Appendix – ExploreDAS Software Documentation

Open source is about collaborating; not competing. – Kelsey Hightower

In open source, we feel strongly that to really do something well, you have to get a lot of people involved. – Linus Torvalds

A. ExploreDAS – an open source software package

Software applications are a key part of a scientist's and engineer's toolbox allowing them to stand on the shoulders of those who have gone ahead of them and apply their learnings to new problems. I developed this open source, MATLAB graphical user interface software package, called ExploreDAS, for this course to help you build a more intuitive understanding of the strengths and potential weakness of DAS seismic data acquisition and processing. The software allows you to quickly build a geologic structure, perform forward modeling to obtain seismic data, and create a migrated image with that data. It is available for download from this link: DOI: XXXXXX

My objective in writing this software is to allow you to develop an intuitive understanding of DAS data sets and to compare them with equivalent geophone data. Some of its characteristics are:

1. Creating structures, fiber geometry, and shot locations is extremely easy.
2. Layers with any arbitrary geometry can be formed.
3. It has two velocity options – constant or v(z).

4. Each layer has the same reflection coefficient.
5. It creates geophone data and the corresponding strain rate data.
6. Only straight fiber is modeled with the software (no helically wound fiber).
7. The gauge length can be changed as desired.
8. The P- and S-waves are modeled separately.
9. It uses a very simple Kirchhoff migration algorithm to form the migrated images.

Several disclaimers to note:

1. I don't claim that the amplitudes are totally accurate – but were created to be sufficient for teaching purposes.
2. Many better modeling and migration algorithms are available for purchase from vendors – but this one is free for you to use.
3. To evaluate an actual acquisition project, I strongly recommend using a professional modeling and migration package to be able to capture the complex velocities and amplitudes of your geologic environment.

An example of the starting user interface is shown in Figure A.1. It is divided into seven panels, each providing control of the modeling and migration features. The Model panel allows the dimensions of the model and the velocity information to be entered. The Well panel allows for the geometry of the borehole or surface fiber to be entered. The Reflector panel allows for the subsurface layers to be defined and controlled. The Simulation panel controls the forward modeling parameters of the source, wave types, gauge length, and trace sampling information. The

Noise panel allows the forward-modeled data to be displayed and various levels of noise to be added to the data. Finally, the Migration panel allows the modeled data to be migrated.

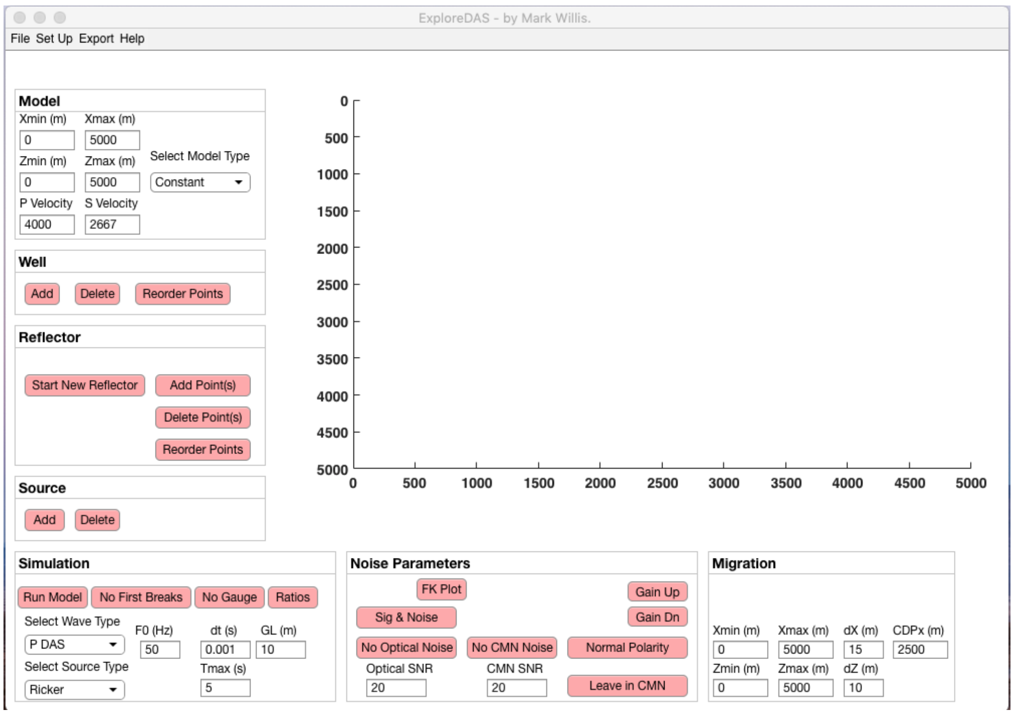


Figure A.1 The opening user interface for ExploreDAS

A.1. Creating a model

After launching the ExploreDAS application the first task is to set the data directory where all of your modeling results will be stored. In Figure A.2 the “File” menu item has been selected showing the “Set Data Directory” option.

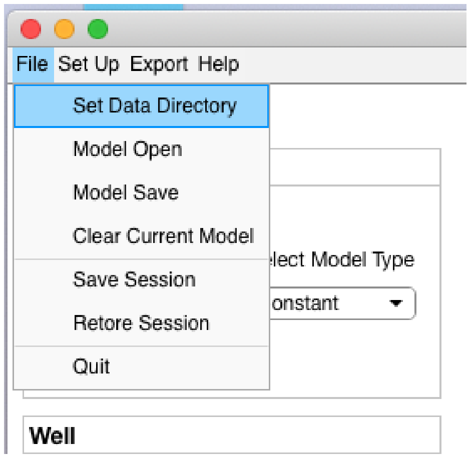


Figure A.2 File menu drop down showing how to set the data directory.

If you have already used ExploreDAS and saved a velocity model, the you can open the saved model from the File menu drop down Model Open, as shown in Figure A.3.

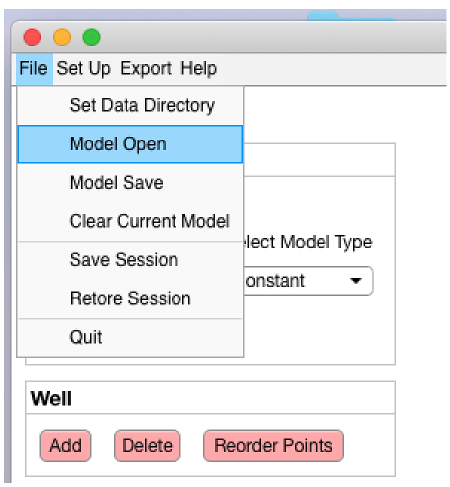


Figure A.3 File menu drop down showing how to read in a model already saved on disk.

If you want to start a new model from scratch, then enter the model dimensions in the Model panel, as shown in Figure A.4. The Xmin and Xmax editable fields set the lateral size of the model. The Zmin and Zmax editable fields set the depth range of the model. Both of these units are in meters.

The drop down selection box entitled “Select Model Type” allows you to select whether the velocity model will be constant or have a vertical gradient. When the “Constant” model type is selected, then the two fields labeled “P Velocity” and “S Velocity” allow you to set the constant velocity of the model. The units are in m/s.

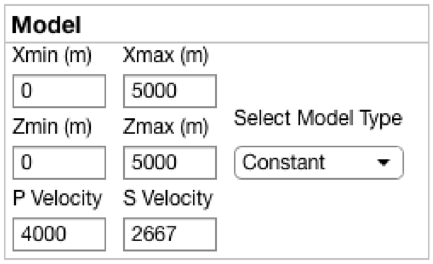


Figure A.4 Model panel allowing the size of the model and velocity information to be set.

