially important to set Shift Traces to Yes if further data processing on the GPR line is required. Many processes like any of the Spatial Filters or the 2D filters use calculations on amplitude values in adjacent traces. If there is much drift in the data, these processes may not work as well.

Repick First Break Parameters

Method	Select the Method used to Repick the First Break: Absolute or Relative.
Relative Threshold (% of Peak)	Percentage of the peak GPR signal amplitude in the trace that defines the first break. Values are 0% to +100%. Default is 5%
AbsoluteThreshold (mV)	Signal amplitude in milliVolts in the trace that defines the first break. Values are -50 to +50 mV. Default is 5 mV
Transition	The trace deflection direction to pick the first break point on. Options are Positive, to pick the threshold on the first positive part of the trace that exceeds the threshold, Negative, to pick the threshold on the first negative part of the trace that exceeds the threshold or Both (first positive or negative, whichever occurs first in the GPR trace that exceeds the threshold. Default is Both.
Shift Traces	Option to permanently shift the re-picked traces so they align horizontally to the threshold value. Options are Yes to shift traces or No to just re-pick the first break but not to align the traces. Default is Yes.

7.6 Gains

Since the radar signal strength normally decreases with increasing time, it is usually necessary to apply some sort of gain function to boost the weaker signals at later times.

The raw, ungained data shows little signal except for the strong near-surface reflectors (Figure 14). No gain may be useful in areas where the radar signal is very strong or in areas where the targets are very shallow.

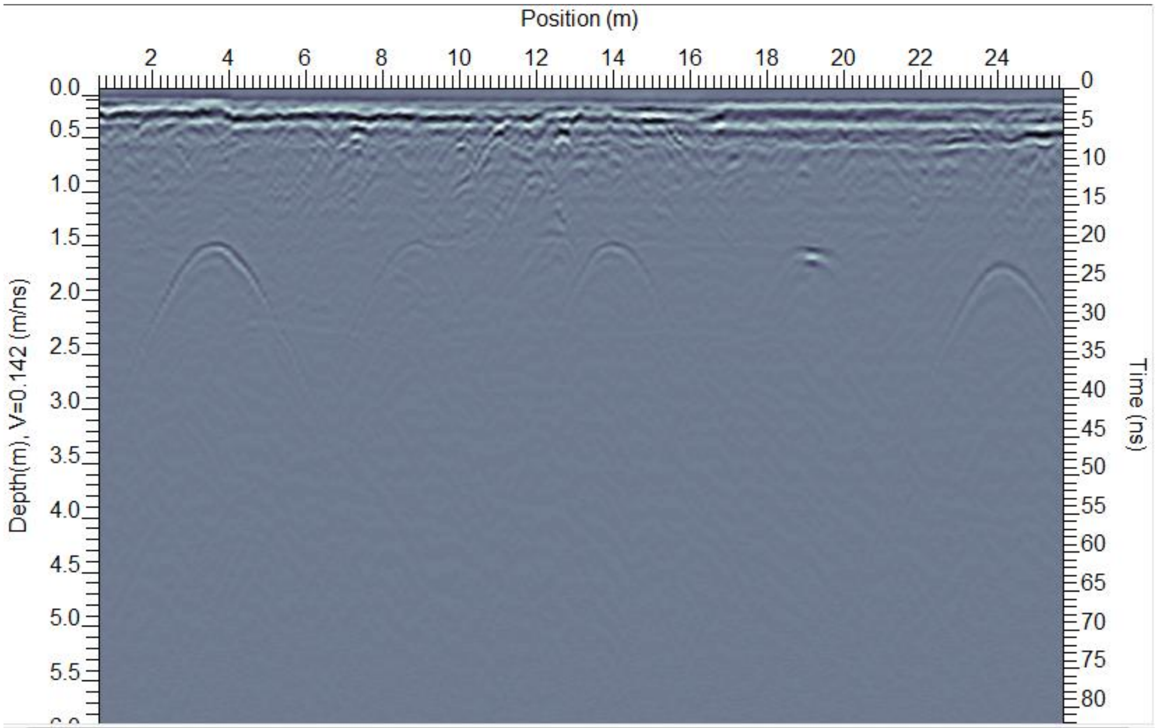


***Figure 14**: GPR line with no gain applied.*

None of the gain functions are permitted to boost a data point value to greater than + or – 50 mV. Values where this occurs are trapped and forced to 50 or -50 mV.

7.6.1 Automatic Gain Control (AGC)

The Automatic Gain Control (AGC) gain attempts to equalize the amplitudes of all GPR signals by applying a gain which is inversely proportional to the signal strength (Figure 15). This type of gain is most useful for defining continuity of reflecting events. AGC does not preserve relative amplitude information, so once AGC has been applied to the data, you can no longer make reliable deductions concerning the strength of any particular reflector relative to other reflectors.

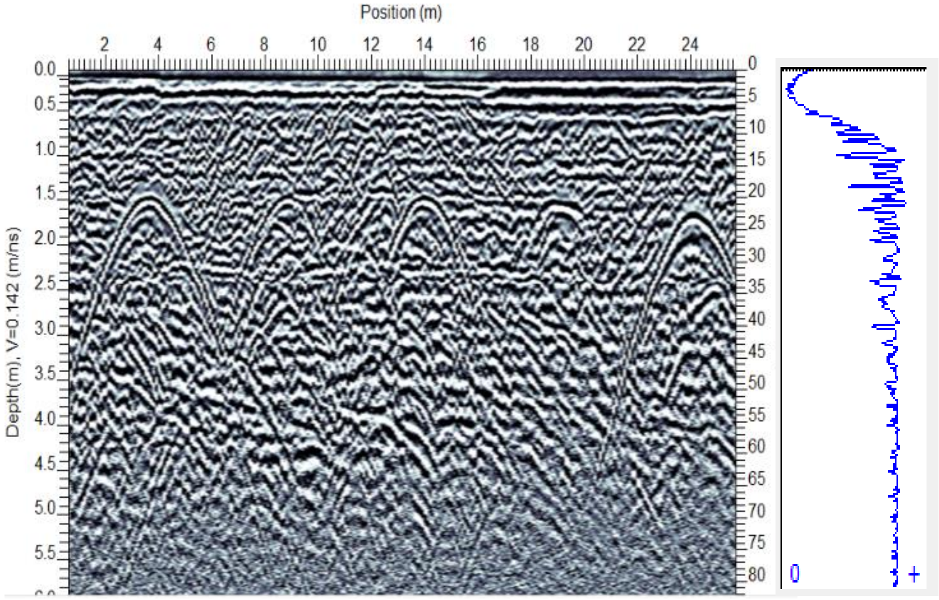


Figure 15: *GPR line with AGC gain applied with the AGC gain function on the right. AGC applies a gain inverse to the signal strength. The gain function varies for each trace.*

Since the AGC gain is inversely proportional to the signal strength, very small signals can produce very large gains. To avoid this, a gain-limiting scheme called Maximum Gain is applied.

AGC Parameters

Window Width:

To calculate the gain to be applied at each point in the trace, AGC locates the average signal level over a window of width given by Window Width and centered about the point. The Window Width is specified in units of pulse width based on the antenna center frequency. In the case of data collected at 100 MHz with a sampling interval of 800 ps, and a window width of 1.5 pulse widths, 27 points would be used to compute the average signal strength.

The default of 1.5 is adequate in most cases.

Maximum Gain:

A number between 1 and 32767 can be used to determine the maximum gain that can be applied to any data point. If the calculated gain value for any point along the trace exceeds the Maximum Gain value, the Maximum gain value is applied to the data instead. This maximum gain is fixed for the whole data set.

A typical value would be 50 - 2000 depending on the noise and average signal levels.

7.6.2 Constant Gain

This routine will apply a constant gain factor to the GPR Line. Only one parameter is needed, namely the constant factor to multiply all data points by. Thus if the user enters the number 10, all data points will be multiplied by a factor of 10. This will gain strong signals and weak signals equally and result in the clipping of strong signals.

The advantages of a constant gain are:

- It is easy to understand how the amplification works and,
- There is only has one parameter to adjust.

