SIGkit: Software for Introductory Geophysics Toolkit

Activity sheets

SIGkit working team, April 2019

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1 Introduction

Predicting what geophysical data may look like and making basic inferences from data are critical learning outcomes of introductory geophysics courses whether they happen in a classroom or in a field setting. SIGkit (Software for Introductory Geophysics toolkit) is a software and a set of learning activities which allows students taking introductory geophysics to engage with geophysical models and data. Students learn through data modeling, data visualization, and simple analysis of field data acquired through gravimetric, magnetic, resistivity, electromagnetic, ground-penetrating radar, and seismic refraction. To our knowledge this toolkit provides the first teaching software that brings together various methods and data sets into a comprehensive learning software.

For the various methods, the toolkit allows students to
- explore how changes in parameters translate to changes in modelled data,
- create synthetic data and compare those to real data,
- visualize field data,
- perform basic processing of data, and
- extract a random profile from a gridded dataset (if applicable, eg, from magnetic maps).

Activities are self-contained, so can be used in any order or one may stand on its own. They take a very similar approach, and if several activities are used they reinforce the learning of new concepts and comparison between methods without the distraction caused by new software. Each activity has a main script in which students specify parameters, while calculations and manipulations are done via separate scripts. Thus we try to strike a balance between not overwhelming novice learners, while avoiding a ”black-box” approach and allowing more advanced learners to adjust and add to the separate scripts.

SIGkit is intended for teaching and the basic analysis of field data; it does not aim to replace commercial software. Students working on advanced projects will probably want to use more specialized analysis programs, but we hope that their entry will be easier because they already understand first steps.

SIGkit has been developed with funding from MathWorks and the University of Toronto Instructional Technology Innovation Fund and with the help of several students (Eva Zhang, Sacha Papadimitrios, Alex Cadmus, Jessica Liu, Nathan Stoikopoulos, Ophelia George, Sanaz Esmaeili, Sajad Jazayeri) who also coded prototype versions for GUI-based activities. These however were not free of bugs, and therefore we are here presenting a package with scripts. Future releases will include more data sets, capability to read different types of field data formats, GUI input of parameters, making parts of the code more efficient, and possibly simple inversion routines. While the final toolkit may still be based on MATLAB scripts, our aim is to make it self-contained without requiring a MATLAB installation. We welcome any feedback, including suggestions for improvement, from teachers and their students using our toolkit.

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2 A note on MATLAB and SIGkit

This toolkit was programmed in MATLAB, and you will need a working MATLAB installation to run it. Many academic institutions offer MATLAB licenses for free or for a reasonable amount to students; your instructor will let you know how to obtain and install such a license (or run it off a server). Our goal is that you can run the software with only very basic knowledge of MATLAB, yet if you are curious about programming in MATLAB we suggest you tackle the onramp tutorial (see ...). The activities linked to modeling and analysing data do not assume that you did. However, if you want to work with your own data you may need to do some MATLAB programming...

We suggest you copy the source file `SIGkit_noGUI.zip` to a folder on your computer (eg, the folder containing your geophysics course notes). Once you start MATLAB you will see a window like the one shown in Figure 1 with various subwindows that are labeled here for you.

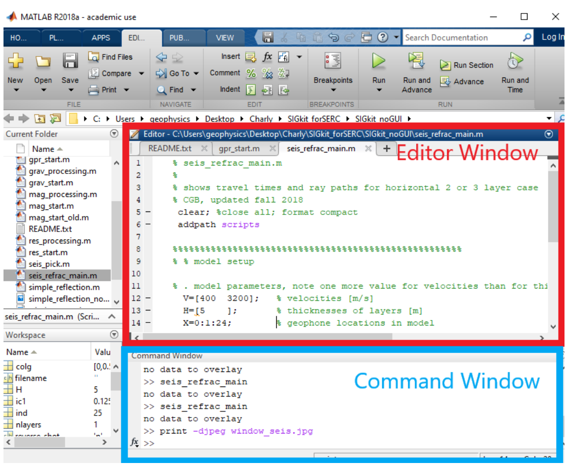

Figure 1: Sample MATLAB window as it may appear on your computer screen. Highlighted are the Editor Window (in red) and the Command Window (in blue).