However, if you select the “Gradient” option, then a different set of editable fields are displayed as shown in Figure A.5. In this display the “Vp0” and “Vs0” fields show the initial velocity of the model for the P- and S-waves, respectively, of the at depth = 0 m. The velocity gradient, kZ, is set in the corresponding editable field with units of 1/s.

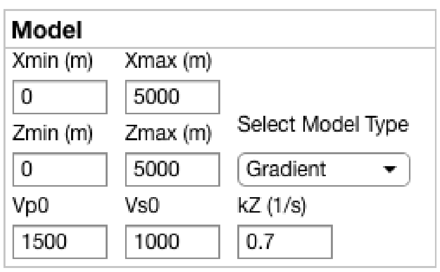


Figure A.5 Model panel allowing the velocity gradients to be set.

A.2. Defining the well geometry

The Well panel allows you to create the trajectory for the fiber and geophone sensors. The geometry can be completely arbitrary. This means the "well" can be along the surface of the ground, or in the subsurface along a path that you digitize. You start by pushing the "Add" button in the Well panel, shown in Figure A.6.

Figure A.6 The Well panel.

After the "Add" button is pushed, you can start to digitize the well path by depressing the left mouse button at the locations in the model you would like to cover, as shown in Figure A.7. The label at the top of the model gives you directions on how to digitize the model. Right mouse button click (anywhere in the model) when you are finished digitizing the well trajectory. (The right mouse button click is one of those things users tend to forget which leaves the well trajectory incomplete.)

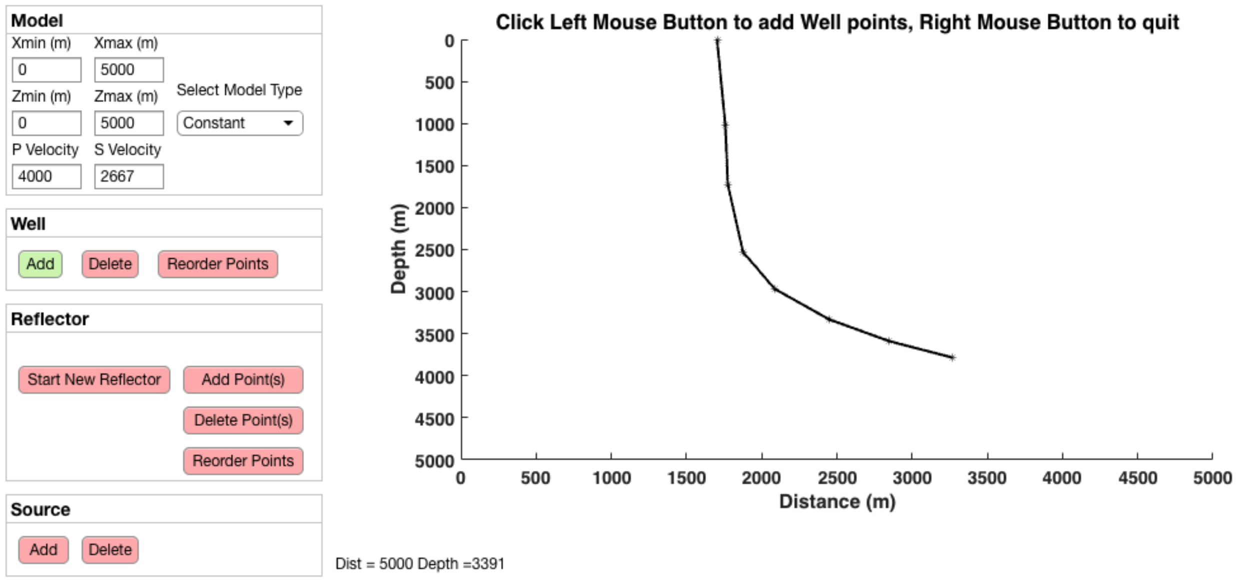


Figure A.7 The user interface while the well path is being digitized after pressing the "Add" button.

If you want to make a correction you can press the "Delete" button and where ever you click, it will search for the nearest point and delete it. On the other hand, if you want to insert some more points, you can press the "Add" button again in the Well panel and start digitizing. When all the new points have been digitized, remember to Right Mouse Button click to stop adding points. The new points will be added after the last point that was digitized which will likely not be what you want to have happen, as shown in Figure A.8.

However, if you push the "Reorder Points" button, the digitized points will be reordered by sorting them starting with the first point originally digitized and then finding the nearest digitized point one after each other, as shown in Figure A.9.

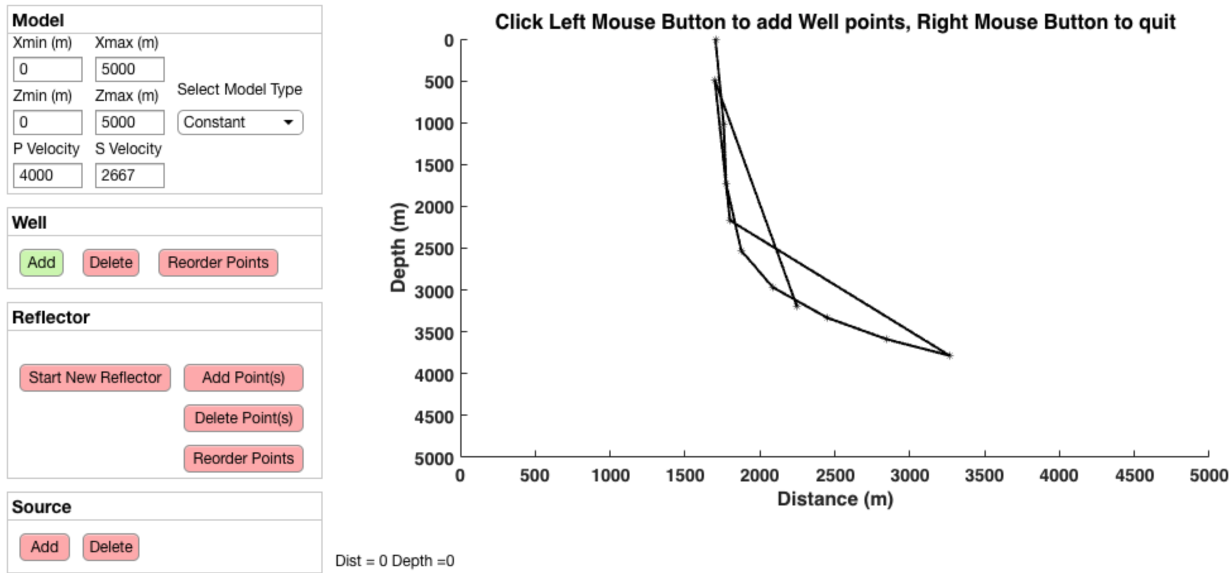


Figure A.8 The well trajectory after inserting 3 new points – this will require the "Reorder Points" button to be pressed to put them into a reasonable order.

