GPR data processing and visualization with GPR-O

Alain Plattner (plattner@alumni.ethz.ch)
Austin Robbins (austin.r.robbins@gmail.com)

June 29, 2017

Contents

1 General remarks

You can download Octave for free from `https://www.gnu.org/software/octave/`

If you already possess Octave, we recommend updating to the current version, to avoid potential issues with package installation.

In the following, whenever we say "run xxxx" we mean in Octave or Matlab, type xxxx and press enter.

Whenever you use an Octave (or Matlab) program for the first time, for example by the name xyz, run

```
help xyz
```

This will display the required input(s) and show the output(s) of that program or function. In general, well-documented programs will also provide a description of what the function does.

For all GPR-O programs to run, your current directory (shown at the top of your Octave or Matlab program window) must be the GPR-O folder. If you are an advanced user, you can add all the subfolders to your Octave or Matlab path.

In the command window you can recall previously entered commands by pressing the up and down keys and you can let the computer suggest completions of commands with the tab key.

2 GPR-O installation

If you have yet to install GPR-O (you downloaded the documentation only), follow the installation instructions here

`https://github.com/NSGeophysics/GPR-O`

Once you have downloaded the GPR-O program files and folders, run, in Octave or Matlab (in the GPR-O folder)

```
setup
```

This will download some external program files that are necessary to run GPR-O.

Keep your software and this documentation updated by regularly running, in a command prompt/terminal in the folder GPR-O

```
git pull origin master
```

3 Data structure and data preparation

To use GPR-O, switch to the GPR-O folder on your computer. This folder contains a few subfolders and a few m-files. Each m-file is a computer program that was written for Octave (or Matlab; they are, for our programs here, interchangeable).

If you are using Matlab, to access to all the subprograms you need to run

```
initialize
```

If you are using Octave, run

```
initialize_octave
```

The first time you run this initialization, it will check if all required Octave packages are already installed and if not, will automatically install them. This may take a few minutes. Next time you run it, it will not need to install the packages anymore.

We will use a variety of programs that are stored in the subfolders. Whenever you want to know what a program does and what variables you need to give it, run "help programname". For example, we have a program that is named "`readdata`". To find out how to use it, run

```
help readdata
```

Octave will show you a text saying from where the function is stored, what input it requires, and what output it gives.

For the required input, the help page says:

`surveyparams` A struct with the following fields:

- `minline` Lowest line number
- `nmorelines` Would be 3 if you had 4 parallel line with the numbers 0 1 2 3
- `lineincr` The distance between the lines (in meters)
- `pnameraw` String containing the directory of the raw files dt1
- `pnametrf` String containing the directory for the processed files

This variable named `surveyparams` will play a key role in GPR-O. For each survey you will need to set it up. This is easily done by writing your own m-file as described in the following.

Double-click on "`Example1.m`" in the file browser directory within Matlab/Octave. The command window will disappear and a new window named "Editor" will appear.

On the first line of the script, you will see "surveyparams.minline=0;" and then a percent sign and then some comment. This tells GPR-O that the first data file to call will have a value of zero in the filename, such as "XLine00". If the first line of your data set starts with, for example, "XLine02", then you would enter a "2" instead.

The second line says "surveyparams.nmorelines=24;" which means that GPR-O will search for 24 more data files after the initial one is found. In order to view a single line from your data, you would simply input the line number in "surveyparams.minline=?;" and "surveyparams.nmorelines=0;".

The next line says "surveyparams.lineincr=0.2;". This means that the distance between each profile line is 0.2 m.

The following line says "surveyparams.pnameraw='data/raw/example1/';". This means that the data that we recorded with the GPR is stored in the folder "data/raw/example1/". Open that folder on your desktop and you will see that it contains several files that are named "XLINE00.DT1" etc, and "XLINE00.HD" etc. These are data files from an actual GPR survey and we will be working with these as an example. For your own data files you will create a folder besides the "exercise1" etc folders in the data directory and store your GPR files in there.

The last line in "example1.m" says "surveyparams.pnametrf='data/processed/example1/';". This means that the processed data will be stored in the folder "data/processed/example1/". If you open, on your desktop, the folder "'data/processed', then you will see that it is empty. We need to create this folder to continue. **If you don't create this folder the program will create an error when you try to pre-process the data. So make a folder "example1" in the directory "processed".**

For your own data you must create your own m-file (just overwrite "example1.m" with a new file name and your particular survey parameters). Also, you must ensure that you created the proper folder structure that corresponds to your m-file.

4 Data preprocessing and data loading

To return to the Command Window when the Editor is visible, click on the tab at the bottom of the Octave program window.

Once you have set up the folder structure and the m-file for your data, you can, back in the Command Window, set the "surveyparam" variable by running

```
example1
```

or whatever the name of your m-file is. Notice that running your program loads the "surveyparam" variable into the workspace. You can display the components of the surveyparams variable by running

```
surveyparams
```

This should show you all the information you previously put into your m-file. Now run

```
preprawdata(surveyparams)
```

to preprocess your data. If it doesn't work it is likely that you made one of the following mistakes:

- You did not enter the correct folder for your raw data in your m-file
- you did not enter the correct folder for your processed data in your m-file, or you did not create that folder
- when collecting the GPR data, you did not select "record grid data" and then "X-lines". You can see this by looking at your raw data folder. If the files say "YLINE00.DT1" etc, or just "LINE00.DT1" etc, then that's what happened. No worries, in that case you can just run `preprawdata(surveyparams,1)` if the names are "YLINE00.DT1", or `preprawdata(surveyparams,2)` if the names are "LINE00.DT1".

After successfully preprocessing the data, you can load it by running

```
data=readdata(surveyparams);
```

The semicolon at the end is necessary to avoid that your screen gets filled up with numbers. If that happens you can press "ctrl-c" to abort and run it again with the semicolon.

The "data=readdata(surveyparams)" command takes the variable structure "surveyparams" as input for the function "readdata", and stores the data as the variable "data" in the workspace.

