SeisImager/SW™ Manual

Windows™ Software for Analysis of Surface Waves

Pickwin v. 3.14
WaveEq v. 2.07

Manual v. 1.4

Including explanation of Geometrics Seismodule Controller Software
Surface Wave Data Acquisition Wizards

May 25, 2005

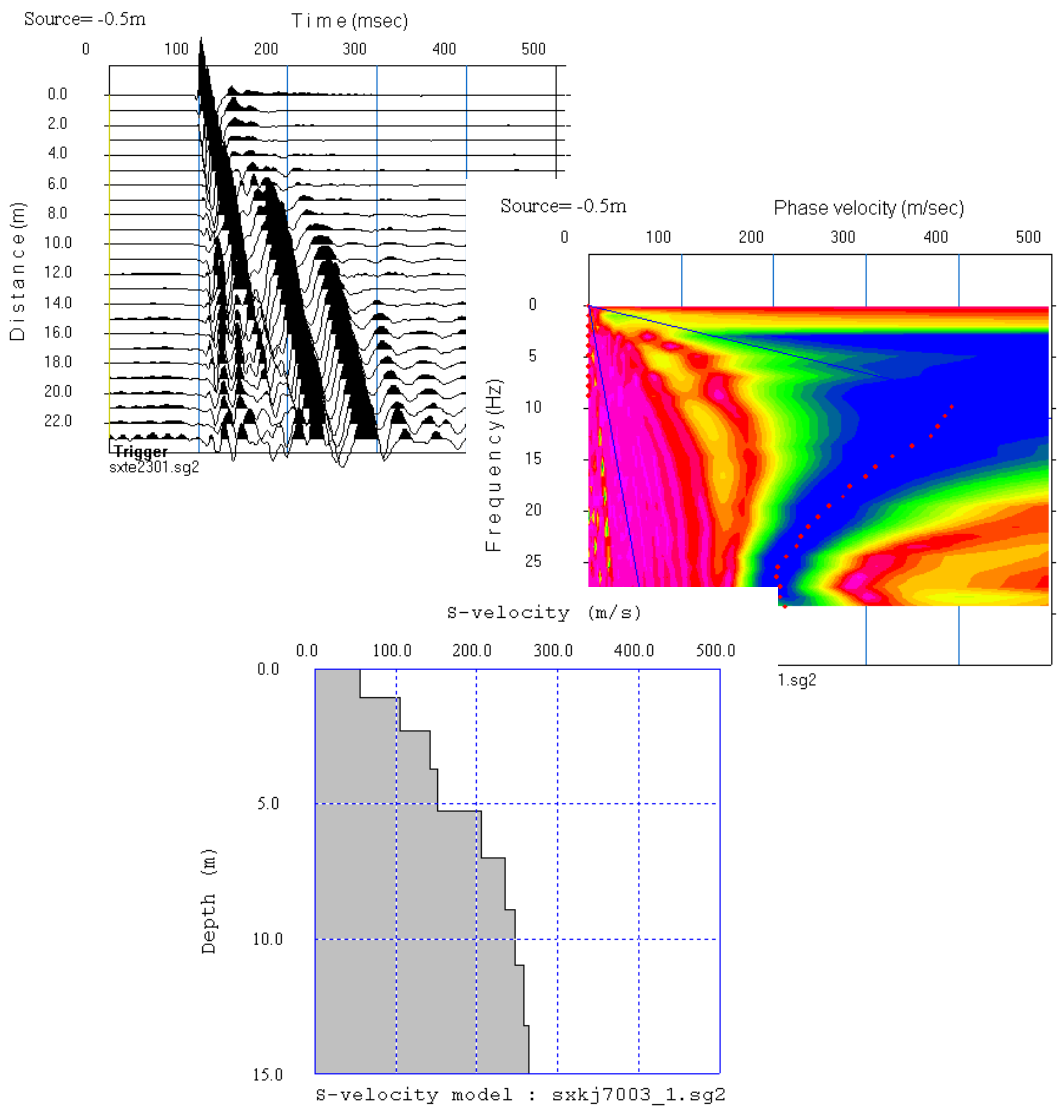


Table of Contents

1 Introduction

Welcome to SeisImager/SW™! SeisImager/SW is an easy-to-use, yet powerful program that allows you to analyze multi-channel active and passive source (micro-tremor) surface wave data. SeisImager/SW includes functions to perform the following basic procedures, and more.

- Read in and display your data.
- Control how your data is displayed.
- Make changes/corrections to your data files and save them.
- Calculate and edit dispersion curves.
- Invert your data for a one-dimensional shear wave velocity profile.
- Output the results in tabulated and graphical form.

SeisImager is the master program that consists of three modules for surface wave and refraction data analysis. The individual modules are Pickwin™, Plotrefa™, and WaveEq™. Pickwin and WaveEq are used for surface wave data analysis and make up the program called SeisImager/SW. Pickwin and Plotrefa are used for refraction data analysis and make up the program called SeisImager/2D™. A separate manual exists for SeisImager/2D, and due to the overlap of Pickwin with SeisImager/SW, reference is made to the SeisImager/2D manual for explanation of the common Pickwin menus.

XX Section 2 of this manual describes the software installation process, Section 3 describes the process of data collection, Sections 4, 5, 6, and 7 describe how to process data, and Section 8 provides data examples. Some theory is touched on, but this manual is not meant to be a treatise on multi-channel analysis of surface waves (MASW) or micro-tremor array measurements (MAM). It is assumed that the user has a reasonable grasp of the main principals of seismology and mathematics in order to understand the principals behind the analysis techniques employed by the software. Please see Section 9 for a recommended reading list on surface wave theory and techniques.

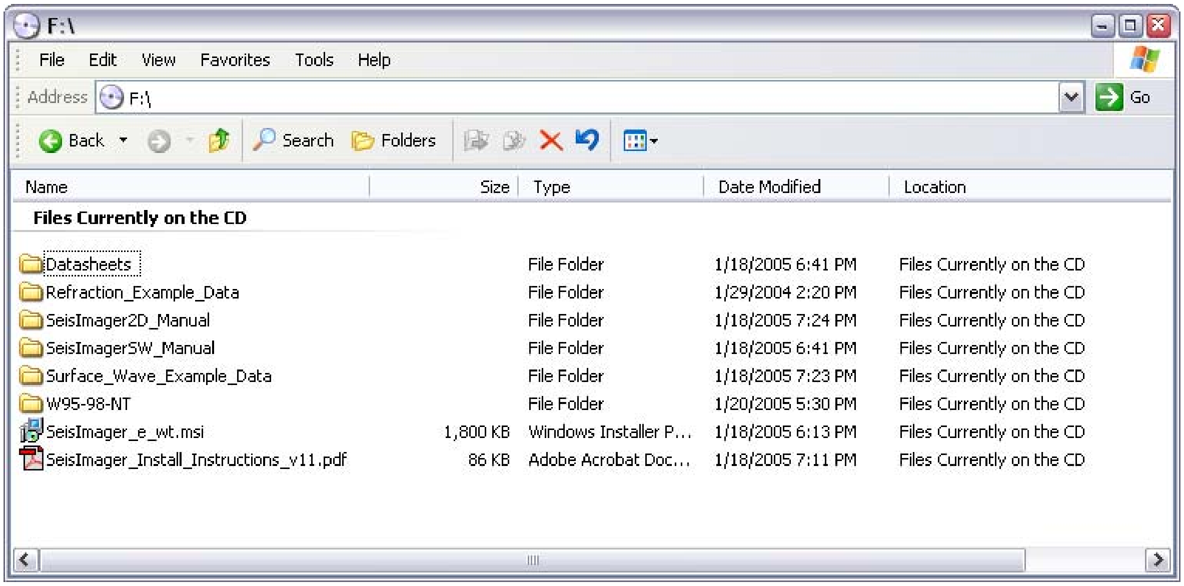
Although the manual can be printed, it was designed as an online resource. It will be updated on a semi-regular basis, and a current version will always be available for download on our ftp site (ftp://geom.geometrics.com/pub/seismic/SeisImager/). The manual makes liberal use of color, so if you elect to print it, using color is highly recommended.

Finally, we are very interested in your constructive criticism of both this manual and the software itself. Please contact us at seismicsales@mail.geometrics.com with any comments you might have.

Note: *All screens in this manual were captured in Windows XP Home Edition. If you are running a different version of Windows, some dialog boxes may look slightly different than they appear here.*

2 Installing the Software

Insert the SeisImager CD, click on My Computer, click on the CD icon, and then double-click on file named SeisImager_e_wt.msi.



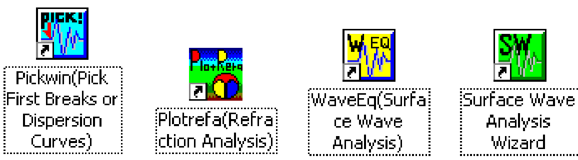
The Welcome to the SeisImager_e Setup Wizard window will appear as follows.

a. If you are presented with the option to “Repair SeisImager_e” or “Remove SeisImager_e”, the installer has detected an older version. Select “**Remove SeisImager_e**” and click on Finish, then Close after the uninstall is complete. Double click again on the file SeisImager_e_wt.msi to install the new version as described in the next step.
b. If an old version is not detected, you will be presented with the installer. Click on Next, indicate the directory for installation (we recommend you use the default directory), click on Next, Next, and Close.

Next, you may copy the SeisImager manuals to your hard drive. It will require about 150 Mb. If you want to save hard drive space, you can also use the manuals directly from the CD. If you decide to copy the manuals to your hard drive, follow these steps.

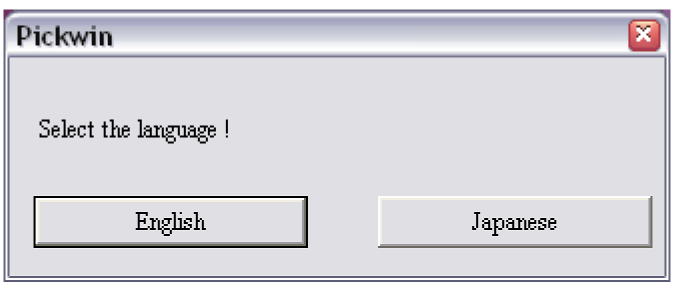
a. Select the folders SeisImager2D_Manual and SeisImagerSW_Manual on the CD and copy to your hard drive in the location you choose. Note that the SeisImager2D folder contains avi video clips that must reside in the same location as the files SeisImager2D_Manual_vX.X.pdf and SeisImager2D_Examples_vX.X.pdf (where X.X is the applicable version number).
b. You will need Adobe’s freeware program Acrobat Reader to view the manual files. If you need this program, go to http://www.adobe.com/products/acrobat/readermain.html to download the latest version compatible with your operating system

Once the installation is complete, four shortcuts will appear on your desktop. As noted above, Pickwin and WaveEq comprise SeisImager/SW and the Surface Wave Analysis Wizard uses Pickwin and WaveEq. SeisImager/2D, the program for refraction data processing, consists of the modules Pickwin and Plotrefa. **All of the icons will be showing regardless of which program you have purchased**. Note that a lite version of SeisImager/2D comes free with all seismograph purchases, so if you have purchased SeisImager/SW with a seismograph, you are also entitled to the lite version of SeisImager/2D. If you do not already have a license of SeisImager/2D, lite or otherwise, but would like to order a copy, please contact us at seismicsales@mail.geometrics.com.

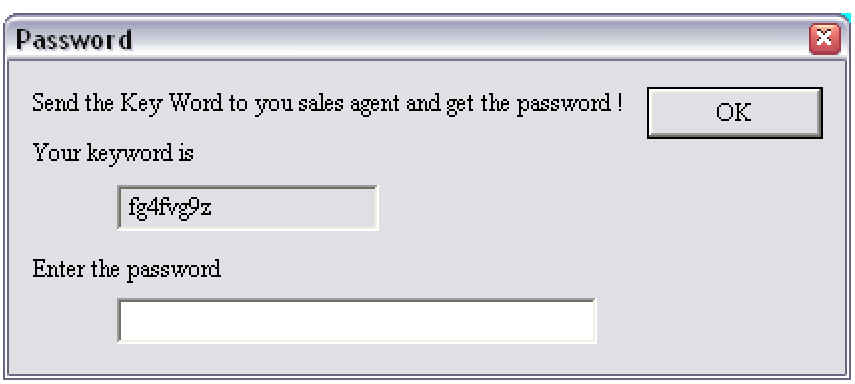


In addition to the icons, you can also run the software from your **Start** menu.

You are now ready to use SeisImager/SW. Double-click on the Pickwin or Surface Wave Analysis Wizard icon. Upon startup, you will be prompted to choose a language, click on "English". Once selected, this prompt will not appear again.



Next, you will be presented with a user code:



Email (seismicsales@mail.geometrics.com) (preferred) or fax (408-954-0902) the user code, and we will provide you with a password to register your software. Note that passwords are provided only for the program you have purchased. You will need a password for both Pickwin and WaveEq for SeisImager/SW. Or if you have launched the

Surface Wave Analysis Wizard, which calls on Pickwin and WaveEq, you will only need one password.

A general suggestion when using SeisImager/SW is to close and reopen the software modules or open a second instance of the software modules to start new, separate analyses. The programs are efficient and easy to launch so this is easy to do, and will help prevent complications when data processing.

3 Data Acquisition

SeisImager/SW includes the functions for two main processing flows, one for analyzing active source data records and another for passive source data records. Methods for collecting both data types for input to SeisImager/SW are discussed in this section with specific set-up instructions for use of the ES-3000, Geode, and StrataVisor NZ seismographs. The basics of running the acquisition and data analysis software are covered, with a brief introduction to surface waves. We recommend and refer you to the published body of literature for an in-depth discussion of surface wave theory and survey methods.

Dispersion, or change in phase velocity with frequency, is the fundamental property utilized in surface wave methods. Shear wave velocity can be derived by inverting the dispersive phase velocity of surface waves. Surface wave dispersion can be significant in the presence of velocity layering, which is common in the near-surface environment (upper 100 meters). There are other types of surface waves (waves that propagate along the earth's surface), but for this application we are concerned with the Rayleigh wave, also known as "ground roll". Although there are other wave types, the term "surface wave" when used in the SASW (Spectral Analysis or Surface Waves), MASW (Multi-channel Analysis of Surface Waves), or MAM (Micro-tremor Array Measurement) context has come to mean the Raleigh wave.

There are two ways surface waves are generated. "Active source" means that seismic energy is intentionally generated at a specific location and recording begins when the source energy is imparted into the ground. This is in contrast to "passive source" or "micro-tremor" surveying where there is no time break and motion from passive, ambient energy generated by cultural noise, traffic, factories, wind, wave motion, etc. is recorded.

Surface wave energy decays exponentially with depth beneath the surface. The energy or amplitude of any particular frequency is dependent on the ratio of depth to wavelength. Thus, for each frequency, the amplitude decreases by the same factor when the depth increases by a wavelength. This means that the longer wavelength (longer-period, lower-frequency) surface waves travel deeper and thus contain more information about deeper velocity structure and shorter wavelength (shorter-period, higher-frequency) surface waves travel shallower and thus contain more information about shallower velocity structure.

In this context, by their nature and proximity to the geophone spread, it can be said that active source surface waves resolve the shallower velocity structure and passive source surface waves sample the deeper velocity structure. Since the shallower section can have a relatively large impact on the average shear-wave velocity profile, it is important to sufficiently sample the shallower depths. In SeisImager/SW the results from active and passive source surveys can be combined to maximize the depth of investigation and yield a composite high-resolution result over all depths (to the maximum depth of penetration).

3.1 Active Source Data Acquisition

Seismic energy for active source surface wave surveys can be created various ways, but we recommend using a sledgehammer to impact a striker plate on the ground since it is a low-cost, readily available item. To signal to the seismograph when the energy has been generated, a trigger switch is used as the interface between the hammer and the seismograph. When the sledgehammer hits the ground, a signal is sent to the seismograph to tell it to start recording.