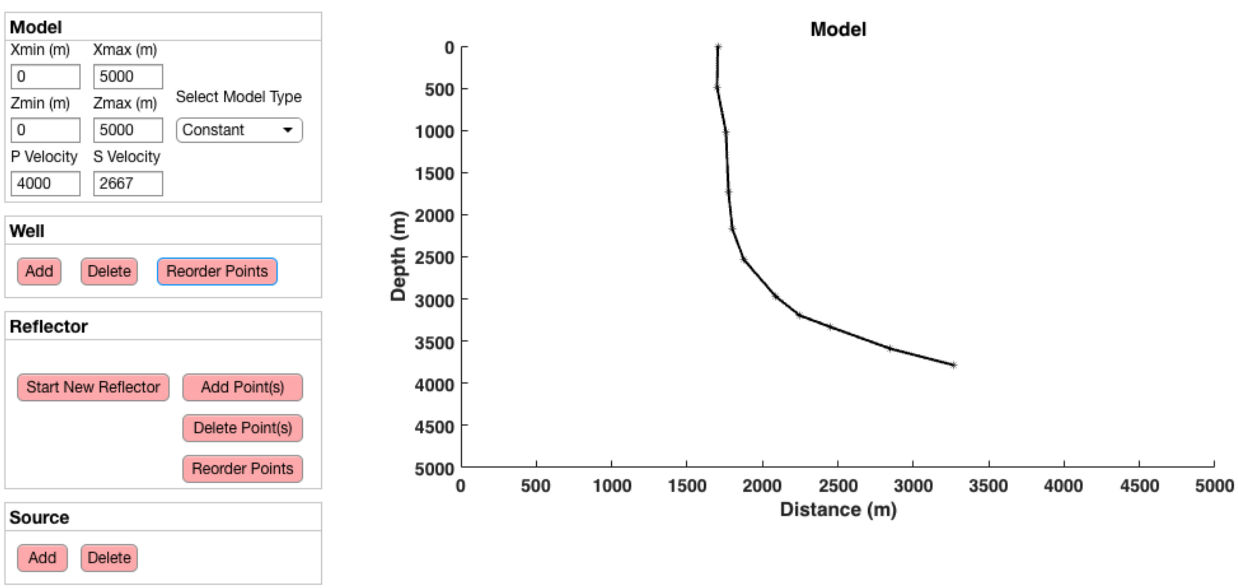


Figure A.9 The well trajectory after pressing the button "Reorder Points" in the Well panel.

The digitized points for the well trajectory can be of arbitrary spacing and the code will perform linear interpolation between the digitized points with a new spacing of 10 m when it is used for computing the seismic traces.

A.3. Creating the reflector geometry

Next the reflections are created. Note again that the model is either a simple constant velocity or simple linear gradient in depth. Therefore, there is no contrast in impedance – meaning that the reflections are all of the same amplitude and only the kinematic (arrival times) are correct. To add the first layer, push the "Start New Reflector" button in the Reflector panel. When this button is pushed it creates a new layer, for first time it is labeled "1" as shown by the drop down menu in the Reflector panel, as shown in Figure A.10.

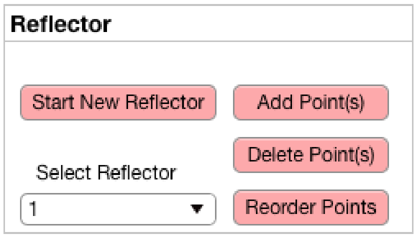


Figure A.10 Reflector panel after pushing "Start New Reflector" button and the first reflector is populated in the drop-down list.

To digitize points for this reflector, push the "Add Point(s)" button and digitize as shown in Figure A.11, like you did for the well trajectory. Note that the current reflector being digitized will show as a blue line with the red asterisks as the digitized points. Remember again to finish digitizing by right mouse button clicking.

To add a new reflector, push the “Start New Reflector” button and repeat the operations just described.

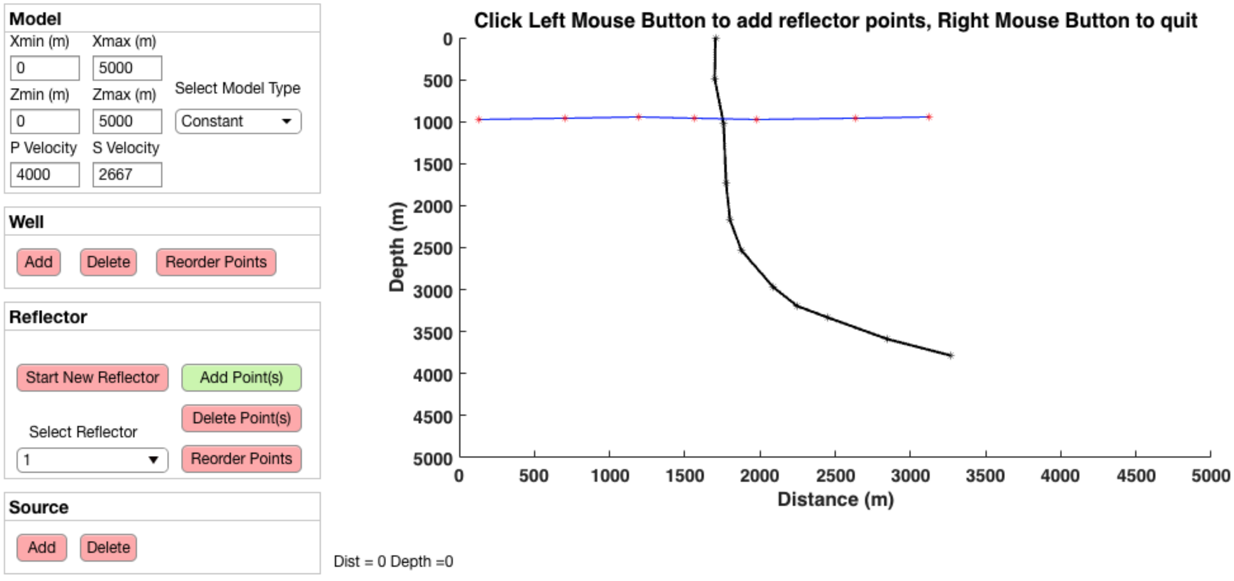


Figure A.11 The first reflector is being digitized.

You can modify the reflector points by first selecting the reflector number you want to modify in the drop-down list in the Reflector panel. Then, as you did with the well trajectory editing, push the “Delete Points(s)” button in the Reflector panel to remove unwanted points. New points can be added by pushing the “Add Points(s)” button and digitizing again. Pushing the “Reorder Points” button will again sort the reflection points into the best reasonable nearest neighbor order. Figure A.12 shows the result of adding 5 reflectors to the model.

The geometry of the reflectors you create is completely arbitrary. The layers do not have to extend across the entire model. They can cross each other and have any geometry. Of course, the more crazy you make the layers the less realistic the modeling results will be.

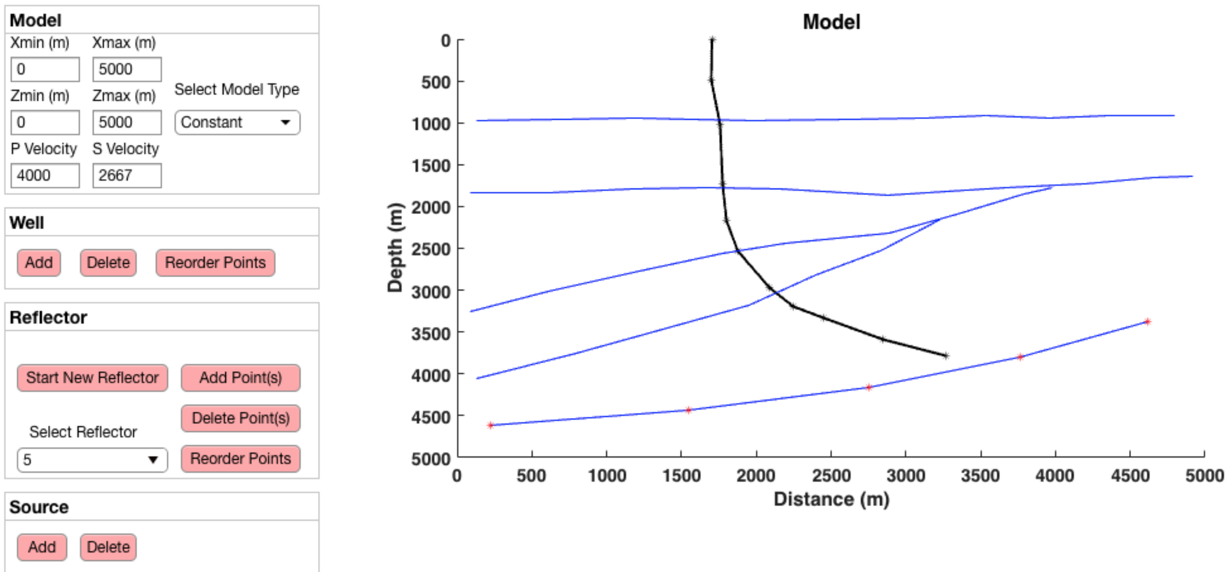


Figure A.12 The geometry of the well trajectory and reflectors after entering 5 reflectors.