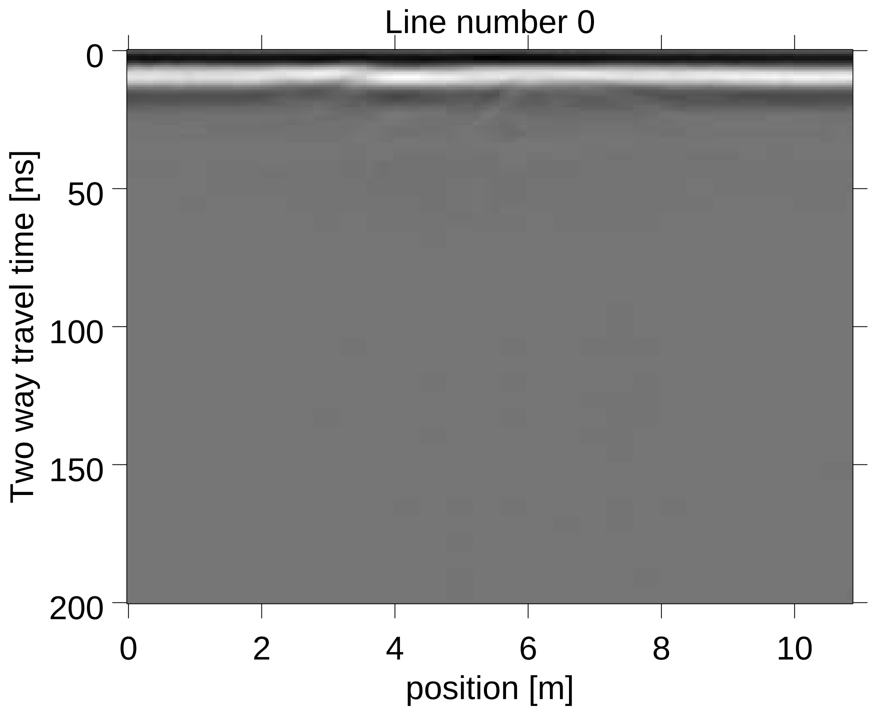
5 Profile data plotting and processing

5.1 Plotting the raw data

Let's have a look at the data you just loaded. Remember that we have 25 parallel lines that are numbered from 0 to 24. We can plot the first line (number 0) by running

```
plotGPRline(data,0);
```

It should look something like



Notice the function "plotGPRline" requires two inputs. The first is the variable that contains the processed data, in our case "data". The second refers to which line we wish to plot. So, if you want to show the second line, run `plotGPRline(data,1);`,
and for the third line `plotGPRline(data,2);`, etc.

You can always export a figure as pdf by clicking, in the figure window, on "File" and then "Save As".

What this figure shows is: along the first profile, at every location, the GPR sent out a wave and recorded what came back (as a function of time). This wave is shown as a row of pixels in grayscale going from the top to the bottom. The way we obtain a full 2D image instead of just a single wave signal is that we plot all of these lines next to each other.

In this profile we did not see much else but the black and white horizontal stripes in roughly the first 12 nanoseconds. This is because the wave that left the transmitter antenna flew directly into the receiver antenna without going through the ground. This wave is called *air-wave*. In this setup, the antennae were 0.5 m apart and the frequency was 100 MHz. A radar wave moves with the speed of light. In air this is roughly 0.3 m/ns. A wave of this frequency has length $0.3 * 10^9$ m/s divided by $100 * 10^6$ 1/s, which is 3 m. For the entire 3 m wave to completely pass by the receiver antenna located 0.5 m away, the wave needs to travel 3.5 m. At the speed of light, it takes this wave 3.5 m divided by 0.3 m/ns, which is 11.67 ns, exactly the time where we see the black and white stripe end.

5.2 Removing the air-wave

So we just saw that our image is dominated by the radar wave traveling through air and we don't see much from the waves traveling through ground (which are slower but also more weakened when they travel through the ground). We therefore want to remove the air-wave to see what is in the ground. Because the distance between the antennae is always the same in this profile (they were fixed at 0.5 m apart), the air-wave always looks the same at each recorded position (in each trace). On the other hand, the subsurface will vary along our profile unless there is a perfectly horizontal object in the subsurface all the way from the first to the last recorded position (which is rarely the case but can happen, so keep this in mind when doing this processing step). If the subsurface does not look the same all the way from the first to the last recorded position, but the air-wave does, then the average of all recorded traces should look like like the air-wave. Therefore if we average the traces for all recorded positions and subtract the result from each trace, then we should be able to remove the air-wave but keep all the signals from the subsurface. We can do this with the function `removeHorizontal`. Run

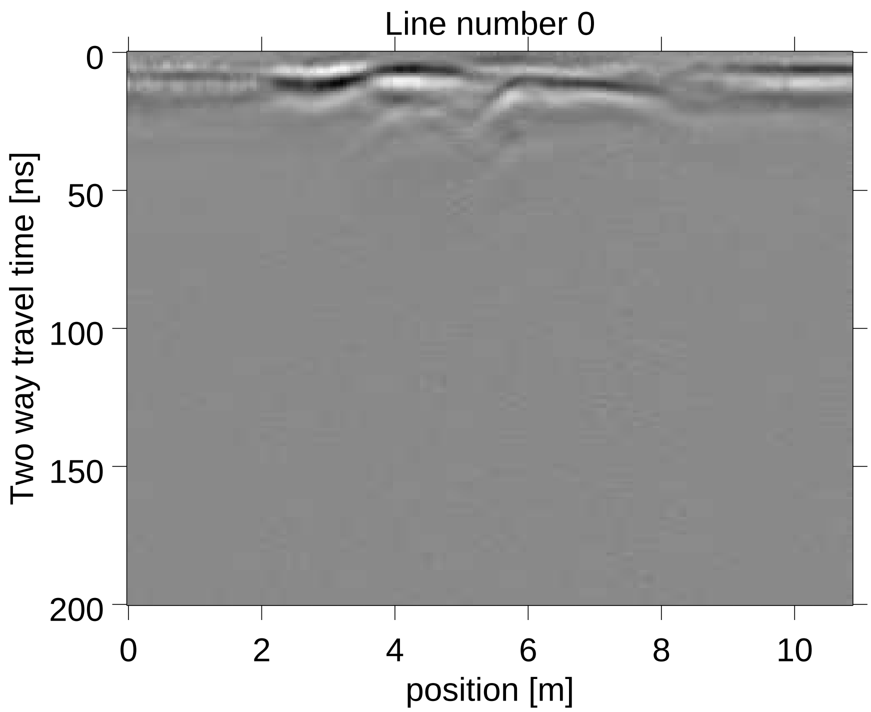
```
dataH=removeHorizontal(data,10000);
```

This creates a new variable "dataH" which now has the air-wave removed. We needed to give the program the number of measurement locations it should use to average. By giving it a very high number, say "10000" we just average all locations per profile. The less locations you average, the more aggressively you remove horizontal features. The most extreme is if you say 1, because then you remove everything and end up with no signal at all.

Let's see how the processed data looks like. Run

```
plotGPRline(dataH,0);
```

It should look something like



Much better. We can actually see something. But everything we see is at early, two-way travel times and therefore close to the surface. Why could that be?