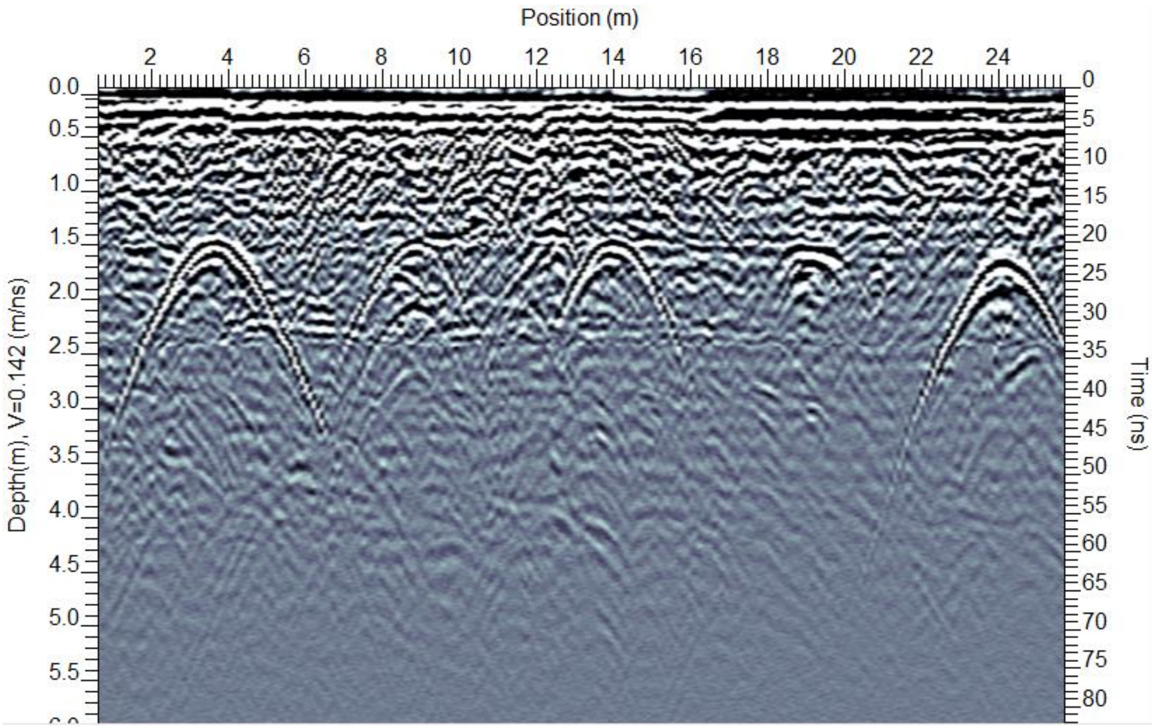


Figure 16*: GPR line with a constant gain of 100 applied.*

The disadvantage of a constant gain is that it tends to over-gain the strong signals at the beginning of the trace (Figure 16).

Constant Gain Parameter

Gain:

- The constant gain factor that the data set will be multiplied by.
- The default value is 100 and typical values for the Constant gain are in the range from 2 to 1000

7.6.3 SEC2

The SEC2 (Spreading & Exponential Calibrated Compensation) gain is a composite of a linear time gain and an exponential time gain. This gain attempts to compensate for the spherical spreading losses and the exponential ohmic dissipation of energy in the GPR Line. Since GPR data is attenuated exponentially and the SEC2 is an exponential gain, it tends to be the gain closest to physical reality. Therefore, unlike the AGC gain, after an SEC2 gain is applied to a GPR Line, reflections can be compared for relative signal strength. SEC2 is the preferred gain for GPR data (after applying Dewow).

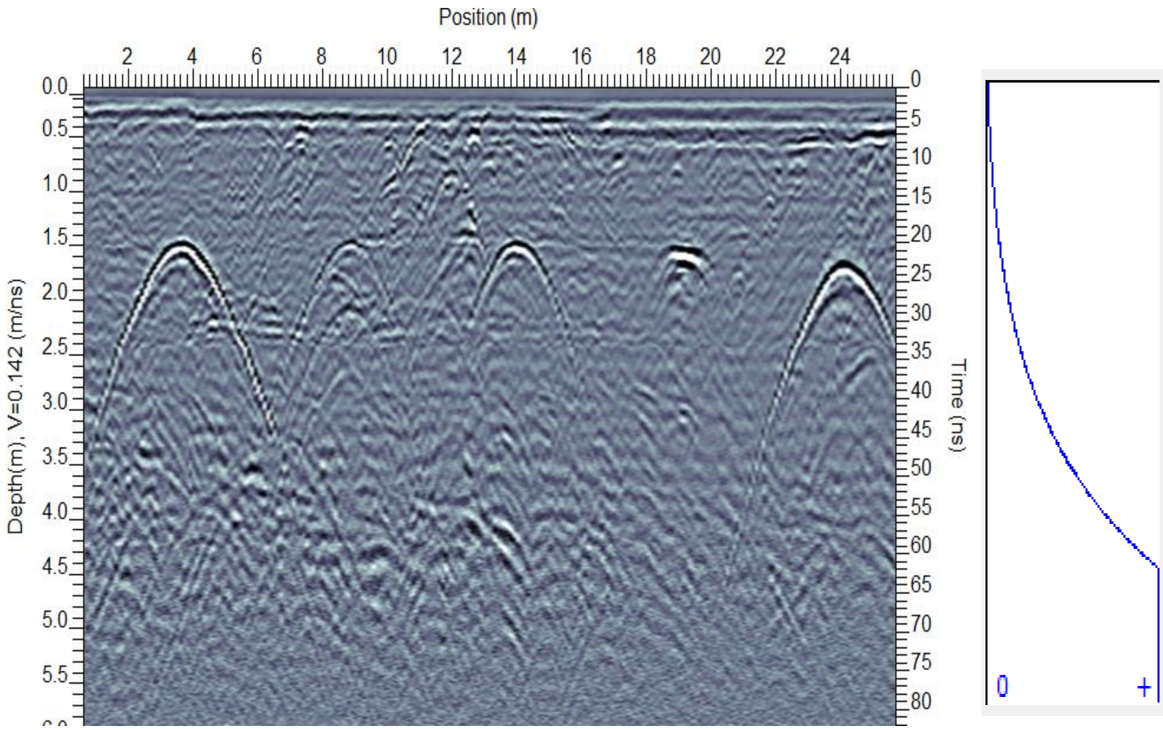


***Figure 17**: GPR line with an SEC2 gain applied and the SEC2 gain function on the right. This type of gain is the closest to physical reality because it compensates for the attenuation of the signal with depth.*

This gain is essentially an exponential function. This exponential function could, in fact, go to infinity. Therefore, as with the AGC gain some gain limiting factor must be applied so a Maximum Gain value is used.

SEC2 Parameters

Attenuation

This quantity represents the radar wave attenuation given in decibels/meter.

The higher the attenuation value, the faster the exponential function rises the more gain applied at earlier times on the GPR Line. Data collected on low attenuation materials like sand and hard rock may only require an attenuation of 0 to perhaps 5. Data collected on high attenuation materials like silts, clay and concrete may require an attenuation of 10 perhaps as high as 40 or 50.

Typical value: 0.5 to 5.

Start Value

This is a constant value (or DC) added to the exponential function. The SEC2 gain rises from this value; normally it will be 1 but for those data sets where more gain is required at early times, this value can be increased accordingly.

Typical value: 0 to 10

Maximum Gain

This is a number between 1 and 32767 which determines the maximum gain that can be applied to any data point. When the exponential gain function exceeds the Maximum gain value, the function levels off at the Maximum Gain value. All points in the GPR trace later in time are gained by the Maximum Gain value. This maximum gain is fixed for the whole data set.

Typical value: 50 to 2000.

7.7 Line Editing

7.7.1 Antenna Separation

This is the distance between the transmitting and receiving antennas. For reflection data this distance is normally kept fixed for every trace collected. Appropriate values of antenna separation for each antenna frequency are given on the table in the data acquisition program.

This option is available for editing the antenna separation saved in the data file. It is important that the correct antenna separation be entered since this value is used in the computation of the depth axis.

This parameter has no meaning for any mode of operation where the antenna separation changes (as in a CMP/WARR profile).

7.7.2 Crop Data - Horizontal

Sometimes a GPR Line is too long and needs to be cropped. For example, the ends of a line may contain poor or uninteresting traces.

Crop Data - Horizontal is used to delete data outside the input minimum and maximum position.

Crop Data - Horizontal Parameters

Minimum, Maximum Positions

Minimum and Maximum positions of traces are used to retain in the cropped GPR Line. The Minimum position must be less than the Maximum position. The default values are the current start and end positions.

7.7.3 Crop Data - Vertical

Sometimes a GPR Line contains too much data in time. For example, if the chosen time window was too long, the data of interest might occur at early times and the later times on the GPR line may contain poor, noisy or otherwise useless data.

Crop Data – Vertical is used to delete data outside the input minimum and maximum time range.

Crop Data - Vertical Parameters

Minimum, Maximum Times

Minimum and maximum times (in nanoseconds) are used to retain in the cropped GPR Line. The minimum time must be less than the maximum time. Times can be positive or negative (data before the first break). If the Start Time is positive, the first break offset is removed and is recorded in the Acquisition tab (see **Figure 1**) as a negative time.

7.7.4 Pad Data - Horizontal

Sometimes a GPR Line needs to be padded out so two or more lines have exactly the same start and end positions or number of traces.

Pad Data - Horizontal is used to add data traces from the input minimum position to the current start position and add data from the current end position to the input maximum position.

Data traces added to the GPR line have zero (0) amplitude values.

Pad Data - Horizontal Parameters

Minimum, Maximum Positions

Minimum and Maximum positions of the padded GPR Line; the Minimum position must be less than the maximum position.

7.7.5 Pad Data - Vertical

Sometimes a GPR Line needs to be padded out so two or more lines have exactly the same minimum and maximum times.