A.4. Creating the source geometry

Next the locations of the seismic sources are entered. You can have one or any number of sources. To create a source location, push the "Add" pushbutton in the Source panel. Then digitize wherever you want a source to be located. As before, remember to right mouse button click to stop entering in source locations. You can delete individual source locations by pushing the "Delete" pushbutton in the Source panel. Figure A.13 shows an example of 3 source locations digitized, as indicated by the red asterisks.

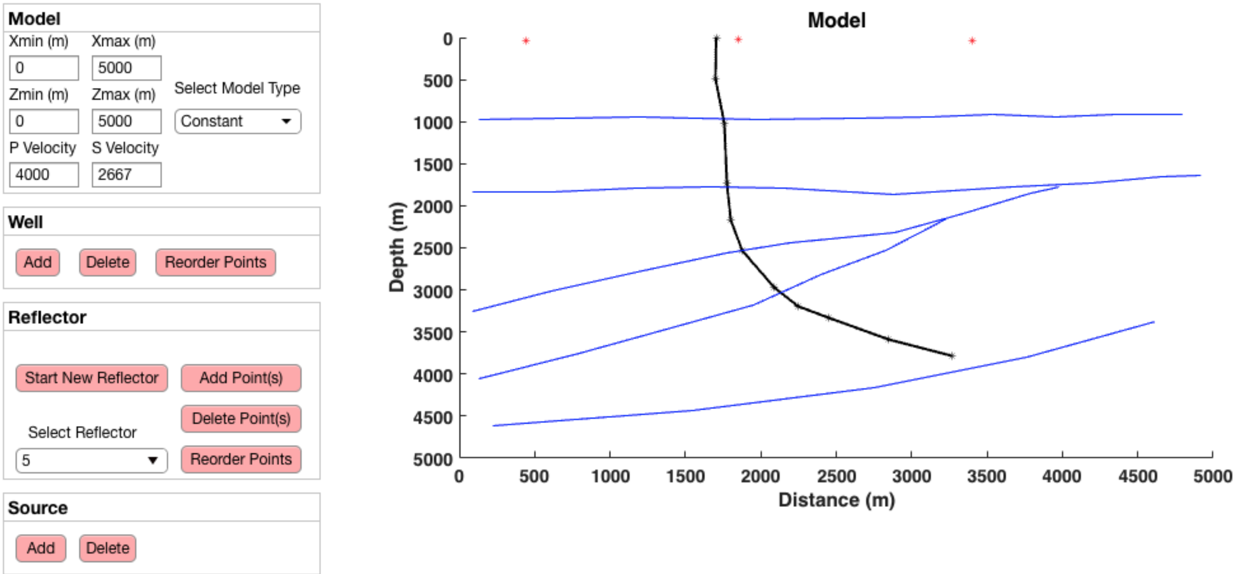


Figure A.13 Model after the well, reflectors, and 3 shot locations have been digitized.

A.5. Digitizing from an image

I've described how you can create a model using "free hand" digitizing. However, if you have an image of a model or seismic section, you put that behind the model you are creating. To import a jpeg image, select the "Read in Image Behind Model" option from the "Setup" menu as shown in Figure A.14. It will ask you to select an image to import. It then reads in that image, displays it in a new figure, as shown in Figure A.15, and asks you to digitize the upper left corner, then the lower right corner, corresponding to the dimensions of the model you have specified in the Model panel.

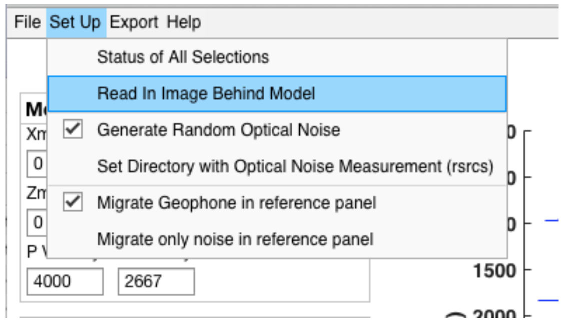


Figure A.14 Use the "Read In Image Behind Model" menu option to import an image to add in creating the model.

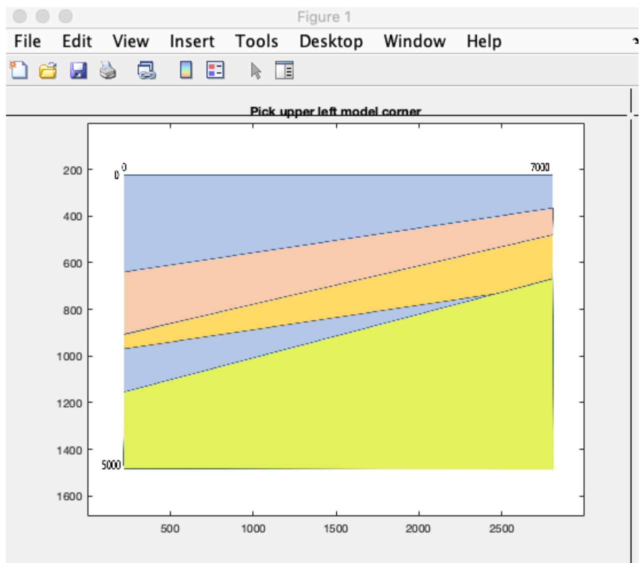


Figure A.15 After you select a jpeg file to use as a background, a new figure appears for you to digitize the upper left corner and lower right corner of the image corresponding to your model limits.

The model will appear in the user interface, as shown in Figure A.16, and you can start to create the Well, Reflector, and Source geometries. You can toggle off and on the image behind the geometry by pushing the "No Image" button in the Model panel.

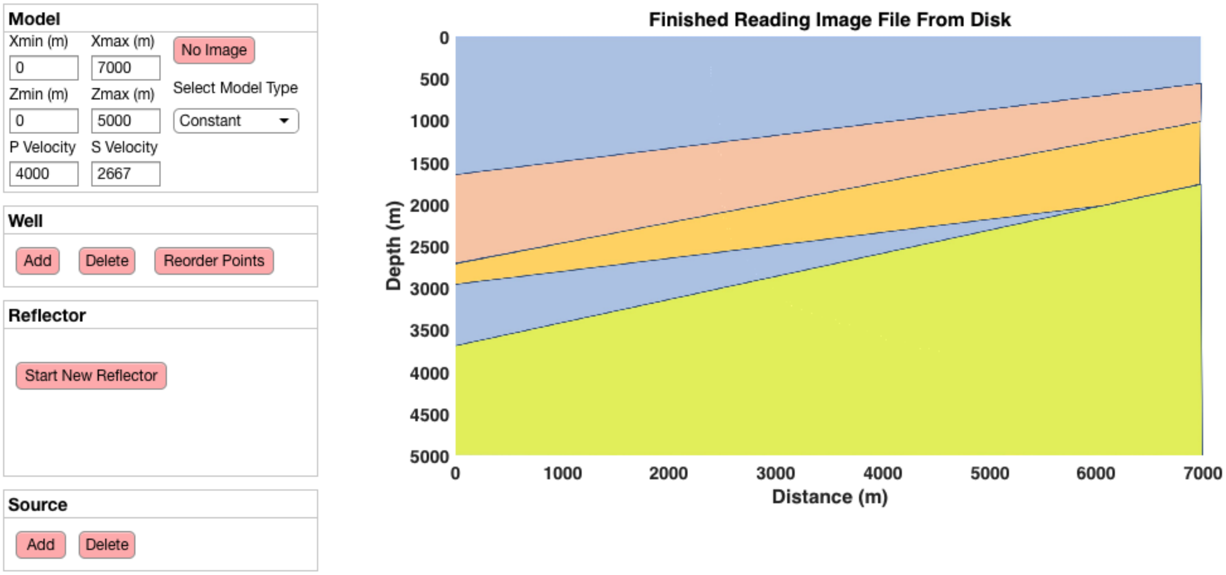


Figure A.16 User interface after reading in a background image.