Table 1 summarizes the parameters used for active source MASW surveys. Most parameters are self-evident, but one setting to consider further is the geophone interval and resultant spread length.

There is a general rule of thumb that surface waves sample to an approximate depth of their wavelength divided by two. In surface wave surveying it is assumed that the longest wavelength that can be sampled is as long as the spread length. When combining active and passive results, because the passive source survey will be used to sample the greater depths, the active source survey spread length need not be two times the depth of interest. To determine the spread length, we suggest that you consider the maximum distance that source energy propagates and the shallowest depth of interest.

For an active source survey with a 10 to 20-pound sledgehammer, a geophone interval of 5 to 10 feet is suggested. Using a 24-channel seismograph, this would give a spread length of 115 feet using the 5-foot geophone interval. Applying the one-half-wavelength rule of thumb, the depth of penetration would be about 58 feet. Depending on the site materials and conditions, source energy may not strongly propagate to an offset of 115 feet, and stacking may be needed and/or the geophone interval may need to be reduced. Note that the spread length has more importance on data resolution than geophone interval. You need to find the balance between signal propagation and maximizing the spread length. Site-specific testing and judgment should always be applied to confirm that the suggested recording parameters are appropriate.

If you were only doing active source survey and would not have passive data to resolve greater depths, it is recommended that the spread length equal about two times depth of interest. Additionally, the active source testing can include two (or more) spreads, one with a shorter and lighter weight hammer and one with a longer spread length and heavier weight hammer, to sufficiently sample a range of depths.

Table 1. Active Source Acquisition Parameters

Parameter	Setting
Spread configuration	Linear
Spread length	About equal to depth of interest when supplementing with passive source data; about equal to two times depth of interest if no passive data available*
Geophone interval	2 to 3 m or 5 to 10 ft*
Total number of geophones	16 or more
Geophone type	4.5 Hz vertical geophones, with base plates for surveys on paved ground
Shot location	Minimum of one shot, located in-line and off-end (either end) of spread by about 10 to 20% of spread length; an additional shot located at about 40% of spread length and reverse shots also recommended
Source equipment	Sledgehammer, 8 lbs (3.6 kgs), 16 lbs (7.2 kg), 20 lbs (9 kg), scale hammer weight up with increase in spread length*, and striker plate
Trigger	Hammer switch taped to sledgehammer handle and connected to seismograph trigger port
Sample interval	0.5 or 1 milliseconds (ms)
Record length	1 to 2 seconds (s)
Stacking	As needed to improve data quality

*also refer to preceding discussion in text

3.1.1 Active Source Survey Spread Configuration

SeisImager/SW allows one type of active source spread configuration, linear (Figure 1). The geophones are configured in a straight line on the ground and interconnected with a spread cable (black line).

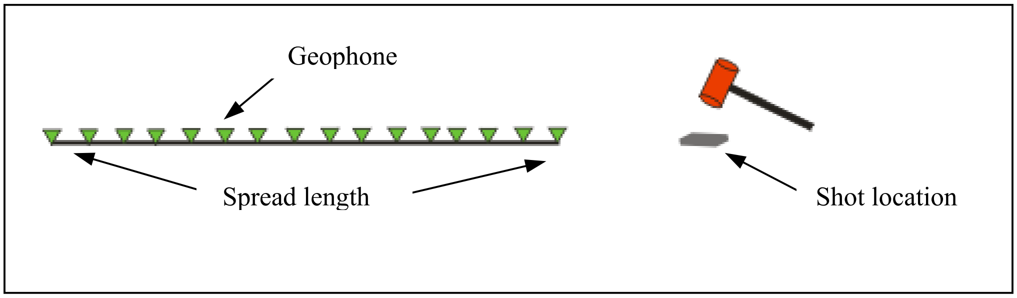
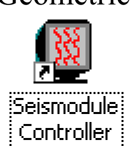


Figure 1. Schematic of linear active source spread configuration.

3.1.2 Active Source MASW Wizard

To facilitate surface wave data acquisition, the Seismodule Controller Software (SCS), version 9.10 and above, will include automatic wizards, called *Active Source MASW Wizard* and *Passive Source MAM Wizard*, that walk you through the survey set-up process and prompt you to set particular parameters. The wizards come standard with the controller software for the ES-3000 Surface Wave seismograph and are options for the regular ES-3000 and single Geode seismographs. The wizards are based on dialog boxes from the standard SCS menus so if you are using an older version or have not purchased these SCS options, you can simply open the dialog boxes manually. In this section, only use of wizards for acquisition of surface wave data is discussed. Please refer to the seismograph manual specific to your instrument for a complete explanation of SCS and for directions on how to set up the seismograph hardware.

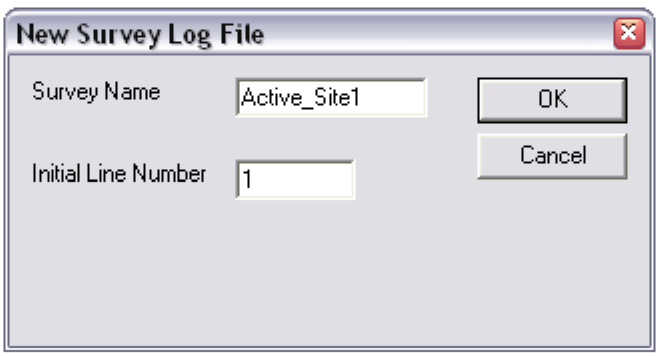
To use the wizards, the first step is to install SCS. Once this is done, launch SCS from the icon on your desktop, shown below, or from the Start menu under All Programs, Geometrics, Seismodule Controller.



If this is the first installation of SCS on your PC, you will be presented with a 12-digit code and asked for a registration password. Copy and paste the 12-digit code in an email and send along with the serial number of your seismograph to seismicsales@mail.geometrics.com. We will reply with a 40-digit registration password. We recommend email because it is easy to mistype or misspeak the code and registration password.

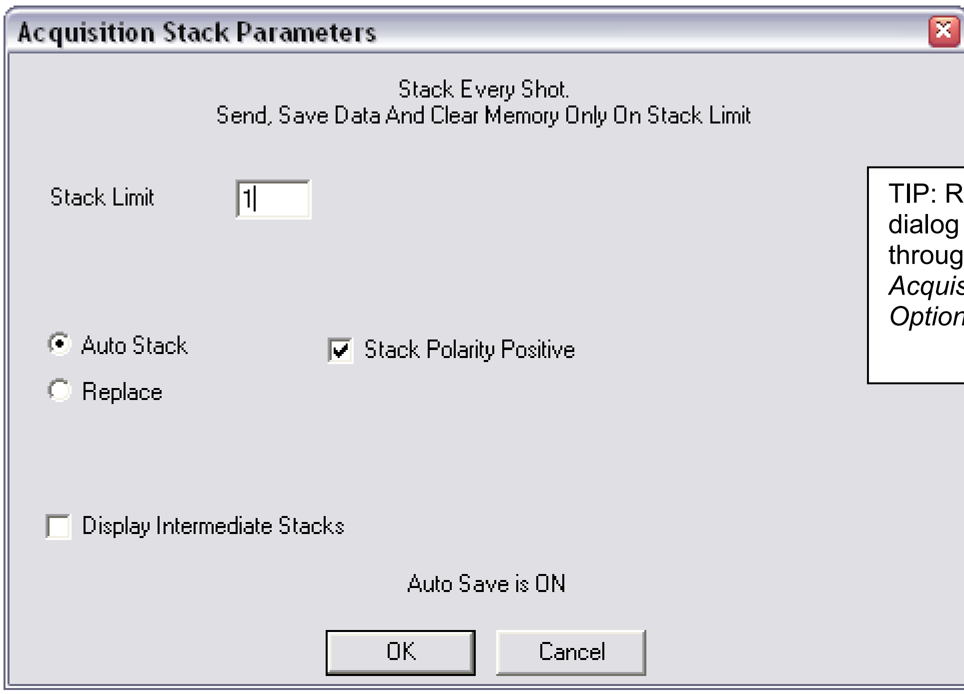
The first time the software launches you will be prompted to choose which type of survey wizard to run. If you did not purchase the surface wave wizards, choose to run the *General Start-up Wizard*. Even if you have not purchased the MASW Wizards, the *General Start-up Wizard* can be used to set your data acquisition parameters for surface wave surveys. The *General Start-up Wizard* includes the same dialog boxes plus a few others compared to the surface wave wizards and uses different default parameters. All of the dialog boxes shown in the wizards can be accessed through the normal menus in the acquisition software. Refer to the TIP boxes below for the exact menu paths.

The first dialog box you will see is shown below. Enter a *Survey Name* pertinent to your job. You can enter the actual name of your site instead of "Site1" but we recommend that you retain the term "Active" to help identify the active source phase of your survey. What you enter is also used as the name for the survey log that is maintained during your survey. All software activities, such as parameters set or files written to the hard drive, during that survey are saved to the survey log. The survey log is a text file that you can recall at a later time. Click *OK* when you are done.



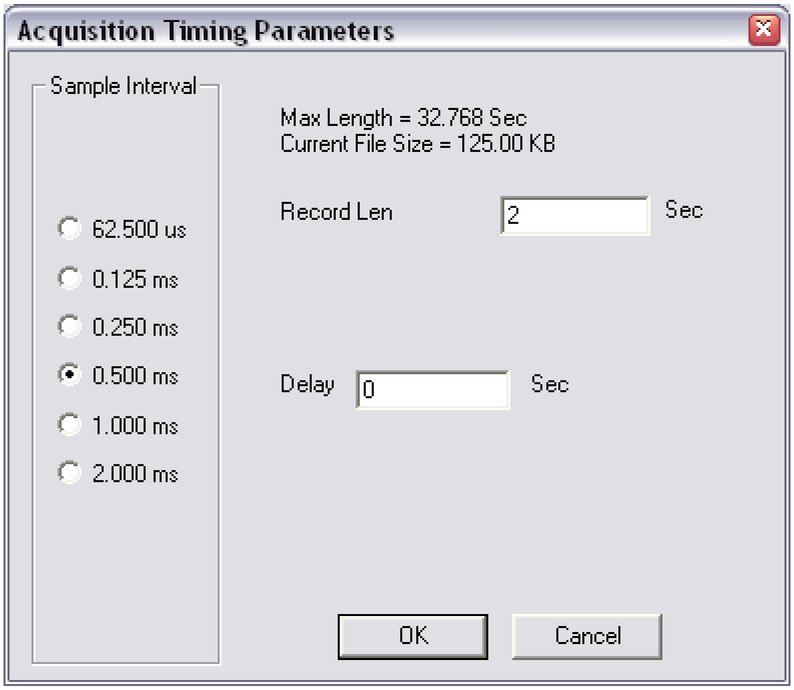
TIP: Return to this dialog box later through the *Survey* menu.

Next, you will be prompted to set the stack options. Stacking is a way to increase the signal-to-noise ratio by hitting the striker plate repeatedly and adding files together as they are collected. In many cases, stacking will not be needed, and thus, the *Stack Limit* is set to 1. If you are in an urban environment and there is a high level of noise, you can stack records by hitting the striker plate with the sledgehammer in the same location multiple times. Note that what is called "noise" in an active source survey is actually what is recorded during a passive source survey. The benefits of stacking taper off after ~6 stacks. To stack 6 times, enter 6 as the *Stack Limit*. Click *OK* when you are done.



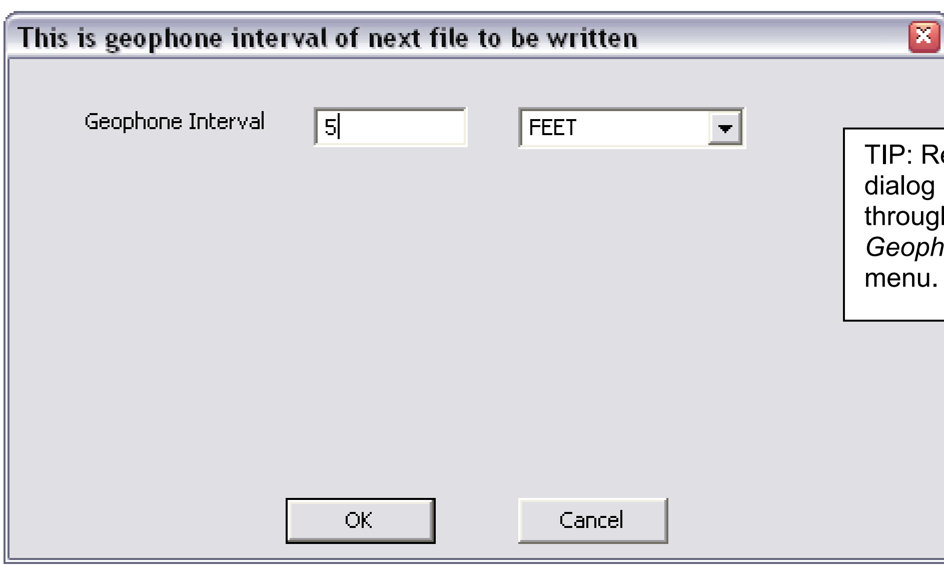
TIP: Return to this dialog box later through the *Acquisition > Stack Options* menu.

Next, you will be prompted to set the sample interval and record length. The defaults are already equal to the recommended settings for active source MASW surveys. Click *OK* when you are done.



TIP: Return to this dialog box later through the *Acquisition > Sample Interval/Record Length* menu.

The next dialog box allows you to set the *Geophone Interval*, or distance between each geophone in the line, and the units you are using. The default is the suggested geophone interval in English units. Click *OK* when you are done.



TIP: Return to this dialog box later through the *Geom > Geophone Interval* menu.

Next, you will be prompted to set up the spread geometry, or coordinates. Note that in this window, it is recommended to navigate using the keyboard keys and not the mouse. The up/down arrows will move the cursor between rows and the right/left arrows will move the cursor between traces.

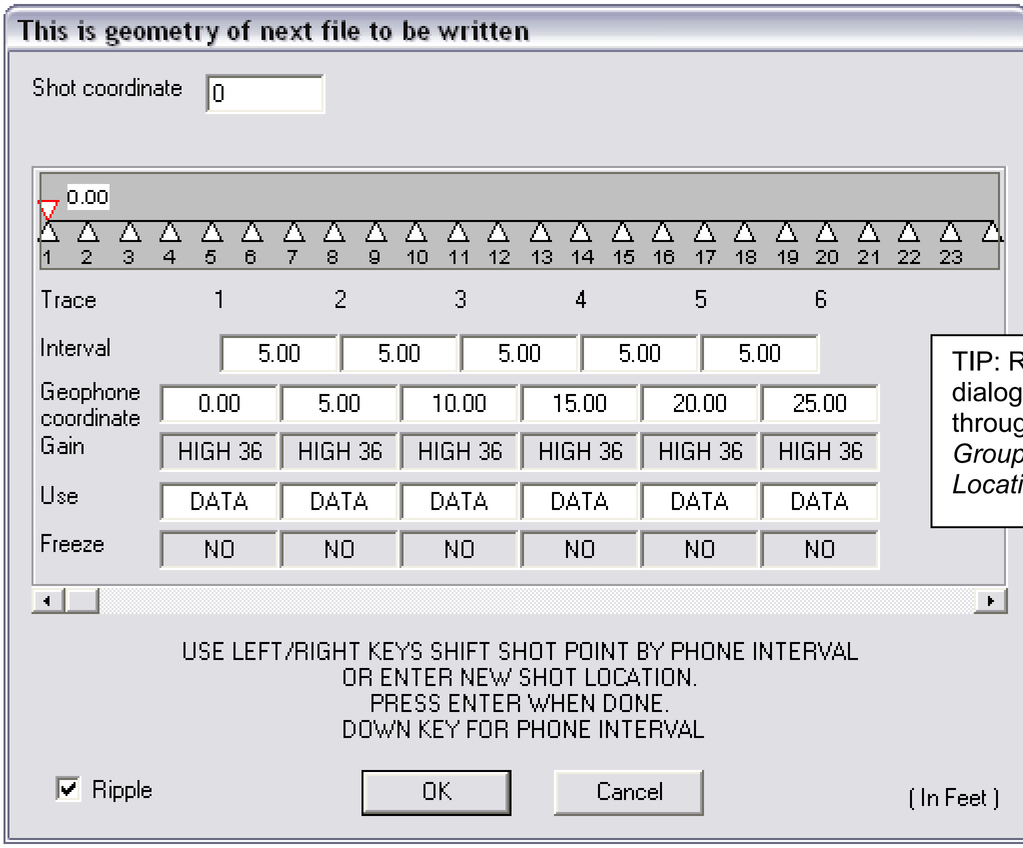
The way to view this window below the spread graphic is as rows and columns. The names of the rows are shown on the left hand side and the name of the columns is the *Trace* number shown just below the spread graphic. The cells for *Interval* are offset to indicate that the entered value is the distance between Trace 1 and 2, 2 and 3, etc.