Pad Data - Vertical is used to add data to the top and bottom of a GPR Line; from the input minimum time to the current start time and/or add data from the current end time to the input maximum time.

Sample points added to the top of the GPR line have the same amplitude value as the first sample point while sample points added to the bottom of a GPR Line have the same amplitude value as the last sample point.

Pad Data - Vertical Parameters

Minimum, Maximum Times

When using minimum and maximum times (in nanoseconds) in the padded GPR Line, Minimum Time must be smaller than the Maximum Time. To pad the GPR Line on the top, the input Minimum Time must be less than the current Start Time. To pad the GPR Line on the bottom, the input Maximum Time must be greater than the current End Time.

Times can be positive or negative (data before the first break).

7.7.6 Reposition Traces

Before a GPR Line is collected, the Start Position and Step Size are defined. These two parameters are used to calculate the position of each trace and the end position of the GPR Line. Often, for a variety of reasons, it is necessary or desirable to change the trace positions after the survey was run.

For example, a survey run at a step size of 0.5 meters between two survey stakes 100 meters apart should produce 201 traces. However, if the step between traces was estimated during the survey, the 100-meter stake will likely be encountered before or after the 201st trace is collected. This means that over the course of the survey the actual step size was not exactly 0.50 meters, but more like 0.54 or 0.45 meters. Reposition is used to correct the step size so the GPR Line is the proper length.

Other examples where Reposition Traces may be useful are:

- The wrong start position was input so all the traces are in the wrong position.
- The wrong step size was input, or the odometer calibration was incorrect, so all the traces are in the wrong position.

Reposition would be used in these situations to adjust the trace positions to their actual position on the GPR line.

Reposition can be used to adjust the trace positions in four different ways (the Reposition using option determines which):

- **Input a new Start Position**: The Step Size and Length stay the same and the End Position is adjusted.
- **Input a new End Position**: The Step Size and Length stay the same and the Start Position is adjusted.
- **Input a new Step Size**: The Start Position stays the same and the Length and End Position are adjusted.
- **Input a new GPR line Length**: The Start Position stays the same and Step Size and End Position are adjusted.

Reposition Parameters

The parameters needed for this application are:

- **Start Position**: The Start Position (in meters or feet) of the GPR line.
- **End Position**: The End Position (in meters or feet) of the GPR line.
- **Length**: The length (in meters or feet) of the GPR line.
- **Step size**: The distance between traces (in meters or feet) in the GPR line.

Note: Only one parameter can be changed with each call to this routine so in some situations it may be necessary to call the routine more than once to modify the trace positions the way you want.

Example 1

A data file was collected from Start Position of 0.0 and an End Position of 100.0 with a step size of 0.5. An error was made in that the Start Position should be 10.0. To correct this, set the Start Position to 10.0. This will adjust all the trace positions with respect to the new Start Position. The End Position will change to 110.0.

Example 2

A data file was collected from Start Position of 0.0 and an End Position of 100.0 with a Step size of 0.5. An error was made in that the End Position should be 120.0. To correct this, set the Length to 120.0. A new Step size will be calculated to allow the traces to fit within the set Start (0.0) and end positions (120.0). For example, if the data file contains 201 traces, the new calculated Step size is 120.0/(201-1) = 0.6 meters.

Example 3

A data file was collected from Start Position of 0.0 and an End Position of 100.0 with a Step size of 0.5. An error was made in that the Start Position should be 10 and the step size should be 0.25. To correct this, call the routine first and set the Start Position to 10.0. Then call the routine a second time with the Step size set to 0.25. The two calls will result in a final GPR line that starts at 10.0 and has a step size of 0.25.

7.7.7 Reposition Using GPS

If a GPR line was collected with GPS, every trace has a GPS position saved with it.

Reposition with GPS uses the GPS positions to reposition each trace in the GPR line. First, using all the GPS positions collected along the GPR line, it calculates the total path length for the GPR line. Then it divides the distance by the number of traces to compute a new average step size. The trace number and average step size are then used to calculate a new position for each trace in the GPR line.

This routine is very useful for data collected in Free Run mode with GPS because lines collected in Free Run use an estimated step size so the length of the line in the Acquisition tab (see **Figure 1**) is usually not very accurate. Using GPS provides a good estimate of the actual length of the line.

7.7.8 Reverse Line

Reverse Line reverses the direction of the GPR Line.

For example, if a line were collected beginning at a position of 0 m using a 0.1 m step size, the position of the last trace would be set to 0 m, the second last trace's position would be set to 0.1 m, etc.

The Start Position, End Position and Step Size stay the same and the total number of traces in the line is not changed.

This routine is useful for permanently reversing GPR lines that were collected in the opposite direction of other lines, for example, when zigzagging across an area. By reversing every second line, all the lines can be plotted in the same direction for display and processing.

7.8 Operations

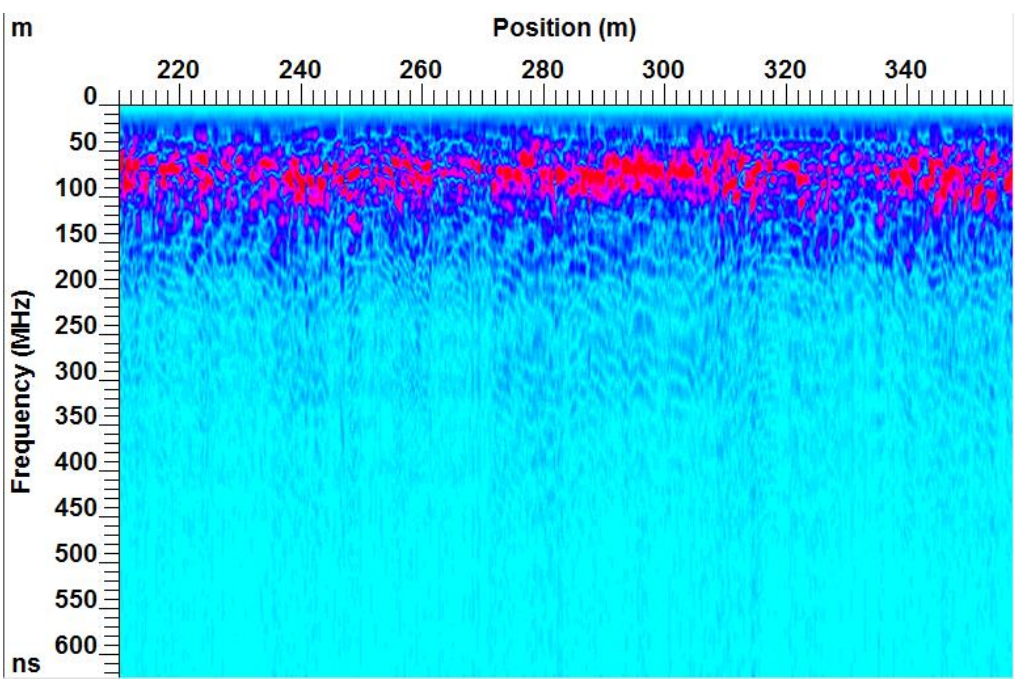
7.8.1 Amplitude Spectra

Amplitude Spectra uses the Fourier Transform to calculate the amplitude spectrum of each trace in the GPR line.

The amplitude spectrum is a plot of amplitude versus frequency and consequently reveals the frequency composition of the trace. This can be extremely useful information in determining which filter or processing technique would be the most effective in eliminating noise or emphasizing the desired signal.

Probably the most popular processing stream using Amplitude Spectra is used by the **View > Average Frequency Spectrum (AFS)** routine (see EKKO_Project User's Guide for more details). Amplitude Spectra is run on the radar profile to calculate the amplitude spectrum of each trace. Then the average amplitude spectrum is calculated and displayed. This can be used to decide an appropriate filter to apply to the profile data.