A.6. Creating shot records

Next you will want to create shot records for the model you have built. The Simulation panel provides choices for the forward modeling. The bottom left drop-down provides a choice of using a Ricker or Klauder wavelet. The Ricker wavelet has only one parameter and that is the center frequency of the source wavelet. For the Klauder wavelet, there are two parameters – the lower and upper frequency limits. The Klauder wavelet is broader band but has ringing side lobes. So, for "pretty" clean-looking data choose a Ricker source. But actually, the Klauder wavelet is more representative of a broad-band vibrator source.

You set the sampling interval of the seismic trace using the "dt" parameter specified in seconds. Most surface seismic data is recorded at 2 to 4 milliseconds. Most VSP and microseismic data is recorded at 1 millisecond or smaller sampling interval. Thus providing a “dt” value of 0.001 s is a good compromise. The value of “Tmax” is the maximum time length of the seismic record in seconds. The value you want depends upon the velocities you choose, the depth of your model, the offset of your sources, the if you have surface or VSP type well geometry.

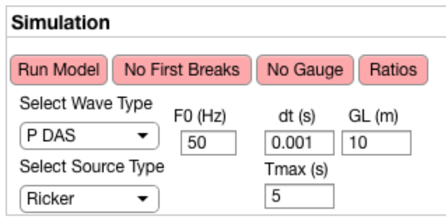


Figure A.17 The Simulation panel

The GL parameter is the gauge length in meters. You will most likely want to test several different values to see what its effect will be on your data.

Across the top of the Simulation panel are four buttons. Pressing the “Run Model” button will start the forward modeling job. The “No First Breaks” button allows you to remove the first break events from the seismic record by not simulating the direct arrival. This is useful because for migration of field data you usually want to remove the first breaks. The label on the button indicates whether the first breaks are being removed or included. If it is red and reads “No First Breaks” the first breaks will not be computed. If you toggle it to green is now reads “First Breaks” and the shot records will contain the first breaks.

The next button is labeled “No Gauge”. In this state it means that no gauge length will be applied to the shot records. It will have the appropriate angle of incidence response for fiber but not the gauge length. By toggling this button to green the label will now read "Use Gauge" and the seismic data generated will have the gauge applied. The editable field entitled "GL (m)" allows you to specify the desired gauge length.

The drop-down labeled "Select Wave Type" allows you to select the type of seismic data you want to create. The "P DAS" and "S DAS" options creates the P-wave and S-wave responses for a DAS sensor, respectively. The "P Vertical" and "S Horizontal" provide the single component geophone response.

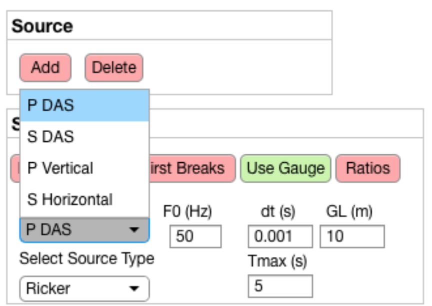


Figure A.18. The Select Wave Type drop-down list providing the choice of response to model.

For this example, we will select the P DAS wave type, a Ricker wavelet, 70 Hz, use a 10 m gauge length, and the maximum time (Tmax) as 2.5 s. After you push the "Run Model" button in the Simulation panel, two windows will pop up. The first window will contain the shot record images. The left image will be of the reference P-wave response, similar to a geophone response, and the right image will be the P-wave DAS response, as shown in Figure A.19. The second window will display one trace from geophone and DAS records on top of each other for comparison, as shown in Figure A.20.

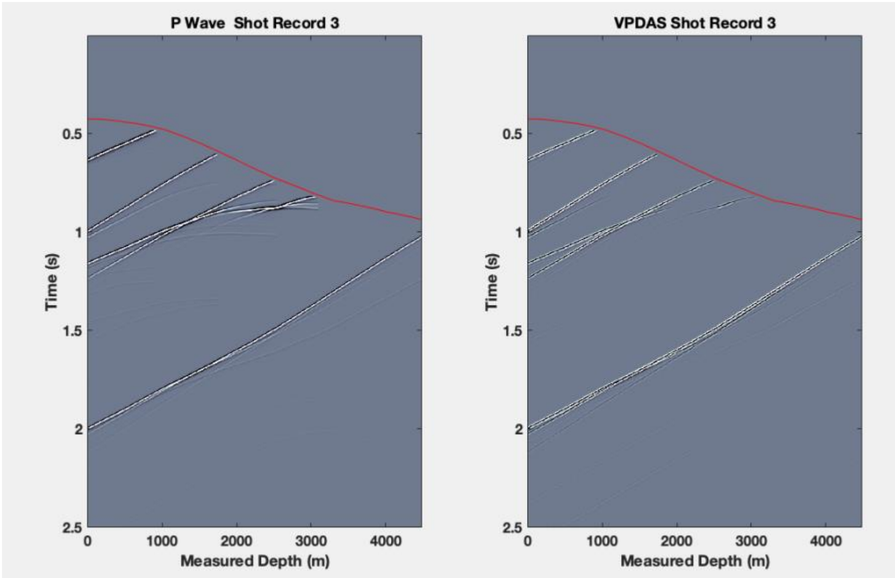


Figure A.19 A P-wave seismic shot record modeled for (left) geophone, and (right) DAS.

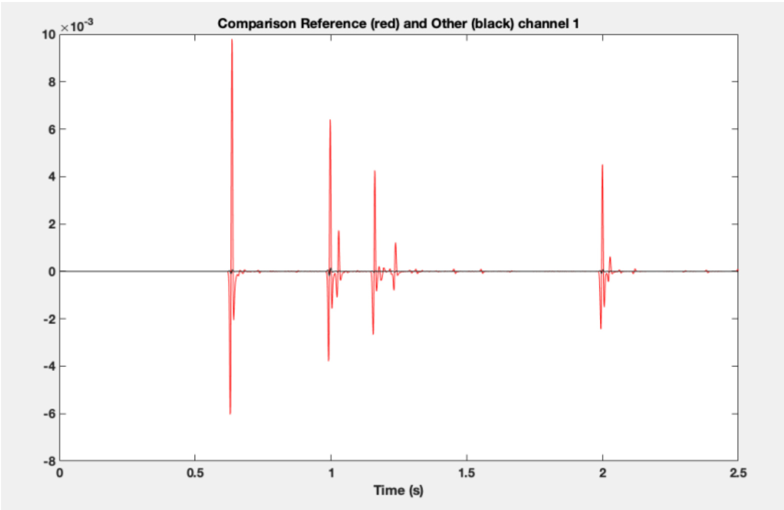


Figure A.20 Single trace comparison of the geophone (red) and DAS (black) simulations.