The *Geophone Interval* you entered in the previous dialog box is shown. The default *Shot Coordinate* and *Geophone Coordinate* is zero, but you can set whatever value you wish corresponding to the desired coordinate system. If you change a value, the change will ripple through the rest of the coordinates if *Ripple* is checked (default).

Note that the seismograph is wired so it is always on the "high-side". In native configuration, the nearest channel or geophone to the seismograph will always be the highest channel number. For example, if you have a Geode seismograph with 24 channels, when you have your line set up, the nearest geophone to the Geode will be 24. (Later in this section you will see how to test which channel is nearest.) Further on this point, if you want your source location to be off the end nearest the seismograph, you will need to change the *Shot Coordinate* value from 0 to the appropriate value greater than the coordinate of geophone 24.

If you record your data with the wrong geophone interval or shot location compared to how the equipment was actually positioned during the survey, it can be corrected in SeisImager/SW, but it is easiest to get it correct here.

The default settings in the other rows, *Gain*, *Use*, and *Freeze,* are fine and require no adjustment. Click *OK* when you are done.

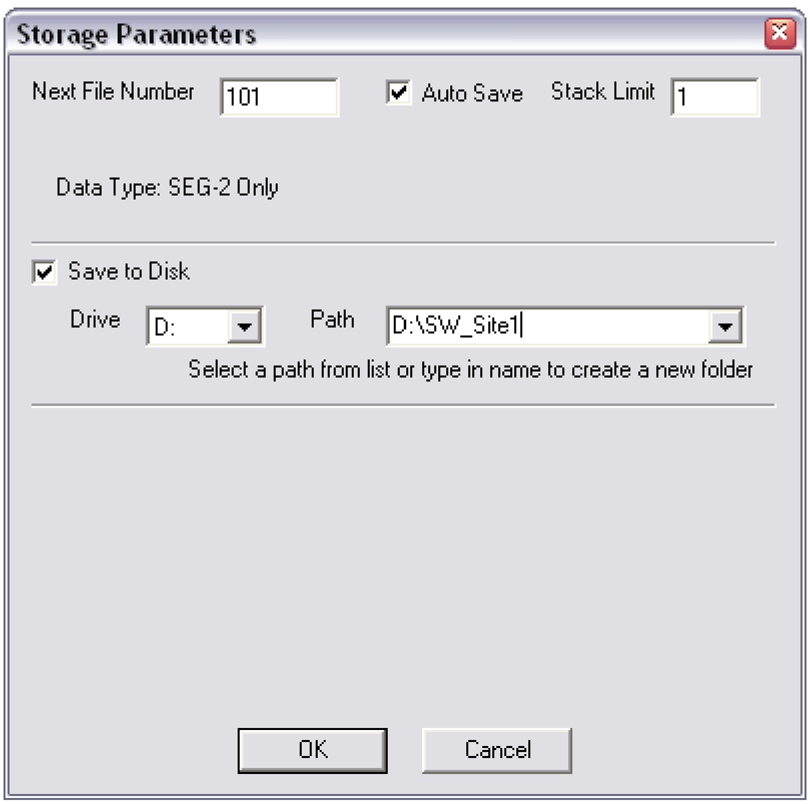


TIP: Return to this dialog box later through the *Geom > Group/Shot Locations* menu.

The next dialog box, called Storage Parameters, in the wizard allows you to set-up how to save your data files. The *Next File Number* should be a numerical value; after each save, the name will automatically increment by one. For the default values, since the active source survey is considered Line 1, the File Number names start with the 100 series.

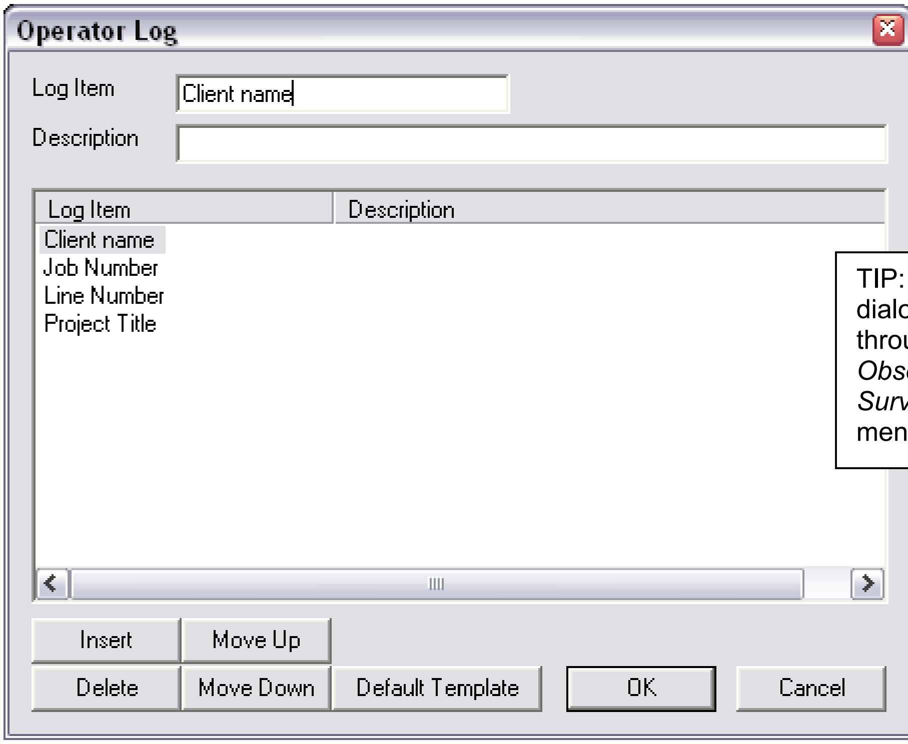
Auto Save checked means that each file will be automatically saved after the *Stack Limit* is reached. If this is unchecked, you will need to manually save (and clear) each file. The *Stack Limit* reflects what was entered in the previous *Acquisition Stack Parameters* dialog box.

For the disk path to save your data, note that you can only create one folder deep. You can enter the actual name of your site instead of "Site1" but we recommend that you retain the term "SW" to help identify the type of survey. Click *OK* when you are done.



TIP: Return to this dialog box later through the *File > Storage Parameters* menu.

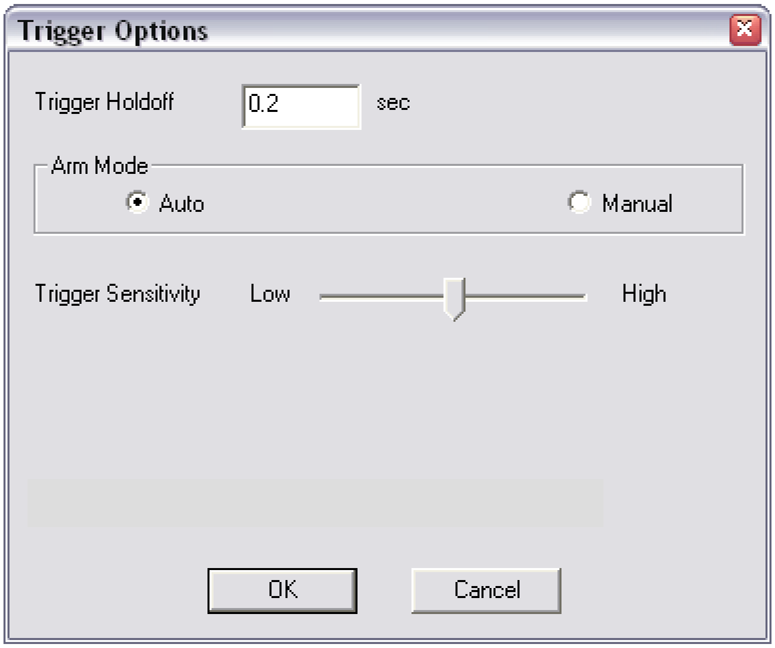
The Operator Log dialog box allows you to log information specific to your survey. This is fully customizable with your own *Log Items* and *Descriptions*. It is also not necessary to complete, it is for your records. All entries are saved in the survey log mentioned earlier. Click *OK* when you are done.



TIP: Return to this dialog box later through the *Observer > Edit Survey Description* menu.

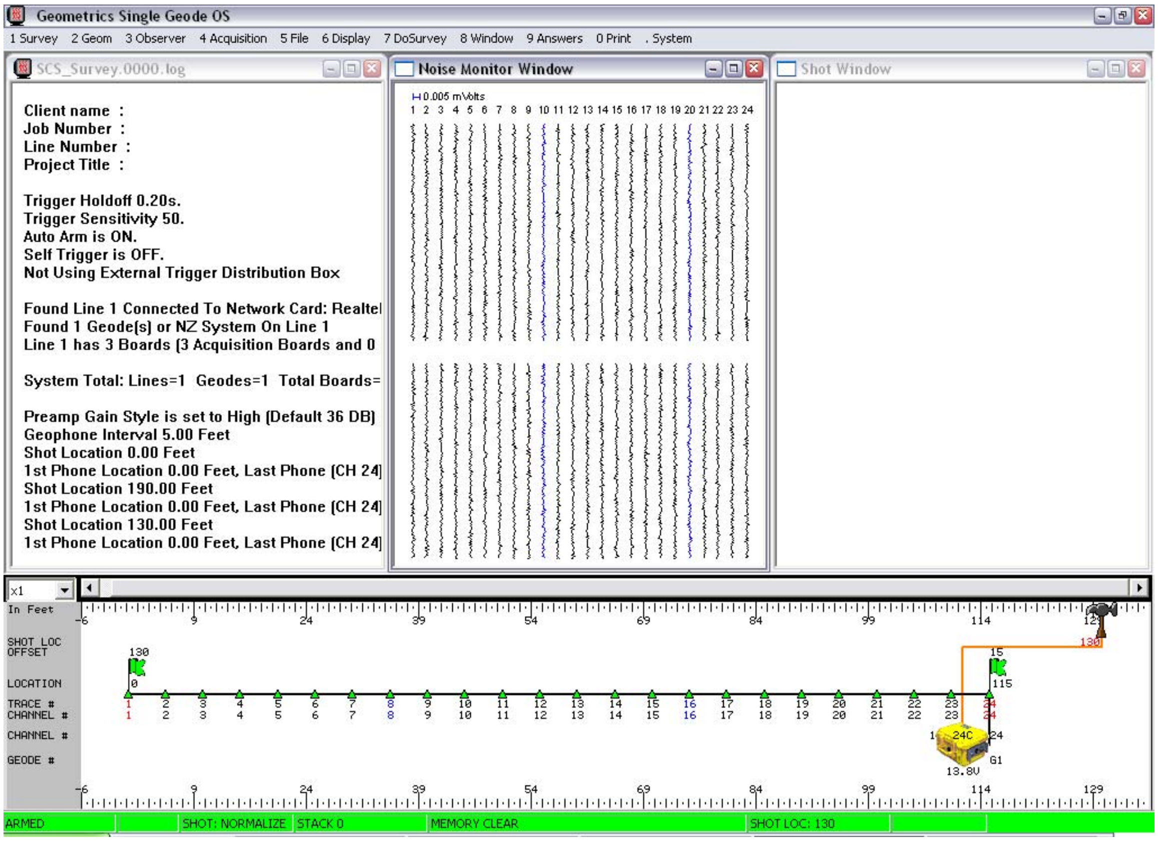
The only trigger option to really consider is *Arm Mode*. The default is *Auto* for automatically rearm of the system. This means that the system will automatically return to an armed state, ready for the next trigger. If you change the setting to *Manual*, you will need to manually arm the system before each trigger. *Auto* ensures that you will not miss any records.

This is the last dialog box in the wizard. Click *OK* when you are done.



TIP: Return to this dialog box later through the *System > Trigger Options* menu.

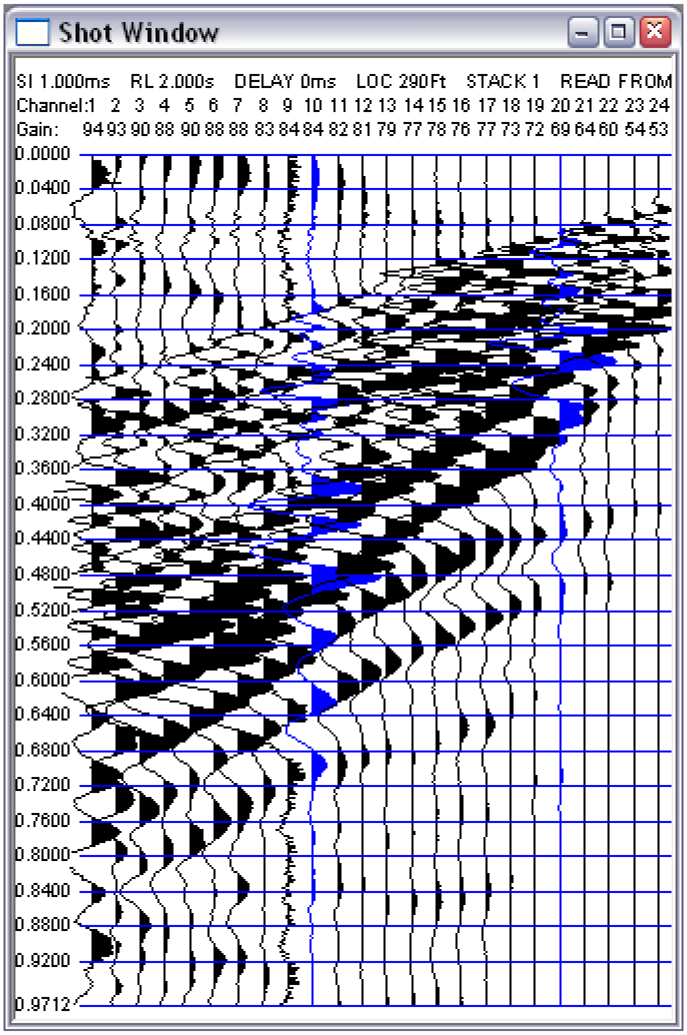
Now that you have finished the wizard, you are ready to begin data collection. The window you will see next is as shown below. The number of traces in the *Noise Monitor Window* will match the number of channels in the seismograph, this example shows 24 traces.



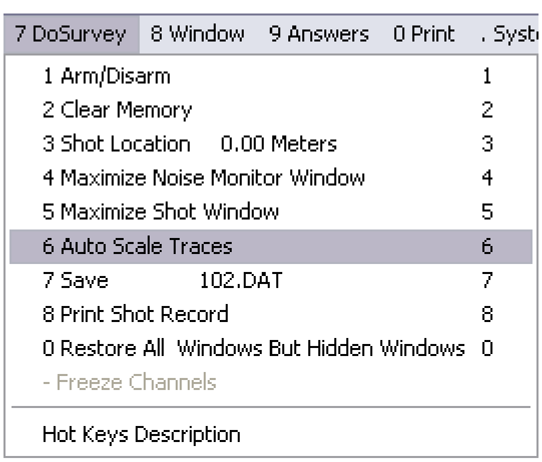
Before you record your data, use the *Noise Monitor Window* to confirm the spread layout. Tap the top of the nearest geophone and watch which trace shows a response. This geophone should be the highest channel number. Check that the response level of all the geophones is about the same. If there is a trace with a dissimilar or atypical level of noise, walk down the line to check that the internal sensor element is able to vibrate freely (give a gentle shake). Make sure the geophone is correctly planted and that it is connected to the spread cable. It is best practice to make sure all traces are responding properly before collecting data.