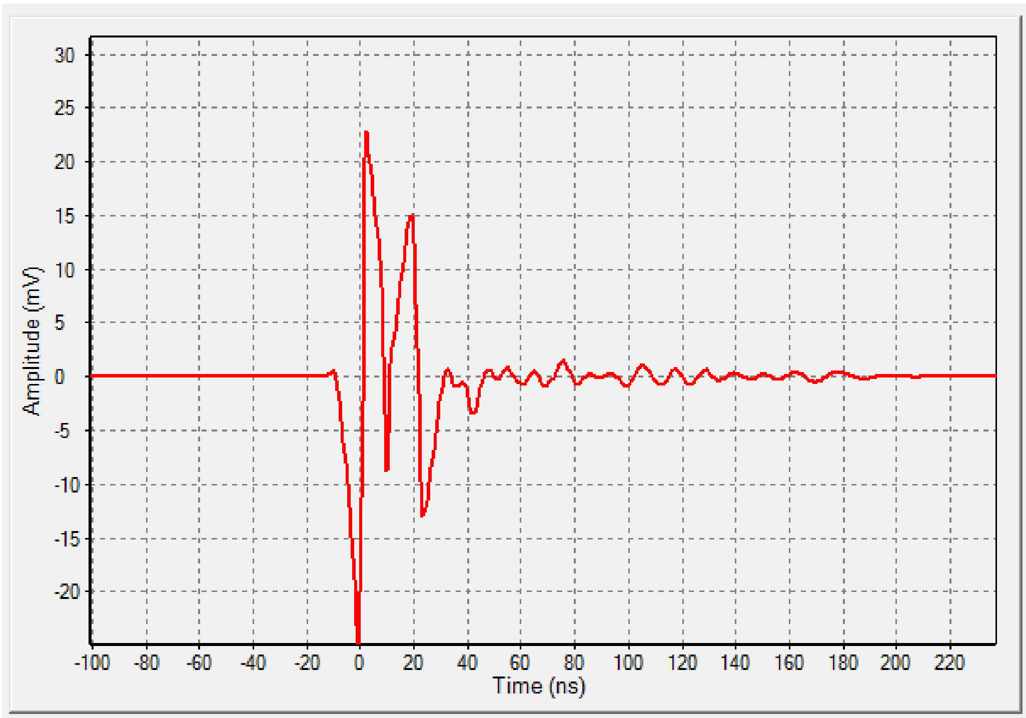
It is also possible to plot an amplitude spectrum section like a GPR line in LineView to see how the frequency content varies over the survey line. Note: when plotting amplitude spectra data in LineView, the frequency is plotted along the Time Axis where 1 ns = 1 MHz. The title of the "Time" axis can be edited to plot "Frequency (MHz)".



The plot above displays amplitude spectra data for 100 MHz geological data.

7.8.2 Average Trace

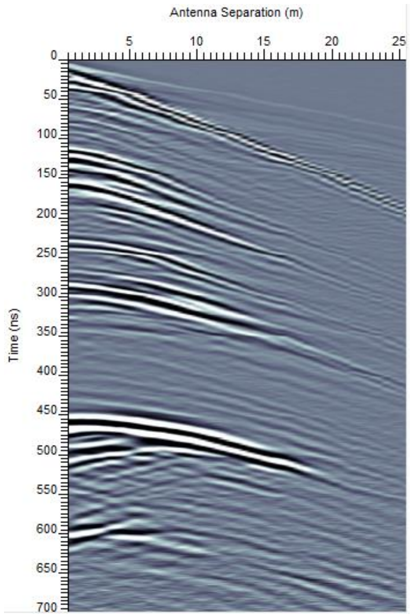
Average trace uses all the traces in the GPR line and calculates the average trace. The resulting GPR line only contains one trace so it is difficult to plot with LineView but can be plotted using the View > Trace Plot (see EKKO_Project User's Guide).



The average trace shows signals that are common to all or many traces; for example, horizontal signals such as the direct air wave, direct ground wave, banding and reverberations as well as flat reflectors.

7.8.3 CMP/WARR Analysis

The CMP/WARR analysis routine is based on a concept commonly used in the petroleum seismic industry. The analysis is based on the assumption that the arrival time for signals from reflectors varies hyperbolically as the separation between the transmitter and receiver increases. In many situations this approximation is so close to being valid that departures from it are not detectable.



Mathematically the arrival time of a reflection is mathematically expressed as:

$$t^2 = t_0^2 + x^2/V^2$$

where:

x = antenna separation,
t = arrival time,
t_0 = arrival time at zero antenna separation,
V = move out, stacking or RMS velocity.

There are times when the hyperbolic move out assumption breaks down. This is normally encountered where reflectors with significant dip are encountered. Such situations should be recognizable from the standard reflection profile survey of the area where the CMP/WARR sounding is carried out. It is good practice to position the soundings in areas of relatively flat stratigraphy.

The Velocity Analysis program uses the concept of a velocity stack. The concept is simple and consists of assuming a constant velocity model for the earth. The traces of a CMP/WARR are then added together after compensation for normal move out assuming the constant velocity hyperbolic equation form. When the velocity assumed matches the normal move out velocity, a reflector will be stacked together coherently for all the traces and result in a large amplitude for that stack reflection. If the velocity does not match that of the reflector then individual traces add together incoherently with little if any enhancement of the reflector.

It is common practice to apply a pre and post CMP/WARR Analysis processing to the CMP/WARR data; typically a gain before and various processes after including Background Subtraction, Envelope, and a Constant Gain (see CMP/WARR Analysis).

Air Waves

Unlike seismic data, GPR data can contain waves which travel with the velocity of air. These air velocity waves can become stronger than waves which propagate in the ground at large antenna separations because they only travel part of the time in the ground. At large angle separations one has to judiciously apply a velocity stack. If a CMP/WARR sounding has been carried out where the antennas are not close to the ground, then air waves may dominate at large angle separations. For the velocity analysis program to work effectively only those data traces from relatively small move- out angle should be used in the velocity stacks so as not to heavily bias the results with the airwave signals. It is possible to set the range of traces used in the velocity analysis calculation (see Start/End Trace below).

CMP/WARR Analysis Parameters

Start/End Trace

Start and End Trace are the trace range used in the velocity calculation. These values default to the first and last traces in the file. See **Air Waves** above for an example of when it may be useful to restrict the trace range.

Start/End Velocity

Start and End Velocity is the velocity range that will be stacked. The default radar velocity range is 0.01 to 0.30 m/ns which covers all possible materials. However, radar velocities in geological materials generally range from about 0.05 to 0.16 m/ns and if the material is known, this velocity range can be limited further. The user may want to limit the velocity range to stack if information on the material is known.

Velocity Step

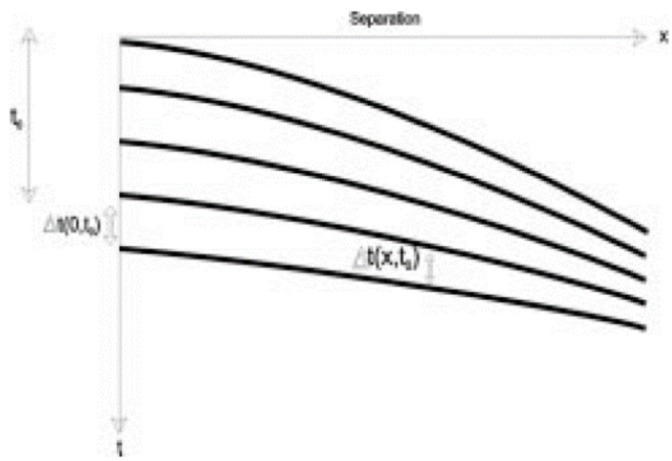
Velocity Step is the difference between each stacking velocity in the Start to End velocity range. For example, if the velocity range is 0.01 to 0.3 m/ns and the velocity increment is 0.01 then there will be 30 stacking velocities: 0.01, 0.02, 0.03 ... 0.29 and 0.3. For finer stacking velocities make the velocity increment smaller. For example, if the velocity increment above is changed to 0.0025 m/ns then there will be 120 stacking velocities: 0.01, 0.0125, 0.0150, 0.0175, 0.02, 0.0225 ... 0.2975 and 0.30. This value is determined by the velocity accuracy required.

Normalization

Normalization determines the type of stacking to be performed. The user may select raw (no normalization) data stacking (the default), or normalized positive (plus), negative (minus) or both polarities (plus/minus) stacking. Raw data stacking uses the raw data for the trace stack. Weak reflectors tend be averaged out so that only the strong reflectors appear on the velocity section.

Stretch

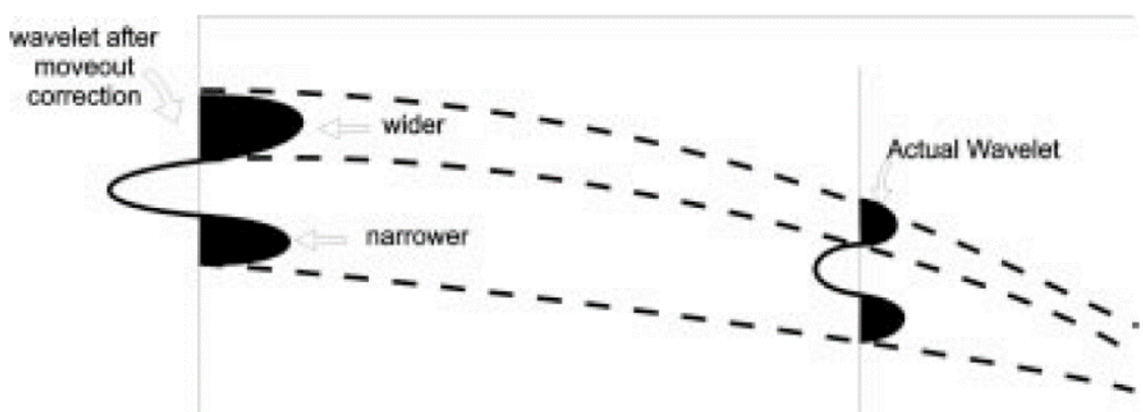
When computing a coherent addition of arrivals for various antenna separations, a move-out velocity which generates the strongest, most coherent addition is an indication of ground velocity. When this calculation is done, the implicit assumption is that the radar wavelet has minimal (ideally negligible) time duration. In reality, the pulse has a finite time extent.