A.7. Viewing the shot records and adding noise

Once you have created the shot records by pushing the "Run Model" button in the Simulation panel, the Noise Parameter panel will fully populate with the options as shown in Figure A.21.

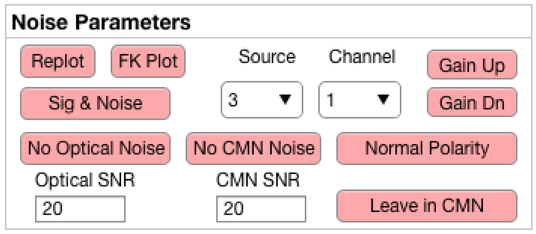


Figure A.21 The fully populated Noise Parameters panel.

From the Source drop-down list you can select the source number and the channel number from the Channel drop-down list. Once they have been selected, push the “Replot” button and the same two figures, as in Figures A.19 and A.20, will appear again. You can increase or decrease the plot gain by pushing the “Gain Up” or “Gain Dn” pushbuttons.

You can add simulated optical noise to the DAS data by toggling the “No Optical Noise” button to “+ Optical Noise”. Below that button is an editable field with a title “Optical SNR” where you can specify the amount of optical noise to add in dB. In a similar fashion you can add common mode noise (CMN) to the DAS data by toggling the “No CMN Noise” to “+ CMN Noise”. Below that button is an editable field entitled “CMN SNR” where you specify the amount of common mode noise to add in dB. Figure A.21 shows the shot records after adding both optical noise and common mode noise. You can remove the common mode noise via processing, like you would for field data, by toggling the “Leave in CMN” to “Remove CMN”.

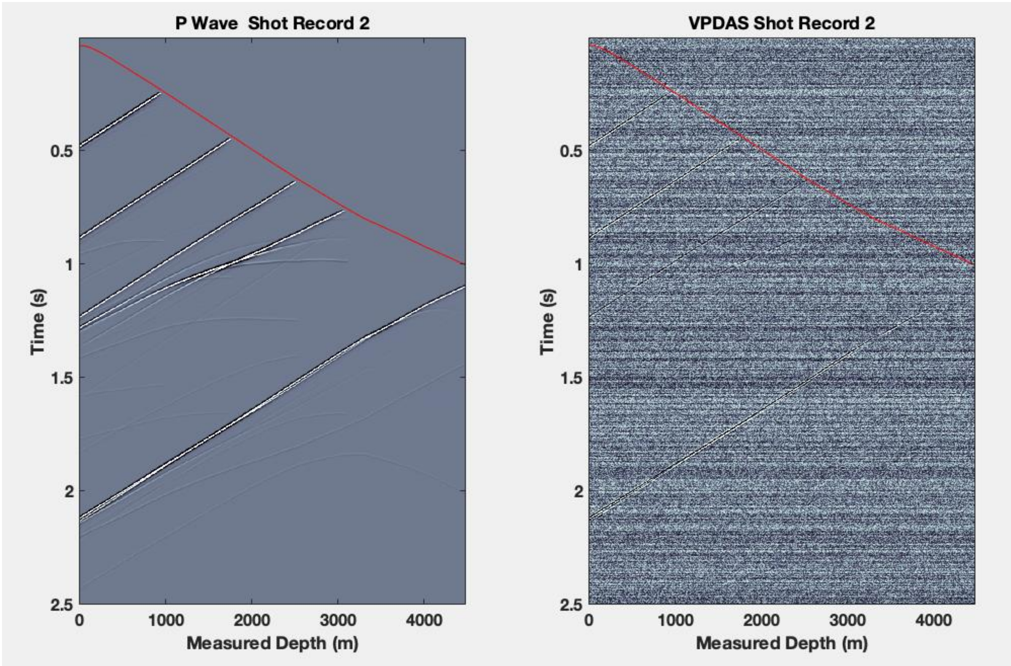


Figure A.22 Result of adding optical and common mode noise to the DAS record (right).

The polarity of the DAS record can be reversed by toggling the “Normal Polarity” push button to “Reversed Polarity”. Another option available is to only plot the noise in the DAS data and not include the modeled DAS record. This is performed by toggling the “Sig & Noise” push button to “Noise Only”. The final option in the Noise Parameters panel is the “FK Plot” push button. If you depress this button it will display the FK transform of the geophone and DAS records in new figure windows.

A.8. Migrating the data

The final step is to see the quality of the migrated image created from your modeled shot records. Figure A.23 shows the Migration panel. The first step in performing a migration of the data is to define the output image location and spacing. The editable fields labeled “Xmin (m)”, “Xmax (m)", and "dX (m)" allow you to define the starting and ending lateral positions, as well as the trace spacing. The editable fields labeled "Zmin (m)", "Zmax (m)", and "dZ (m)" allow you to define the starting and ending depth positions, as well as the trace depth sampling interval. Depending on the frequency content of the source you have chosen, you need to select depth sampling interval (dZ) to be small enough to capture an unaliased signal. A good rule of thumb is to use Equation A.1 to pick dZ.

$$dZ < \frac{2.5C_{min}}{f_{max}} \qquad \text{Eq. A.1}$$

Where C_{min} is the minimum velocity in the model, and f_{max} is the maximum frequency of the source wavelet. For a Ricker wavelet f_{max} can be set at twice the center frequency of the wavelet. For the Klauder wavelet, the specified maximum frequency can be used.

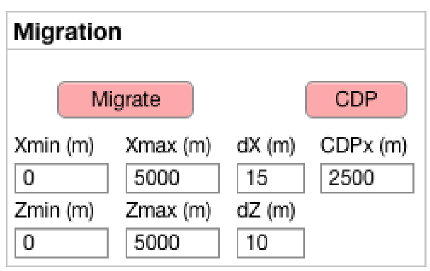


Figure A.23 The Migration panel.

You start the migration process by pushing the "Migrate" pushbutton. All of shot records will be migrated. As each record is used, it will be shown in a new figure and the intermediate results will be displayed. When the migration has finished, the final images will be shown as in Figure A.24.

You can also create a migrated common depth point (CDP) gather. You specify the location of the CDP using the editable field labeled "CDPx (m)". The migrated results for each shot will be created for this CDP location and displayed as a gather, as shown in Figure A.25.

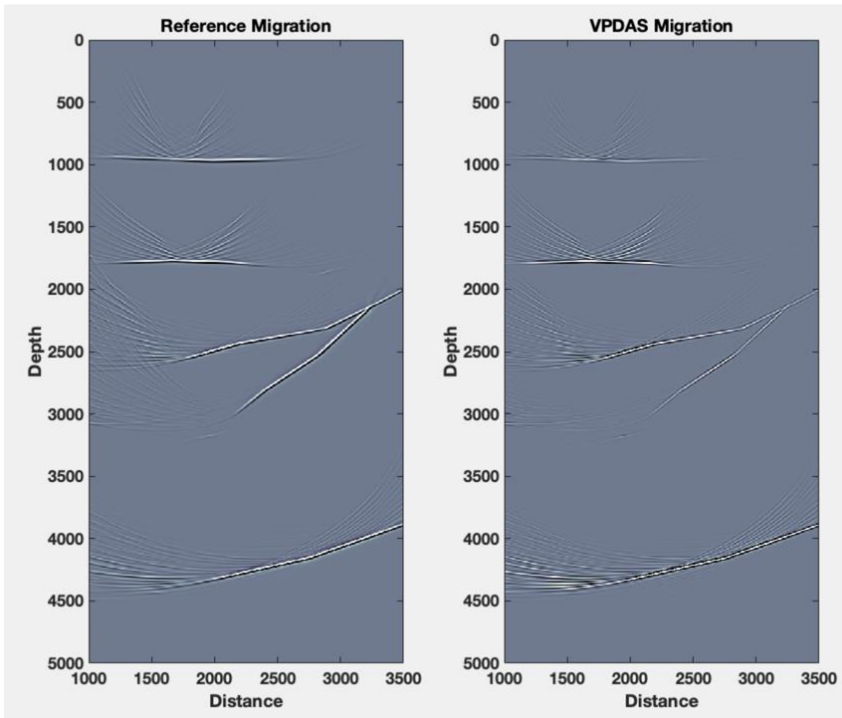


Figure A.24 The migrated results of 12 shots for (left) the geophone data, and (right) DAS data.