To use the toolkit you first need to change into the SIGkit folder, either by typing

```
cd [my_course_directory]/SIGkit_noGUI
```

in the Command Window or by choosing the path in a white bar near the top. Each activity will ask you to set parameters in a script which you can open by double-clicking on the filename in the subwindow called ”Current Folder”; this will make it appear in the ”Editor” subwindow. The actual script appears in black, text in green (which follows a percentage sign) are comments that will not be executed. You run a script by clicking on the green arrow marked ”Run” at the top, or by typing the name of the script in the Command Window.

Several of the parameters are stored in ”arrays” that are surrounded by square brackets. Make sure you only change the values, not the variable names, and don’t accidentally erase the brackets.

3 SIGkit gravity activity

By the end of the SIGkit gravity activity you should be able to
- explain the relationship between depth and density of an object and its gravity anomaly,
- estimate depth of an object from its gravity anomaly, and
- match a synthetic model to real data and estimate depth and/or density parameters.

A. Modeling

Use the script `grav_start` to create profiles of synthetic data collected over some body. An example image is shown below in Figure 2. The bottom panel shows a cross-section, and the top panel the measured gravity data relativ to the background.

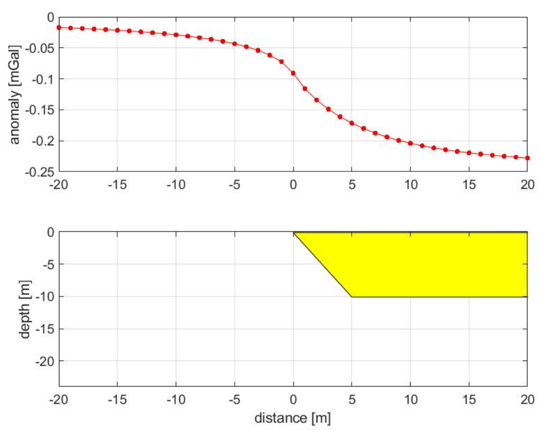

Figure 2: Example of gravity modeling; the calculated anomaly is shown on top, and a cross section of the body in the cross-section below.

To produce synthetic data you need to specify the following parameters in the script:
- density of the object: `rho_a`
- density of the surrounding material: `rho_t`
- if you set `ginput='YES';` then you can create the outline of an object by clicking on points in the lower diagram in clockwise direction; alternatively you may specify [x,z] pairs by writing values into the `xa` and `za` arrays. (Aside: if you place one side of the object outside the plot area the script stretches the object far out).
- location of measurement stations (this also determines size of your cross-section); note that `X=[-50:5:50];` means measurement points at -50, -45, -40,... to 40, 45, and 50 m

a) Create the anomaly of simple object (e.g., a square); you have to click corners in clockwise direction.

b) Place the center of the square at twice the depth.
(Aside: If you used ginput in (a) you can find the corners by typing xa and return, then za and

return, and use these in the script; you may then subtract a value from the za array to obtain a deeper square.)
Compare amplitude and width of this anomaly to that you created in (a), in a sketch and in words.

c) Rerun the script for the same anomaly as in (b), and change the closeness of your measurement lcations. How close do you need to space your measurements to be sure you will not miss an anomaly? How accurate do you need to measure the gravity value?

d) What happens if you change the density of the object you created in (b)?
Can you adjust the object with the new density to match your initial anomaly?

B. Analysing data

You may analyse two datasets (with simple Bouguer anomalies) by trying to find a model which fits the data. In `grav_start` you need to specify the filename in variable verb+datafile+.

Students collected file `data_samples/CC_tunnel_data.txt` over a known tunnel on the Colorado College campus. Determine the location and depth of this tunnel. What assumptions are reasonable to make (about size and density of a tunnel)? You will have to specify measurement points, and may need to shift your anomaly up or down (with the `Gshift` variable).

File `data_samples/arkansas_graben_data.txt` was collected on the West side of the Upper Arkansas graben near Buena Vista, Colorado, along a West-East transect crossing from the mountains into the valley. Assume reasonable values for the densities (granitic mountains, valley filled with loose sediments) and determine the thickness of the sediments. Can you estimate a dip for the fault bounding the graben?

Acknowledgement: Funding for the collection of the Arkansas data set was provided by the Department of Geology at Colorado College.

C. Working with your own data

To read data into the script as in part B your file needs to copy the format as the datafiles used there: two header lines, then each line with a pair of profile distance [in m] and simple Bouguer gravity [in mGal].