If one examines the hyperbolic move-out of a reflection event (ideal spike or impulse in time) with separation, one finds that events separated by time Dt(0,t0) at zero offset are separated by time Dt(x,t0) where x is offset or separation and t0 is the arrival time at zero offset or separation. The concepts are depicted in the figure above. Mathematically, the time stretch is approximately:

$$\frac{\Delta t(0,t_0)}{\Delta t(x,t_0)} \approx \left(1 + \frac{x^2}{2v^2t^2}\right)$$

In other words, events are stretched apart after compensating for separation as x increases or the depth of the target decreases. When computing a velocity stack, a wavelet from offset x will be stretched in time when move-out is corrected to zero offset as depicted below.



When computing velocity stacks, it is desirable to eliminate portions of the data set which suffer undesirably large stretches as this yields a distorted and less meaningful stacked result. The stretch factor is defined by:

$$\frac{\Delta t(0) - \Delta t(x)}{\Delta t(x)} = 1 + \text{stretch factor}$$

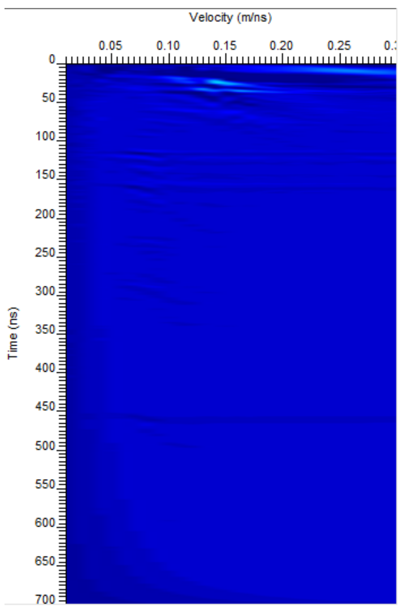
In the velocity analysis program, the stretch factor is expressed as a percentage:

$$\frac{\Delta t(0)}{\Delta t(x)} = 1 + \frac{\text{stretch factor}}{100}$$

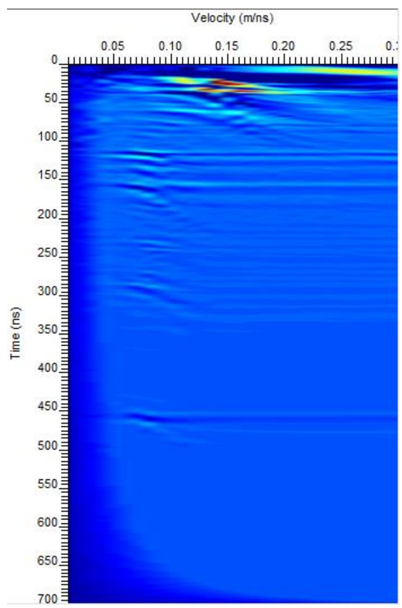
If stretch exceeds the defined amount for a given delay time and offset, the contribution to the stacked result is omitted.

A typical value for stretch will be 10. This will allow trace stretch of 10%. To disregard this stretch factor and include all stacking contributions set stretch to the default of 100%.

For further discussion, refer to text: Yilmaz, O., 1987, Seismic Data Processing; Investigations in Geophysics No. 2: Society of Exploration Geophysicists.



Analyzed CMP Data – no gain

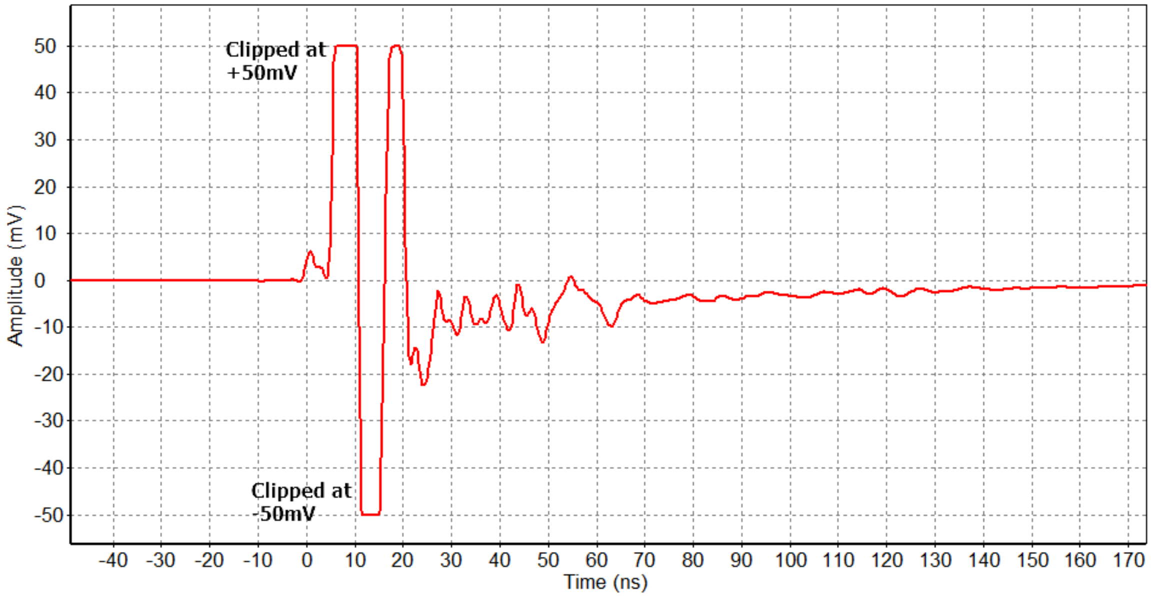


Analyzed CMP data – Auto gain

7.8.4 Declip

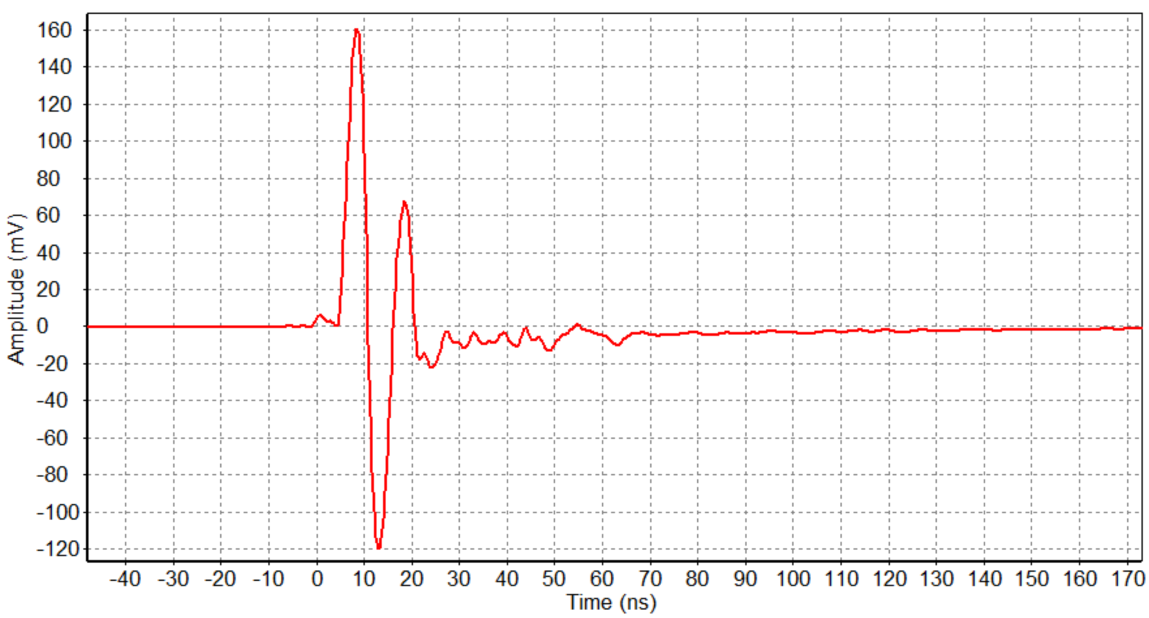
The Declip process is used to correct data exceeding the dynamic recording range of the GPR receiver electronics. When a signal's amplitude exceeds the recording range of the receiver, the receiver outputs the maximum value that it can record until the incoming signal drops back into the recording range of the receiver. The impact is visible in trace plots (without the Dewow filter applied) as flat tops on positive and negative going signals and is called 'signal clipping'.

For most Sensors & Software GPR hardware, the clipping level is ±50 millivolts (the full amplitude range is 100mV).



This value can be higher for newer systems using Ultra Receiver technology with 32-bit signal recording. For systems capable of running Ultra technology, the total amplitude window is reported in the **Acquisition Tab > Additional Info > Amplitude Window (mV)**.

Declip replaces the clipped data points with interpolated values representing the approximate wave form.



The declipping process requires the user to enter a clipping level to identify data points that have been clipped. The value selected is usually slightly less than the anticipated hardware limit. The normal default value is 48mV for systems limited to a 50mV recording limit, but this may differ as hardware designs change and evolve.

