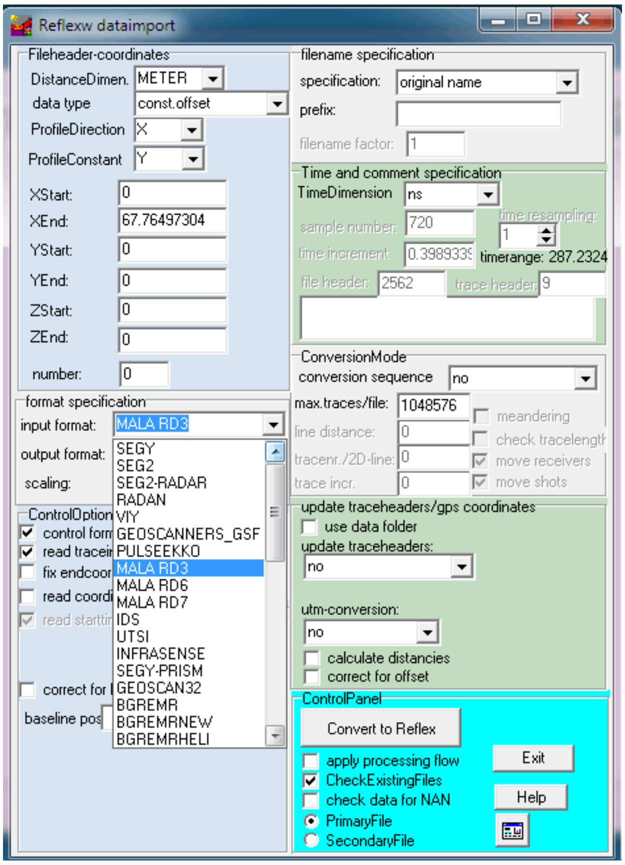
Introduction to the processing of GPR-data within REFLEXW

In the following the processing of 2D-GPR data is discussed. Starting from the different possibilities of data acquisition several filters are discussed later.

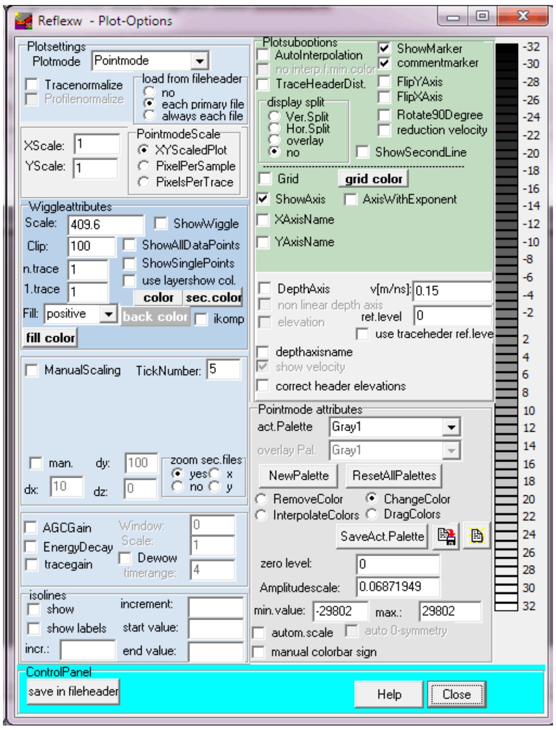
I. Data acquisition and import into Reflexw

I.1 import - general use



In order to use the acquired data within Reflexw the data must be imported. This is done within the 2D-dataanalysis module using the option file/import. Step by step procedure:
1. enter the module **2D-dataanalysis**
2. enter the **import** menu using the option File/Open/import. The REFLEXW-DataImport menu appears (see figure at the right).
3. Make the following inputs:
input format: dependent on the acquistion system, e.g. MALA-RD3
output format: new 16 bit integer or new 32 bit floating point. The 32 bit floating point format must be used is the original data have a higher precision than 16 bit integer. This is often the case for SEG2 or SEGY-data and for the newer GSSI-data.
filename specification: original name for example
Choose X or Y as ProfileDirection and Y or X as ProfileConstant.
Choose if the traceincrement and/or the coordinates shall be read from the original data.
4. You may set the plot options which are also stored with each imported file using the speed option. Here you may choose between Point and Wigglemode, ...

5. Activate the option **Convert to Reflex**. A fileopen menu appears with the directory ASCII under your project directory as the standard import path. You may choose an original RAMAC file (RD3 or RAD-file) from this import path or from any other directory. In any case all necessary original files (for the MALA-RD3 format the RD3 and RAD) must be present. After having choosen the wanted original file the data are converted into the REFLEXW internal format and stored under the path ROHDATA under your project directory. With the option PrimaryFile activated the imported data are automatically displayed into the primary window.

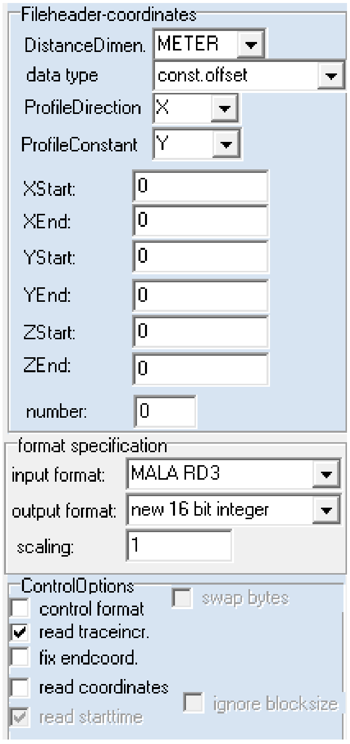


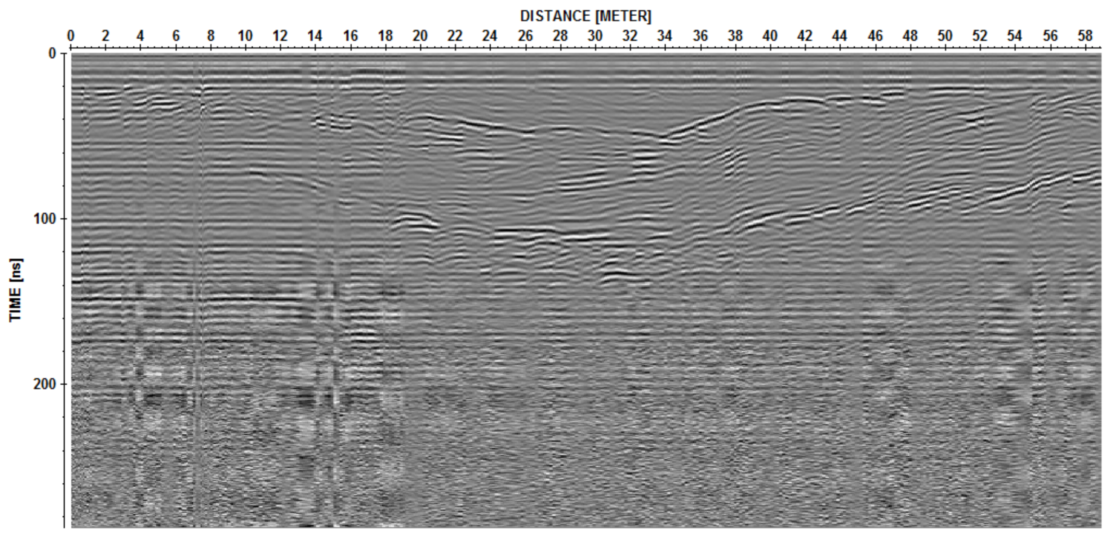
I.2 different data acquisition modes

Normally the data will be acquired along 2D-profiles. The goal are equally spaced data with a start and end coordinate and a traceincrement. This may be achieved by:

I.2.1 equally spaced data

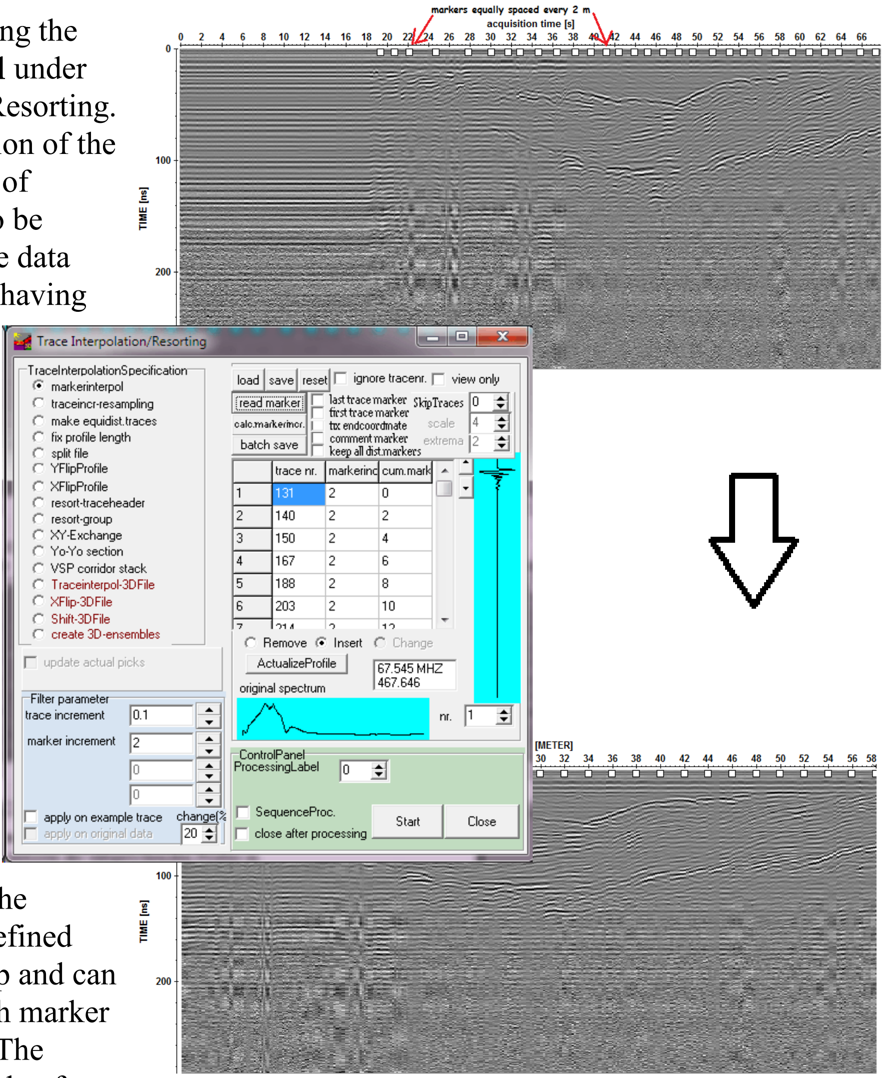
When using a wheel or an equivalent method for an equally spaced data acquisition single traces are only acquired at distinct spatial intervals. These traces are combined into a 2D-line. The x-axis already represents the distance. For the import within Reflexw enter file/import and choose the necessary parameters. For Mala data the traceincrement has been stored within the original data. Therefore the option read traceincr. must be activated. The start coordinate in ProfileDirection (in this case X) will not be changed. The entered end coordinate will be changed according to the number of acquired traces and the original traceincrement. If the option read traceincr. will be deactivated the entered values for the start and endcoordinates will not be changed and the traceincrement will be calculated from the coordinate values and the number of traces. This is necessary if the original traceincrement has not been stored (of course int his case the correct start/end coordinates must be known).





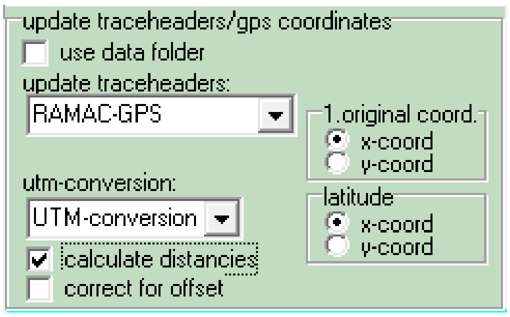
I.2.2 time based data

If the data are acquired based on a fixed time base, e.g. 100 traces every second, the correlation to the distance is not given. In this case equally spaced markers (e.g. every 2 m) may be used for a reinterpolation of the data. During the data acquisition these markers must be placed at distinct intervals. A subsequent data processing step rescales the data from the time base to equally spaced data.