5.3 Gaining the data

Radar waves traveling through ground (as opposed through air or space) are weakened (attenuated) quite quickly. That means that the deeper down the wave travels, the weaker it becomes, and therefore we can't really see much when it gets bounced off an interface in the subsurface and comes back to the surface.

But there is a way to make these deeper signals more visible. We can artificially strengthen later travel times by multiplying them with an increasing factor. This is called "gaining the data", or "applying gain". GPR-O presently has two different ways of gaining the data and :`gainDataTPOW` and `gainDataAGC`. The method you choose depends upon your data and your target of interest.

5.3.1 t-power gain (TPOW)

The simplest way of increasing the strength of the displayed data with depth is to just multiply greater depths with large numbers and shallow depths with small numbers. At this point, we are still looking at position vs two-way travel time (at a later point we will, for constant subsurface velocities, display the data as position vs depth). Therefore, we do not increase the strength of the signal along the depth axis, but along the two-way-travel-time-axis. A simple but flexible way of increasing strength with two-way-travel-time t is to just multiply each trace with a power of t, so multiply with t^a and we can choose a. So if we say for example $a = 1$, then we increase strength linearly with t. If we say $a = 2$, then we increase strength with the square of t, etc. We can also say $a = 1.3$ for example, or $a = 0.3$, or even negative values for a. If we use $a = 0$ then we do nothing with the data and the result looks the same as without gaining. If we use a negative a, then we increase the strength close to the surface and decrease the strength further away (which is usually not what we want).

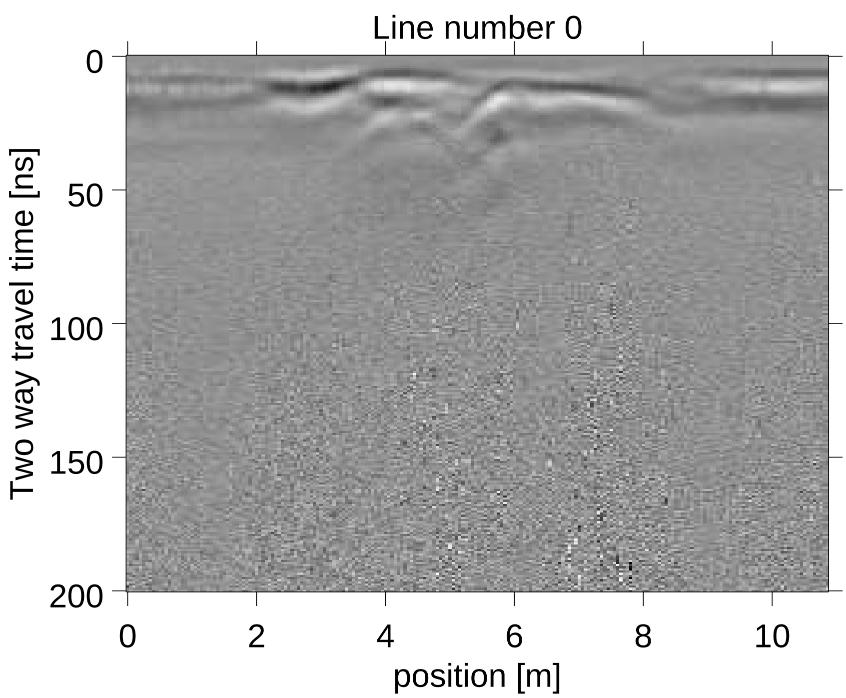
Let's try this with our data set. For example, let's choose $a = 0.85$. This means we have to run

```
dataHGt=gainDataTPOW(dataH,0.85);
```

To plot the first line we run

```
plotGPRline(dataHGt,0);
```

The result should look like



This looks very similar to the data with just the air-wave removed. The difference is that the objects deeper down (just above 50 ns) now look a bit stronger and the shallower objects look a bit weaker. For this (admittedly not very exciting) data set, the t-power gain is not very helpful but for other data sets, where you have interesting objects deeper down, the t-power gain may be superior to other gains. Generally, when playing with gain it is worthwhile to try out different settings. A good philosophy is that you want to enhance the target objects you are looking for if they are also in the raw data, but you do not want to use processing to create objects that are not really in the raw data. While appropriate gaining will provide the best results from a data set, such processing should never replace thoughtful survey design (i.e. antennae frequency selection).

5.3.2 Automated gain control (AGC)

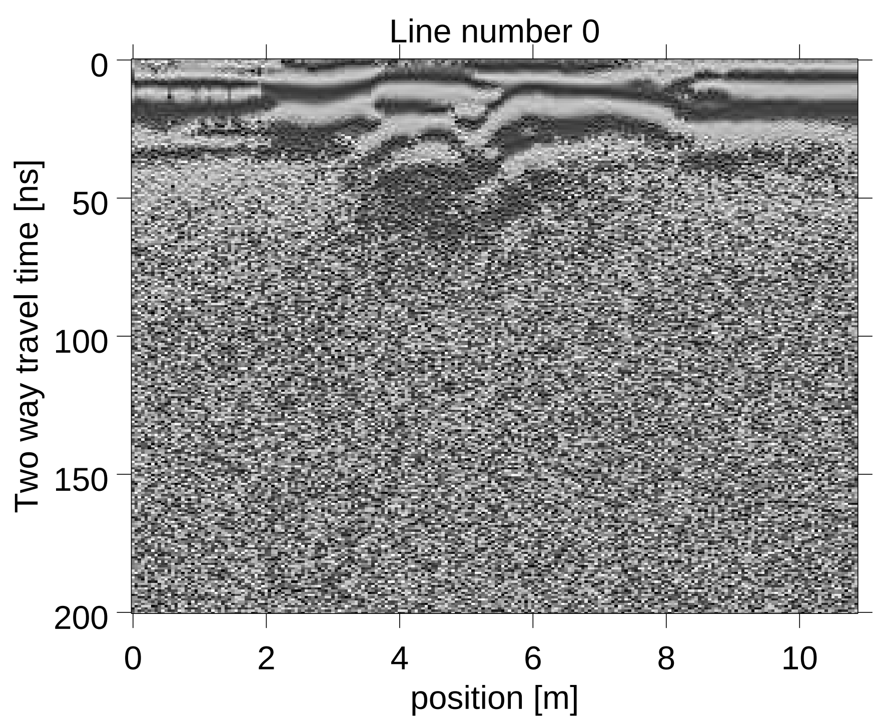
Instead of using a simple power law to increase the strength of the signal at greater depth (later two-way travel time), we could also say that we want the signal to have about the same strength at all depths. One way of doing it is to define a time (depth) window and say that the energy of the signal should be the same within each window. For this we only need to give a window width (in number of time-samples). Let's say that each measurement, or trace, within the profile is composed of 300 time-samples (for a depth resolution of 300 pixels). By using a 5 time-sample window width, AGC forces each of the (300/5)= 60 depth intervals (or 5-sample window) to have the same power. To do that, run

```
dataHGa=gainDataAGC(dataH,5);
```

Let's see how the profile looks like after applying AGC. Run

```
plotGPRline(dataHGa,0);
```

It should look something like



The application of AGC may take a while to calculate, in particular because you apply AGC to all 24 parallel profiles of the data set. To only apply AGC to a single profile, for example line number 0, you can run

```
dataHGa=gainDataAGC(dataH,5,0);
```

This is especially helpful (and time saving) when trying different time-sample settings. Play around with the time-sample window to see which setting helps show the target objects best.