Declip Parameter

Clip Level (mV)	A value slightly less than the receiver hardware recording limit. Defaults to 48mV, a good value for most Sensors & Software GPR systems. For 32-bit Ultra data, use 0.48 * Total Amplitude Window

7.8.5 Delete Traces

Occasionally, extra traces are recorded in a profile that later need to be deleted. Delete Traces allows the user to delete a trace at a specific position or many traces in a range of positions.

After the deletion of the traces, the traces are renumbered and repositioned, so the total length of the line is correct.

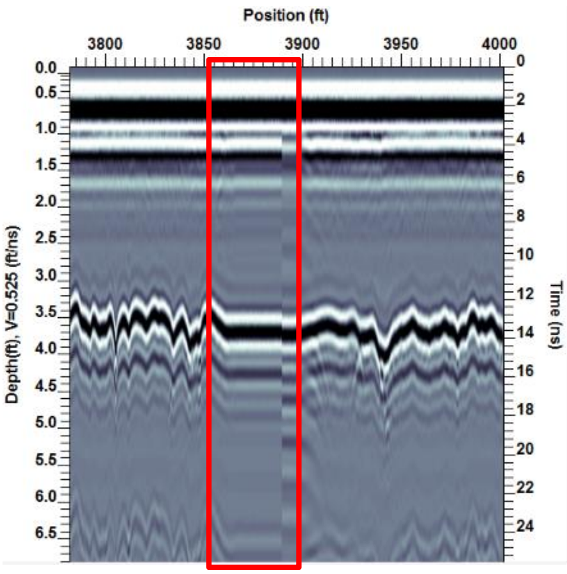
Any interpretations attached to traces that are deleted are permanently removed and **cannot** be recovered using Undo Process. It is advised that processing routines such as Delete Traces are applied before adding interpretation.

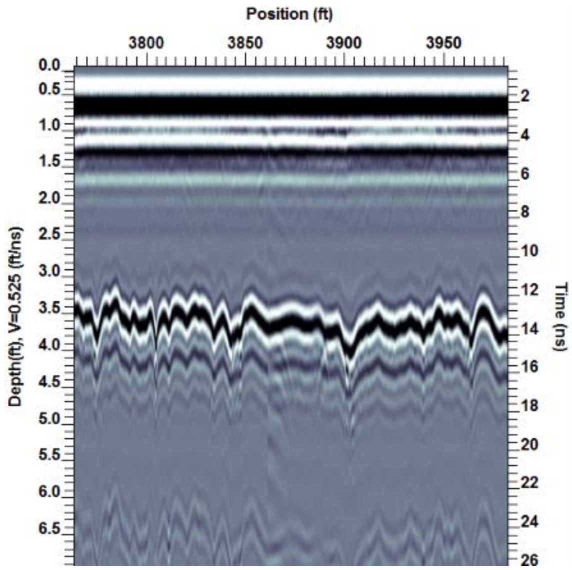
Delete Traces Parameters

Minimum Position Position where first trace is deleted from the GPR line.
Maximum Position Position where the last trace is deleted from the GPR line.

To delete one trace at one position: make that position ***both*** the Minimum and Maximum Positions.

Position ranges are independent of the sign of the step size. For example, if step size is negative, the position range still goes from the minimum position value to the maximum position value.





The most common usage of Delete Traces is to remove traces collected while the GPR was stationary in Free Run mode.

7.8.6 Flip Polarity

Sensors & Software pulseEKKO GPR systems have independent transmitters, receivers and antennas that can be put in any orientation relative to one another. While collected data along a profile line, it is important to keep the relative transmitter and receiver orientation the same, especially after any interruption in data collection to change batteries, etc.

One way to control polarity is to always have the Sensors & Software or pulseEKKO name on the electronic units pointed in the direction of antenna movement.

If the transmitter or receiver is rotated 180 degrees and changes the relative orientation, the signal polarity will reverse. If this happens in the middle of a survey line, negative signals (troughs) will change to positive signals (peaks) and vice-versa. If this occurs, the Flip Polarity routine is used to reverse the polarity of all or part of a GPR line.

Flip Polarity is also useful when one wants to merge two profile lines but they have different signal polarities. Simply reverse the polarity of one of the profile lines and then use the Merge Lines (see the EKKO_Project User's Guide) tool.

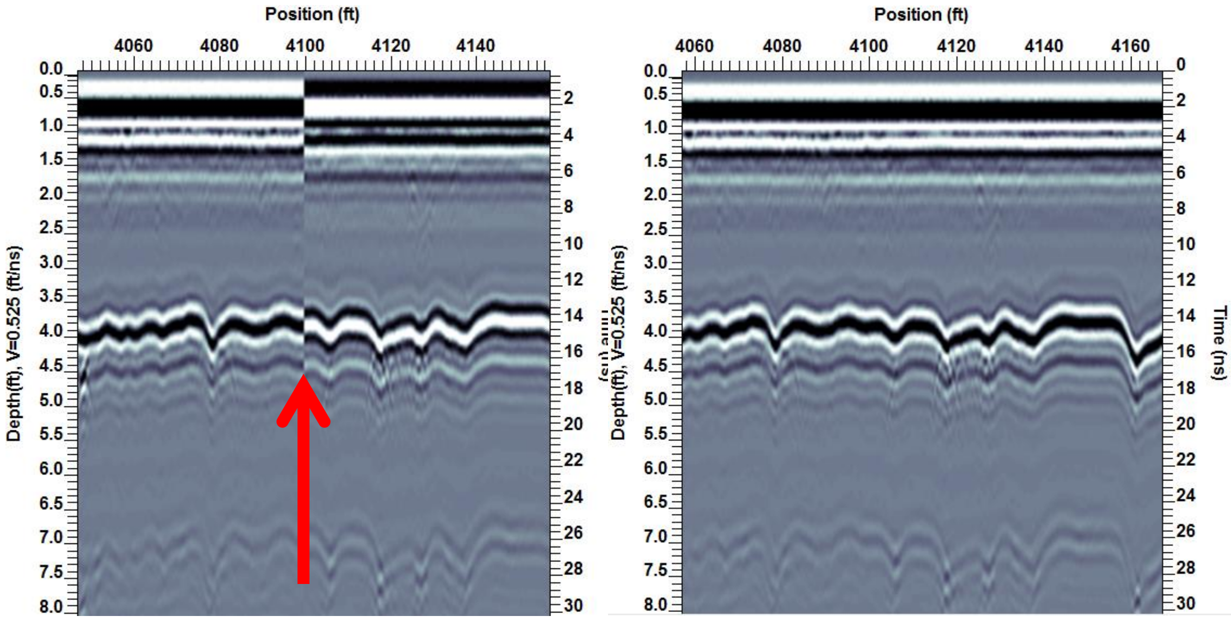
Flip Polarity Parameters

Minimum Position Position of the first trace in the GPR line where polarity is flipped.

Maximum Position Position of the last trace in the GPR line where polarity is flipped.

To flip the polarity of one trace at one position make that position both the Minimum and Maximum Position.

Position ranges are independent of the sign of the step size. For example, if step size is negative, the position range still goes from the minimum position value to the maximum position value.



The images above show a GPR line where the polarity changes in the middle of the line (left) and is corrected on the right.

7.8.7 Insert Traces

The purpose of Insert Traces is to allow blank traces to be inserted at locations which, for one reason or another, had to be skipped while collecting data out in the field. Adding blank traces where necessary, makes the GPR line the proper length. After inserting blank traces, the traces are renumbered and repositioned, so the total length of the line is correct.

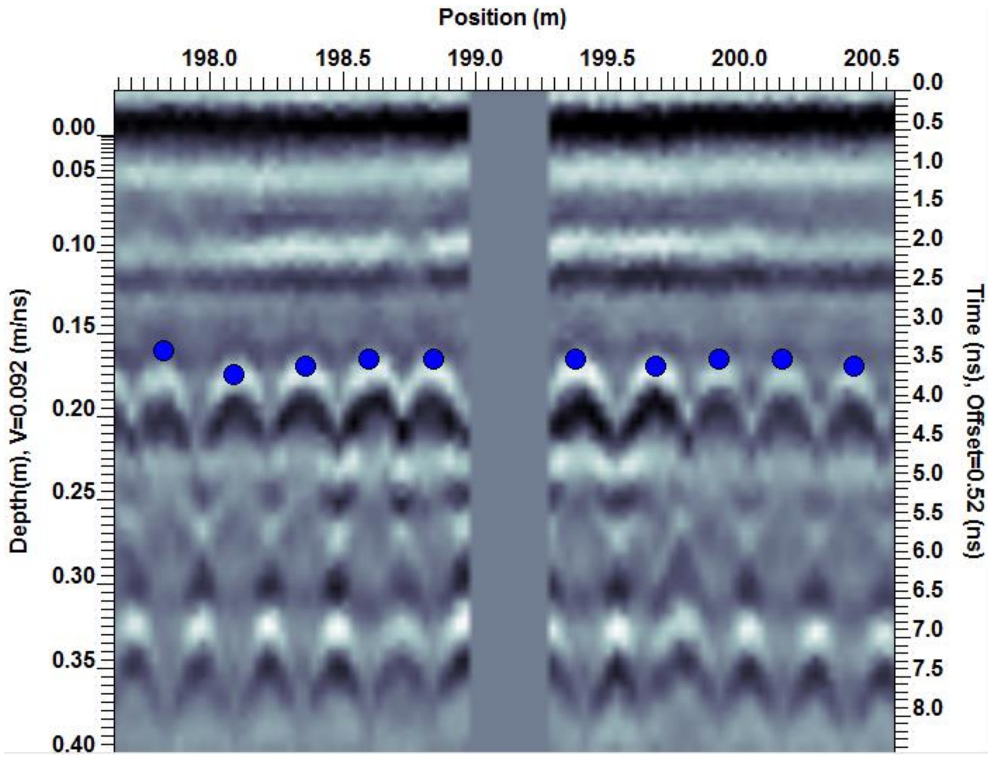
Note that no matter where and how many blank traces are inserted, the start position of the GPR line is preserved; inserting traces only causes the end position to change.