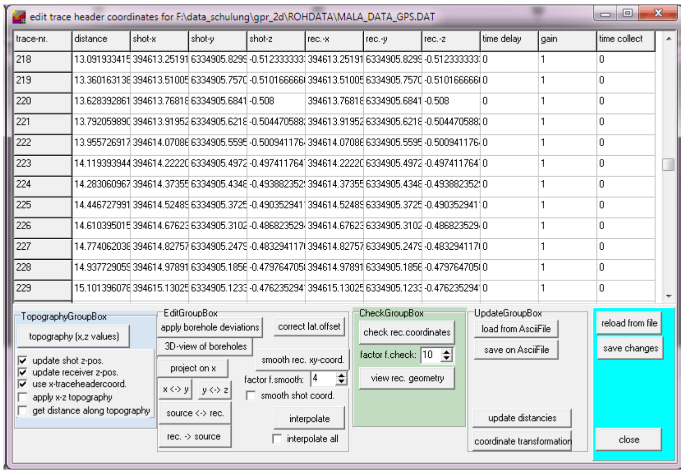


Within Reflexw this is done using the processing option **mark interpol** under processing/TraceInterpolation/Resorting. The option allows an interpolation of the data in X-direction on the basis of markers to be set manually or to be automatically extracted from the data (suboption ReadMarker). After having activated the option a table appears which allows the interactive input of the marker positions in traces (trace nr.) and the distance between successive markers (marker inc.). The program recalculates the number of traces between two set markers based on the wanted trace increment and the current set distance between the two markers (marker inc.) using the following formula: calculated tracenumbers = marker inc. / trace increment. The marker increment must be predefined within the filter parameter group and can be individually changed for each marker position within the table input. The traceincrement must be a multiple of each marker increment. The program determines the corresponding number of traces between all set markers after the selection and executes a recalculation of the traces between successive markers. If more traces within the original profile between successive markers are availabe, some traces are omitted. If less traces are availabe, some trace are added within each marker part until the wanted number of traces are reached (the traces are simply added and not interpolated between successive original traces as such an interpolation may significantly change the shape of the onsets). The data before the first marker and behind the last marker are ignored (exception if the option keep last traces is activated), i.e. the program assumes that the beginning and the end of the profile are always indicated by a marker. Please note that the data are modified by the interpolation. The trace with the last marker position is also included. Therefore the total number of traces is increased by 1.

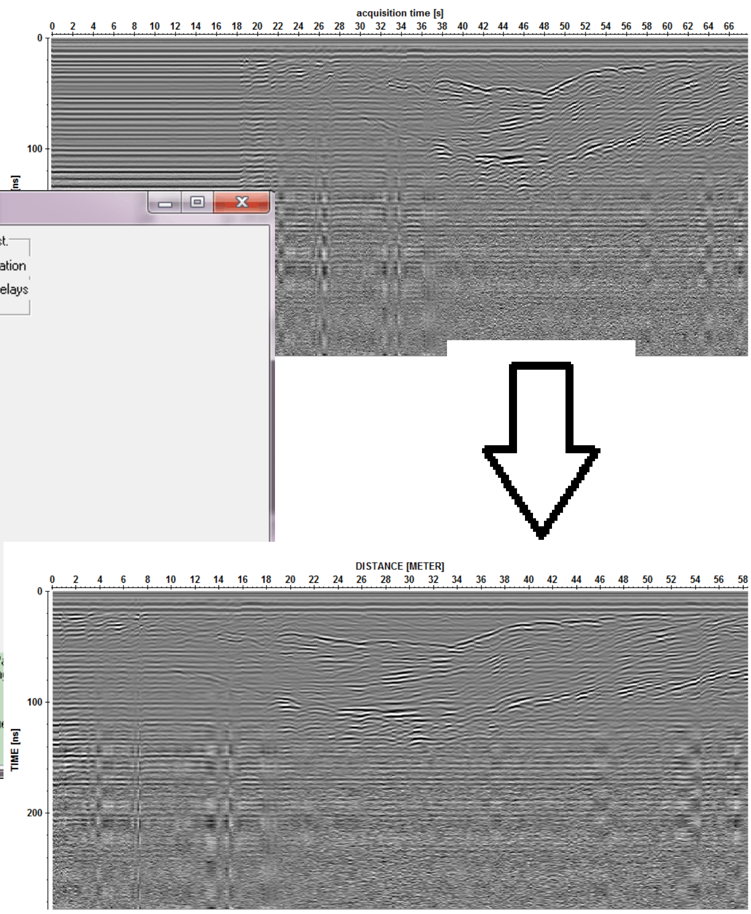
I.2.3 GPS based data

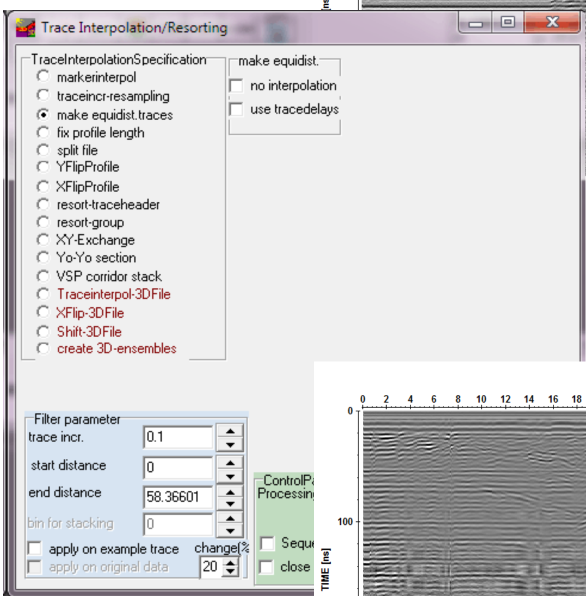


If GPS-data are simultaneously acquired it is possible to synchronize the GPR-data with the GPS-coordinates. The original GPR data may either be time based or based on a wheel. The different GPR-systems use different synchronization types. Mala, Utsi, IDS or PulseEkko generate a gps-file which contains both the tracenumber of the GPR-file and the GPS-coordinates. For most data acquisitions systems it is possible to automatically import the gps-data into the Reflexw file during the import and to perform a subsequent UTM-conversion. A linear interpolation will be automatically done where no GPS-data are present. The option calculate distancies sums up the distance along the gps-line and stores it into the Reflexw traceheader. The GPS-coordinates may be controlled and edited within the edit traceheader tabella.



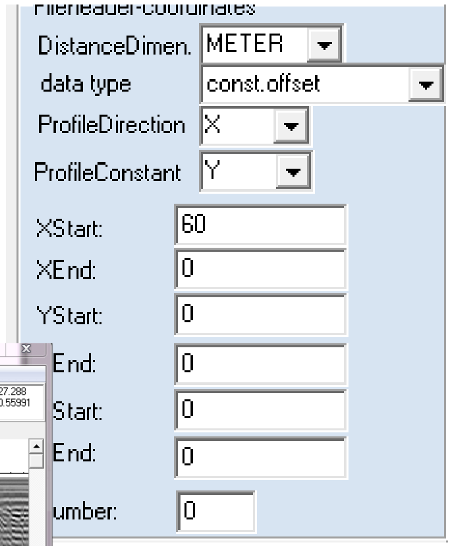
A subsequent processing step named **make equidist.traces** under processing/ TraceInterpolation/ Resorting allows to interpolate the non-equidistant data in such a way that the resulting data are equidistant. The non-equidistant data are resampled in x-direction based on the filter parameter trace incr. and the distance values stored in the individual trace headers of each trace. In addition the start distance and the end distance (starting and ending position of the new profile) have to be specified in the given distance dimension. By default the start distance and the end distance are determined from the traceheaders. By the manual input you may extract a distinct part from the profile.

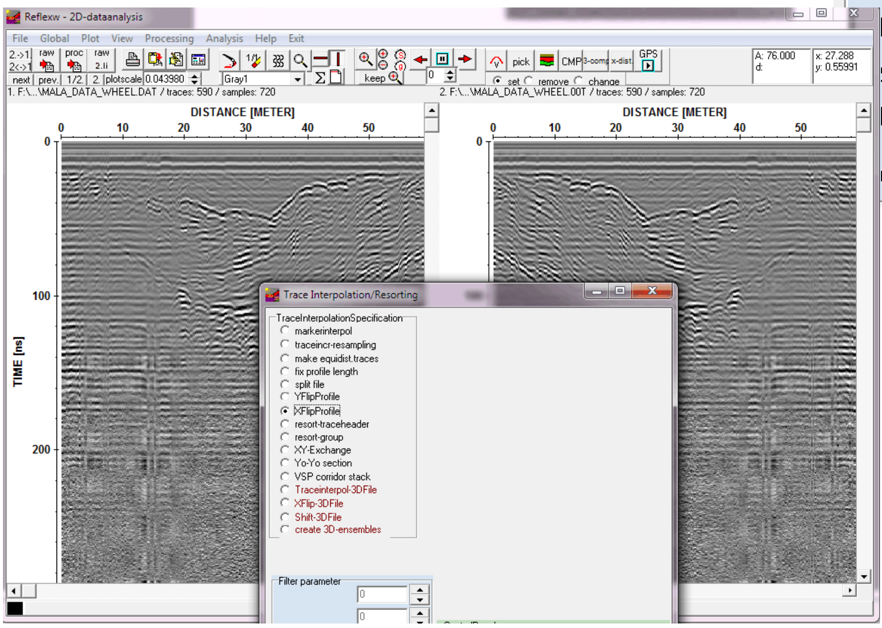




I.2.4 meandering data acquistion

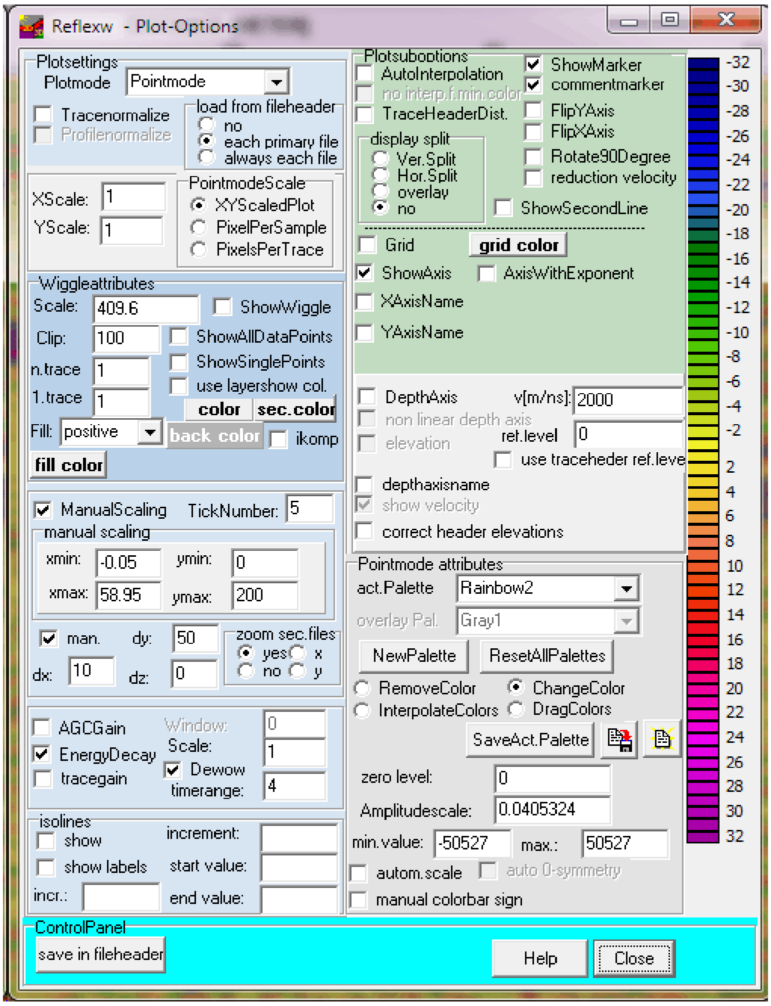
Reflexw only accepts positive trace increment. If the profiles have been acquired in different directions, e.g. using a meandering data acquisition, the corresponding profiles must be flipped in distance direction. This may be done directly during the import by entering a start coordinate which is larger than the endcoordinate in profile direction or using the processing option **XflipProfile** under processing/traceinterpolation.
If GPS-data are present the flipping must be done after the synchronization of the gps-data only as a processing step.





I.3 display the data

After having done the import the data are displayed using the standard plot options. You may change these plot options using the option Plot/Options. Activating this option the Plot Options menu appears (see figure on the right).