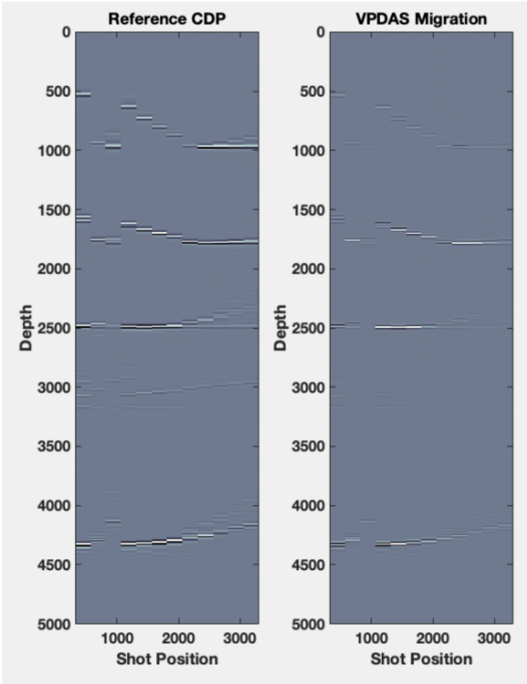


Figure A.25 Migrated CDP gather for (left) geophone, and (right) DAS data.

A.9. Saving the results

There are several ways to save your work in ExploreDAS. The first option is to save your model. This is done by selecting the “Model Save” option in the “File” menu drop-down, as shown in Figure A.26. You then select the directory for storing the model in JSON format using the file name you choose. If you want to start again later with this model, simply start up ExploreDAS and select the “Model Open” option in the “File” menu. Then select the JSON formatted file you created with the model.

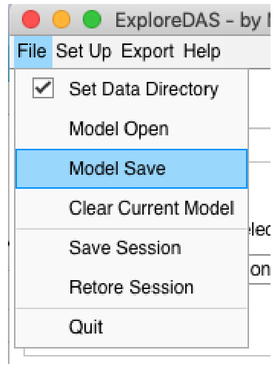


Figure A.26 The "Model Save" option will create a file with your model.

To save your current working session environment, select the "Save Session" option in the "File" menu. You can restore your session at a later date by selecting the "Restore Session" option in the "File" menu and then opening the file you saved in the previous step.

An easy way to summarize the work you've done and view the settings you have made is to select the "Status of All Selections" option from the "Setup" menu option, as shown in Figure A.27. After you make this selection a new window will appear that summarizes all of your work, as shown in Figure A.28.

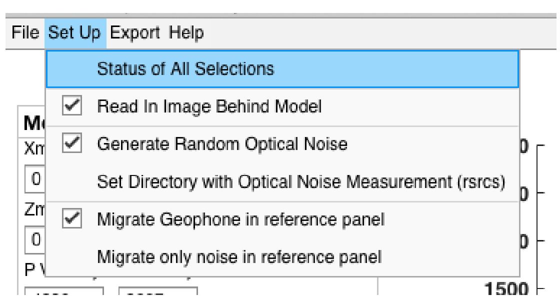
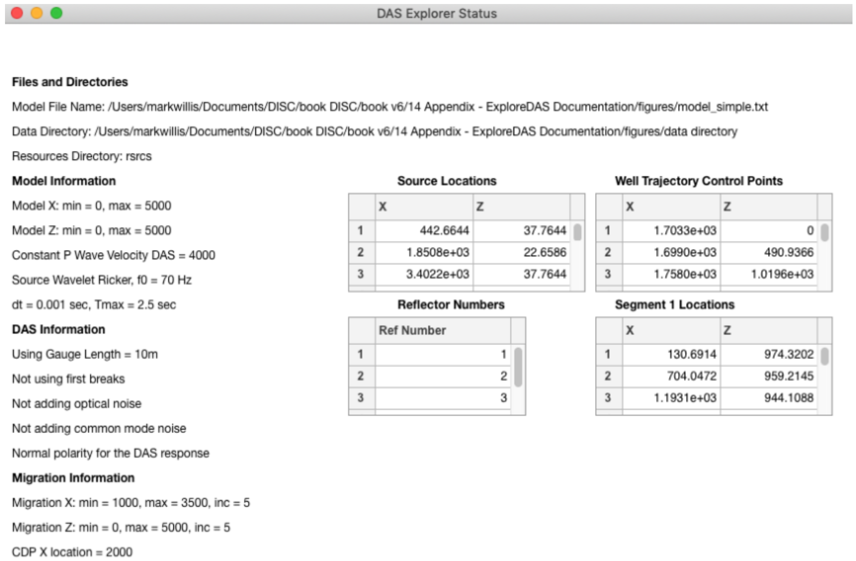


Figure A.27. Status of All Selections menu option.



Source Locations

	X	Z
1	442.6644	37.7644
2	1.8508e+03	22.6586
3	3.4022e+03	37.7644

Well Trajectory Control Points

	X	Z
1	1.7033e+03	0
2	1.6990e+03	490.9366
3	1.7580e+03	1.0196e+03

Reflector Numbers

	Ref Number
1	1
2	2
3	3

Segment 1 Locations

	X	Z
1	130.6914	974.3202
2	704.0472	959.2145
3	1.1931e+03	944.1088

Figure A.28. The window showing all of your selections for this session.

Another option is to export the modeled data either to MATLAB or SEGY formatted files. (For writing SEGY formatted files, I've used the open source release of SegyMAT 1.5.1 available from https://segymat.readthedocs.io/en/latest/ written by Thomas Mejer Hansen. I am very grateful for Thomas making his software freely available as it has proven extremely useful for many of my projects.) To export the shot records, migrated images, and/or CDP gathers select one of the options on the "Export" menu drop-down list, shown in Figure A.29.

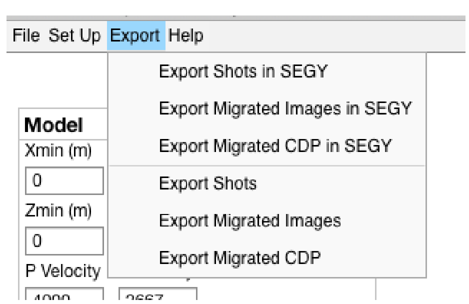


Figure A.29. Use the "Export" menu to write out the data sets in either SEG or MATLAB formats.

A.10. Theory behind the modeling

If you have made it this far in the documentation – I commend you. In my experience most users are way too happy to use software without reading the directions and are loath to trudge through the documentation. Hopefully you have found the user interface of ExploreDAS to be intuitive enough that you can build models easily and explore how DAS data sets are useful. However, if you find yourself reading this section, I'm guessing that you have decided that you are questioning the validity or wanting to know the limitations of this modeling and migration software. So, I'll explain how the software does what it does.

A.10.1 Model well trajectory

You may have noticed that the well trajectory is completely arbitrary. The well can make loop to loops and sharp turns as shown in Figure A.30. The points you digitize are used on the fly, to interpolate to a more finely spaced depth interval. However, there is no smoothing or curve fitting through the points thus there will be some artifacts in the data created with crazy geometries like the one shown in Figure A.30.