Insert Traces Parameters

Minimum Position The position at which to add blank traces in the GPR line.

Number of Traces The number of blank traces to add at the corresponding position.

Traces are always added in the direction of increasing position; there is always at least one real GPR trace BEFORE the blank traces.



A GPR line with 10 blank traces inserted in the middle is shown above.

7.8.8 Mute

Occasionally, a GPR line contains areas of poor data such as noise, a ringing metal response or a system glitch that draws the eye away from the more important data. Mute Data is used to mute (zero) a rectangle of data within a GPR line.

Mute Parameters

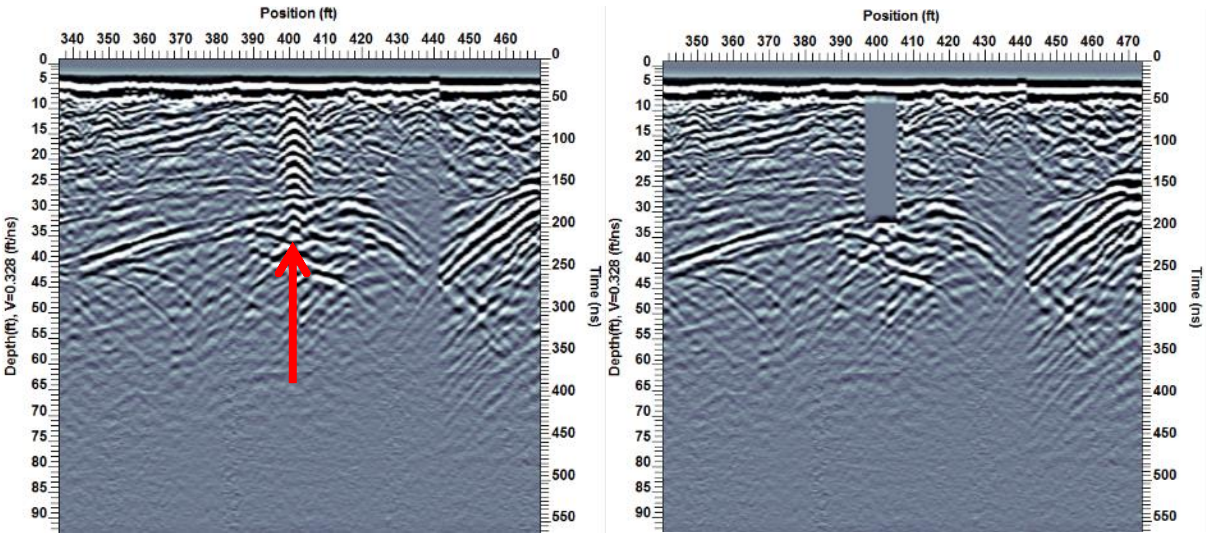
Minimum Position Position of the first trace in the GPR line to mute.
Maximum Position Position of the last trace in the GPR line to mute.

Position ranges are independent of the sign of the step size. For example, if step size is negative, the position range still goes from the minimum position value to the maximum position value.

Minimum Time First time in the GPR line to mute.

Maximum Time Last time in the GPR line to mute.

Minimum time must be less than Maximum Time.



The images above show how the strong ringing from a piece of metal debris (left) was muted out (right).

7.8.9 Normal Move-out Correction

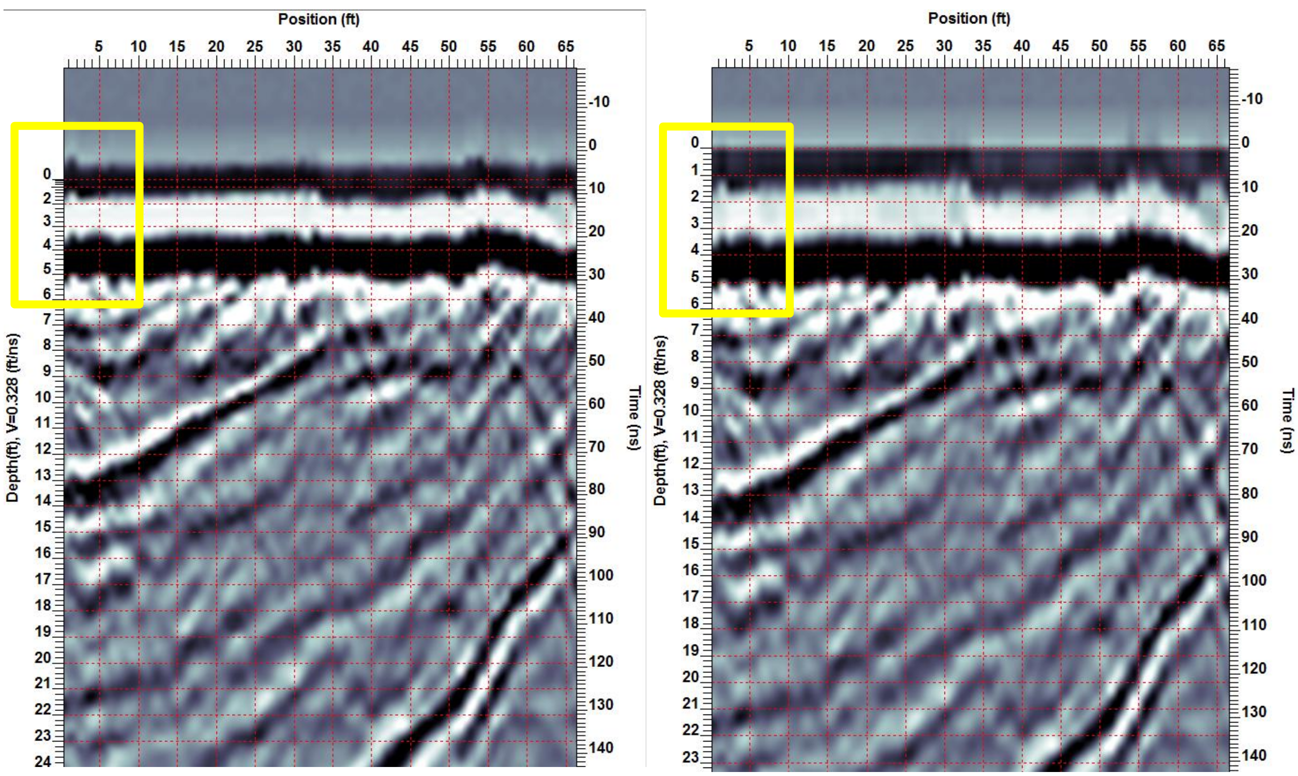
The finite separation between the GPR transmitter and receiver results in the top of the depth scale looking non-linear compared to the rest of the scale. This is because, especially at shallow depths, the depth to a reflector is not equal to half the signal path length.

The Normal Move-Out Correction convert a finite offset GPR line to a zero offset (transmitter and receiver coincident) by correcting for normal move-out using the input velocity.

This process stretches the signals at the top of the section so the depth scale and time start at the same point.

Normal Move-out Parameter

Velocity The average subsurface velocity in meters/nanosecond to use to correct the signal for the normal move-out.



The images above show the effect of applying the Normal Move-out Correction to 100 MHz geological data.

7.8.10 Rectify

Rectify goes through the GPR line and outputs the rectified version of each trace (i.e. the absolute value of each point in the trace).

The Rectify utility is very useful when one wants to look at the L1-norm of a data set. By rectifying a data file and then averaging all the traces together one can obtain a very useful estimate of amplitude fall-off versus time.

Rectifying a trace converts the trace from a wavelet with both positive and negative components to a wavelet with all positives.

L1 norm (rectify equation):

$$x_{Rectify} = \frac{\sum_{i=N}^{M} |x_i|}{N - M + 1}$$

At a single time or depth value the amplitude value will be the same amplitude as the raw value but always positive. When amplitude values are averaged over a time or depth range this will give the average, absolute value.

Rectify Variables: There are no input parameters required for this application.