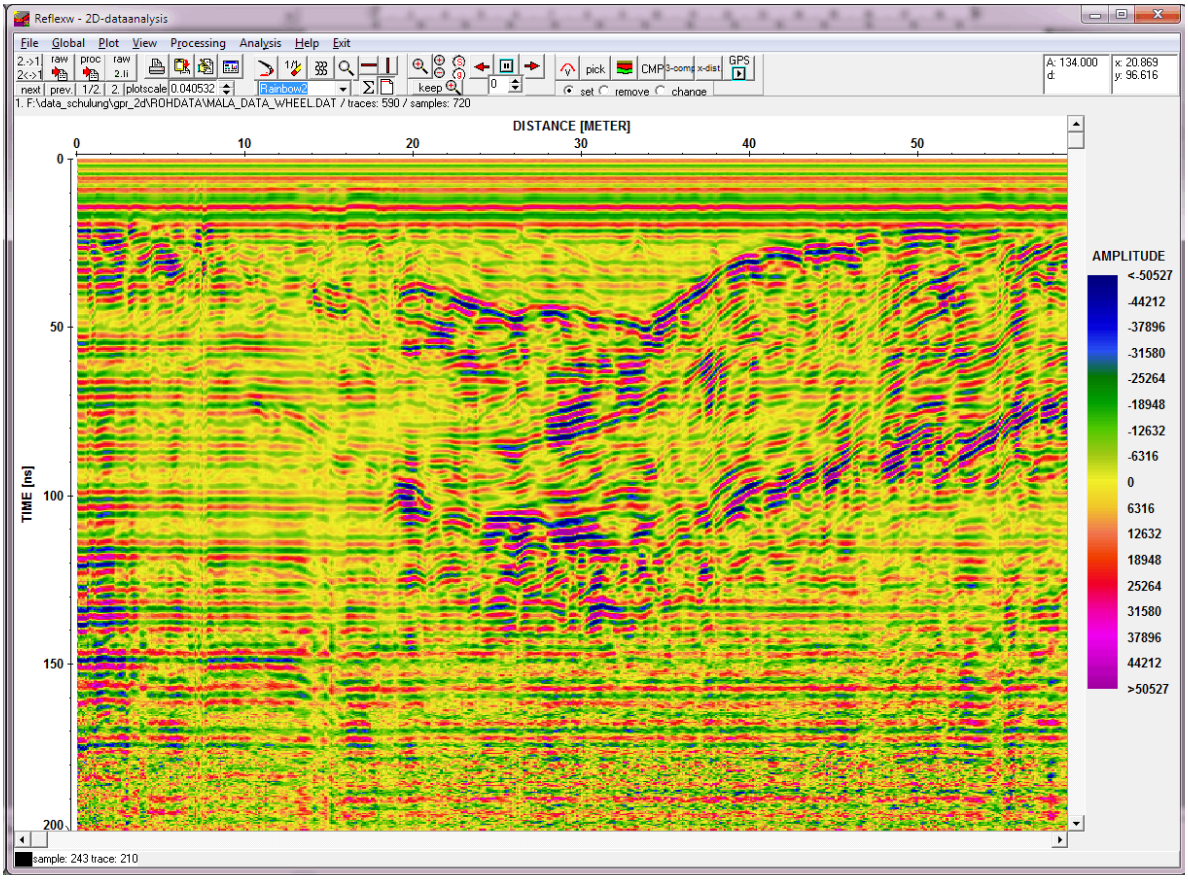


The main plot options for GPR-data are:

- Plotmode
- PointmodeScale
- EnergyDecay
- Dewow
- AmplitudeScale

Plotmode: by default use Pointmode for GPR-data.
PointmodeScale:
XYScaledPlot: the data are completely plotted into the actual window provided that the two scale options XScale and YScale are set to 1. The option may be used for small data (few traces) or if you want to display the complete dataset into the main menu (the Zoom-options are available - see also option Xscale and Yscale)). With no zooming and large datasets the display resolution is quite poor.
PixelPerSample: the plotting size of each data point is given in screen pixels. Zooming or rescaling is only possible in y-direction (option Yscale). The option might be useful for large data.
PixelsPerTrace: the distance between successive traces is given in screen pixels. The complete time series of each trace is plotted corresponding to the size of the actual window. No zooming possibilities are available. For example this option may be used for large data (many traces).
AmplitudeScale: this parameter controls the contrast of the data display.
Some filters may be applied during the display without going through a processing step:
EnergyDecay: most GPR-data are raw data without any gain in time-direction. Therfore activate this option if no gain-filter (see chap. II) has been applied on the GPR-data in order to compensate the energy decay with time.
Dewow: often GPR-data show a low-frequency content or DC-shift. With this option activated a running mean value is calculated for each value of each trace which is subtracted from the central point. Again use this option if no processing step like bandpassfiltering or dewow has been applied.

The following Figure show the data plotted using the options shown above.



To be considered: Normally GPR data must be filtered (see chap. II). The main filters are:
- static correction to compensate for the time delay of the first arrival.
- y(time)-gain
- dewow or bandpassfiltering
- clutter reduction (e.g. background removal)

II. Processing and filtering

The principal goal of data processing is to present an image which can be best possible interpreted. The main purposes of data processing are:

- increase the signal to noise ratio (e.g. stacking, bandpass filtering, averaging)
- remove system induced irregularities (e.g. background removal, static correction)
- correct geometrical effects due to the data acquisition (e.g. migration)

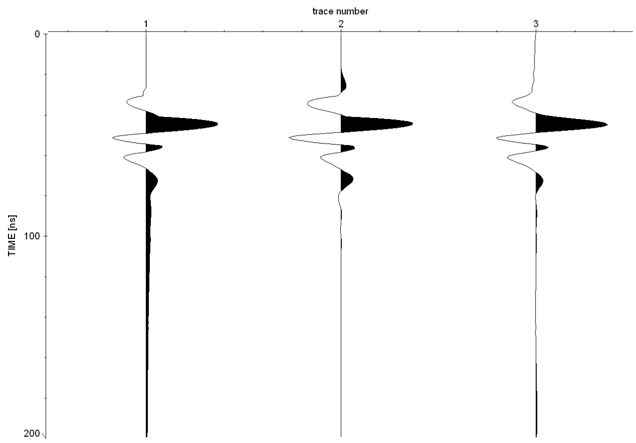
Data processing can be classified as following:

- A-scan processing - the filter acts on each trace independently
- B-scan processing - the filter will be applied on the complete B-(2D-)scan and involves all traces or a part of them. If a complete equidistant 3D dataset exists the processing may not be restricted to one direction but may include data acquired within the complete xy-plane.

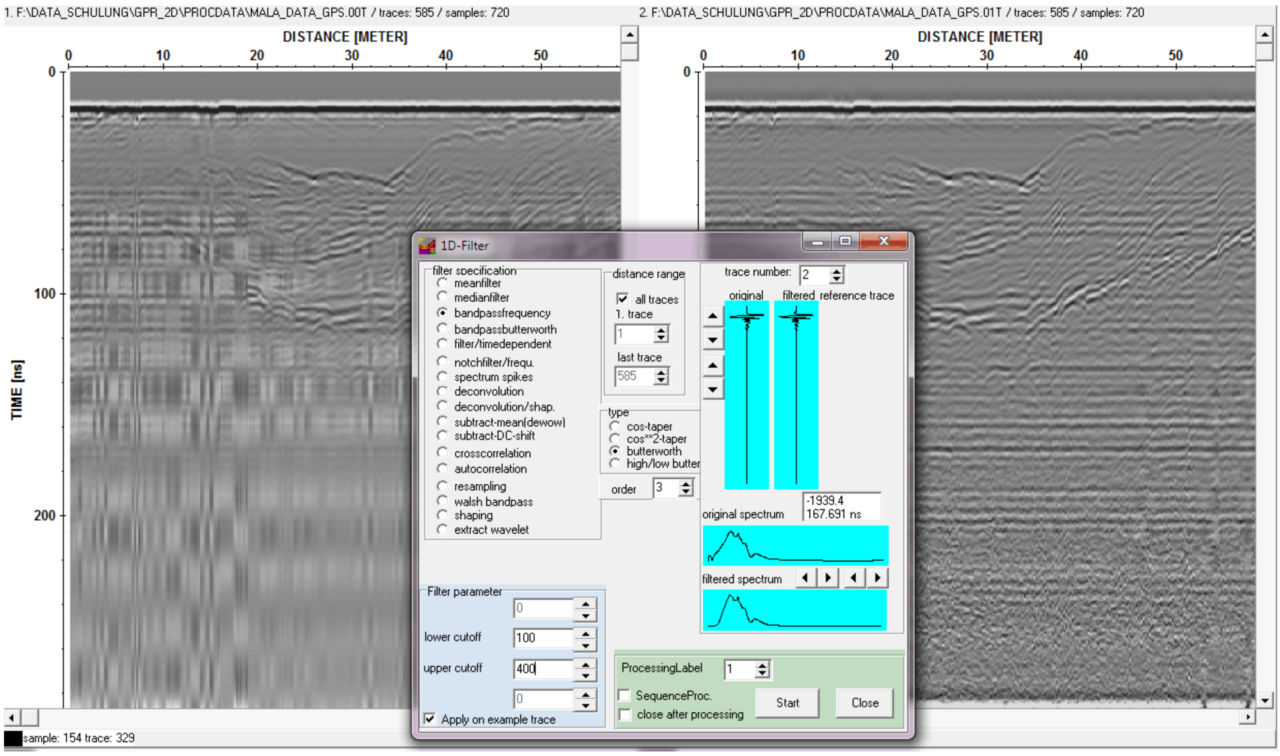
The mathematical background of the following standard data processing methods is quite straightforward. The main problems consist in the best possible adaptation of the methods to the type of data used and in the best possible use of the necessary parameters.

II.1. Dewowing and standard bandpass filtering

Many GPR data show a significantly very low frequency component either due to inductive phenomena or possible instrumentation restrictions. This low frequency range must be removed before applying any other digital filter algorithms. There exist many different ways.
A simple dewow filter acts within the time domain. A running mean value is calculated for each value of each trace. This running mean is subtracted from the central point. As filter parameter the time range for the calculation of the running mean value must be entered which should be set to about one or two principal periods. A possible static shift will also be removed using this filter.
Alternatives to the dewow filter may be a high pass bandpass filter working either within the frequency or time domain or a simple subtract DC-shift filter if only a constant value shall be removed.
The Figure shows an example of the dewowing process. The left trace shows the original data, the middle trace has been filtered using the dewow filter with a filter length of 25 ns and the right trace has been filtered using a bandpass filter working within the frequency domain with cutoff frequencies of 5 and 150 Mhz respectively and an adequate tapering window.

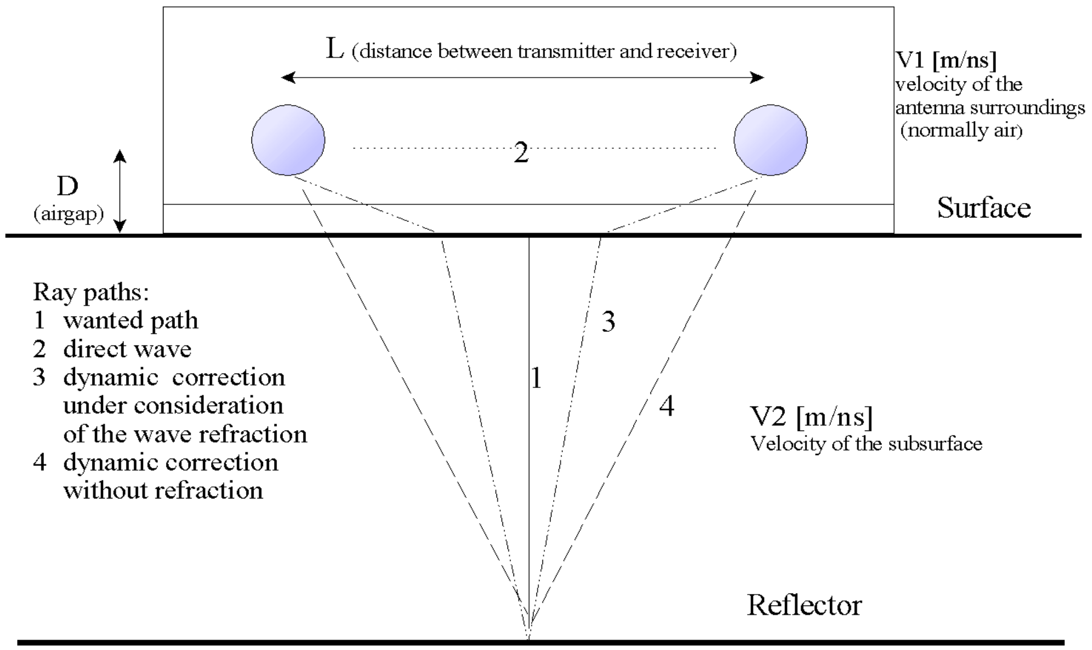


The bandpass filter does not affect the signal shape whereas the simple dewow filter slightly changes the signal due to its non symmetrical shape. Small precursors may occur (in some cases also when using the bandpassfilter) which must be neglected when applying the next processing step, the removal of the time base shift.
The bandpass filter may also be used in order to get rid of high frequency or monochromatic noise (see Figure below).