These are additional scripts you may use to analyse data you have collected: drift correction: `grav_driftcorr.m` (in directory “scripts”) elevation correction (free air and simple slab): `grav_processing.m`

4 SIGkit magnetics activity

By the end of the SIGkit magnetics activity you should be able to
- explain how a magnetic anomaly depends on various parameters,
- recognize whether anomalies are caused by susceptibility alone or remanent magnetization,
- estimate depth of an object from its magnetic anomaly, and
- match a synthetic model to real data and estimate parameters.

A. Modeling

Use the script `mag_start` to create a model. The script will open a window with two panels: the top shows the modeled anomaly profile, while the bottom shows a cross section with the body and schematic arrows for the background field and remanent magnetization as shown in Figure 3.

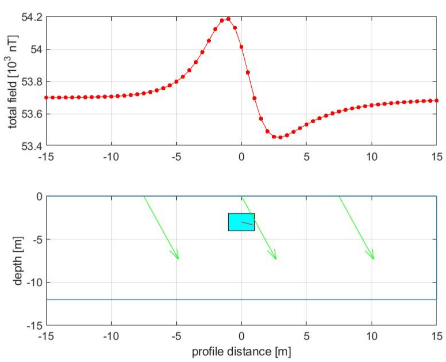

Figure 3: Example of magnetic modeling; the calculated anomaly is shown on top, and a cross section of the body in the cross-section below. The green arrows symbolize the background magnetic field, and the red line shows that the calculation includes remanence.

You need to specify several parameters:
- background field intensity, declination, and inclination (named `Hintn`, `Decl`, `Hincl`)
- if you want to use the mouse to outline a cross-section of the body (`use_ginput='Y'`) or if you specify the distance and depth values (arrays `xa` and `za`)
- susceptibility and/or remanence (plus inclination and declination) of the magnetic body (`msus`, `mrem`, `minc`, `mdec`)
- azimuth of measurement profile, height of sensor above ground, and locations of measurement points

a) Create a total field anomaly for a simple object (eg, a square). We suggest you set the `xa` and `za` (distance and depth) arrays and `use_ginput='n'`. Set a value for susceptibility, and leave the remanence at zero. Also, don't set the `calc_grad` parameter to `'Y'`.

b) How does the anomaly change if you measure above the same object at different latitudes, ie. at different values of total field strength and inclination?

You may determine values for a certain location
- by guessing approximate values for total field and inclination (eg, 54,000 nT and 70° for Toronto),
- using the figure below, which is based on the formulas $\tan I = 2\tan(90° - \theta)$ relating inclination I to latitude θ and $B = 30,000nT\sqrt{1 + 3\cos^2\theta}$ for the total field at latitude θ,
- consulting a recent map showing magnetic components (for example at http://www.geomag.bgs.ac.uk/education/earthmag.html), or
- using an online field calculator (for example https://www.ngdc.noaa.gov/geomag-web/).

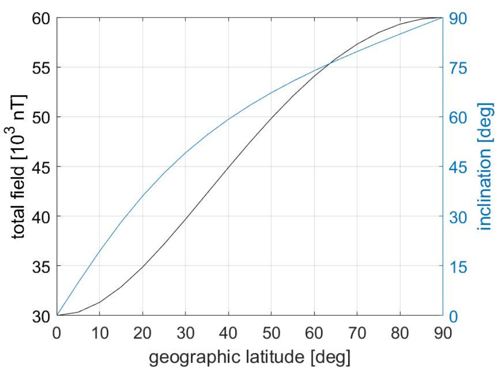

Figure 4: Approximate variations in inclination and total field with geographic latitude.

Sketch the anomalies you find and explain it in words. Think about the location of maxima and minima.

c) An anomaly will also look different depending on the direction of the profile. Create models for different azimuths (S-N, SW-NE, and W-E directions). What do you notice? As a special case, run an EW profile (`pfang=90`) at the equator (`Decl=0` and `Hincl=0`).

d) How does a measured anomaly change if you increase the depth (or elevation of the sensor above ground)?

B. Analysing data

File `data_samples/TroutLake_magdata.txt` includes data students collected along the side of Highway 11 about 4 hrs North of Toronto (at about 46°N). The highway runs S-N. The profile crosses a mafic dike. Find a thickness and tilt of the model to match the data. Look at the datafile first; you can run in the command window
`open data_samples/TroutLake_magdata.txt` to determine approximate values of `Xshift` and `Fshift` to shift your data, or you can adjust the background field strength, otherwise your data will fall outside the range shown by the model.