Next check that the status bar on the bottom of the window shows an *Armed* condition colored green. You may want to first use the 1 key to toggle the arm/disarm off/on and practice swinging the hammer and hitting the striker plate.

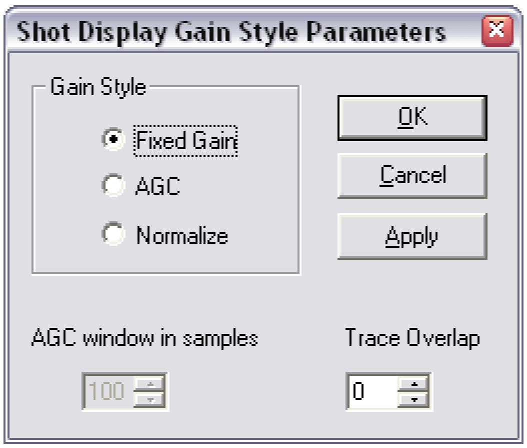
When ready, return the system to an *Armed* state, and swing the hammer at the shot location. Check to confirm that the system triggered and the shot was recorded. A typical active dataset consists of one (or more as needed) shot records as shown below.



You will probably need to adjust the display gains. First *Auto Scale Traces* through the *DoSurvey* menu or hit the "6" hot key.



Next, highlight the *Shot Window* and use the right arrow key to activate the display gain controls. If the *Shot Display Gain Style Parameters* dialog box (see below) appears, choose *Fixed Gai*n, and click *OK*. Then hit the right arrow key again and as directed in the instruction box, use the up and down arrows to increase and decrease the gain by the same amount for all channels. Press the Esc key to end. The Page Down and Page Up keys can also be used to zoom in and out.



After you have collected the active record and are satisfied with the data quality, continue to the passive source survey.

3.2 Passive Source (Micro-tremor) Data Acquisition

During a passive source survey the system will "listen" and record the energy generated by cultural noise, traffic, factories, wind, wave motion, etc. There is no timing device to trigger the seismograph.

The preferred noise sources are steady, at a constant level. The fundamental assumption of micro-tremor array measurements (MAM) analyzed using the spatial autocorrelation method of SeisImager/SW is that the signal wavefront is planar, stable, and isotropic (coming from all directions). A high level of intermittent noise (like passing cars) is tolerable if the sources are relatively distant (greater than one array length). Even if the intermittent noise sources are near, this will usually be countered by recording long records (a minimum of 10 minutes total recommended). Such a body of data will provide a statistically steady representation of noise. Table 2 summarizes the recommended passive source acquisition parameters. Refer to Section 3.2.1 for full discussion of spread length (array size).

Table 2. Passive Source Acquisition Parameters

Parameter	Setting
Spread/array configuration	L-shape, Triangle, Circle, Linear, or custom
Array size	Minimum of 1 times depth of interest
Geophone interval	Up to 10 m or 30 ft, adjust to suit spread configuration
Total number of geophones	Various based on spread configuration
Geophone type	4.5 Hz vertical geophones, with base plates for surveys on paved ground; alternatively, if available, 1 or 2 Hz seismometers can be used, especially if depth of interest is greater than 30 m
Trigger	Manual keyboard or automatic software trigger
Sample interval	2 milliseconds (ms)
Record length	30 seconds (s) each record, total of at least 20 records

3.2.1 Passive Source Survey Spread Configurations

SeisImager/SW allows four types of passive source spread or array configurations as noted in Table 2. Figures 2 through 6 illustrate the various configurations. As in Figure 1, the black line represents the spread cable and the green inverted triangles represent the geophones.

Three of the four arrays are two-dimensional (2D), that is, geophones are distributed in two directions versus a line, on the ground. With a linear array, if micro-tremors only propagated parallel to the survey line the surface wave phase velocity could be calculated directly. Conversely, if the micro-tremors only propagated perpendicular to the survey line and reached all of the geophones at the same time, the phase velocity could not be calculated. In reality, the sources of micro-tremors are studded and energy radiates from many directions at unknown angles to the geophones. Since the angles of propagation are unknown, if a linear array is used the calculated phase velocity may be higher than the actual phase velocity. For this reason it is important to record with a 2D array. Some sites may not allow for construction of a 2D array, and thus, the secondary option of a linear passive source array is still included in SeisImager/SW.

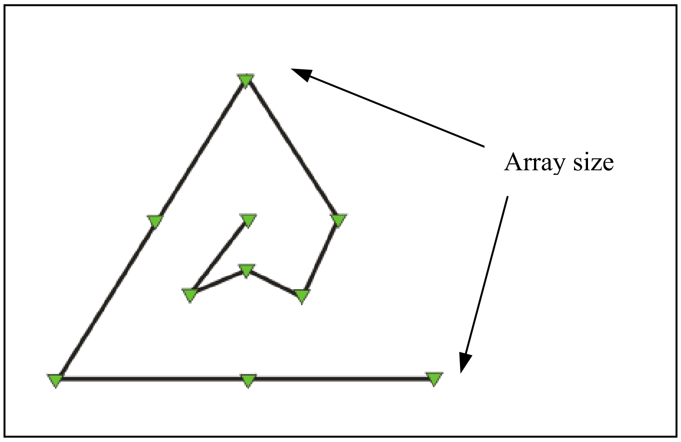


Figure 2. Schematic of passive source equilateral triangle spread configuration with 10 geophones (*Triangle 10*). The *Array size* is equal to the side length.

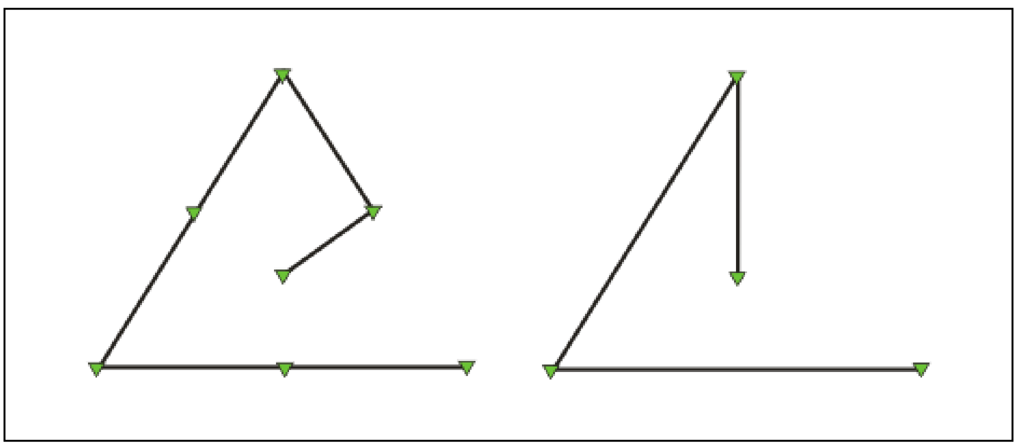


Figure 3. Schematic of passive source equilateral triangle spread configurations with 7 (*Triangle 7*) and 4 geophones (*Triangle 4*).

For a triangle array, the resultant shear wave velocity curve is representative of the center of the triangle.

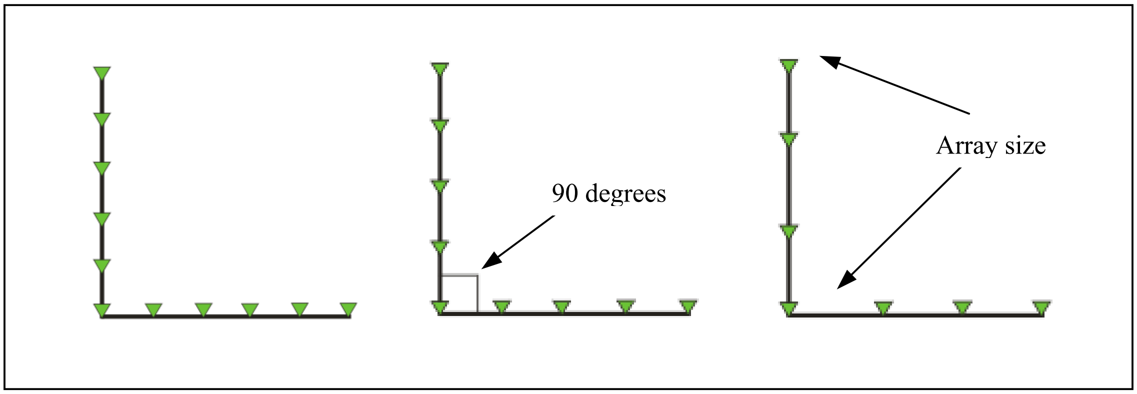


Figure 4. Schematic of passive source L-shape spread configurations with 11 (*L11*), 9 (*L9*), and 7 (*L7*) geophones. The *Angle* between the branches of the L is typically 60 to 90 degrees, but technically can be as small as 0 degrees, which is a linear array. Both branches are the same length; *Array size* equals the length of the branches.

For a L-shape array, the velocity curve is representative of a point between the two branches of the L, close to the origin. The L-shape array is the two-dimensional array that is easiest to construct in the field. The L-shaped array can easily be constructed after an active source survey by turning one-half of the spread 90 degrees.

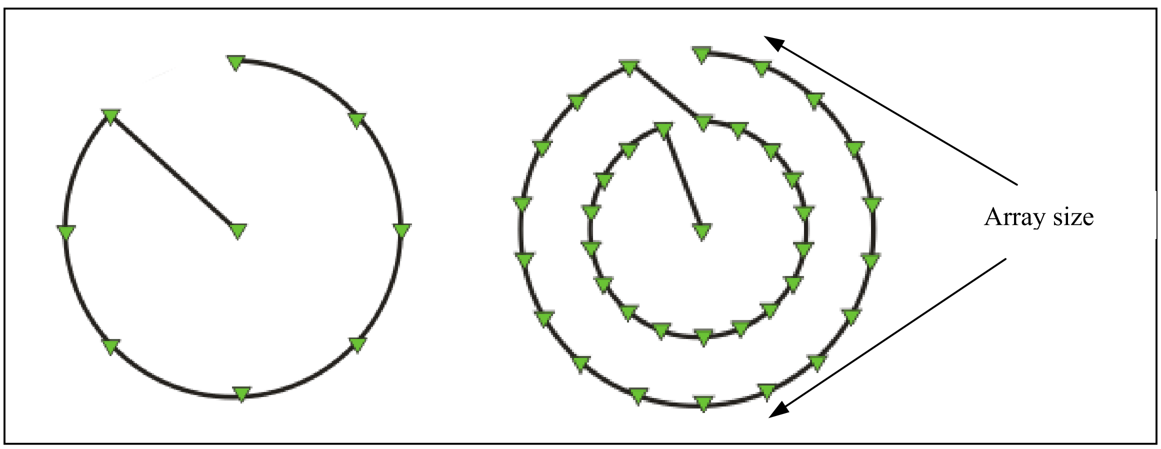


Figure 5. Schematic of passive source circle spread configurations with 8 outer geophones on one circle and one center geophone (*Single circle 9*) and 18 geophones in two circles and one center geophone (*Double circle 37*). The *Array size* equals the diameter of the outer circle.

For a circular array, the resultant shear wave velocity curve is representative of the center of the circle.

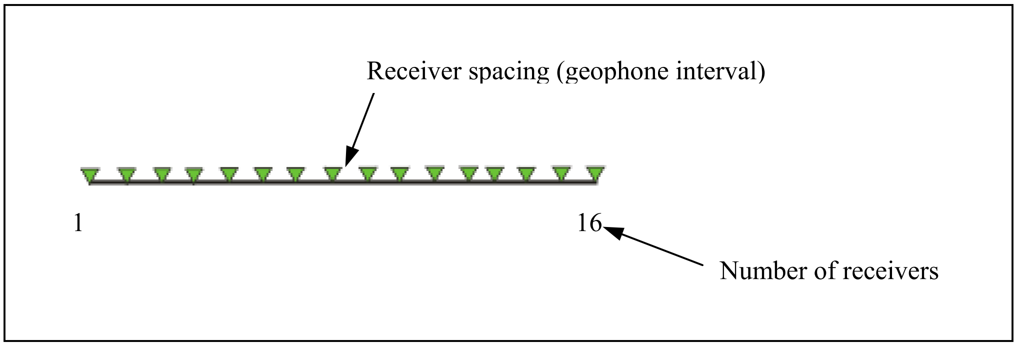


Figure 6. Schematic of passive source linear spread configuration using all channels, one per geophone.   The *Receiver spacing* equals the geophone interval and the *Number of receivers* equals the number of geophones.

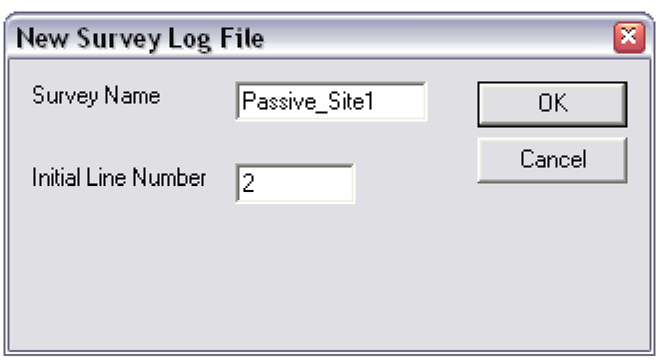
For a linear array, the velocity curve is representative of the center of the spread.

3.2.2 Passive Source MAM Wizard

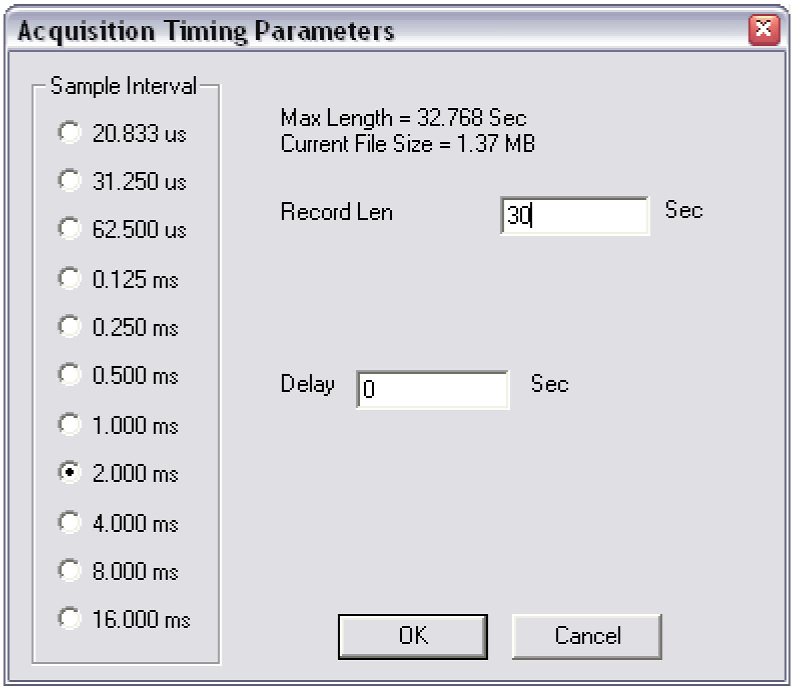
The dialog boxes (but not the settings) in the *Passive Source MAM (Micro-tremor Array Measurement) Wizard* you will find are the same as in the *Active Source MASW Wizard* (Section 3.1.2), and this section assumes that you have already worked through the *Active Source MASW Wizard*. Refer to Section 3.1.2 for introduction to the wizards and the TIP boxes on how to access each dialog box manually through the menus, and for more explanation on the dialog boxes common to both wizards.