II.2 Time zero and time base shift correction

An exact definition of time zero is nearly impossible. It is not a constant value but depends on the surface material type and the antenna set up configuration (see Figure below).



geometry sketch of a standard transmitter receiver configuration and possible raypaths.

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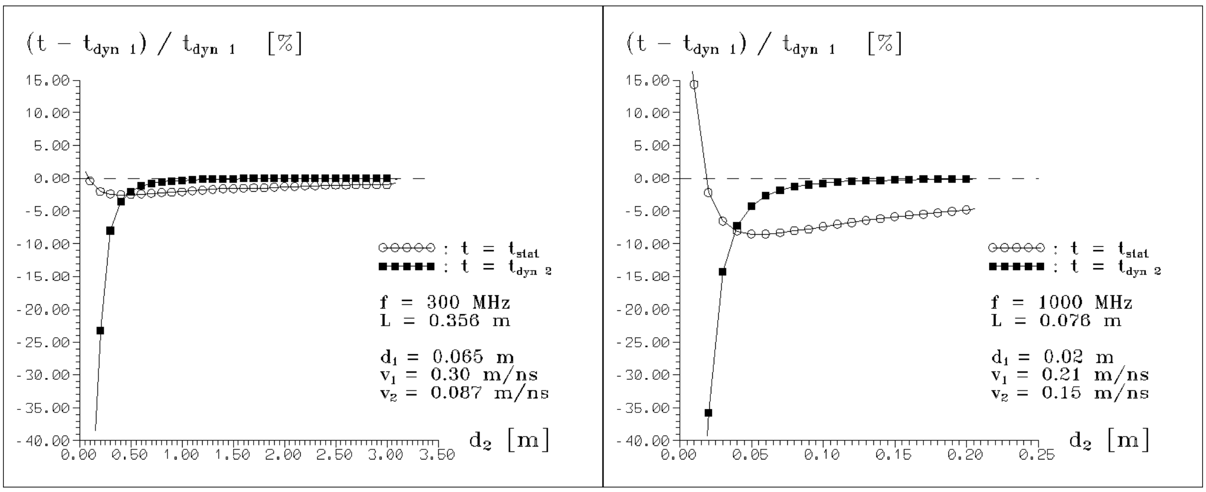
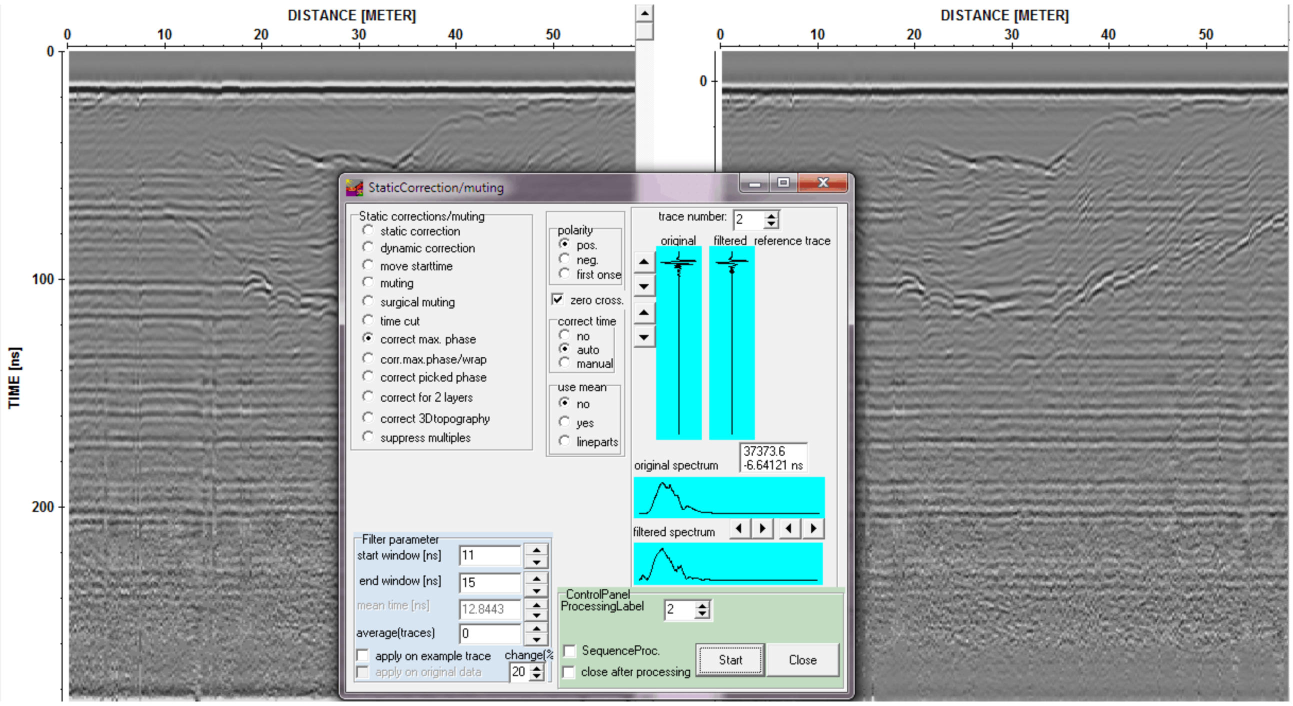
The following Figure shows a comparison between the simple correction to the first onset (circles within the Figure) and the dynamic correction (dots) under consideration of the source receiver distance and the velocity of the medium. The reference builds the dynamic correction based on the source receiver distance, the size of the air gap und the velocities of air and the medium therefore taking into account the refraction of the omitted waves. If the velocity contrast is sufficiently high (> 2:1, left panel) the error using the simple static correction is small enough in order to ensure a sufficient accuracy for the complete time range.

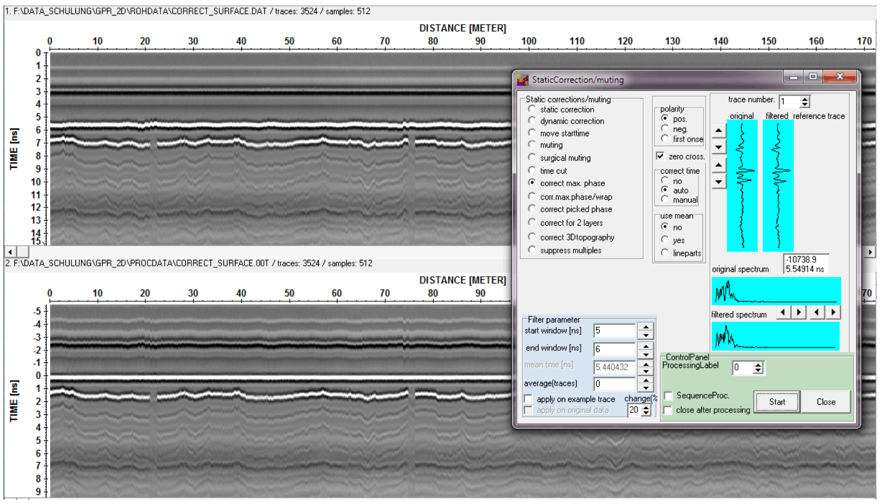


comparison of the errors for the time zero correction when using a static correction (open circles) and a dynamic correction (filled rectangles) for a high velocity (left panel) and a low velocity contrast (right panel)

An automatic and stable static correction may be done either on the first negative, first zero crossing or first positive peak. A correction to the first break position might be the best solution but may be unstable in time due to variations of the electromagnetic properties of the underground in the near-field of the antenna. An alternative may be the automatic correction to the first zero-crossing and then performing a static shift to positive times with a signal length of the first peak.
In any case the picking of the reflections or diffractions and the subsequent depth calculation must consider the chosen time zero method.
The time base of GPR measurements is also not exactly given and it may exhibit a significant drift due to a temperature difference between the instrument electronics (especially concerning the avalanche transistor effect) and the air temperature or damaged cables. Such a drift causes misalignment of the reflections. The following Figure shows the application of the **correct max.phase** filter under processing/satatic correction which automatically corrects to the first positive onset within a distinct time window, makes a correction to the zero crossing and then corrects the time zero to that zero crossing.



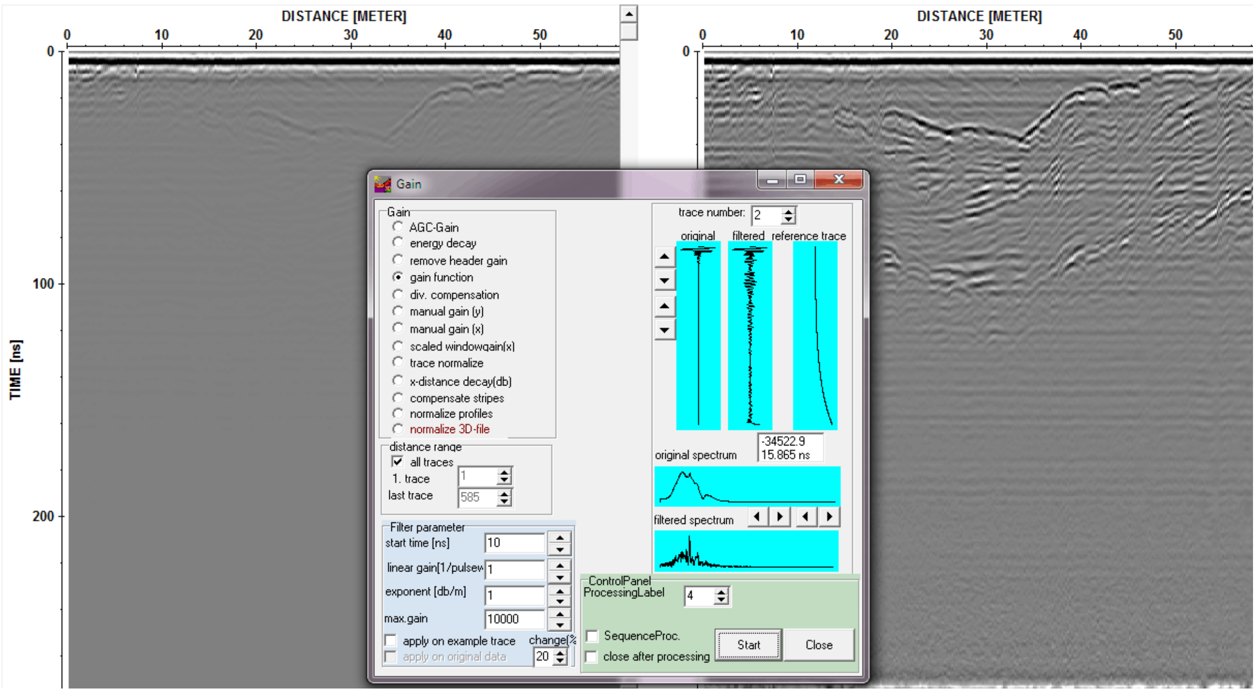
The subsequent filter **move starttime** may be used in order to remove all data in front of the time zero.
Another cause of such a drift may be the use of an air coupled antenna with a distinct distance from the surface, e.g. a horn antenna. This distance may vary during the data acquisition. The figure shows an example of such a horn antenna acquisition (top raw data, bottom time base corrected data). The filter correct max. phase with an automatic correction of the time zero position has been used for this purpose.



A well-corrected time base is also very important for the interpretation of a 3D-dataset especially when looking at the timeslices (C-scans) as different time bases may significantly destroy the coherent character of the reflecting elements..