The `data_samples` directory includes a map for data collected on the cemetery of the British American Institute (Uncle Tom's Cabin historical site in Dresden, Ontario). To view the data copy the following commands into the Command Window

```
clear;
load data_samples\BAI_magXXYYFF.mat
figure; pcolor(XX,YY,FF);      % to plot map
shading interp; axis image;    % aspect ratio 1:1
caxis([-25 25]); colorbar;     % range of data
```

and hit enter. Now run
`[D,fP,xg,yg]=extract_profile(XX,YY,FF)`
to extract a profile for one of the anomalies. Your profile data will be written to file ”profile.txt”. Find a model that matches the data on your profile. This is gradient data, the bottom sensor was 25 cm above ground, and sensor separation was 56 cm. Could your anomaly be linked to a magnetic object at approximately 1.5 m depth (which is the expected burial depth)?

Acknowledgement: Funding for the collection of both data sets was provided by the UofT Faculty of Arts & Science.

C. Working with your own data

You can read in textfiles as in part 2 if they confer to the data format used there (2 header lines, then one pair of location and field per line). Read script `mag_processing.m` to see steps you can take to analyse your own data (including despiking, diurnal correction, zero-mean traversing, upward continuation, reduction to the pole, and analytical signal).

5 SIGkit resistivity activity

By the end of the SIGkit resistivity activity you should be able to
- explain the difference between apparent resistivity and true resistivity,
- recognize both resistivity and thickness of a layer as key parameters, and
- argue why resistivity data do not provide unique solutions.

A. Modeling

Script `res_start` allows you to model a resistivity sounding curve for the 1D case, i.e., homogenous horizontal layers. Both the true resistivity curve as well as the modeled one are plotted on a log-log scale (see Figure 5).

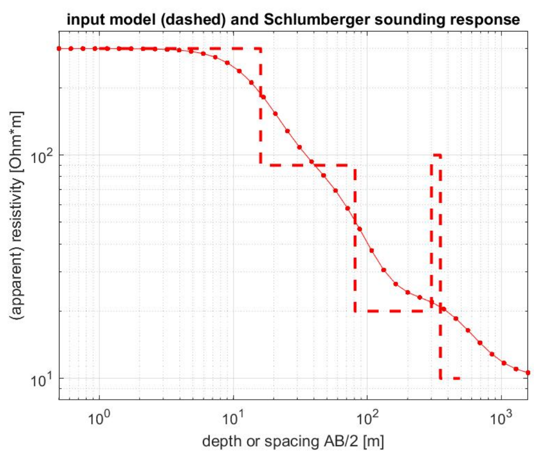

Figure 5: Example of resistivity modeling; the calculated apparent resistivity is shown as solid line (with dots marking measurement points) and actual resistivity change with depth as dashed line.

a) Start with a two layer case for which you specify one thickness and two resistivity values. Run a few models for which you change the resistivity of the bottom layer. What is the range of spacings you think is sufficient to determine both resistivities?

b) Now leave the resistivities unchanged and vary the thickness of the top layer. How do the resulting sounding curves change?

c) Run the model for a 3-layer case. Change the resistivity of the middle layer from a value less than the bracketing resistivities to a value above.

Tip: It will be easier to compare sounding curves if you overlay them. For that you may save the model results to a file, by typing into the Command Window

```
AB1=AB; rho1=rho; save myfile AB1 rho1 -append
```

and do this for different runs by changing the variable name to `AB2` and `rho2` etc. If you then want to overlay sounding curves onto the same plot do

```
clear; load myfile; figure;
loglog(AB1/2,rho1); hold on;
loglog(AB2/2,rho2)
```

B. Analysing data

File `data_samples\DR_schlum.dat.txt` is extracted from a resistivity section measured at the Deep River field camp. The stratigraphy consists of a dry sand at the top, overlying saturated sand (which forms the unconfined aquifer) and glacial till below. On your own or with a partner find a 3-layer model that fits the data.

Once you are satisfied with the fit you found compare your model to that of your neighbours. Did they come up with a similar model? If not, how do the models compare?

C. Working with your own data

Nowadays resistivity data is usually collected as pseudosections rather than sounding curves. To use the modeling script from this activity you can extract datapoints collected around the same midpoint from a pseudosection and write them to a file that has the same format as the datafile in 2 (two header lines, followed by one pair of electrode spacing and measured apparent resistivity per line).