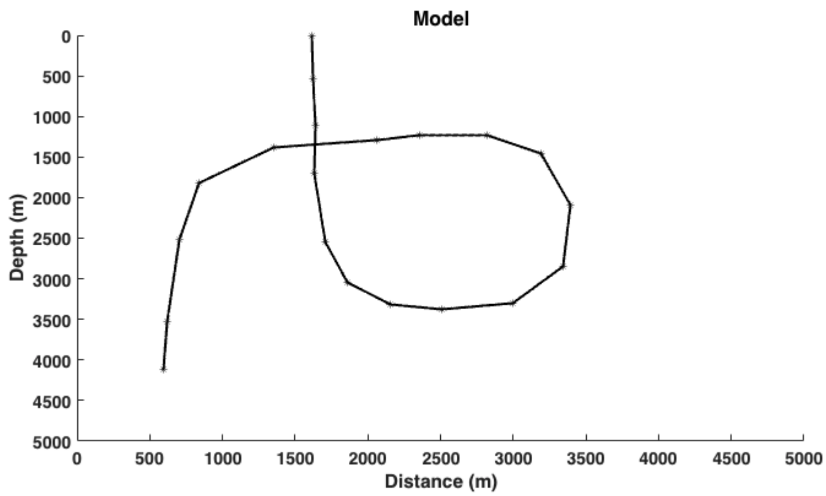


Figure A.30. Well trajectory that is absolutely unreasonable and crazy!

A.10.2 Model reflector geometry

In a similar fashion to the well trajectory, the reflector geometry is not enforced to be regular or conformal. The reflectors do not have to go from edge to edge of the model. The reflectors do not have to define enclosed regions. Because the velocity model is simple, either constant or v(z), the reflector positions just create locations that scatter (and reflect) the incident seismic energy. Figure A.31 shows a model with 3 simple planar layers and a crazy loop to loop layer. Before each reflector is used in the modeling, it is more finely interpolated so that there are many scattering points along it. Since the modeling is performed by scattering off of each of the reflector points, this means there will be artifacts generated from the first and last points of each reflector. Sharp corners will also cause scattering. The software does not attempt to correct or modify any of the features you put into the model. So your synthetic shot records will be just as valid as the model you create.

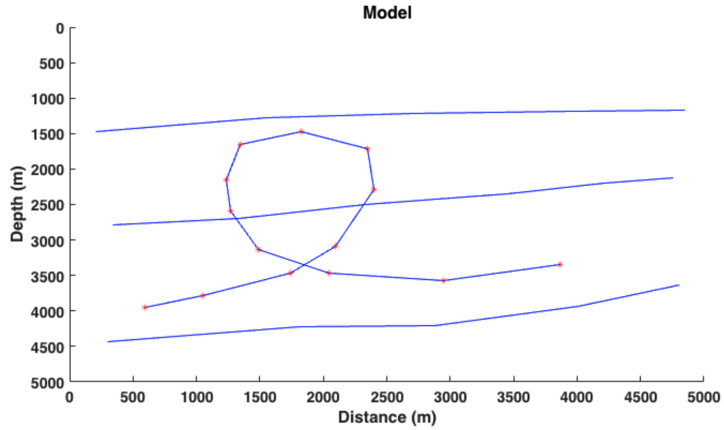


Figure A.31. A four-reflector model with one crazy reflector.

A.10.4 Generation of shot records

The geophone shot records are created by simple scattering of each point of the reflector (Willis et al., 2015). For a trace associated with a given pair of shot and receiver locations, the travel time is computed from the shot to a point on a reflector and then onward to the receiver. This travel time is used to delay the source wavelet and is summed into the trace. The contribution from each point along each reflector is added into the trace. The current code assigns the same, unity reflection coefficient for each reflector.

The vertical and horizontal geophone components, if selected for output from the drop-down list, are computed using the appropriate $\cos(\theta)$ (P-wave) or $\sin(\theta)$ (S-wave) weighting for the angle of incidence at the well.

To compute the DAS traces, the geophone response is computed for a pair of locations about the receiver (or channel) location space apart by the gauge length. Then the difference of the two traces are taken. Then the appropriate $\cos^2(\theta)$ (P-wave) or $\sin(2\theta)$ angle of incidence weighting is performed for the angle of incidence at the well.

A.11 Theory of migration

To create the migrated images, a simple Kirchhoff depth migration is performed (Hill and Ruger, 2019). I'll give an extremely quick overview of Kirchhoff migration. (Those new to migration will be totally confused, and those who are experts will be upset that I explained it poorly. Sorry to both groups! Hopefully somebody will be happy with my rapid explanation.) Each trace in the data set has a source position and a receiver location, as shown in Figure A.32. Each trace is migrated into the image separately. For each point in the migrated image, the travel time from the source to that image point (magenta line) is added to the travel time from that image point to the receiver (blue line). The sum of the two travel times gives the time in the trace (red arrow) from which is extracted the amplitude of the trace at that time. This amplitude value is added to the point in the evolving migrated image. Thus, each trace contributes to all samples in the migrated image. Constructive interference will reveal the reflectors in the subsurface. This is simplicity at its finest. I have not implemented any fancy weighting or filtering.

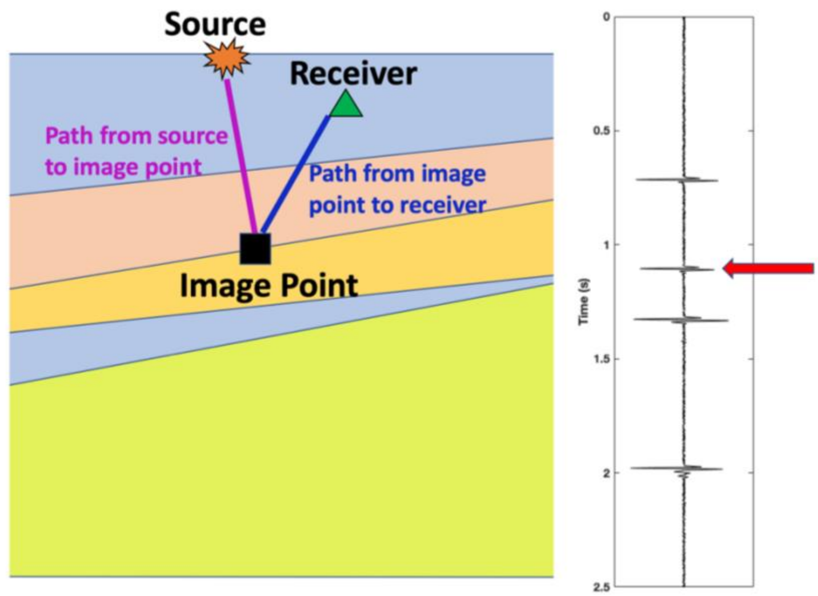


Figure A.32. (Left) The subsurface showing the geometry for a source (red), receiver (green), and image point (black). (Right) The seismic trace from this source and receiver location. The red arrow shows the computed time from the source, to an image point, and the to the receiver.

A.12 Summary

This open source software package is being freely provided to you with the desire that it proves useful and instructive. There are many improvements that could be made for example: adding ray tracing for more complex models, the addition of anisotropy, the addition of the response of helically wound fibers, etc. If you are so inspired, I hope you will take up the initiative and share your results. However, even in its current form I believe ExploreDAS will be sufficient for you to learn about the power that DAS data sets provide to learn more about the earth's subsurface.

A.13 References

Hill, S. and A. Ruger, 2015, Chapter 10: Kirchhoff prestack depth migration, in Illustrated Seismic Processing Vol 1: Imaging, SEG.

Willis, M., R. Foy, A. Padhi, and O., Barrios, 2015, A quick, flexible, layer-based VSP modeling algorithm, Geophysical Society of Houston presentation, 17 March 2015.