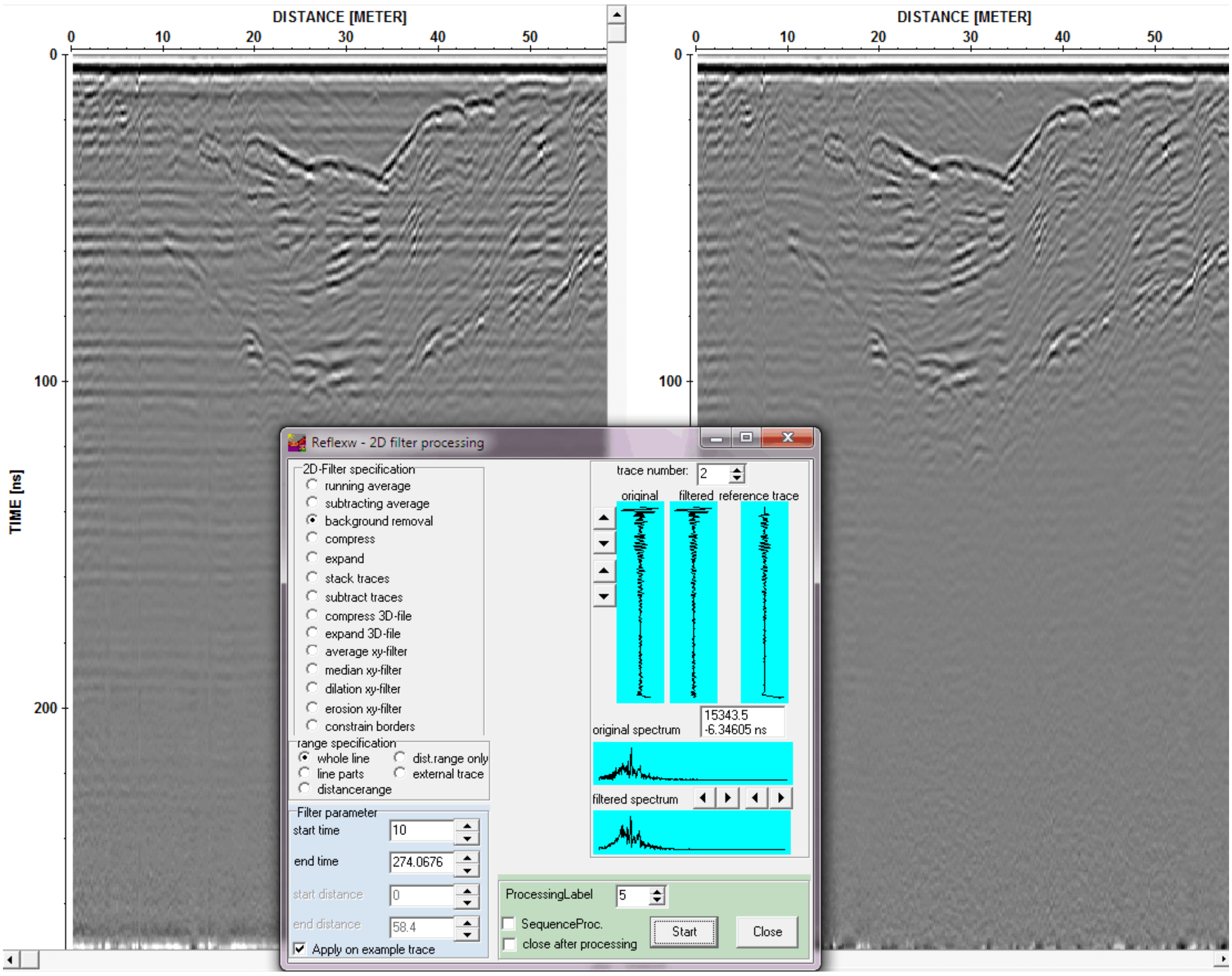
II.3 Time varying gain

The waves will loose significant energy during travelling through the subsurface due to spherical divergence and intrinsic and scattering attenuation. Therefore, these energy losses have to be compensated. Several conditions have to be kept: The time series must have a zero mean value, otherwise a significant DC offset especially at later times may occur. In addition the noise level at greater times should be as small as possible.
It is possible to enter a manual gain value or to use a continuous gain function (see Figure below).
When manual gain values will be applied, rapid changes of the gain values should be avoided because these may introduce unwanted artificial wavelets.
It is strongly recommended to use the same gain function for all profiles which shall be interpreted together. This also holds true for 3D-data especially when looking at timeslices.



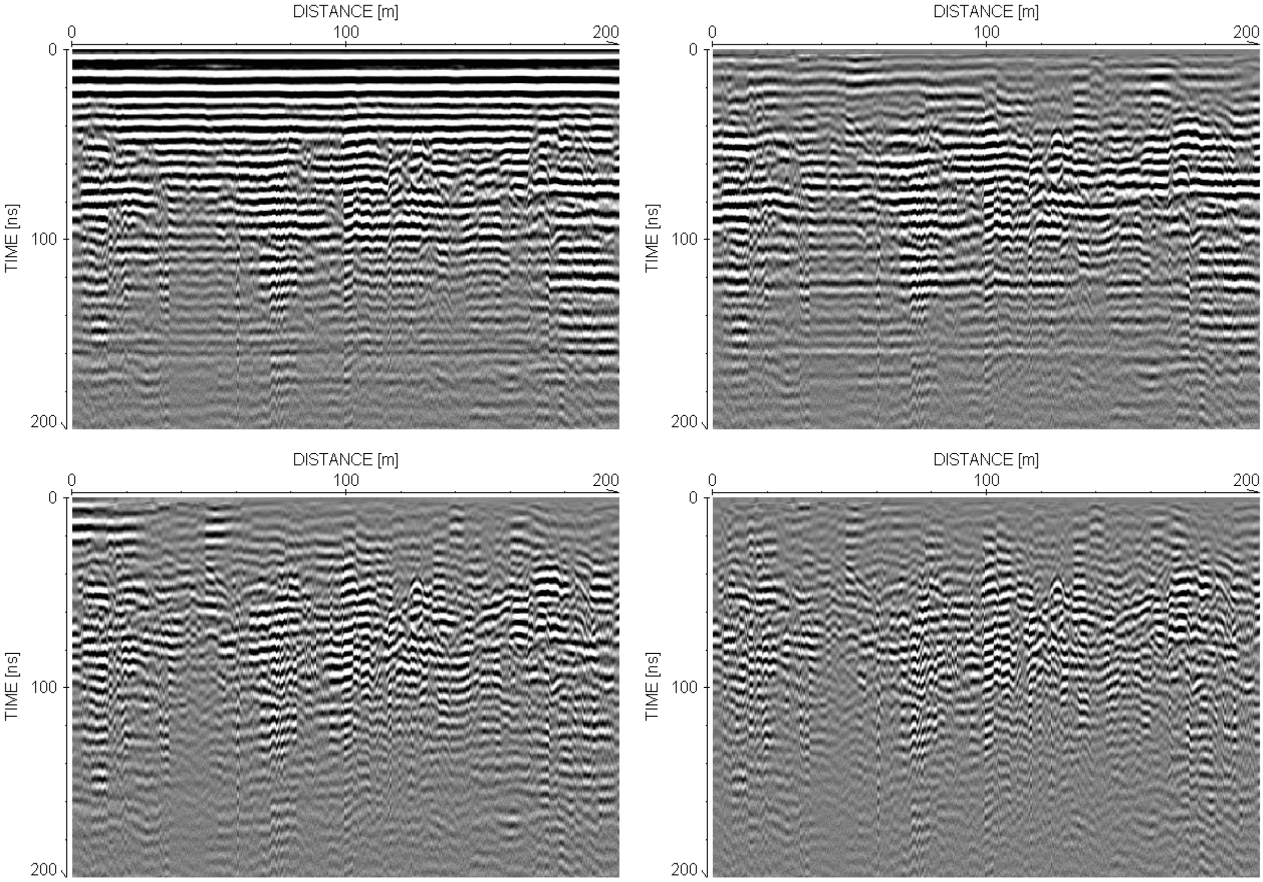
II.4 Clutter reduction, background removal

GPR data are often contaminated by clutter. The clutter mainly consists of the GPR system noise, ground bounce, soil roughness scattering and reflection signals from external anomalies. The clutter mostly appears as nearly horizontal and periodic ringing.
Clutter reduction is therefore one of the most important challenges as especially deeper or weak events are often completely masked by this clutter.
The GPR system based coherent noise ringing can be easily eliminated using a simple background removal (subtraction of an average trace) filter as the statistical properties of the clutter have only weak variations along the distance axis (see following Figure).



The situation is much more complicated if the statistical properties of the clutter vary along the distance axis due to different ground coupling and/or due to subsurface scattering. In this case more sophisticated methods must be used. Two-dimensional filters like fk-filter or Radon transform, predictive and deterministic deconvolution or eigenimage processing techniques are the most used ones. For all these methods the definition of the filter parameters must be adapted at the individual situation in order to keep horizontal events but to guarantee a high performance of ringing elimination. Especially deconvolution and eigenimage processing require careful setting of the entered parameters. A good compromise between easy use and performance may often be given by the fk-filter or the subtracting mean in combination with a notch filter if the noise exhibits monochromatic characteristics.
The following Figure shows the comparison of the raw data which include both system induced coherent clutter and incoherent ringing due to the subsurface conditions. The background removal fails in the elimination of the incoherent clutter but both the fk-filter and the subtracting mean within a moving trace interval seem to be a sufficient approach. In addition the background removal

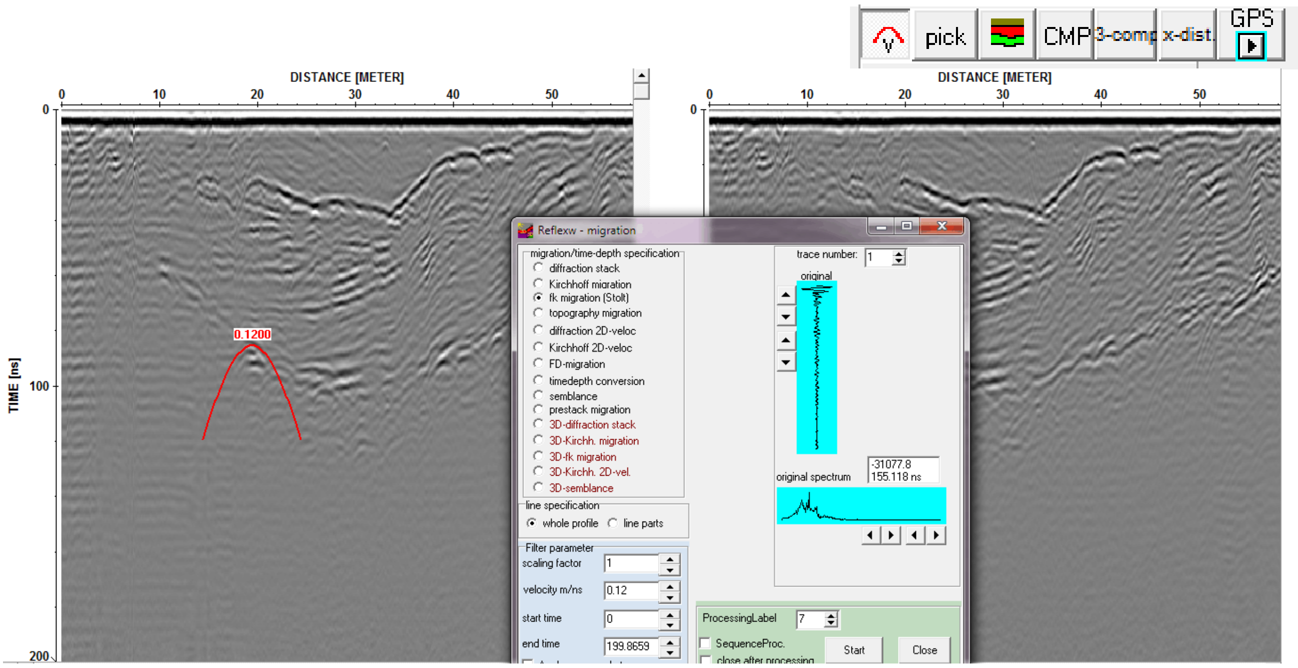
filter introduces some artefacts resulting from stronger ringing within some ranges, e.g. between 160 m and 200 m, which has been smoothed over the complete distance range.



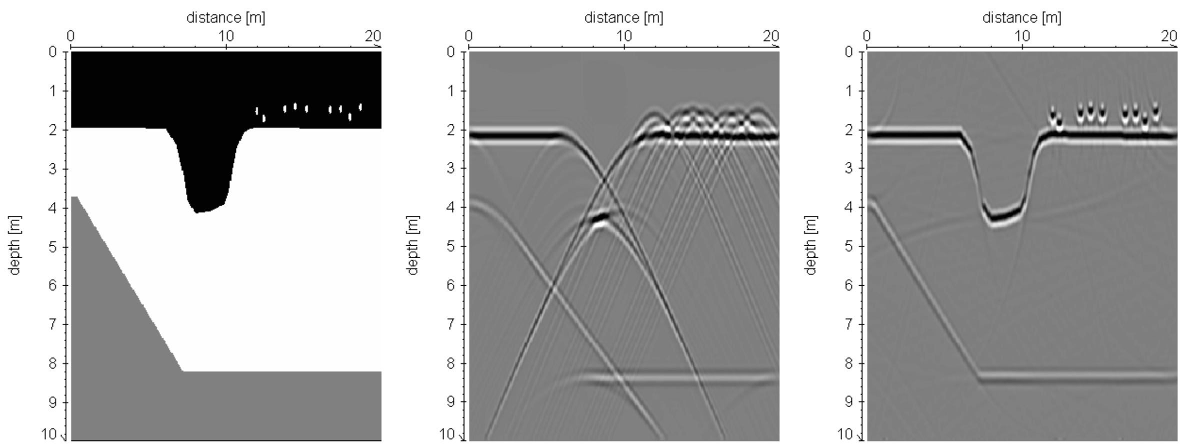
comparison of different methods for incoherent clutter reduction. The upper left panel shows the original data, the upper right panel the background removal filtered, the lower left panel the application of the fk-filter and the lower right panel the use of the subtracting average filter.