To run the *Passive Source MAM Wizard*, launch SCS and select the wizard.

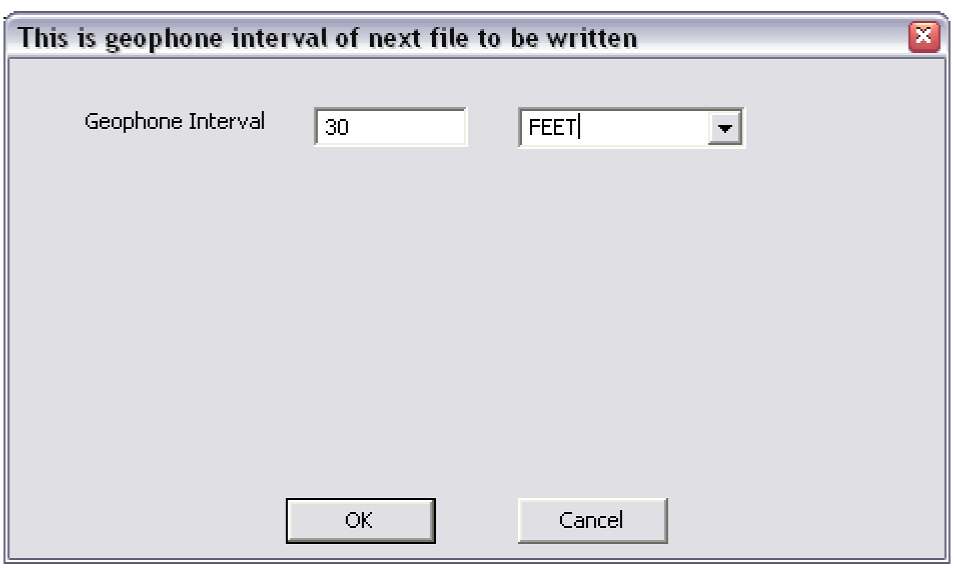
As with the *Active Source MASW Wizard*, the first dialog box you will see is for entry of *Survey Name* and *Line Number*.



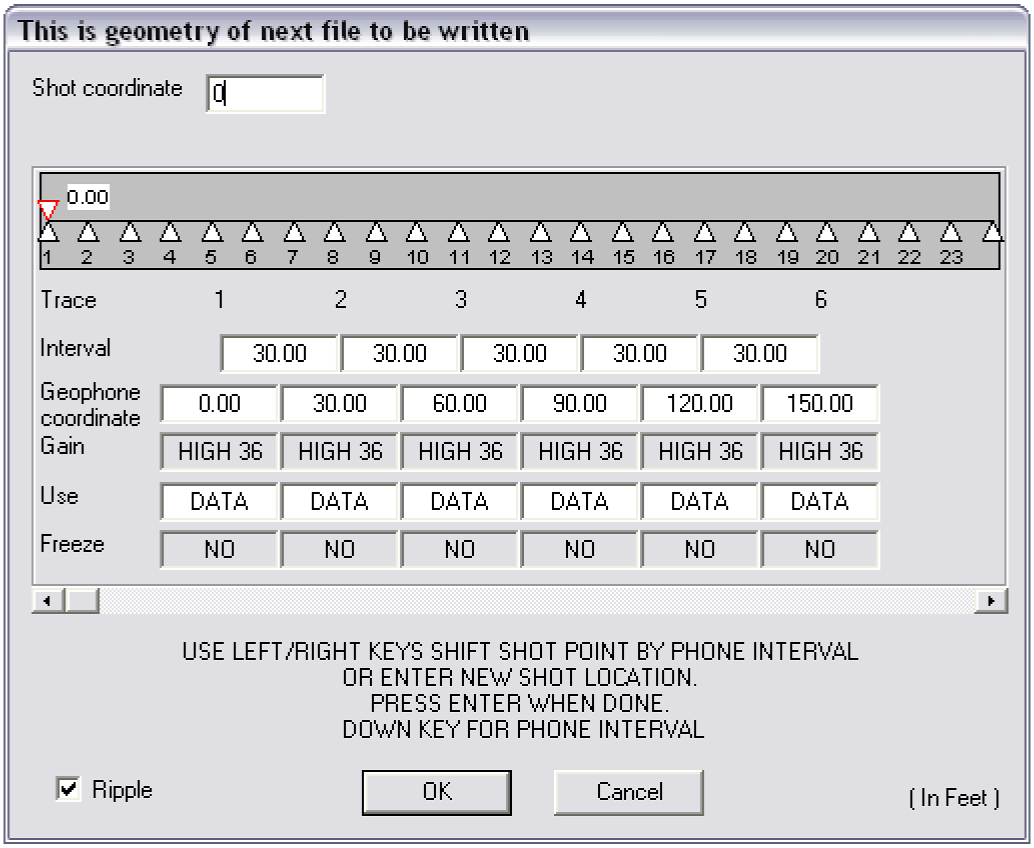
Next, you will be prompted to set the sample interval and record length. The defaults are already equal to the recommended settings for passive source MAM surveys.



The next dialog box allows you to set the *Geophone Interval* and the units you are using. The default is the suggested geophone interval (in English units) for an *L11* array.



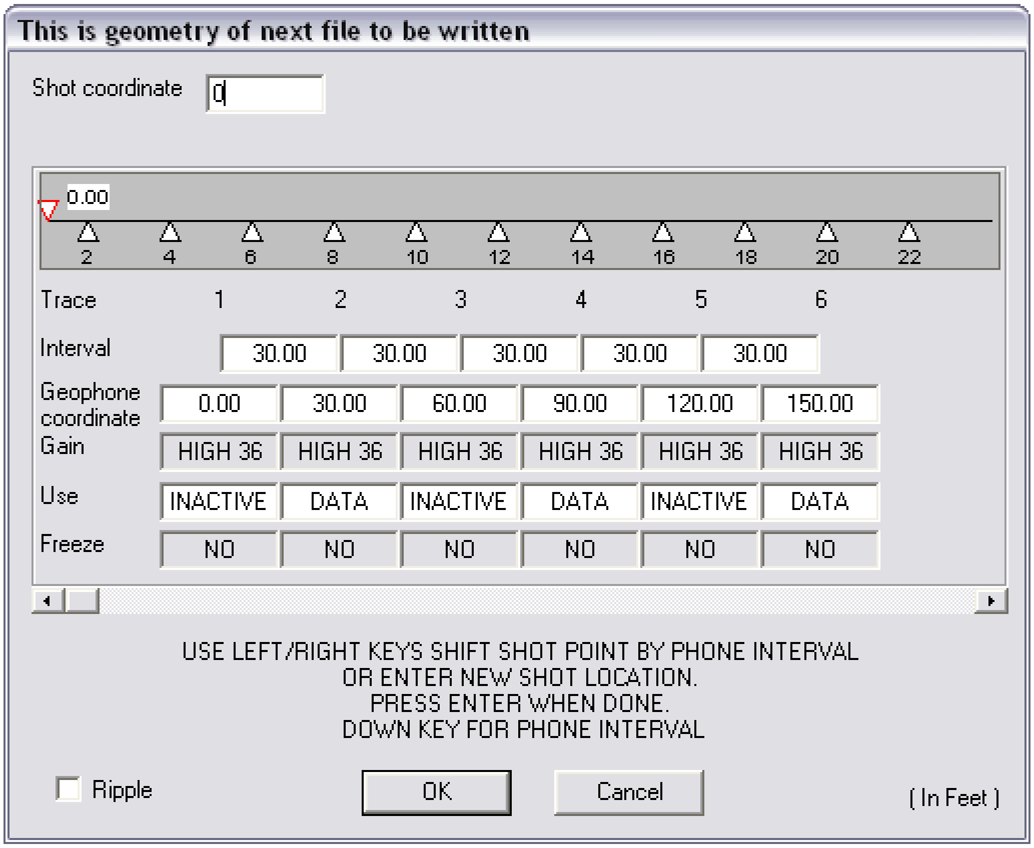
Next, you will be prompted to set up the geometry of the array.



Since there is no active source at a single location, the *Shot Coordinate* is non-applicable and should equal zero.

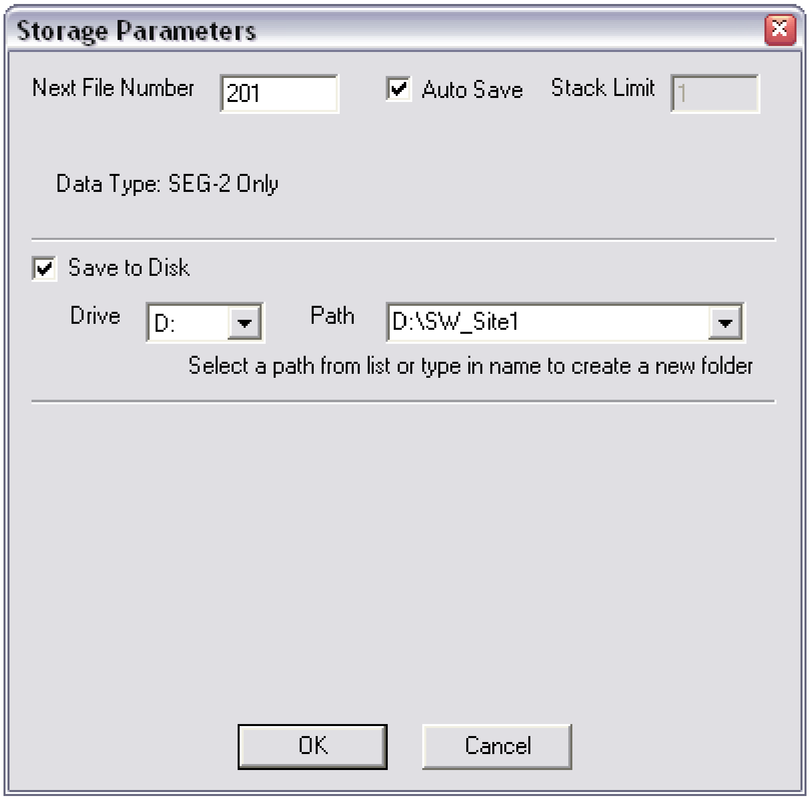
For most of the 2D array configurations, you will most likely be recording on fewer channels than the total number of channels of the seismograph. These channels should be deactivated. Deleting of dead channels can be done in SeisImager/SW, but it is best to do it at the time of acquisition. Uncheck the *Ripple* box and in the row called *Use*, use the number 4 key and the right arrow key to individually deactivate the channels that have no geophone connected to that takeout.

For example, if you are using a 16-channel seismograph and 30-foot interval spread cable, for an L-shaped array with 11 geophones positioned 30 feet apart, you would deactivate the channels on the end of the spread that are not connected to geophones. This would be channels 1 through 5 if channel 11 is positioned at the corner of the L, or channels 12 through 16 if channel 6 is positioned at the corner of the L. If you are using a 24-channel seismograph and 5-meter interval spread cable, for an L-shaped array with 11 geophones 10-meters apart, and channel 12 positioned at the corner of the L, you would deactivate channels 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, and 24. This set-up is shown in the following display; you would see this after clicking *OK* and reopening the geometry dialog box.

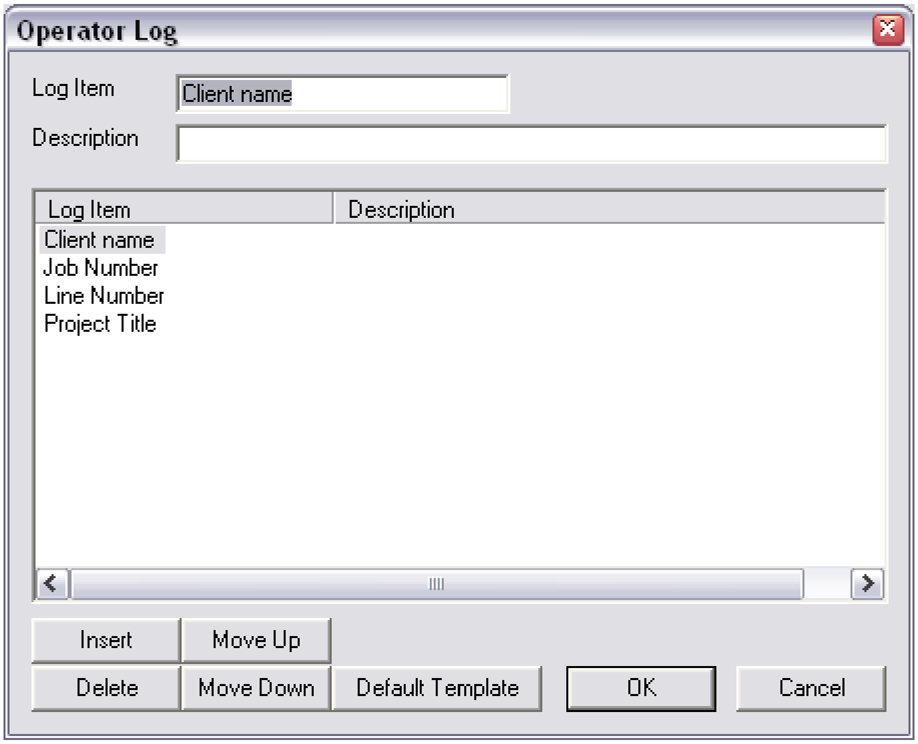


The geometry dialog box only shows linear configurations of geophones, you will not see a graphic of the actual two-dimensional array. That is fine, the shape of the array is indicated in SeisImager/SW. The main setting here is deactivating unused channels.

Next change or accept the default *Next File Number*. It helps to use a different series than that used for the active source data records. Leave *Auto Save* on and the *Stack Limit* grayed out since stacking is non-applicable to passive source surveys. For the disk path to save your data, enter the actual name of your site instead of "Site1" if you wish.



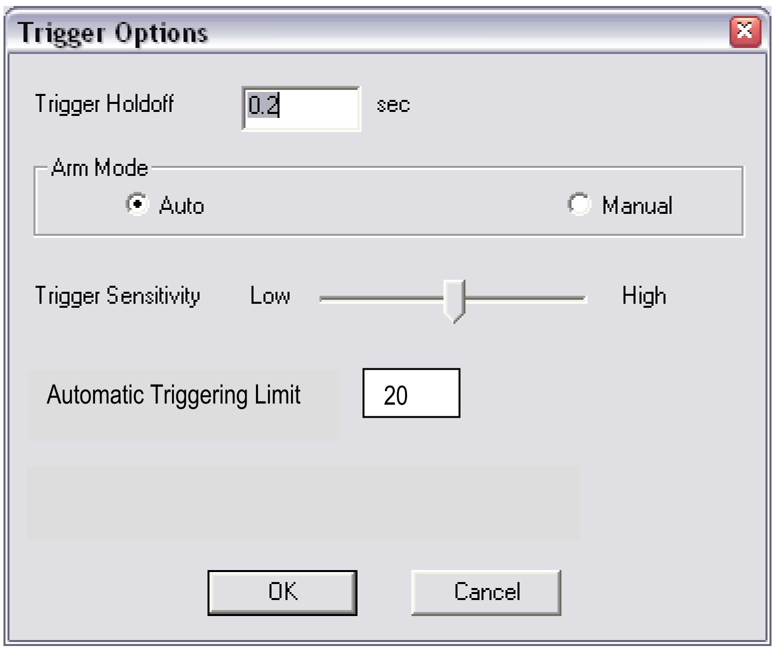
Complete the *Operator Log* if you wish.