See

```
help gainDataAGC
```

for more information.

5.4 Plotting with depth

Up until now we have always plotted our profile lines as a function of two-way travel time. But ultimately, we want to know the depth of an object. To do that we need to know the speed of radar waves in the ground and this depends on the ground itself. We will learn later how to use Common Mid-Point (CMP) and Wide Aperture Reflection and Refraction (WARR) measurements to estimate the velocity of our ground but for now we simply use a lookup table:

`http://gpg.geosci.xyz/content/GPR/table_velocity.html`

If we scroll down on that page we see that clays have a velocity of around 0.06 m/ns. We now simply use this number in the function `plotGPRline`

```
plotGPRline(dataHGa,0,[],0.06);
```

The time axes is now a depth axes in meters. in the previous call we needed to add the "[" and "]" characters because the velocity is the fourth input of the function `plotGPRline`. The third input would be display contrast. If we just want to go with standard display contrast, we can use the placeholder "[ ]" to say just that. We could increase the contrast by running

```
plotGPRline(dataHGa,0,3,0.06);
```

Here we are assuming that the radar velocity is constant with depth. This is of course not true. We could, for example, encounter a situation where we have soil on top of bedrock and the two have very different radar velocities. Time-to-depth transformations for varying subsurface velocities are currently not implemented in GPR-O.

5.5 Saving processed data and comparing profiles

Some of the processing is quite fast, but the AGC can be relatively slow. After it is finished you might want to save your processed data such that you do not need to start all over next time. You can save your data with the command

```
save('exercise1dataHGa.mat','dataHGa');
```

This created a new file named "exercise1dataHGa.mat" in your directory. You can also give it any other name or store any other processed data this way. You can always load this data set now by double clicking on it. Try first deleting everything in your current Octave session by running

```
clear all
```

If you would now try to redo the plots from before you would get an error message. Now run

```
load exercise1dataHGa.mat
```

to load it again. The loading takes a few seconds. Try again to plot the data as before.

Have you noticed that whenever you plotted something new, you just overwrote the old plot? You can avoid this by running

```
figure
```

to open a new figure before you plot something new.

Let's try this to see how the profile right next to profile 0 looks like. Open a new figure and then run

```
plotGPRline(dataHGa,1);
```

When you compare the two profiles, you will probably notice that they look very similar. That is a good sign; it means that our data measurements are reproducible and that we didn't just record random noise.

6 Area plotting

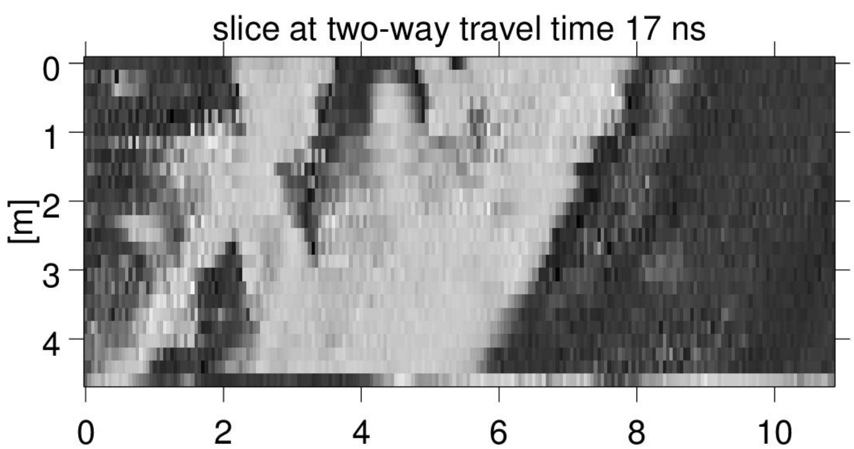
You have now learned to process and visualize profile data. In example1 we have 24 such profiles. We can visualize them by plotting each of them individually but for geological interpretations it would be good to look at them together simultaneously. We can do that by creating a map view where we display each of these profiles as a strip next to each other and provide the two way travel time (corresponding to depth) for which we want to look at them. Let's say we want to cut through all of the profiles at 17 ns two way travel time and look at it from bird's eye perspective.

First, make sure that you have loaded or preprocessed the data and that you have set the variable `surveyparams` (you probably deleted it earlier when you ran `clear all`. You can reload it by running `example1`).

To make the bird's eye plot of a horizontal cut at 17 ns two way travel time run

```
plotdata2Dgpr(dataHGa,surveyparams,17);
```

It should look like this



The x-axis here is the along-profile axis, while the y-axis contains the profile starting points. If your second profile is to the left of your first profile and the third profile is to the left of the second profile, etc, you can plot your bird's eye view with

```
plotdata2Dgpr(dataHGa,surveyparams,17,1);
```

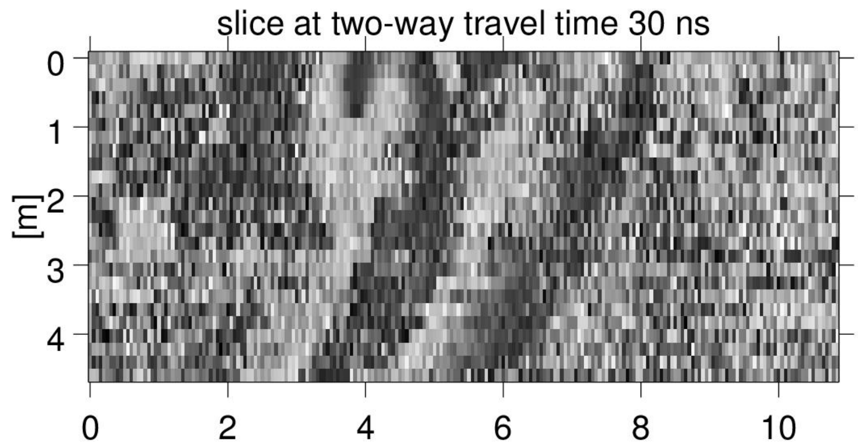
You will see that the entire plot is flipped.