6 SIGkit EM activity (incomplete)

By the end of the SIGkit electromagnetics activity you should be able to
- recognize how conductivity and thickness of a surface layer affect readings in a two layer case.

A. Modeling

Script `em_modeling.m` provides 4 examples of subsurface models with two layers. The parameter `C` inputs the conductivities of the two layers, while the parameter `A` is made up of distance and depth pairs in both columns. A percentage sign shows that anything behind on that line will not be executed; so to run one of the example models delete the percentage signs at the start of the corresponding lines.

B. Analysing data

No data set...

C. Working with your own data

Not ready...

7 SIGkit GPR activity

By the end of the SIGkit GPR activity you should be able to:
- explain the concept of two-way time
- recognize imaging artefacts (eg, diffraction hyperbolae and "bow ties"), and
- convert time to depth in radargram sections.

A. Modeling

a) Script `simple_reflection` simulates a GPR survey over an area with one interface. Two examples are provided in the code: a syncline and a normal fault. To view one of these take out the percentage signs that comment out the array `A`. You can also create your own interface by commenting out both model arrays, and uncommenting the line: `[xi,zi] = ginput;` (as you select points to mark that interface make sure you move to larger distances between clicks, not back and forth).

Run the syncline model. The bottom panel shows a cross section with the interface and the ray paths that create reflections being picked up, and the top shows individual GPR traces and two-way times when those reflections are being picked up as they return to the radar unit. How does the radargram section image the syncline? Also run the normal fault example.

b) Common artefacts are diffraction hyperbolae that may be caused by rocks, roots, or pipes. In this activity you will compare hyperbolae that originate in material with different dielectric constant (ie, radar velocity) and at different depths.

Run script `gpr_hyperbolamod` which will ask you to input a value for the dielectric constant (type it into the Command Window) and select the apex of the hyperbola by clicking on the figure. Once you have done both the figure will show you the diffraction hyperbola and how the two-way time (axis on the left side) converts to depth (axis on the right side), like the example in Figure 6.

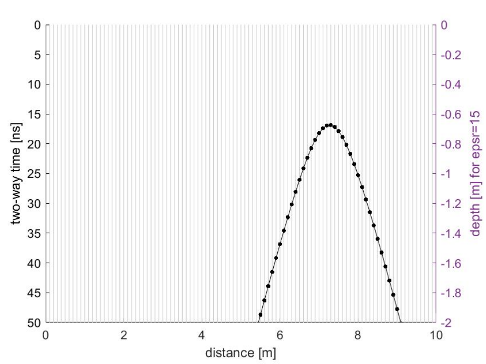

Figure 6: Example of GPR diffraction hyperbola with time on the left and depth on the right.

Do successive runs using the same value for dielectric constant, but selecting different values of two-way time. How do the resulting hyperbolae differ? What about the conversion from time to depth?

Now run other values for dielectric constant and observe how the shape of the hyperbola and/or the depth axis change.

B. Analysing data

Open `gpr_start` and run it. You will see a radarfile collected between two cabins at the Whitefish Falls fieldcamp (SW of Sudbury, Ontario) in 2011 (thanks to the UofT Faculty of Arts & Science for funding this trip). Several downward opening hyperbolae are very obvious. Set `hypfit='Y'` and vary the dielectric constant to fit a calculated hyperbola to one in the data. If you want to test different values you don't need to rerun the program, but can just use the Command Window to type
`epsr=15; hyperbolafit`
(this selects $\epsilon_r = 15$, change this value to your choice) which will allow you to add another hyperbola to the existing figure until you are satisfied with your result.

C. Working with your own data

At this time the `gpr_start` script reads .DZT data files collected with the GSSI SIR-3000 unit.

8 SIGkit seismic refraction activity

By the end of the SIGkit refraction activity you should be able to
- link travel time curves to ray paths for the horizontal 3-layer case,
- recognize that layers may remain "hidden", and
- determine a plausible subsurface model from first breaks.

A. Modeling

Script `seis_refrac_main` allows you to model travel times for the horizontal 3-layer problem. Parameters you specify are the seismic velocities in array `V` and the thickness of the top two layers in array `H`. You can also specify the locations of geophones (for example `X=0:4:48` means that geophones will be placed every 4 m from 0 to 48 m) this will show as vertical gray lines overlaying on the resulting travel time curves. If you want to highlight the first arrivals at those geophone locations you can set parameter `show_arrivals='Y'`. An example of the output is shown in Figure 7, with the top panel showing the travel time curves and the bottom panel indicating the ray paths between shot at zero distance and the geophones.