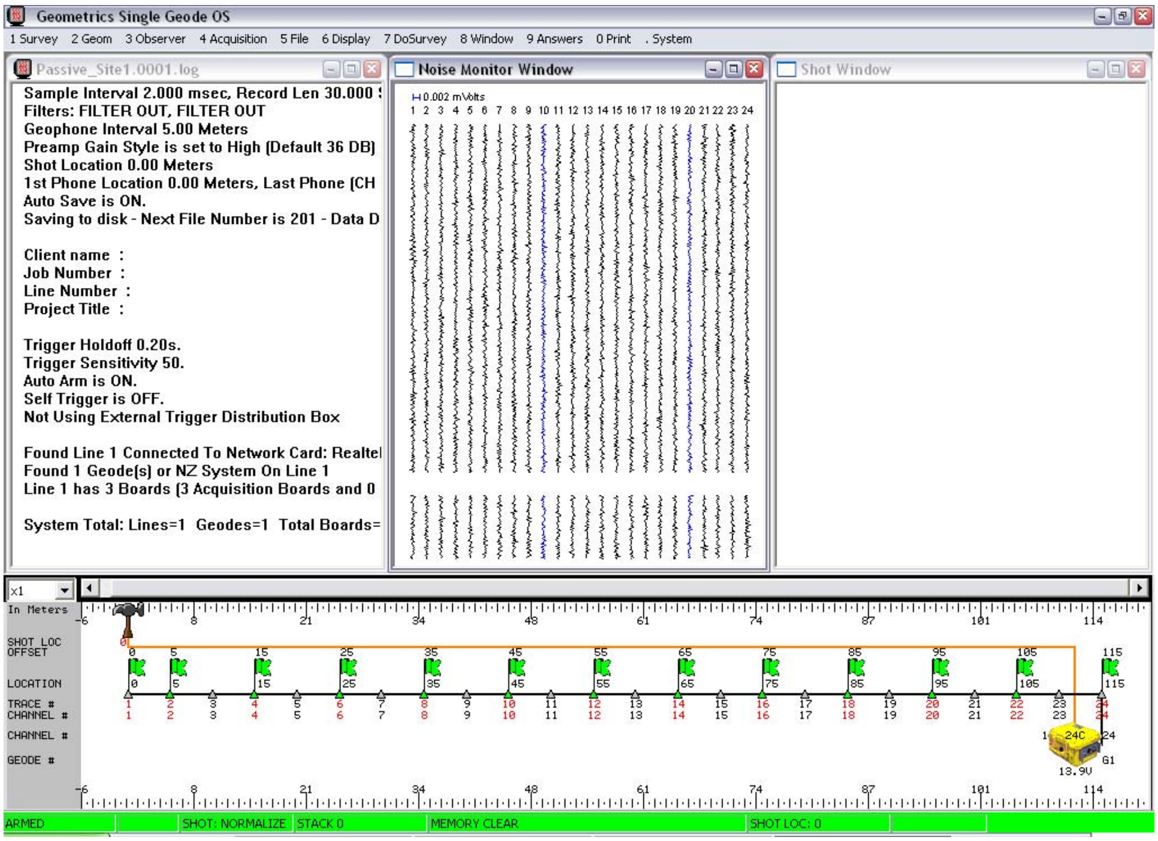
Lastly, set up how you will trigger the system. The default *Arm Mode* is set on *Auto* so the system will automatically rearm itself.

For passive source surveys, at least 20 data records (10 minutes) must be collected. At the time of acquisition, you can manually trigger the seismograph by hitting the "t" hot key for manual trigger or configure the software here to automatically trigger to a limit you set. To automatically trigger, enter a value of 20 for the *Automatic Triggering Limit*. A value of zero means that triggering will be done manually. (Note: automatic triggering was not yet released at time of publishing.)

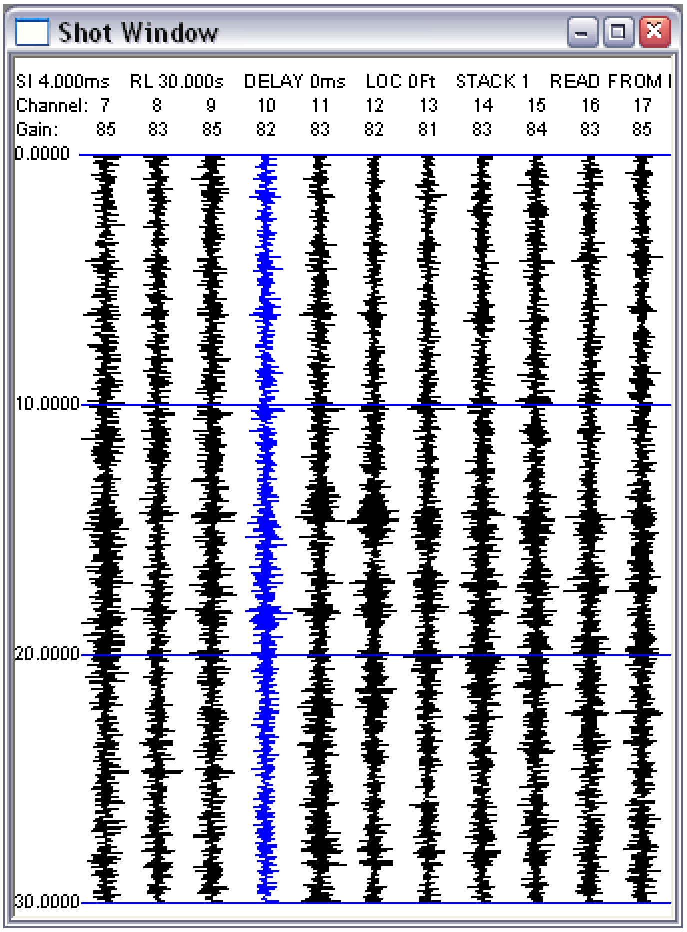
This is the last dialog box in the wizard.



The window you will see next will look as shown below. As with the active source survey, check that the geophones are responding properly before starting acquisition. Check that the status bar on the bottom of the window shows an *Armed* condition colored green. Once ready, if you are manually triggering, hit the “t” hot key, wait for the record to be acquired and saved, then repeat 19 more times. If you are automatically triggering, hit the “Ctrl-t” hot keys to start automatic acquisition to the limit specified.



A typical passive source record is shown below.



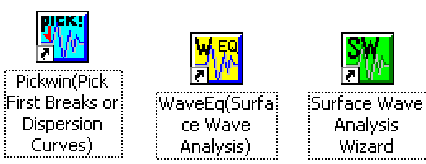
You will likely see some coherent noise events representing when cars have passed or such. What is preferred is a steady signal of noise, without strong changes in amplitude throughout the record and from trace-to-trace. Some isolated variation in amplitude is usually fine.

4 Data Analysis Using the Wizards

SeisImager/SW is capable of MASW (Multi-channel Analysis of Surface Waves) from active sources and MAM (Micro-tremor Array Measurement) data analysis from passive sources. The result is a one-dimensional (1D) profile of shear-wave (V_s) velocity with depth. In the near future, a version additionally capable of two-dimensional (2D) V_s profiling from active source data will be available separately and as an upgrade for users that have already purchased the 1D version.

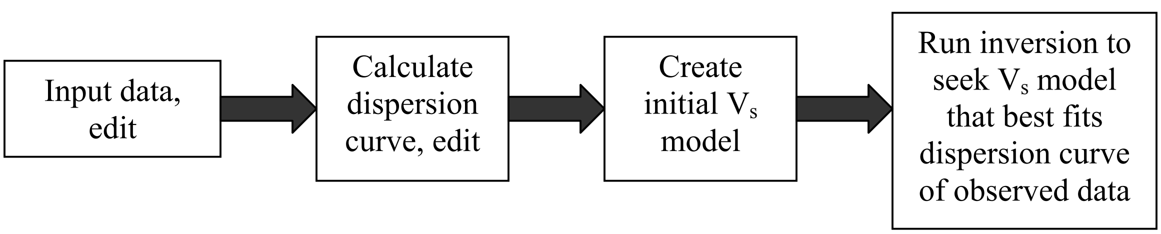
4.1 Surface Wave Analysis Wizards

As mentioned in Section 2, the modules Pickwin and WaveEq comprise SeisImager/SW and there is the Surface Wave Analysis Wizard that automatically calls on Pickwin and WaveEq to walk you through the processing flows. There is a flow for active source data and passive source data.



This section provides an explanation of the wizard operation, processing flow, and basic dialog box parameters. Please refer to Sections 5 and 6 for complete description and explanation of menu items and dialog box parameters and Section 7 for a summary of the functions used in the wizards so that you can manually reproduce the processing flow.

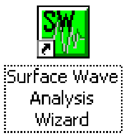
The processing flows as follows:



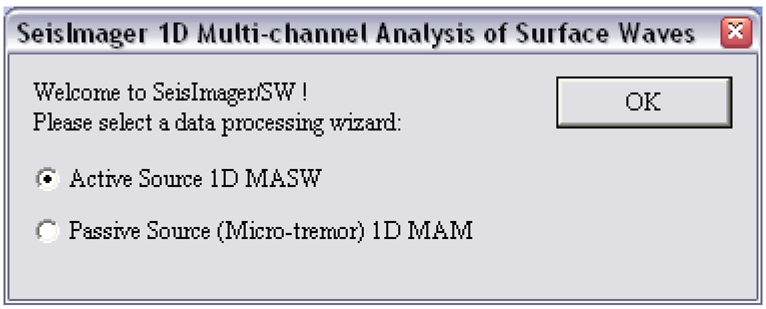
The wizard is based on the Enter key. At any time you can manually override the wizard by entering the menus. The wizard assumes that your geometry was correctly assigned and saved in the file header during acquisition. A complete dataset is considered to consist of a set of active data and a set of passive data for each site.

4.1.1 Active Source 1D MASW Wizard

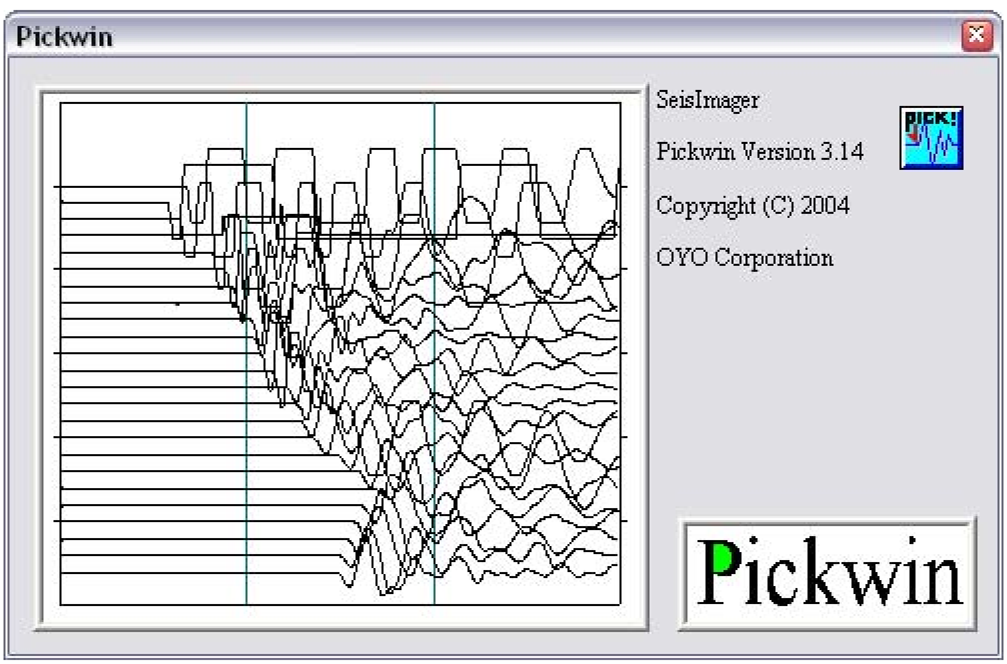
Double-click on the Surface Wave Analysis Wizard icon.



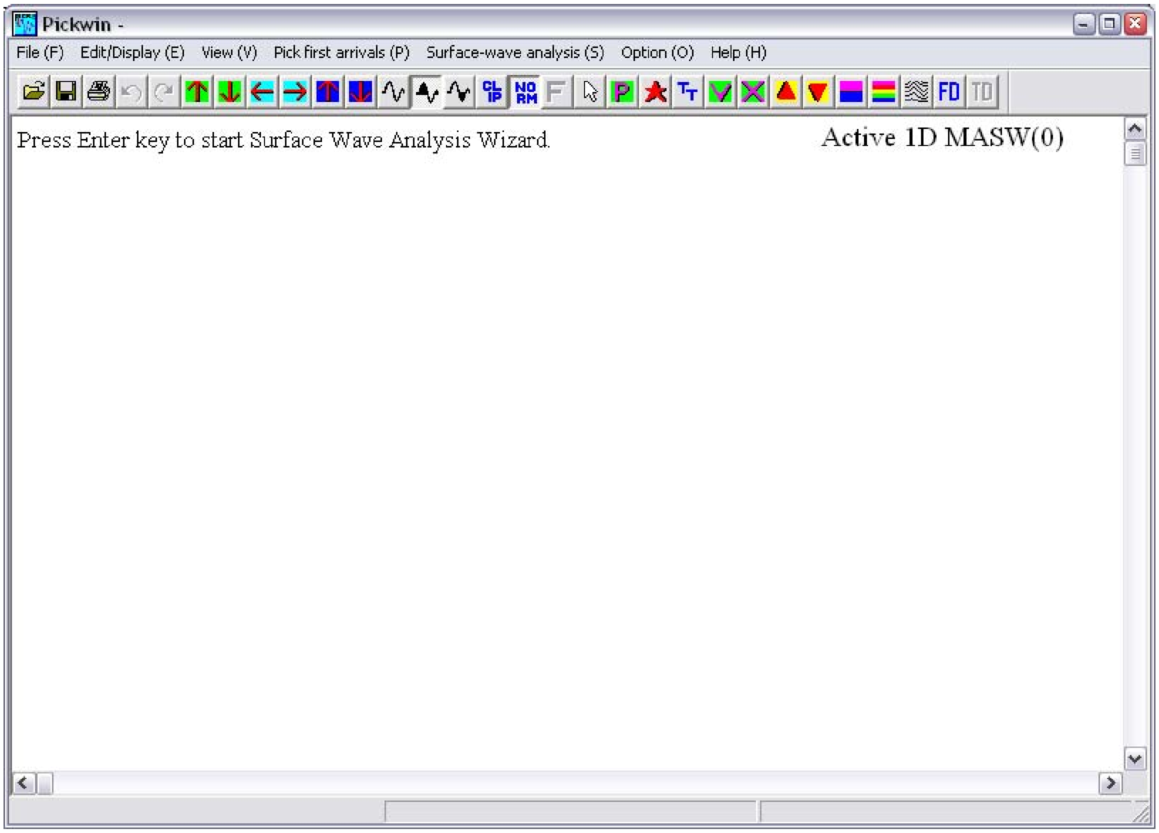
The following dialog box appears. Select *Active Source 1D MASW* and click *OK*.