Hint: If you save your figure as pdf, then you'll see that it will be a bit blurry. You can avoid this by saving your figure as jpg. There are ways to get a less blurry pdf by using the `print` *function in the Octave / Matlab Command Window.*

There is clearly a lot of structure in this depth slice. Remember that each profile was measured independently. So structure that shows up cross-cutting across several profile lines is some sort of structure. But interpreting what it is is the difficult part. Let's first get an estimation for the actual depth of this bird's eye plot. It is at 17 ns two-way travel time, which means the signal travelled 17/2 = 8.5 ns one way. If we assume a speed of 0.06 m/ns (as we got from the lookup table), then this will give us a depth of 8.5 ns * 0.06 m/ns = 0.51 m.

If we look at greater two-way travel times, corresponding to deeper slices, then we see that the structure is less and less well visible.

A slice at 30 ns should look like this



We can still see some structure but there is much more noise in the image.
The depth is 1/2 * 30 ns * 0.06 m/ns = 0.9 m. Considering that this is a 100 MHz system it is a bit disappointing that we can only see that far. This has to do with signal attenuation (weakening) because of the type of soil. The soil where these data were collected is clay-rich and is irrigated, making the subsurface rather electrically conductive. From general GPR theory(for example GPG's GPR section) we know that attenuation is proportional to electrical conductivity. Therefore, in general, conductive soils are bad for GPR depth investigations and electrically resistive soils (sand, rock, etc) are good.

7 CMP and WARR

To turn travel time into depth we have so far always used a value from a lookup table. This is based on the assumption that the velocity does not change with depth and that we made the right guess for the soil in the lookup table. Of course there are field-based ways of obtaining the subsurface velocity. Two classical and very similar methods are Common MidPoint (CMP) measurements and Wide Aperture Reflection and Refraction (WARR). In both cases we assume that there is a subsurface reflector that is (at least where we do our measurements) horizontal.

Here we will not go into detail about the theory of CMP and WARR measurements but will talk about how you can use GPR-O to analyze and visualize CMP and WARR data. We will work with the data in the folder "example2", which is WARR data. GPR-O has dedicated programs for

WARR and CMP. Here we will only work with the WARR programs. The CMP programs work the same, you simply need to switch WARR with CMP such as for example switch `plotWARRhyperbola` to `plotCMPhyperbola`.

Make sure that you use the WARR programs for WARR data and the CMP programs for CMP data, otherwise you will get wrong velocity estimations.

As before, we first need to prepare the `surveyparams` variable and the data directories. When you open "example2.m" you see that the raw data directory is "data/raw/example2/". In that directory you will only see a single line "XLINE00".

It is generally a good procedure to not mix CMP/WARR lines with for example GPR profiles. The reason is that when GPR-O reads the data it adjusts every profile such that they all have the same length (needed for the bird's eye slices). So if you have a 5 m CMP data set and a 20 m profile in the same folder, the profile will get truncated at 5 m. So keep them in separate folders and treat them as individual surveys.

The processed directory in the m-file "example2.m" says "data/processed/example2/". If we go to the folder "data/processed/" we see that this folder does not yet exist. So we need to make it.

Then, go back to the Command Window (using the tab at the bottom) and run

```
example2
```

and as before, prepare the raw data using

```
preprawdata(surveyparams)
```

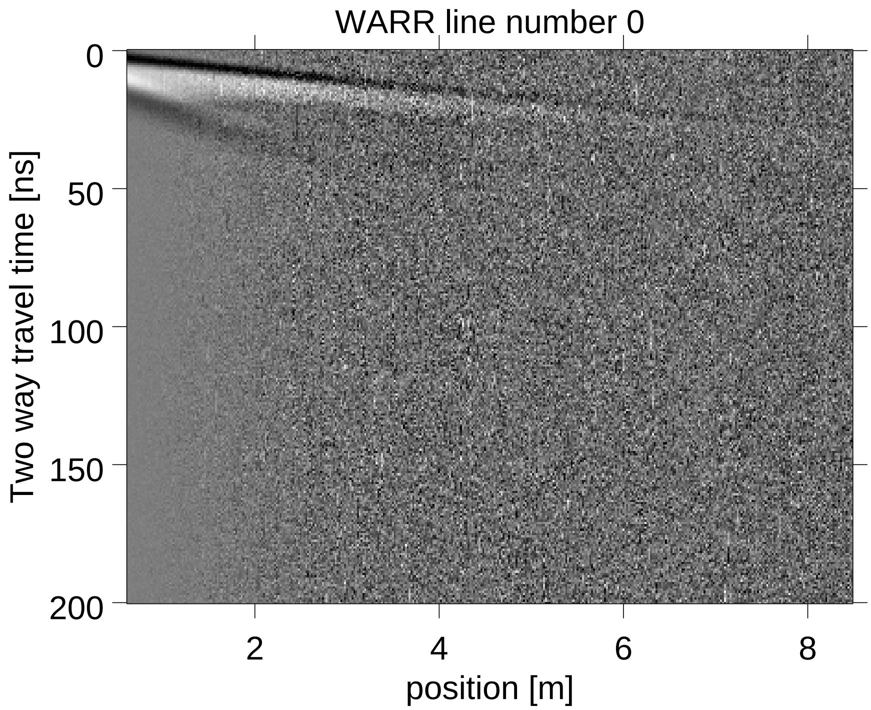
The data is now prepared and stored. You can now load the data with

```
data=readdata(surveyparams);
```

Now we need the right plotting program for this WARR data set to visualize it:

```
plotWARR(data)
```

The result should be



What we see is, as for the GPR profiles, position versus two way travel time. But here, position does not mean location of the GPR system but distance between the transmitter and receiver antenna. As you can see, the larger the antenna distance, the greater the noise. Why would that be?

The answer is: the farther away the antennae are, the more the signal gets attenuated. To compensate for that effect and to still be able to see the signal when the antennae are 8 m apart, we amplify the measured traces for larger antennae distances. But with that, we also amplify the noise.