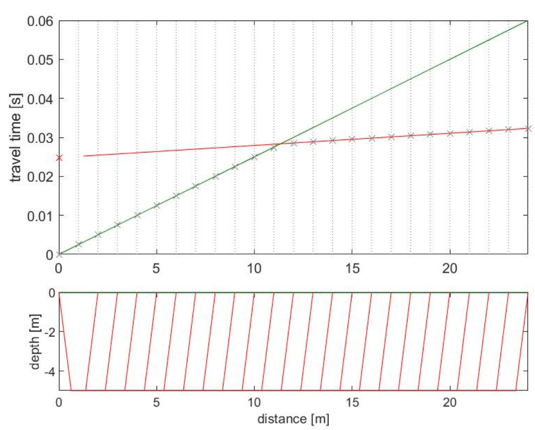

Figure 7: Example of seismic modeling; calculated travel time curves in top panel, and corresponding ray paths at the bottom.

a) We start with a two layer case. Think of a scenario (eg, loose sediment on bedrock) and choose reasonable values for thickness of the top layer and velocities of both layers. If you run the script the direct arrivals will fall along the line marked in green, while the refracted arrivals fall along a line marked in red. This red line will not start at zero distance, but at the critical distance where refracted waves first reach the surface. The x on the time axis marks the intercept time.

b) Change the thickness of the top layer, and the velocities and see how the result varies. Summarize it as a sketch and in words.

c) For a given scenario change the distance between geophones. How close would you suggest to space them in your example to be able to determine both velocities?

d) You will now explore a 3-layer case. To create a model select the thicknesses for the top two layers in array H and the three velocities in array V. As a starting example you may try V=[400 1100 3200]; H=[2 5]; X=0:1:24; which could represent an aquifer (middle layer) between loose sediment and bedrock. The refraction from the bottom interface is shown in blue on both panels (travel time starting at critical distance on top, ray paths on bottom). Change the thickness of the middle layer and notice that as it becomes thinner its travel time may not be noticeable in the first arrivals, either because your geophones are spaced too far apart, or because it never is a first arrival!

B. Analysing data

Students recorded two sample seismogram sections at Bestwood near Kathu, South Africa, in 2014 (with funding from the U of T Faculty of Arts % Science Research Excursions Program as well as the brazilian Sciences without Borders program). Geophones were spaced 2 m apart, the geology of the site is loose Kalahari sand on top of banded iron formation.

a) To see one of the sample sections copy and paste:

```
% read in data file
[traces,header] = seg2load('data_samples/2014-06-24_301.dat');
```

if you get an error at this point, retype the apostrophes in this command

```
dt=header.tr.sampling(1);   % find sampling interval in header
% show wiggle traces (first 400 samples)
figure; wiggleplot(traces(1:400,:)',0,dt,[2:2:48],1,3);
```

and to overlay the students' picks for this shot's first breaks do:

```
% read file with picks
fid=fopen('data_samples/2014-06-24_301_picks.txt','r');
C=textscan(fid,'%f %f \n','headerlines',3);
X=C{1}; T=C{2}; % extract variables for distance and time
hold on; plot(T,X,'r+');  % show saved picks
```

b) Use the script you worked with in 1 to determine velocities and thicknesses of subsurface layers that match your data. As a strategy we suggest you work from the top down: match the direct wave arrivals first, then the velocity of the second layer, followed by its thickness, then move on to the third layer (if you think there is one). Aside: If your travel times are shown at negative distances try toggling the `reverse_shot` parameter. The modeling script assumes that the shot is at zero and geophones set in positive direction...

c) File `data_samples/2014-06-24_315.dat` used the same geophone layout, but with the shotpoint at the opposite end. Run script `seis_pick` to determine first breaks for this shot (these will be written to a file called ”picks.txt”) and find a best-fitting model as in b. Because this is a reverse shot from the other end of the line, remember to set `reverse_shot='Y'` in `seis_refrac_main`

C. Working with your own data

The data you analysed in B was recorded by a Geometrics Geode, but the `seis_pick` script should also work for other data recorded in the SEG2 format. If you have first breaks you can write them in the same format as the text file created in B and try to match a model.