Appendix A Glossary

1. Definitions

Term	Description
Attenuation	Represents the radar wave attenuation given in decibels/meter. The higher the attenuation value, the faster the exponential function rises the more gain applied at earlier times on the GPR Line.
Attributes	Characteristics derived from original data. Examples are the average amplitude of the dominant frequency between two times or depths.
Automatic Gain Control (AGC)	The Automatic Gain Control (AGC) gain attempts to equalize the amplitudes of all GPR signals by applying a gain which is inversely proportional to the signal strength. This type of gain is most useful for defining continuity of reflecting events.
Average Frequency Spectrum (AFS)	Use AFS plots to determine the frequency of a signal on which to base processing and filtering, similar to band-pass.
Average Trace Amplitude (ATA)	The Average Trace Amplitude (ATA) plot displays the average signal amplitudes (in microvolts) for an entire data file. This plot is a good way to display how rapidly the signal amplitude decays to the background level, giving you an idea of the maximum penetration for the data file.
Background Average Subtraction (BAS)	Use BAS to subtract the average trace of the entire GPR line from every trace in the line. This process enhances dipping events (such as hyperbolas from point targets) and removes horizontal responses common to all traces in the line. It is also used to remove the direct air and direct ground waves (transmit pulse) visible at the top of the line. BAS also removes horizontal bands in the data present throughout the length of the line.
Background Subtraction	Use Background Subtraction to apply a running-average background subtraction to the data set. This process enhances dipping events (such as hyperbolas from point targets) and suppresses or completely removes horizontal responses. This can be very useful for removing localized flat-lying events.
Bandpass Filter	Use bandpass filtering when the GPR signal is contained in a defined band of frequencies and there is "noise" energy in the remainder of the spectrum. Applying bandpass filtering enhances the desired signals at the expense of the out-of-band noise (Dewow). Bandpass is based on Fourier transform filtering concepts.
Dewow	The process of removing a very low frequency component from GPR data. These low frequency data components are associated with either inductive phenomena or possible instrumentation dynamic range limitations.

Term	Description
DynaQ	DynaQ is an advanced, patented technology that dynamically adjusts stacking as system speed varies. In most situations, moving the system at a comfortable speed stacks enough to generate good quality data.
Enveloping	Enveloping converts a trace from a wavelet with both positive and negative components to a monopulse wavelet with all positive components. The process removes the oscillatory nature of the radar wavelet and shows the data in its true resolution. Enveloping can also simplify radar section display making it easier to interpret.
Filter Type	Dictates the weighting the traces on the edges of the Filter Width have on the average trace calculation.
First Break Offset	The number of nanoseconds from the start of the trace to the first break.
GPS Files	Attaching a GPS file adds Latitude and Longitude, UTM coordinates, and GPS elevation to every trace in the GPR line. A GPS file is created by attaching a GPS system to the GPR system during data collection. GPS files contain lines of standard GPS positional output text (called NMEA strings) and the associated GPR trace number. When the GPS file is attached, latitude, longitude, and GPS elevations for every GPR trace are saved into the GPR file.
GPZ Files	Compressed files containing GPR lineset and grid data
Grid	A square or rectilinear set of straight lines which cover an area. Acquiring data on a grid means acquiring data along each line forming the grid. Acquiring data on a grid is a pre-requisite for creating depth or time slice images. Conventional notation is to use a Cartesian coordinate system with X and Y axes.
Highpass Filter	Removes frequencies below a cut-off frequency. Used for removing low frequency content in the GPR data; sometimes used instead of the Dewow filter. High Pass is a recursive filter designed for filtering GPR lines in the time domain. It is an infinite impulse response zero phase filter.
Interpretation Module	Interpretation module in LineView to create interpretations of Points, Polylines, Boxes, and Annotations, view them in GPR lines, and then output the interpretational information in reports.
KMZ Files	The KMZ files generated by a Noggin contain GPS information describing the path travelled during line collection. These files can be configured to display depth measurements along the line, making the data easier to interpret. Noggin enables you to export KMZ files which can be opened in Google Earth.
Lineset	All GPR lines in a project contained in one folder; collections of GPR lines that may or may not be related to one another. Linesets can be edited to add or delete GPR lines. GPR lines in linesets can also be cut and/or copied and pasted into other linesets.

Term	Description
LineView	Shows GPR line data cross sections. Launched from EKKO_Project.
Lowpass Filter	Removes frequencies above a cut-off frequency - useful for removing high frequency noise in GPR data. Low pass is a recursive filter designed for filtering GPR lines in the time domain. It is an infinite impulse response zero phase filter.
Migration	The migration process applies a synthetic aperture image reconstruction process to the GPR line.
nanosecond	A nanosecond is 10^{-9} seconds (one billionth of a second).
Overlap	Overlap (% of slice thickness) between the adjacent depth/time slices.
picosecond	A picosecond is 10^{-12} seconds (one trillionth of a second).
Polylines	A polyline is a list of points, where line segments are drawn between consecutive points.
Polyline Output Interval	The horizontal distance (meters or feet) between points on any polylines in the project. To interpolate and list more points than just the input observation points, enter them text box. A common interval is the step size for the GPR line
Project Explorer	The Project Explorer is similar to Windows Explorer, which lists folders and files. In Project Explorer, grids and linesets are used just like folders in Windows, and GPR lines are similar to Window Explorer files.
Processing Module	The optional Processing module allows you to edit and process data, including cropping data, time filters, migration and gain. Popular processing streams can be saved as Recipes and applied to other GPR projects.
Properties Window	Displays details of each GPR line including acquisition parameters and associated files
Slice	Describes the GPR data in a depth slice when the data is displayed as a computer generated image. Normally shortened to slice.
SliceView (EKKO_Mapper)	SliceView creates and displays GPR depth slice maps quickly and easily. Using the systematic grid data acquisition process common to pulseEKKO PRO, Noggin, or Conquest systems, images at multiple depths are generated in minutes.
Spatial Filter	Spatial filters act on radar data in the spatial (or positional) direction. These filters use adjacent traces during the filtering procedure and alter the shape of the trace through various mathematical manipulations designed to enhance or eliminate certain features.
Spreading & Exponential Calibrated Compensation (SEC2)	SEC2 gain is a composite of a linear time gain and an exponential time gain which attempts to compensate for the spherical spreading losses and the exponential ohmic dissipation of energy in the GPR Line.
Time Window	The maximum time selected for viewing, processing or data acquisition along a line. The length of the time window in nanoseconds (ns).

Term	Description
Time Sampling Interval	The time in picoseconds at which the GPR signal is sampled. Often set automatically by the system based on GPR frequency.
Topography Files	A topography file is a text file containing GPR line positions and the elevations at those positions. When a topography file is attached to a GPR line, elevations for every GPR position are saved into the elevation field of the GPR trace header.
Trace Plot	View Traces when you want to display subtle features in the data file or view the effect of different editing and processing types have on individual traces. Viewing traces can help you determine whether time-zero point needs to be edited. Normally the time-zero point should occur at the first large deflection in the signal. If not, time scales and depth scales on section plots will be inaccurate.
Universal Transverse Mercator (UTM)	UTM is a geographic coordinate system that uses a 2-dimensional Cartesian coordinate system to give locations on the surface of the Earth. It is a horizontal position representation, i.e. it is used to identify locations on the Earth independently of vertical position, but differs from the traditional method of latitude and longitude in several respects.
UTM Zone	The UTM system divides the Earth between 80°S and 84°N latitude into 60 zones, each 6° of longitude in width.
UTM Zone Number	Zone 1 covers longitude 180° to 174° W; zone numbering increases eastward to zone 60 that covers longitude 174 to 180 East.
UTM Letter	Each zone is segmented into 20 latitude bands. Each latitude band is 8 degrees high, and is lettered starting from "C" at 80°S, increasing up the English alphabet until "X", omitting the letters "I" and "O" (because of their similarity to the numerals one and zero). The last latitude band, "X", is extended an extra 4 degrees, so it ends at 84°N latitude, thus covering the northernmost land on Earth. Latitude bands "A" and "B" do exist, as do bands "Y" and "Z". They cover the western and eastern sides of the Antarctic and Arctic regions respectively.
Velocity	Speed at which GPR signals travel. Velocity is a critical parameter when creating depth slice images and estimating target depth since velocity is used to convert travel-time to depth.
Vertical Filter	Applies a running average filter vertically (down the trace) to a GPR line. The signal is averaged by replacing the data value at a given point by the average data value over a window centered about that point. Its primary purpose is to reduce random or high frequency noise by acting as a low pass temporal filter.

2. Abbreviations

Abbreviation	Full Phrase
AFS	Average Frequency Spectrum

Abbreviation	Full Phrase
ATA	Average Trace Amplitude
AGC	Automatic Gain Control
BAS	Background Average Subtraction
GPR	Ground Penetrating Radar
GPZ	GPR Project Zip file
MAPI	Messaging Application Programming Interface
MHz	Megahertz
ns	nanoseconds
ps	picoseconds
SEC2	Spreading & Exponential Calibrated Compensation
UTM	Universal Transverse Mercator