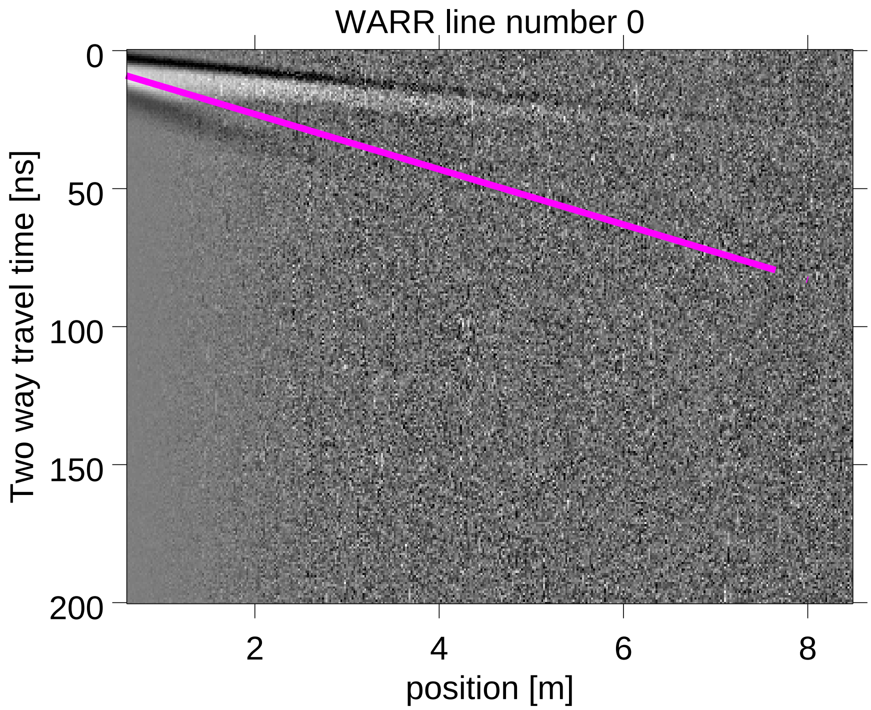
The following part requires you to have a basic understanding of CMP/WARR velocity determination. If you are confused by what we do next, please read it up in your textbook.

How can we obtain subsurface velocity from this WARR data set. We could guess a velocity and whether the wave is being refracted or reflected and then plot the corresponding line/hyperbola over the curve to see if we are right.

Let's assume for now that we can see a refracted wave with velocity 0.1 m/ns that starts (for antenna distance 0 m, which we can't see because we can't physically put the antennae on top of each other) at two-way travel time 3 ns. We can plot how this wave would look like on top of this plot with

```
plotWARRrefraction(3,0.1,8);
```

The last number, 8, was to say how far out we want to draw the refracted wave line.



It seems as if our guess was not so good. But it is generally very hard to tell. If only we had a tool that could help us with this. In fact, we have one. We could just ask our computer to try out many different such lines and see which ones “fit” a line on the WARR plot. But what does it mean to fit a line on the WARR plot? One measure of how well a drawn line fits a line on the WARR plot is to sum up all the pixels along the line. If all pixels have the same positive or negative value, then their sum will be large. On the other hand, if our line crosses lines of positive and negative values, or just runs through noise, then the summands will cancel out and the sum will be small. Let’s do this. The function for it is `plotWARRrefSemblance`.

Before we continue, let’s open a new figure to make sure we do not half-way overwrite the old one with what’s to come. Run

```
figure
```

We need to give this program the WARR data, a range for the different starting two-way travel times, a range for the velocities that it should test, and the maximum antenna separation we want to consider.

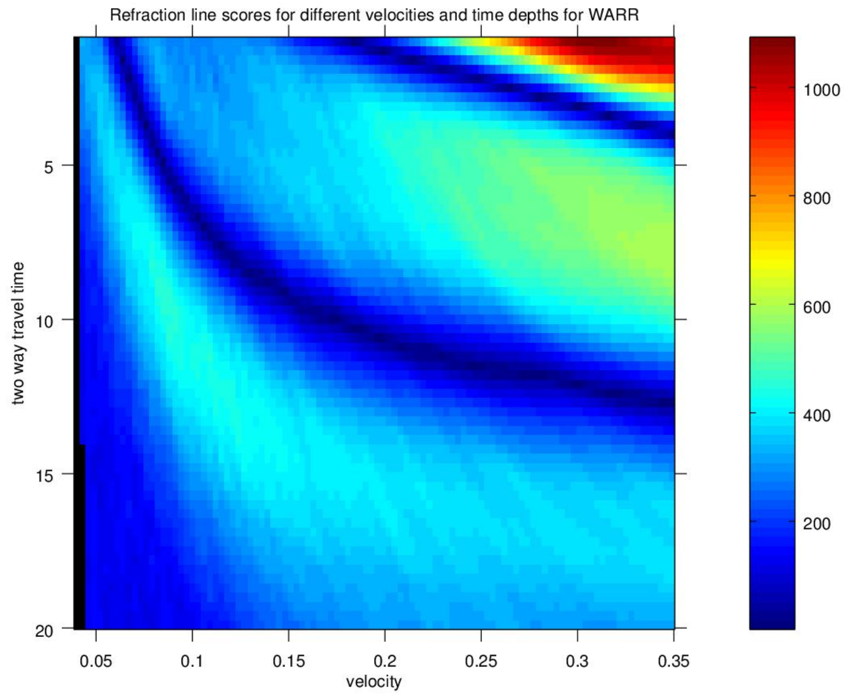
Let’s first see how Octave wants us to provide ranges. If we want to have a list of numbers, between a first number, say 2.3, and a last number, say 3.1, and we want all the numbers in between with step, say 0.1, then we need to write

```
2.3:0.1:3.1
```

So let’s say we want to calculate how well all the lines with starting two way travel times between 0 and 20, step size 0.5, fit when they have velocities between 0.04 and 0.32 with step size 0.005 and we want to use maximum antenna separation 8 m. Run

```
plotWARRrefSemblance(data,1:0.3:20,0.04:0.003:0.35,8);
```

This calculation might take a while. To speed it up you can make the step size a bit larger but that will also make the resulting image coarser.



The x-axis of this plot shows the different velocities that your computer tested and the y-axis shows the different two-way travel times at zero antenna distance. Dark-blue means low sum values, so that means that for these velocity/two-way travel time choices, the refracted wave lines do not fit any lines in the data. Light blue to green to red values means that for these choices of velocity/two-way travel times, the refracted wave lines match a line in the data.

We see three smeared out blobs of good matching. The reason for the smearing out is that the refracted wave lines in the data are relatively wide. So even if the chosen refracted wave line is a bit off, it still lies within the broad actual refracted wave line. Let's look at the centers of the blobs. When you hover your mouse over the figure you can read the two-way travel time and velocity values of the cursor location at the bottom of the figure. The center of the blob at the top right seems to be for travel time roughly 1 ns and velocity 0.3 m/ns. The second blob seems to be very broad. It's center may be at around time 6.5 ns and velocity 0.3 m/ns. Finally, the center of the third blob seems to be at around travel time 9 ns and velocity 0.085.