II.5 Migration

The waves coming to the receiver will be acquired vertically along the acquisition line and therefore do not represent the correct positions of small scale diffractors or sloped reflectors. The goal of the migration is the downward continuation of the acquired wavefield to their origin. The base for this wavefield continuation is a given depth velocity model. During the migration process diffractions will be concentrated and dipped layers will be moved to their correct place. The precondition for the migration is a good knowledge of the underground velocity field. The velocities may be easily examined using the interactive velocity adapation within Reflexw.



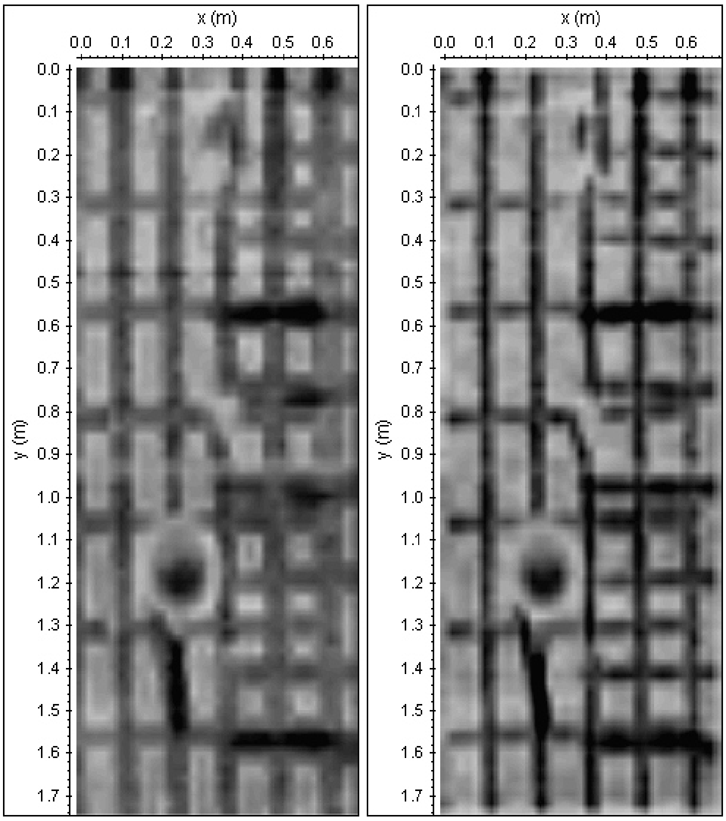
Standard migration is done for 2D-data. Fast algorithms exist for a constant velocity field (e.g. **fk-migration** - see Figure above) but also the more sophisticated methods like the Finite Difference approximation of the one way equation can be applied on standard PC's with reasonable computer time consumption. These methods also allow a 2D-velocity distribution (see also chap. II.7 - time-depth conversion). The following Figure shows a synthetic example (FDTD method) including diffractions and steep reflections. The model shown within the left panel serves as the base for a forward simulation of a ZO-section (middle panel). The small elements within the first layer produce diffractions which interfere each other that does not allow the individual identification. The trough at about 10 m is characterized within the ZO section by two diffractions and a reflection from the bottom. It is evident that only after migration (right panel) the structure elements have been



ZO simulation (middle panel) for a model including small diffractors and steep reflectors (left panel). The right panel shows the migrated ZO section.

shifted to their real location and the diffractions have been concentrated so that they can be distinguished from each other.

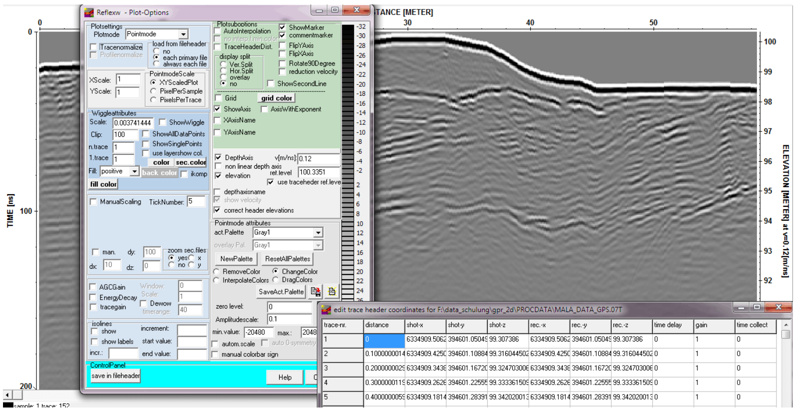
Migration is most useful if timeslices (C-Scans) will be produced for the subsequent interpretation. The Figure on the right shows both the raw data (left panel) and the migrated data (right panel). Again the strong energy concentration within the migrated data is evident which leads to a much better discriminability of the individual elements.



A 3D-migration is useful for a coarse 3D-datagrid with equal spacing in x- and y-direction. Due to the large computer time for a complete 3D-migration methods with a constant migration velocity (e.g. Kirchhoff migration) will be used by default.

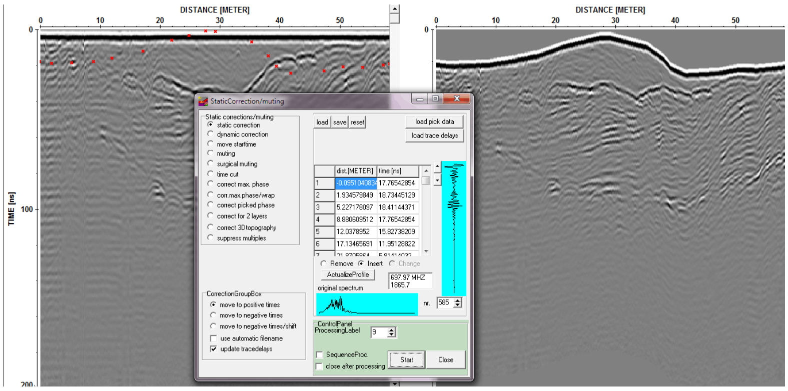
II.6 topographic correction

The GPR-profile normally exhibits the same start time for all traces. Therefore it does not reproduce the surface topography. As a consequence reflections which are more or less flat in reality may exhibit significant curvatures due to the surface topography and the concomitant varying layer thickness above.

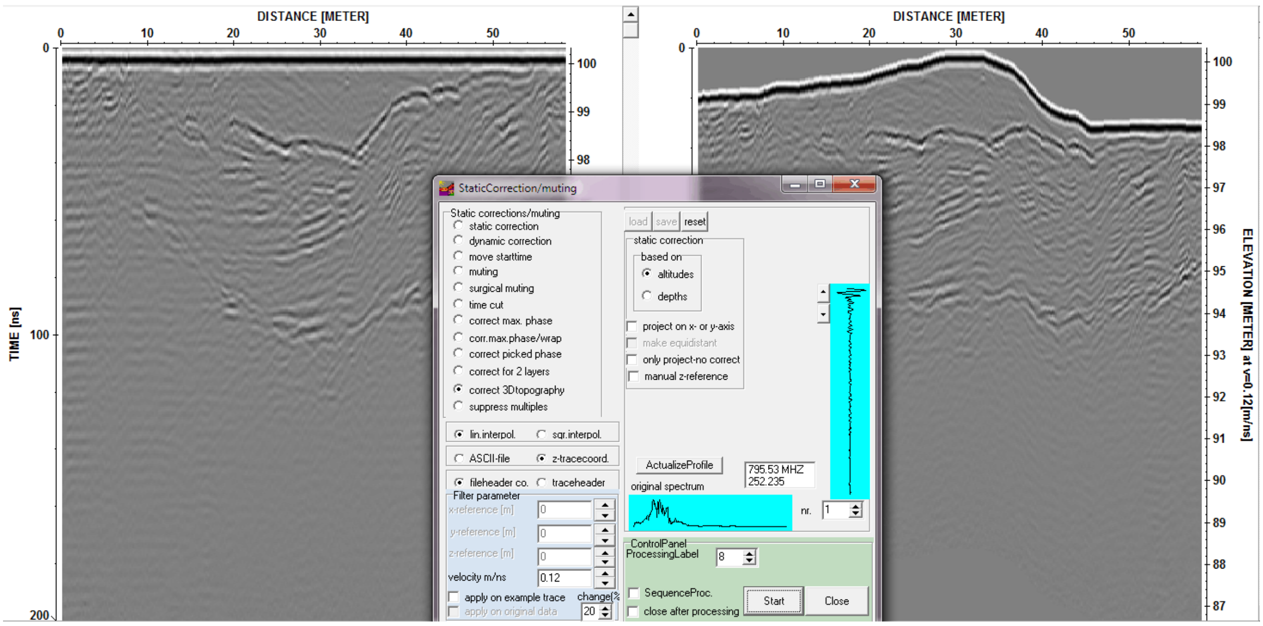


If the topographic values have been stored within the traceheaders (e.g. when a GPS-system has been used) the plotoption **correct header elevations** may be used in order to display the data including the topography (see Figure right).

There are different other possibilities to perform a topographic correction within Reflexw. Al these methods may be found under processing/static correction/muting and they act as a filter (the data will be changed - filled up with zeroes above the topography). The easiest ways is the option **static correction** with the suboption move to positive times. The topographic values may be entered interactively by mouse or within the table (two-way traveltime values).

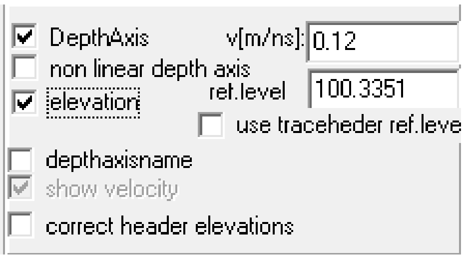


Another possibility is the option **correct 3D-topography**. The elevation or depth values may have been stored within the Reflexw traceheaders (see above) or may be read from an ASCII-file. Different coordinate systems may be used for storing the topographic values.



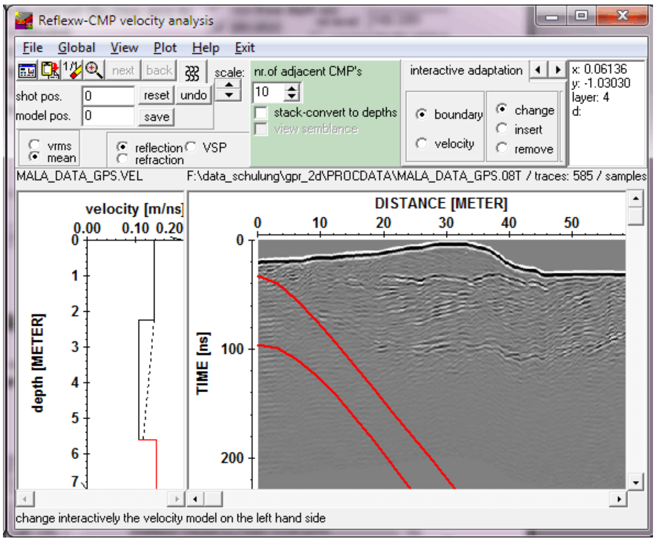
II.7 time depth conversion

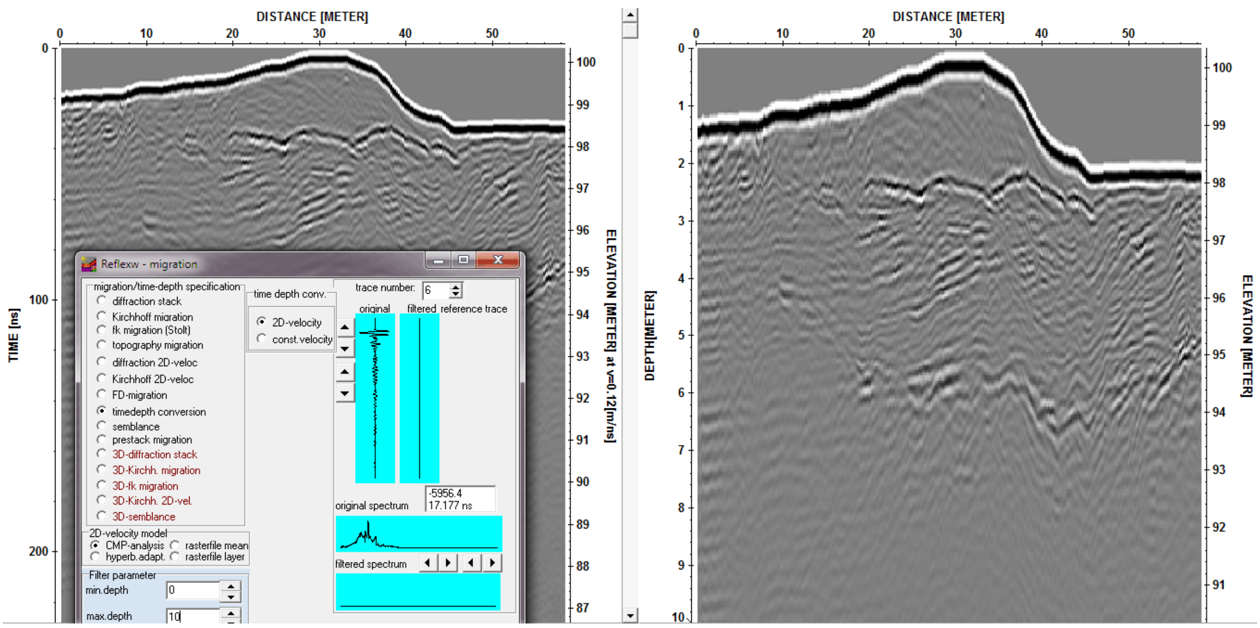
The GPR-profile respresents a two-way traveltime section. All processing steps are normally based on this scale (even the correct topography option). In order to convert the time axis to a depth axis a velocity distribution is needed.