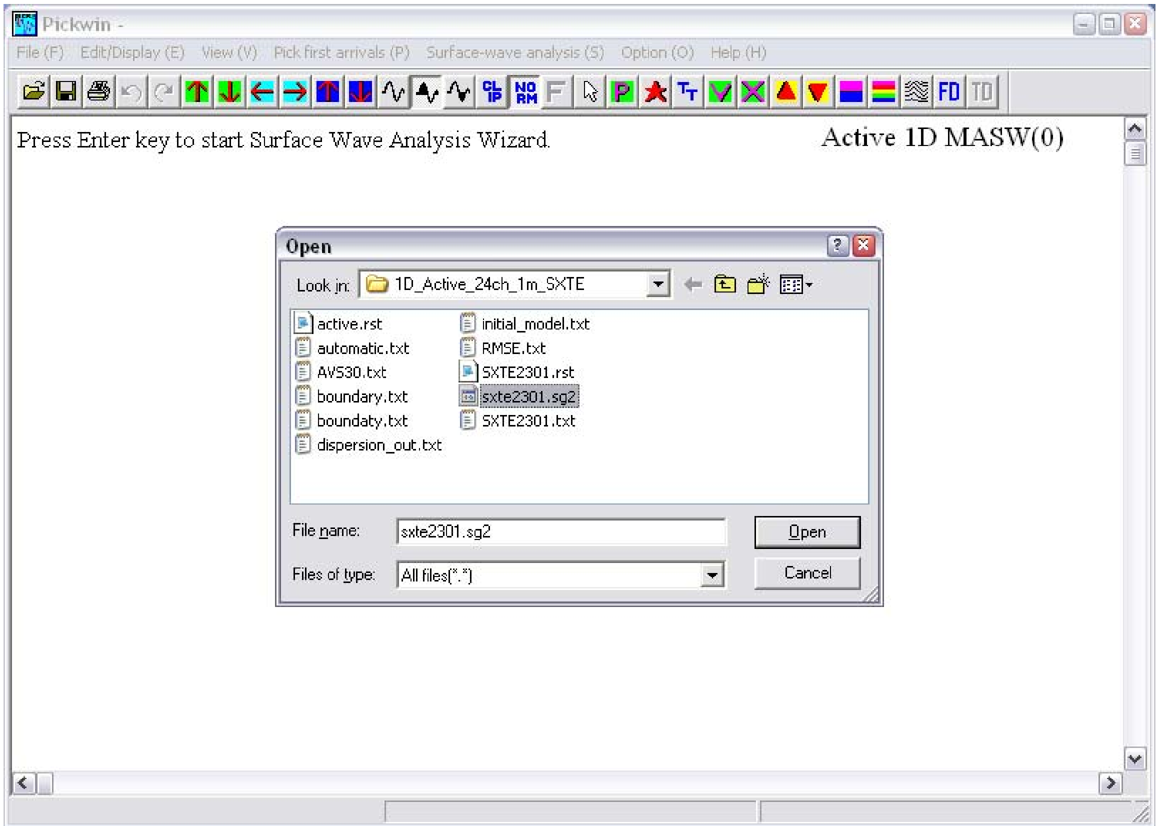
The Pickwin module is then launched.



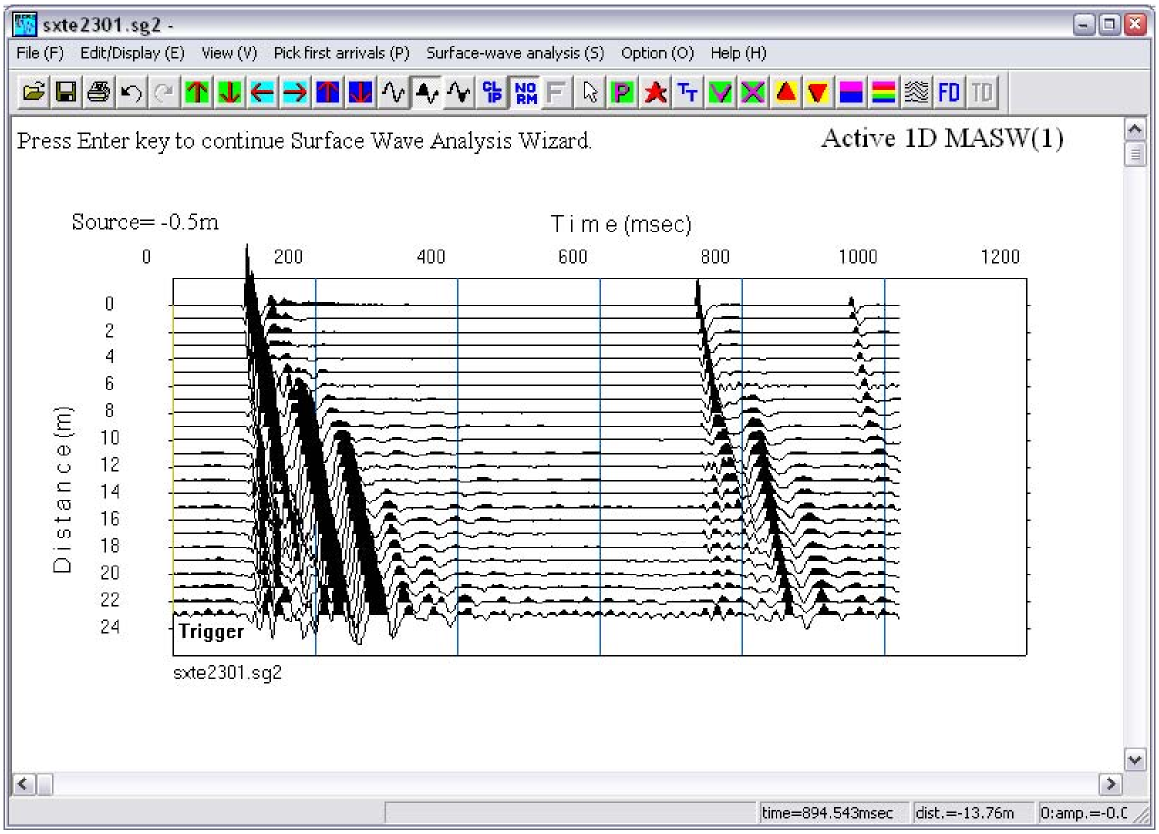
The first window appears as follows. The wizard mainly calls functions from the *File* and *Surface Wave Analysis* menus. Hit the *Enter* key as instructed in the upper left hand corner of the window to begin.



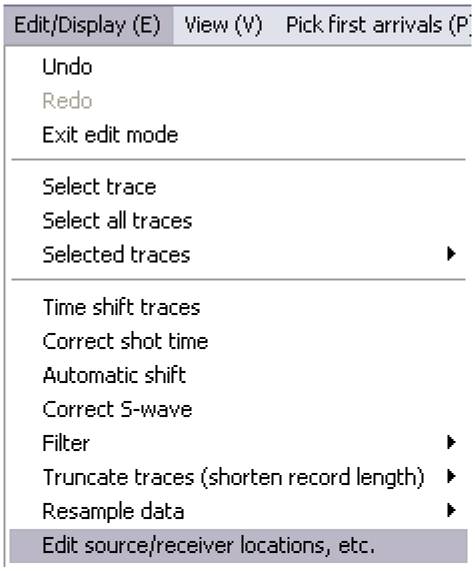
Specify the active source data record that you want to open and click *Open*.



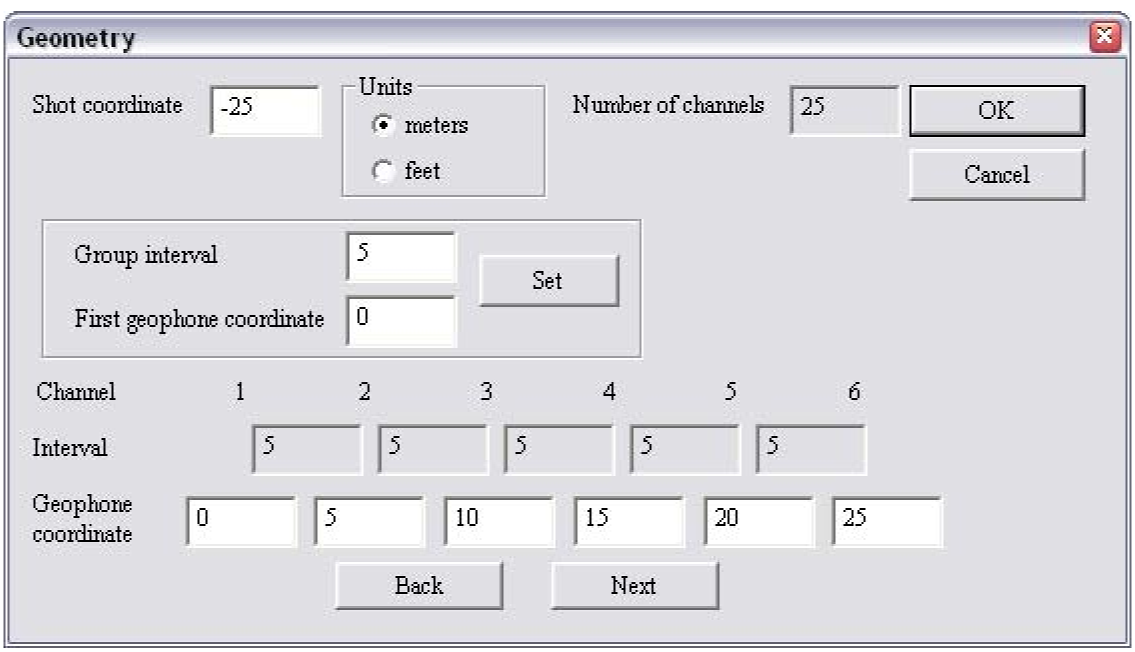
Once the waveform file is open, you can modify the display settings to optimize the view. All of these settings are common with SeisImager/2D for refraction data processing; please refer to the SeisImager/2D manual included on the same CD as this manual for complete explanation. The main functions needed are the *Amplitude gain* buttons, the *Horizontal axis sizing* buttons, the *Vertical axis sizing* buttons and the *Normalize* button.



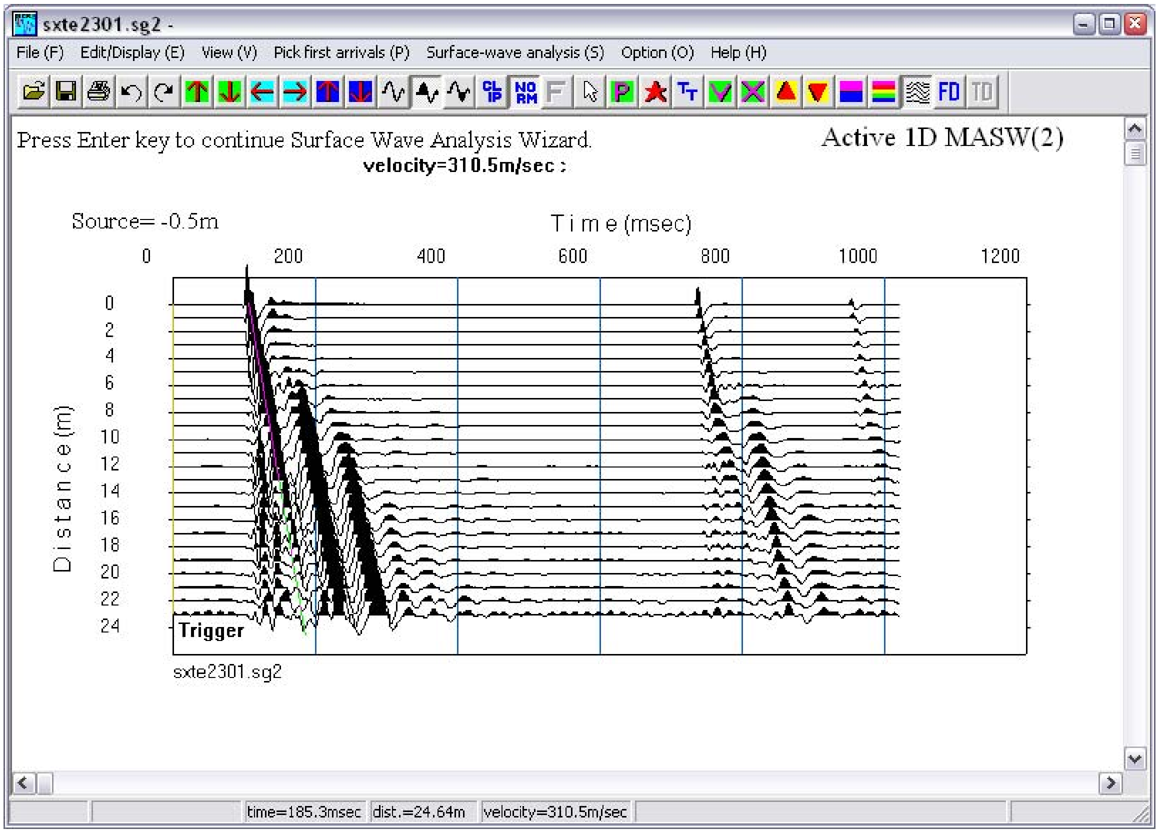
The unit labeling should be changed here to reflect that used at the survey site through the *Edit/Display* menu, *Edit source/receiver locations, etc*. This will affect the units shown in the dialog boxes as well it will update the minimum phase velocity default value, which is either 35 m/s or 100 ft/sec. Once set, the assigned units will be set for subsequent uses of the wizard.



The *Geometry* dialog box allows selection of units and reports the coordinates saved in the file header at the time of acquisition. To set the units, select between *meters* and *feet*. Click *OK* when you are done.

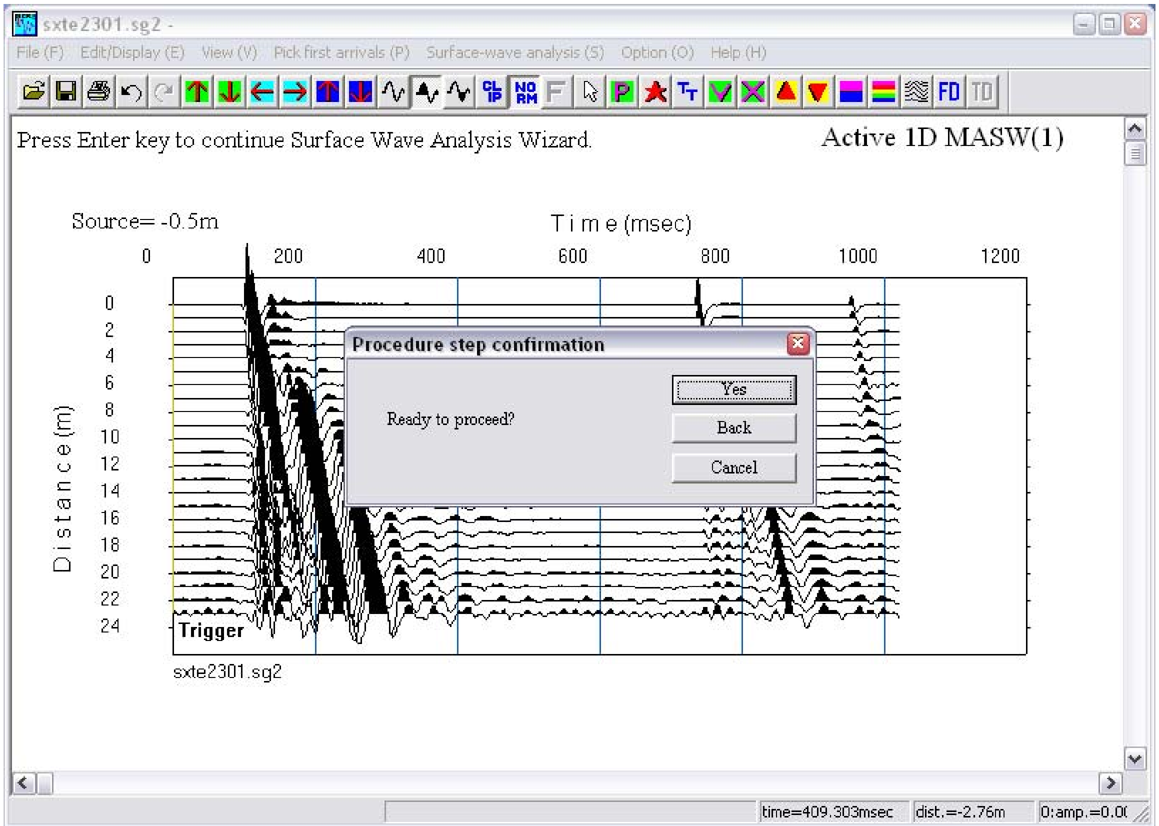


Also at this stage, you can click on the *Show apparent velocity*  button to draw a line with the mouse across the faster part of the surface wave package for an estimate of maximum velocity, which will be used later. The line is shown in green over white areas and in pink over black areas.