Let's see what these blobs could represent. To do that, let's first redo the figure with the WARR data:

```
figure
```

```
plotWARR(data);
```

That's just the WARR data that we already saw. Let's put the refraction curve corresponding to the first blob on top of this:

```
plotWARRrefraction(1,0.3,8);
```

It perfectly overlaps with the first black line in the WARR data. Now the second one:

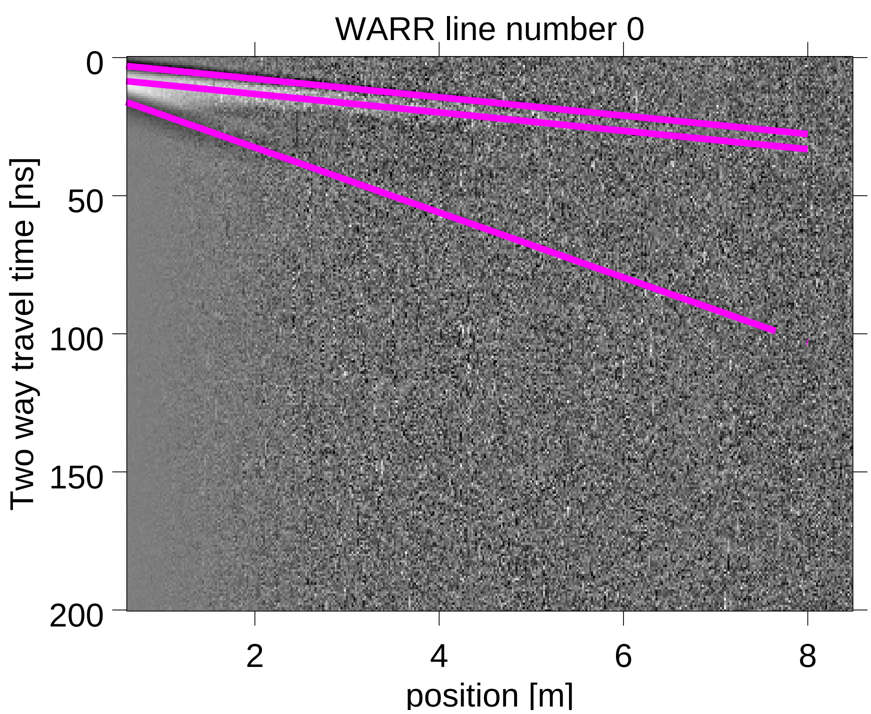
```
plotWARRrefraction(6.5,0.3,8);
```

This one perfectly overlaps with the white line parallel to the black line. Now the third blob:

```
plotWARRrefraction(9,0.085,8);
```

This one follows the black line that was at an angle.

After adding the last line your figure should look like this



So it looks like we have two refracted waves that travel with velocity 0.3 m/ns and one refracted wave that travels with velocity 0.085 m/ns. The speed of radar waves in air is roughly 0.3 m/s. From this we know immediately that the first two waves traveled through air and not through the ground. The separation between them, about 5 ns, corresponds to the distance 0.3 m/ns * 5 ns = 1.5 m. This is exactly half the length of the wave in air (3 m). Therefore the "second" wave is simply the second lobe of the airwave traveling directly from the source antenna to the receiver without going through the ground.

The last wave has a velocity of 0.085 m/ns. This is completely within the normal range we would expect for this type of soil and confirmed that we were a bit off with our guess from the table. This wave is called direct wave. It moves just below the surface as a refracted wave on the air/surface interface.

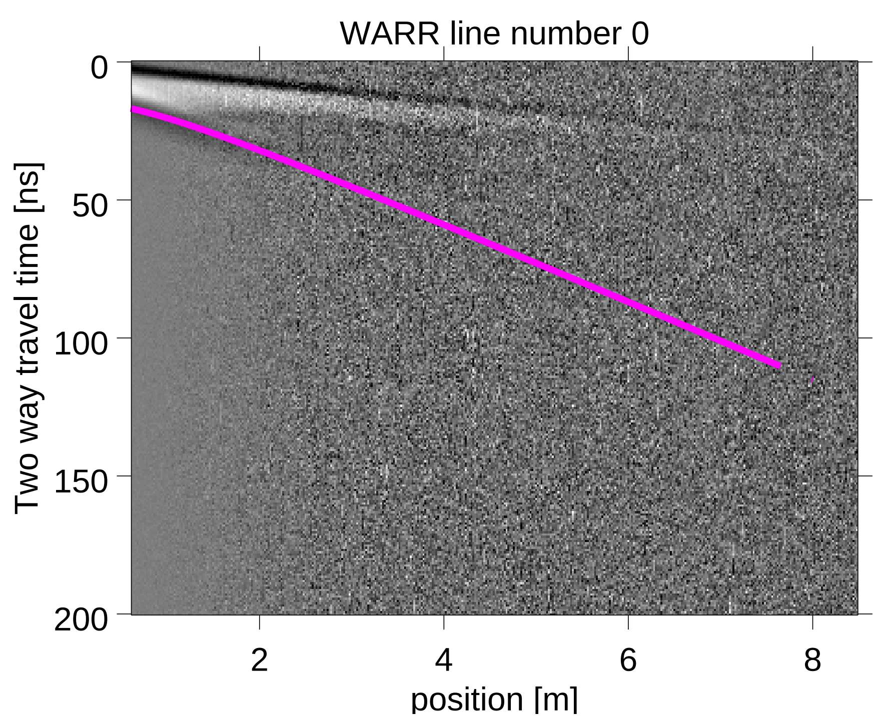
The question is now: How did we know that these are refracted and not reflected waves? For reflected waves we would have needed to fit hyperbolas and use `plotWARRhyperbola` and `plotWARRhypSemblance`.

The answer is: We need to look at the subtle shape of the lines that we see in the WARR data plot. If these lines bend, then they are likely to be hyperbolas. If they are straight, then these are either air- or refracted waves. Another option would be to see what happens when we use `plotWARRhypSemblance`. The first two blobs would be centered at travel time 1.6 ns and velocity 0.28 m/ns, and time 10 ns and velocity 0.25 m/ns. Both of these velocities are outside of what we would expect for any type of soil and they would be too slow for air. The last blob would be centered at velocity 0.07 m/ns and time 14.5 ns, leading to a slightly lower velocity estimation of the soil. To figure out which of the two velocities: 0.07 or 0.085 we should trust more, we can look at the hyperbola drawn over the WARR data and compare it to the refraction line drawn over the WARR data and see which one we thing fits slightly better:

```
figure

plotWARR(data);

plotWARRhyperbola(14.5,0.07,8);
```



It is hard to tell but I think I see that close to the left edge of the graph, the magenta line curves a bit more than the thick line in the WARR data. One approach in such a case of doubt is to give a depth range of an object based on the two different velocities 0.07 m/ns and 0.085 m/ns.