Reflexw allows to view a depth or elevation axis at the right hand side in addition (plotoption **DepthAxis** activated) based on a constant velocity or based on 1D-velocity distribution (option non linear depth axis activated - only variations of the velocity with depth allowed).
A more sophisticated possitility is given as a filter processing step **timedepth conversion** under processing/migration/time-depth conversion. There are several possibilities to get information about the velocities:
- from the curvature of existing diffractions within normal zero offset profiles
- from CMP measurements if a layered medium is given
- from borehole measurement and subsequent comparison of these information within the zero offset data
- from the literature if the material of the underground is known

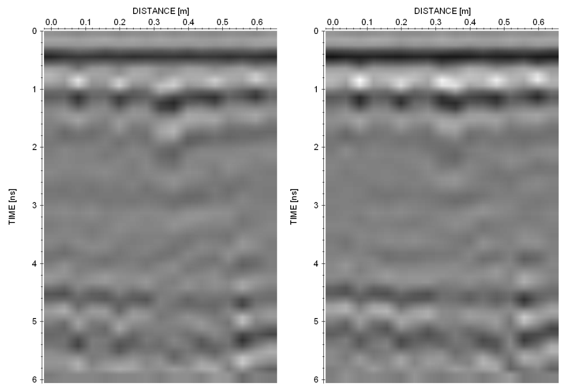
The easiest way is the use of a constant velocity. This does not affect the shape of the signals within the radargram. If using a time varying or even time-distance varying velocity distribution for the time-depth conversion the signal shape may be changed quite strongly. This must be considered for the subsequent interpretation.
For most cases, especailly if a layered model shall be the base for the time depth conversion the **CMP-analysis** might be the right choice even if no CMP-meausrements are present. On the right side a 1D-velocity model has been created based on different informations like diffractions and cores. This velocity model may be used in order to generate a time-depth converted section (see Figure below).

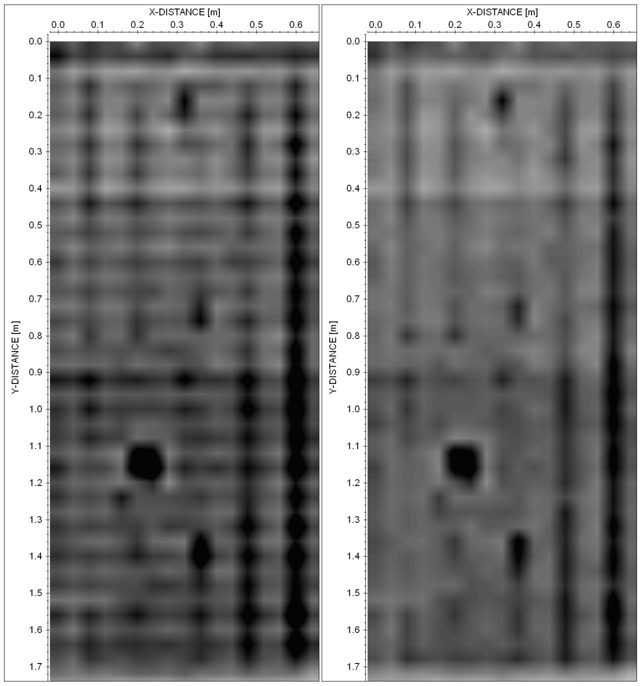




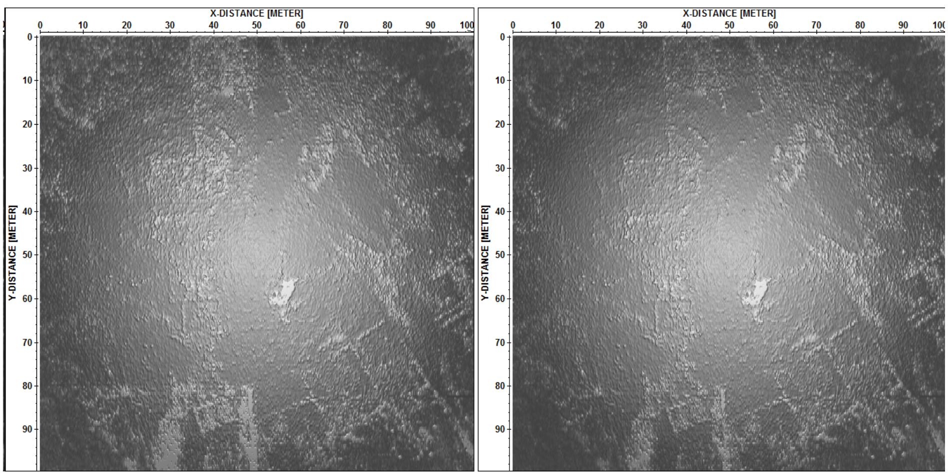
II.8 profile energy balancing

A great problem is the often non-uniform energy feeding-in along a 2D-profile or for different 2D-profiles which shall be interpreted together (e.g. creating time slices). The causes may be varying ground conditions, equipment changes, use of multi antenna systems or differences in the field acquisition. Whereas variations along the profile caused mainly by different coupling conditions can be quite easily compensated using a trace normalization or a gain function in profile direction, more sophisticated methods must be used when dealing with 3D-data especially when the interpretation is based on time slices.





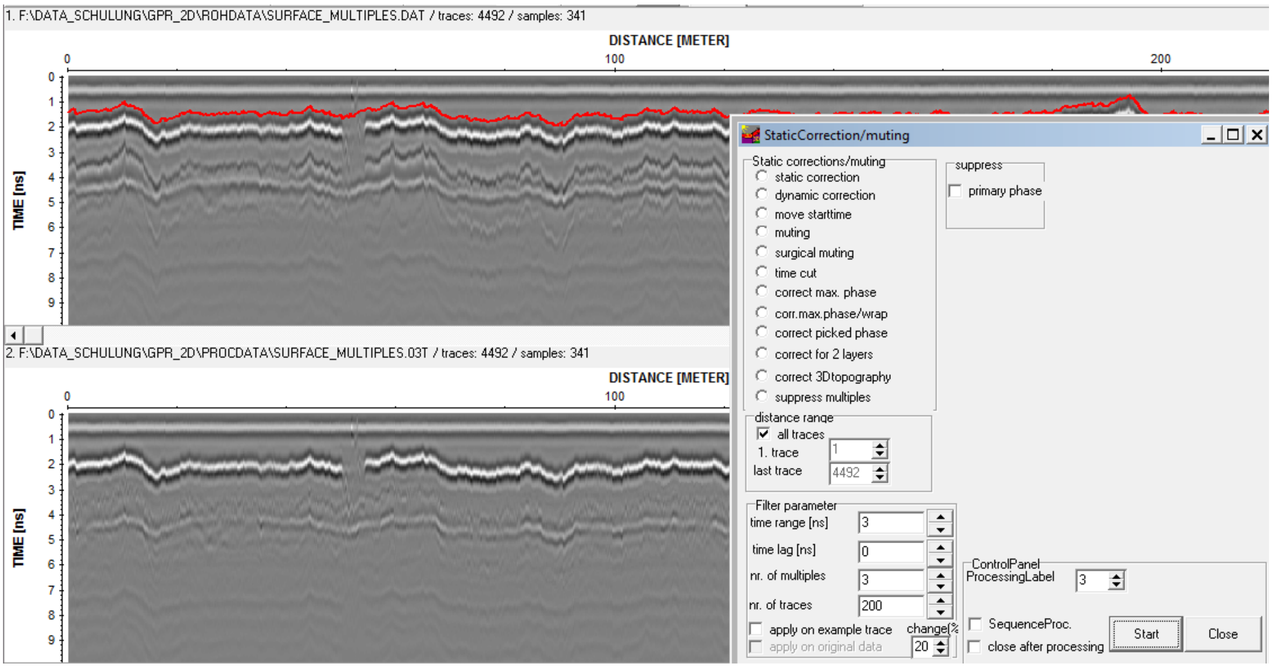
The Figures above show an example of a multi-grid survey using a 2-antenna system with different energy characteristics. The left panel shows 2 parallel 2D-raw profiles (0.05 m increment) indicating the different energy content. The right panel shows two time slices. The left time slice is based on the raw data, for the right time slice an energy compensation has been applied at first. The horizontal stripes on the left time slice are due to the different energy characteristics of the used 2 antennas. They may lead to misinterpretation. The right Figure was acquired with only one antenna but at different conditions. Therefore some areas show different energy distributions (left panel). A careful normalization allows an uniform picture (right panel).



Depending on the used equipment and the existing ground conditions often not only a uniform factor but a time varying curve must be determined for the compensation of the different energy feeding-in. This may lead to an amplitude decrease of reflections which are only present in some profiles (e.g. pipes which are orientated parallel to the acquired profiles). Therefore, such a compensation must be used very accurately.

II.9 suppress multiples

Sometimes surface multiples may occur if a near surface reflector is present with a strong velocity contrast. Possible deeper reflection may be hidden by these multiples. The option suppress multiples under processing/static correction allows to suppress those multiple reflections from the surface. For that purpose the first reflection must be picked (preferably shifted to the very first onset). The picks must be saved under the same filename as the current profile filename.
If using the processing option suppress multiples multiple reflection are first flattened based on the picked primary reflection and then the subtracting average filter is applied within a choosable time range around the flattened multiple.