At this point, in a geophysical investigation, we would go back to the the GPR profiles in Section 5 and replace the velocity there with the velocities that we just obtained.

8 Topography

Realistically, your data will not always be collected on flat terrain. GPR-O can account for changes in topography with a two-step process.

First, run

```
makeElev
```

which prepares an interpolated topography matrix from elevation data. The elevation data can have one of three forms:

- If your data is only a single profile line, then `elevdat` can be just a vector containing the elevation for each profile point coordinate in `xpos`.
- If you have topography data for each profile line of a group of parallel lines, then you can provide the topography data for line 1 as `elevdat{1}` containing elevation for the points given in `xpos{1}`, and for line 2 as `elevdat{2}` containing topography for points in `xpos{2}`, etc.
- If you have elevation points for a couple of random points within your parallel profile lines, then you can just provide `elevdat=[x y el]`, where `x` are the along-profile and `y` the cross-profile coordinates, and `el` is the elevation. Make sure you include at least the four corner points, as `makeElev` will not extrapolate in this mode.

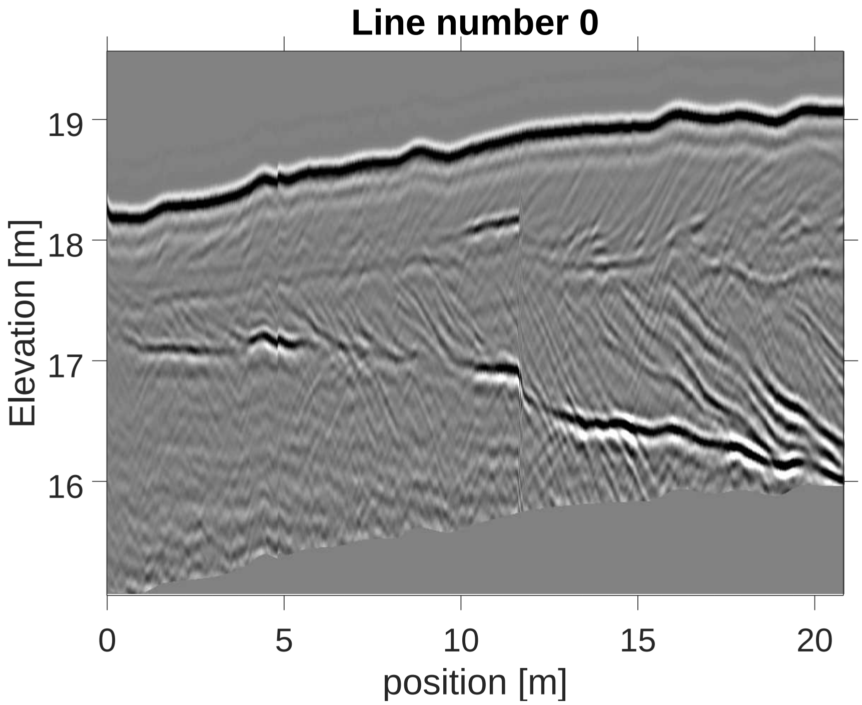
Once you have the variable `elev` from `makeElev`, use the function

```
elevCorrect
```

to shift each trace by the (interpolated) corresponding two-way travel time associated with the topography.

For an example of topography correction, we will use a single line of GPS data located in the folder "data/topo/dune". These elevations correspond to GPR data collected from a sand dune.

The result should look like,



9 Export to VTK

The function

```
gpro2vtk
```

exports GPR-O data to a .vtk file, which can be read by programs like ParaView etc.

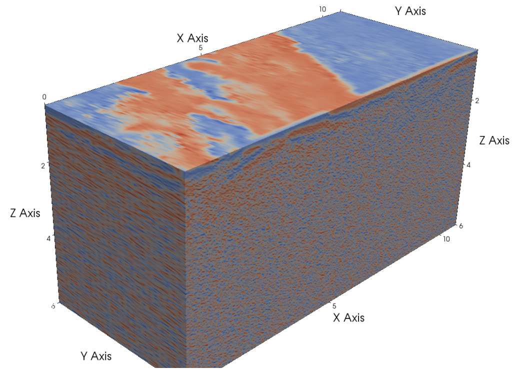
By running

```
help gpro2vtk
```

you will see there are six required inputs. For instance, if you wanted to export the data with AGC gain from the earlier example1, run

```
gpro2vtk(dataHGa,0.06,0.2,0,'Exercise1Data',[]);
```

Programs like Paraview offer powerful 3-D visualization of data. Here is a quick example of the exported data, represented in Paraview.



10 Other potentially useful functions

The function

```
thresh
```

removes values smaller than a percentage of the maximum data point value. In the default GPR profiles we compiled in this documentation, note how the signals (and noise) lie on the greyscale color spectrum. The stronger (black or white) bands are generally the strongest signals, while the noise is usually averaged out as grey. This function reduces the grey by setting small deviations to zero. This can be used to clean up traces before gain and export to VTK.

The function

```
stolt_fk_mig
```

is a migration tool that removes artifacts within GPR profiles that are caused by changing the receiver-transmitter position. The reason that a reflection point in the subsurface generates a parabolic arc in radargrams is that the two-way distance to a point increases when the antennas are moved further from the point in both directions. By incorporating this relationship within your processing, you can improve the accuracy of the GPR profile.

The function

```
readSnS_GPS
```

reads Sensors and Software GPS data, such as the one provided by `https://alaska.usgs.gov/portal/project.php?project_id=384`

11 Command quick-reference

This section is designed for those that are already familiar with GPR-O's functions and general processing steps, but need guick access to various commands. Simply adjust these commands with your particular survey parameters.

```
initialize

initialize_octave

preprawdata(surveyparams)

data=readdata(surveyparams);

dataH=removeHorizontal(data,10000);

dataHGt=gainDataTPOW(dataH,0.85);

dataHGa=gainDataAGC(dataH,5);

plotGPRline(dataHGa,0,[],0.06)

plotWARR(data)    plotCMP(data)

plotWARRrefraction(3,0.1,8);    plotCMPrefraction(3,0.1,8);

plotWARRrefSemblance(data,1:0.3:20,0.04:0.003:0.35,8);

plotCMPrefSemblance(data,1:0.3:20,0.04:0.003:0.35,8);

plotWARRhyperbola(4.5,0.07,8)    plotCMPhyperbola(4.5,0.07,8)

save('exercise1dataHGa.mat',dataHGa);

load exercise1dataHGa.mat

figure

plotdata2Dgpr(dataHGa,surveyparams,17);
```