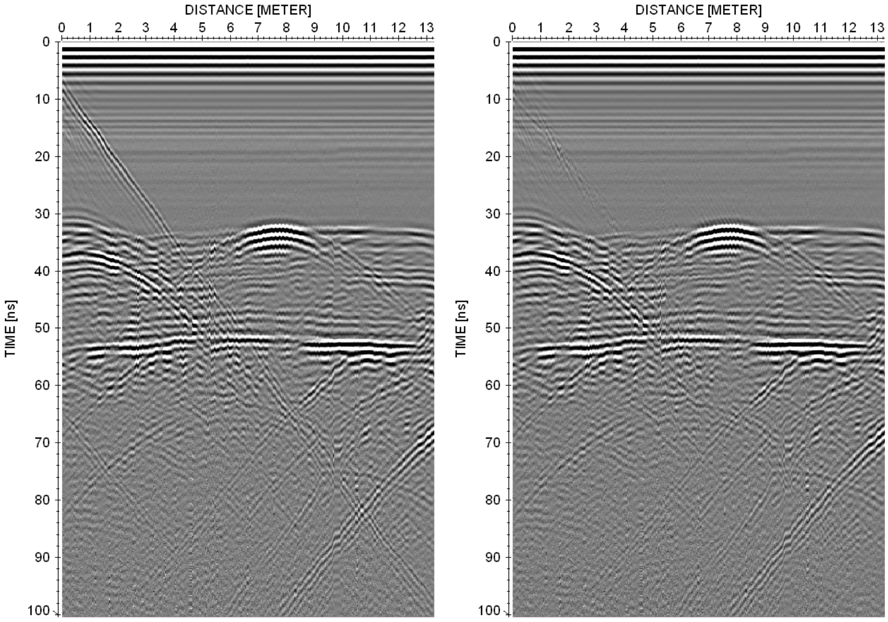


II.10 F-K filter

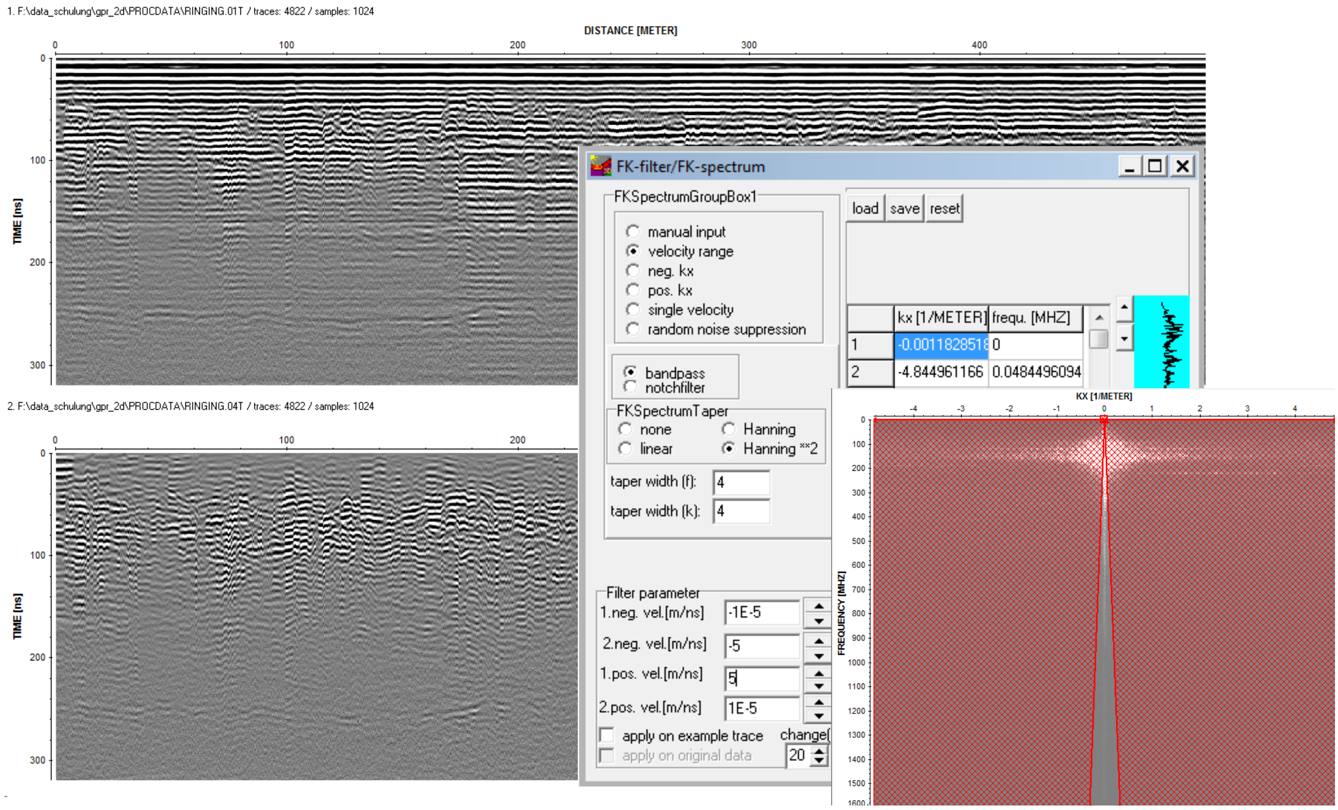
Unwanted reflections from the borders of the investigation medium are often characterized by a distinct slope which corresponds to medium or air velocity. Those structures can be easily removed using a multichannel filter.

The most popular filter is the so-called **frequency-wavenumber (F-K) filter** which works within the frequency wavenumber range.

The Figure on the right shows the raw data (left panel) including a distinct side reflection and the filtered data (right panel). It must be kept in mind that other elements showing the same slope will also be removed using such a filter. In most cases tapering must be used in order to avoid artefacts.

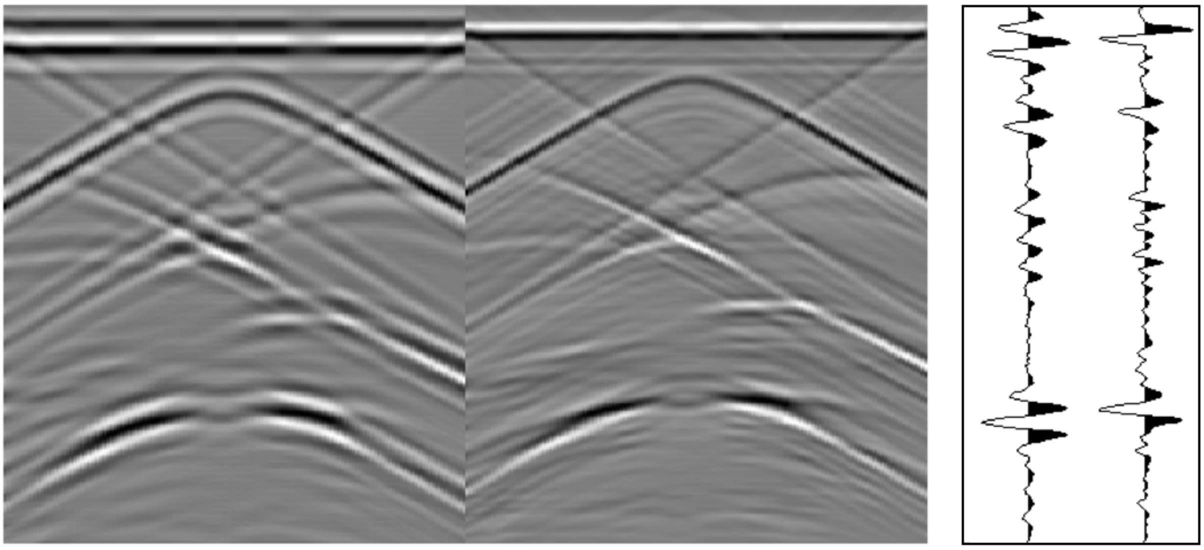


Another application of the fk-filter is the removal of horizontal stripes, e.g. due to a ringing (see also chap. II.4). The definition of a velocity range to be removed or kept allows the elimation of structures characterized by these distinct slopes (corresponding to velocities within time-distance range). The horizontal stripes for example are located arount small kx values within the kx-range corresponding to very high velocities. The Figure below shows the raw data (top panel) and the fk-filtered data (lower panel) based on the filter parameters defined within the fk-filter menu. The resulting filtered fk-range is displayed on the right. The clutter is quite well reduced.



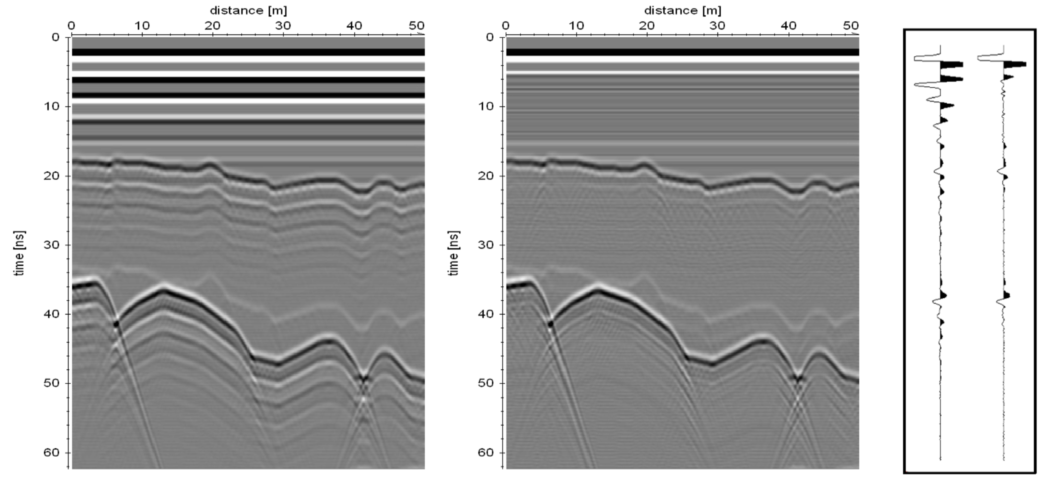
II.11 deconvolution

A major problem in signal interpretation is the lack of resolution of overlapping events due to the reverberation character of the signal. The main purpose of the deconvolution is to invert the convolution process of the medium impulse response and the outgoing signal. The ideal outcome of the filter is again the medium impulse response. Although this ideal cannot be usually achieved, many different methods have been developed for different preconditions. One filter is named Wiener filter which minimizes the differences between output and desired result. Other methods work as direct inverse filter. In general deconvolution techniques are not very well suited for GPR applications as the main preconditions like minimal phase, lag time zeros are normally not satisfied. In many cases predictive deconvolution techniques or wavelet shaping may lead to better result. A suitable filter strongly depends on the characteristics of the signal.
The following Figure shows an application of a wave shaping filter. The wave shaping filter allows to convert the characteristic waveform of the profile to a new desired one. It is obvious that after the shaping filter all signals exhibit a much clearer and sharper form leading to a better resolution in time direction. The precondition is that a characteristic waveform ca be found which fits over the complete time-distance range. Due to different coupling conditions and waveform changes during the propagation this precondition is quite rarely satisfied. The spiking filter is a special case of this filter which is designed to compress as much as possible the original wavelet into a spike (uniform frequency distribution).



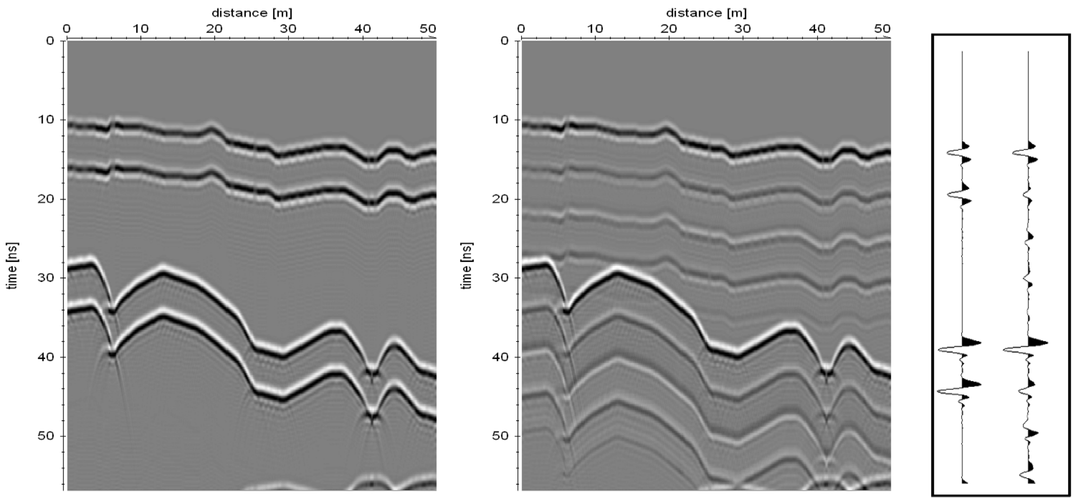
application of a wavelet shaping filter (left panel raw data, besides the filtered data, right panel: one trace of the two datasets respectively).

The main goal of the predictive deconvolution is the suppression of multiples. The desired output is a time advanced version of the input signal. To suppress multiples one has to choose a lag corresponding to the two-way-traveltime of the multiple.
In the following synthetic radargrams have been created using a forward Finite Difference Time Domain method (FDTD method) in order to examine the effectiveness of a predictive deconvolution method for multiple and ghost removal.
The following Figure (left panel) shows an example with strong multiples coming from a very near surface interface with very high velocity contrast. The used predictive deconvolution yields quite good results (middle panel). The reverberating character of the signal could be reduced to a sharp signal with only two maxima both for the primary onset and the reflections and therefore the distinguishability has been significantly improved.



application of the predictive deconvolution (middle panel) on a synthetic radargram with strong multiples (left panel). The right panel shows one trace of these datasets respectively.

Some further investigations had been done introducing a ghost by bringing in a strong reflector above the receiver line. The amplitudes of the ghost had been varied. Whereas the weak ghost can be quite well eliminated using the predictive deconvolution, no good results have been achieved for a ghost with amplitudes similar to those of the primary onset (see Figure below). After having applied the predictive deconvolution the ghost is still visible although with smaller amplitudes (middle panel). In addition the deconvolution process produces multiples.



application of the predictive deconvolution (middle panel) on a synthetic radargram with strong ghosts (left panel). The right panel shows one trace of these datasets respectively

In summary it can be said, therefore, that the predictive deconvolution method used for this investigation was able to reduce multiples and weak ghosts. The signals presented within the synthetitic seismograms are minimal phase. The effectiveness of the deconvolution will be lower if this does not hold true or if reverberations are present in addition. Therefore, in reality the results of the predivitive deconvolution may be significantly poorer.

In any case the methods always need an intensive adaptation of the filter parameters and a manual check for possible artefacts.