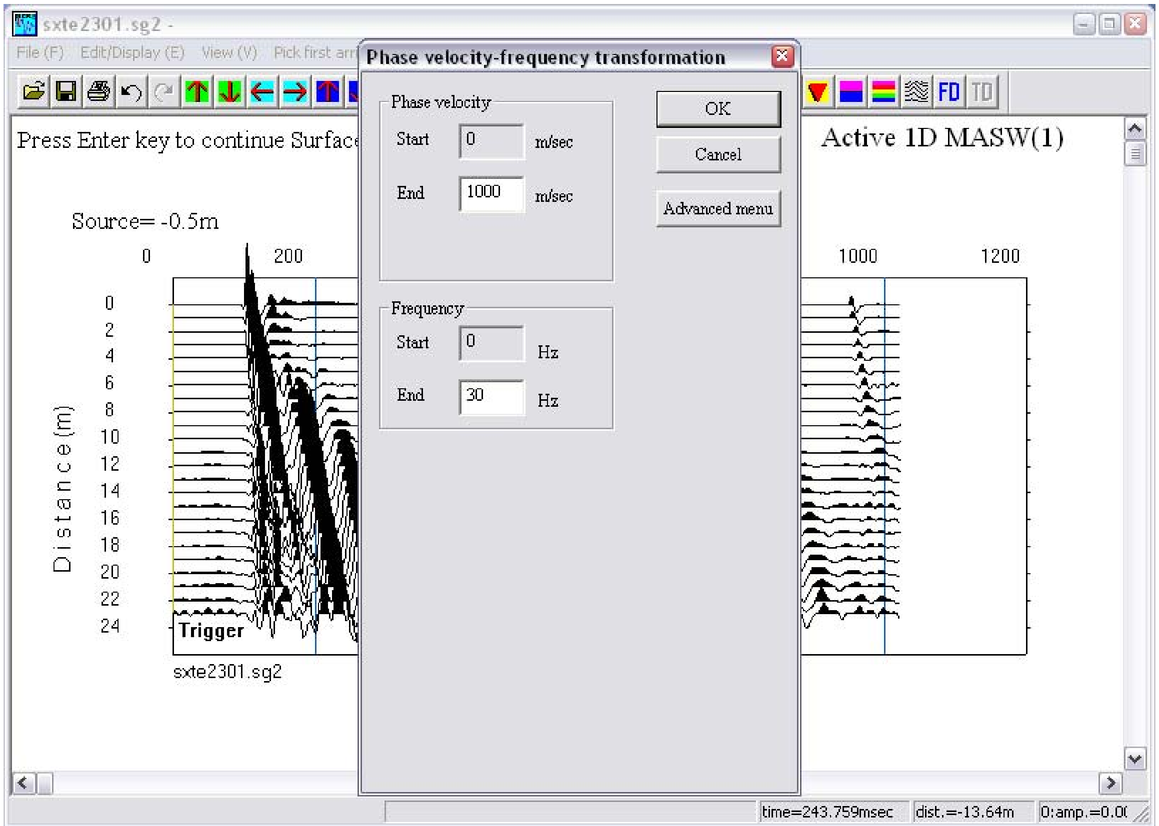
Hit the *Esc* key to exit the *Show apparent velocity* tool and then hit the *Enter* key to continue with the wizard.

Click *Yes* to proceed.



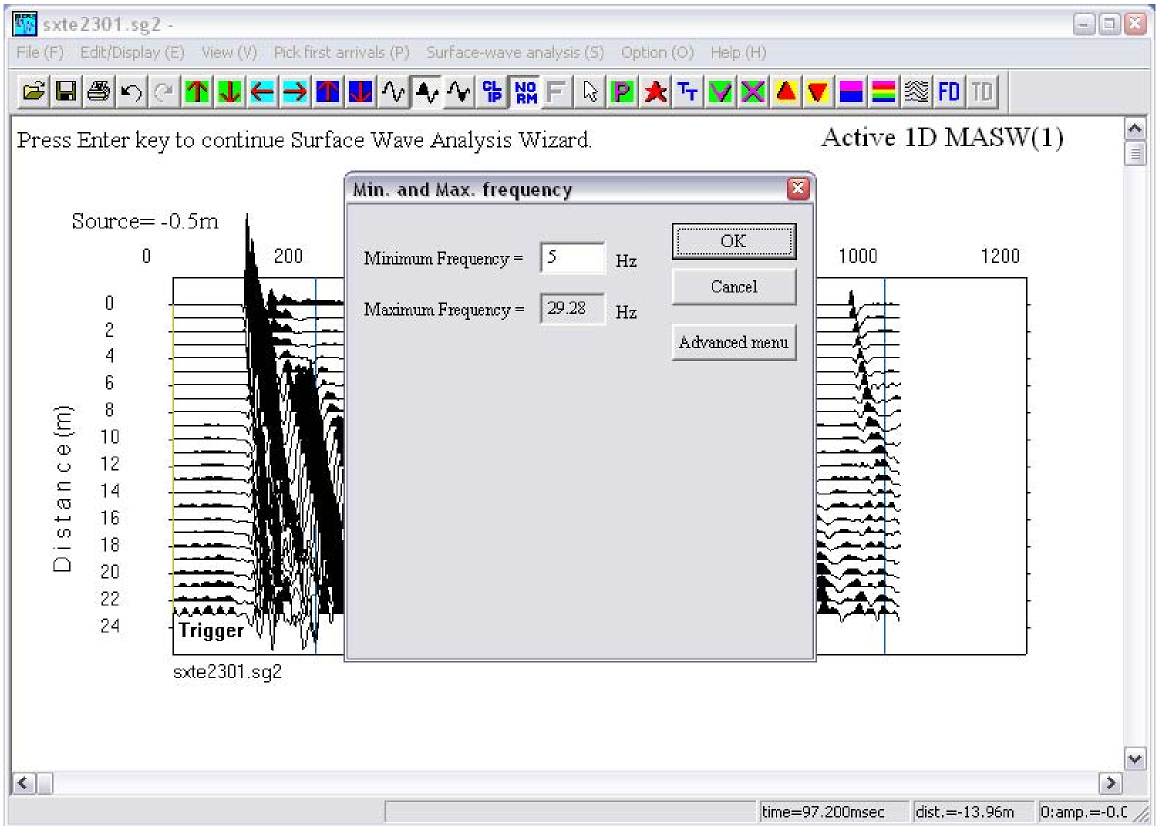
Set the *Phase Velocity End* to suit the maximum velocity you expect for your site (at least greater that what you measured with the *Show apparent velocity* tool). This sets an outer bound for the dispersion calculation. The default is 500 m/sec or ft/sec.

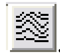
Accept the default value for *Frequency End*.

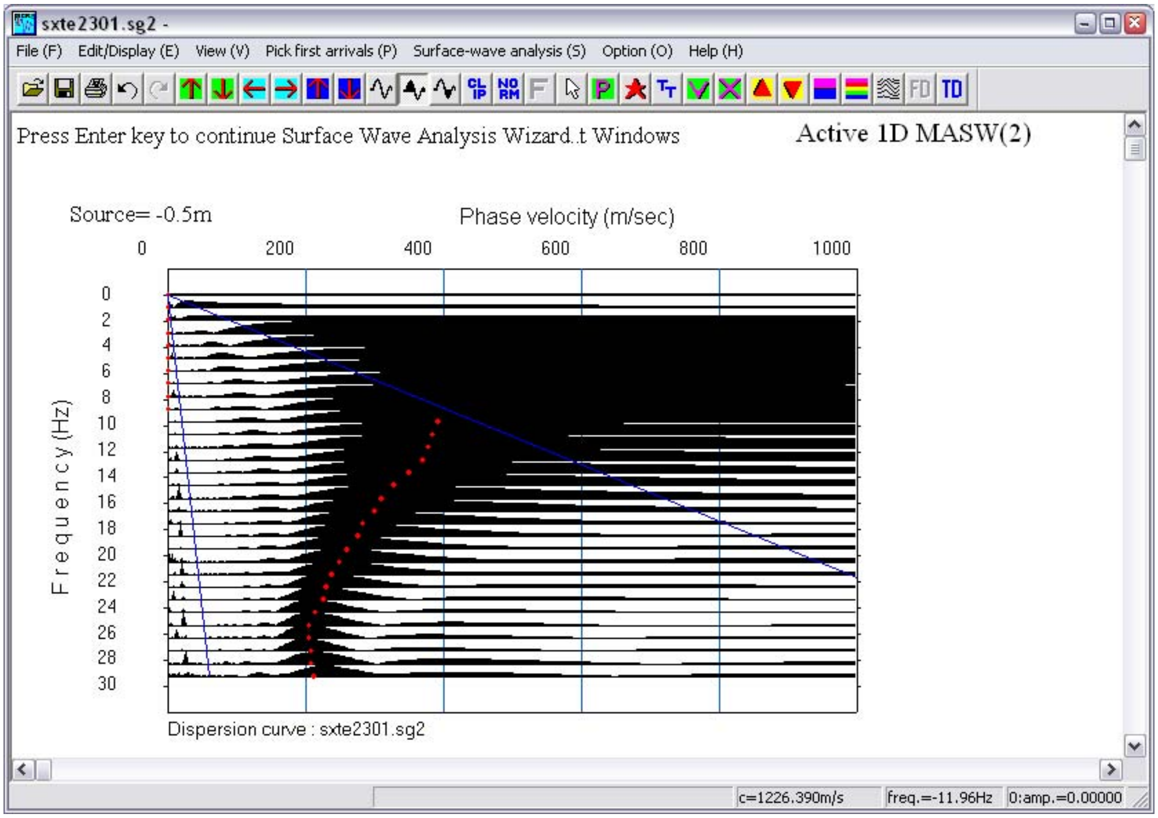


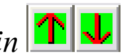
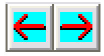
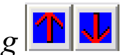
The *Minimum Frequency* default is 5 Hz assuming that 4.5 Hz geophones were used. If you have used other frequency geophones, enter the value of their natural frequency.

The *Maximum Frequency* reflects the value entered in the previous screen, except it appears approximate because it has been recalculated in Fourier space. Click *OK* when you are done.

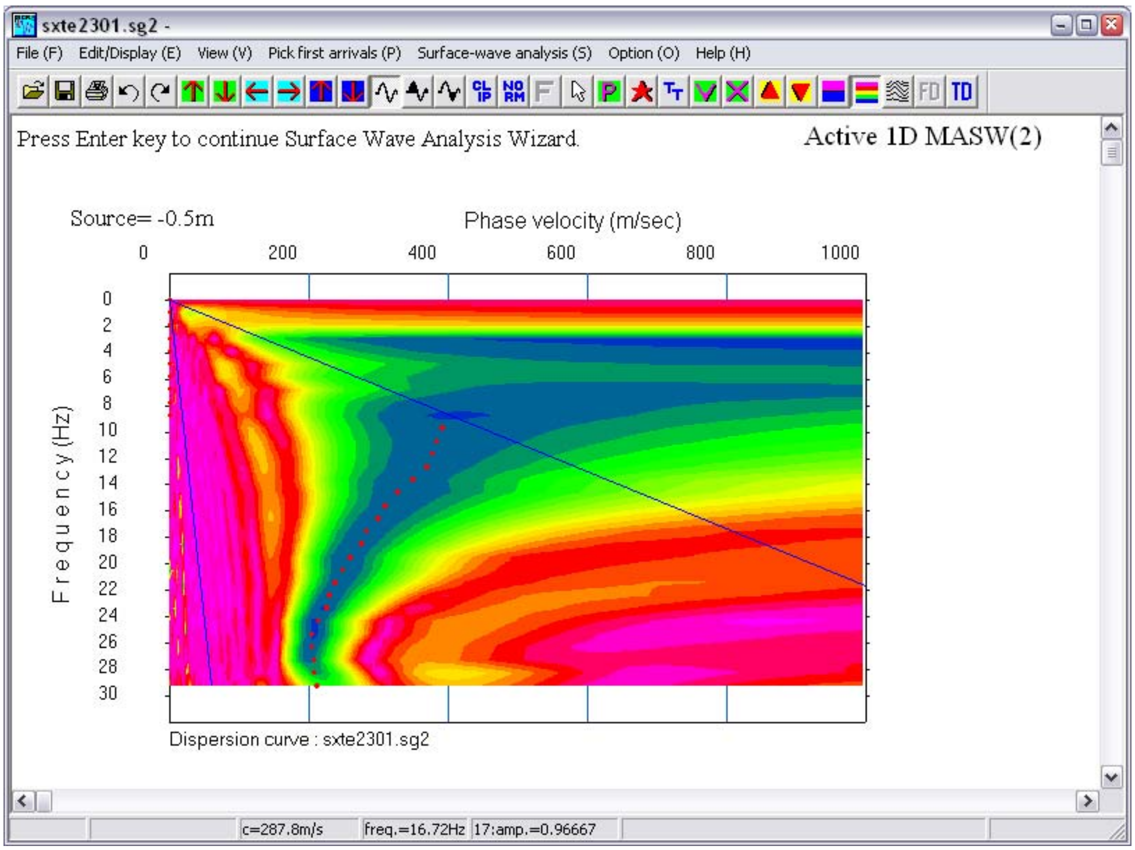


The next window you will see shows a plot of phase velocity versus frequency. The default view is wiggle trace shaded black . The software automatically picks the mathematical maximum amplitude for each frequency (red points), which defines the dispersion curve.

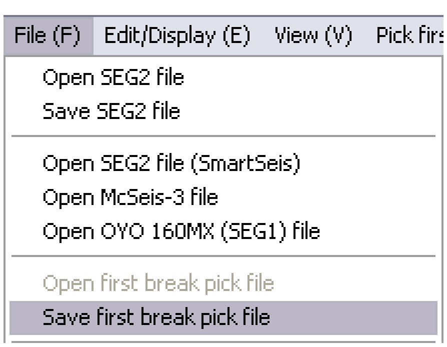


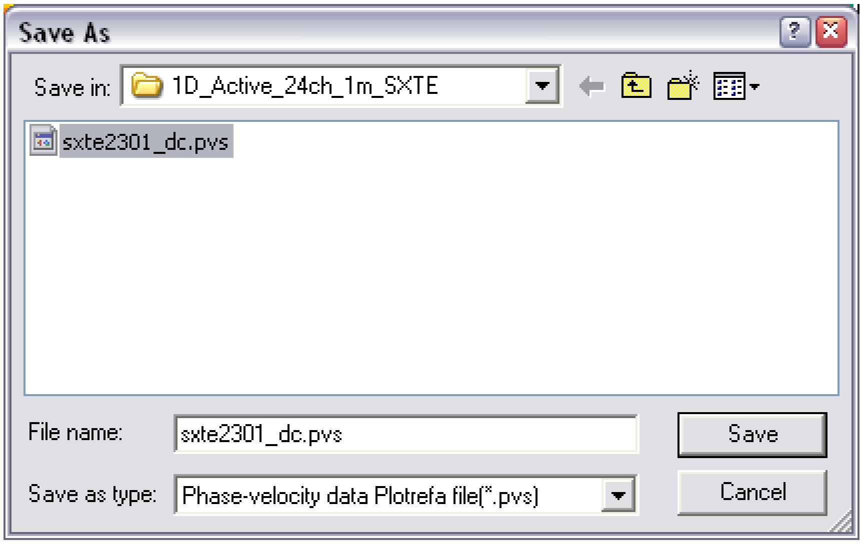
Usually the dispersion curve is more obvious in color contours. Select the *Fine color contour*  button to switch to a color plot and use the *Amplitude gain*  buttons, the *Horizontal axis sizing*  buttons, and the *Vertical axis sizing*  buttons to optimize the view.

If you need to manually make or edit picks, you can do so by clicking the mouse at the desired pick location. As you drag the mouse over the plot, refer to the amplitude value read-out on the bottom bar to help identify the maxima.

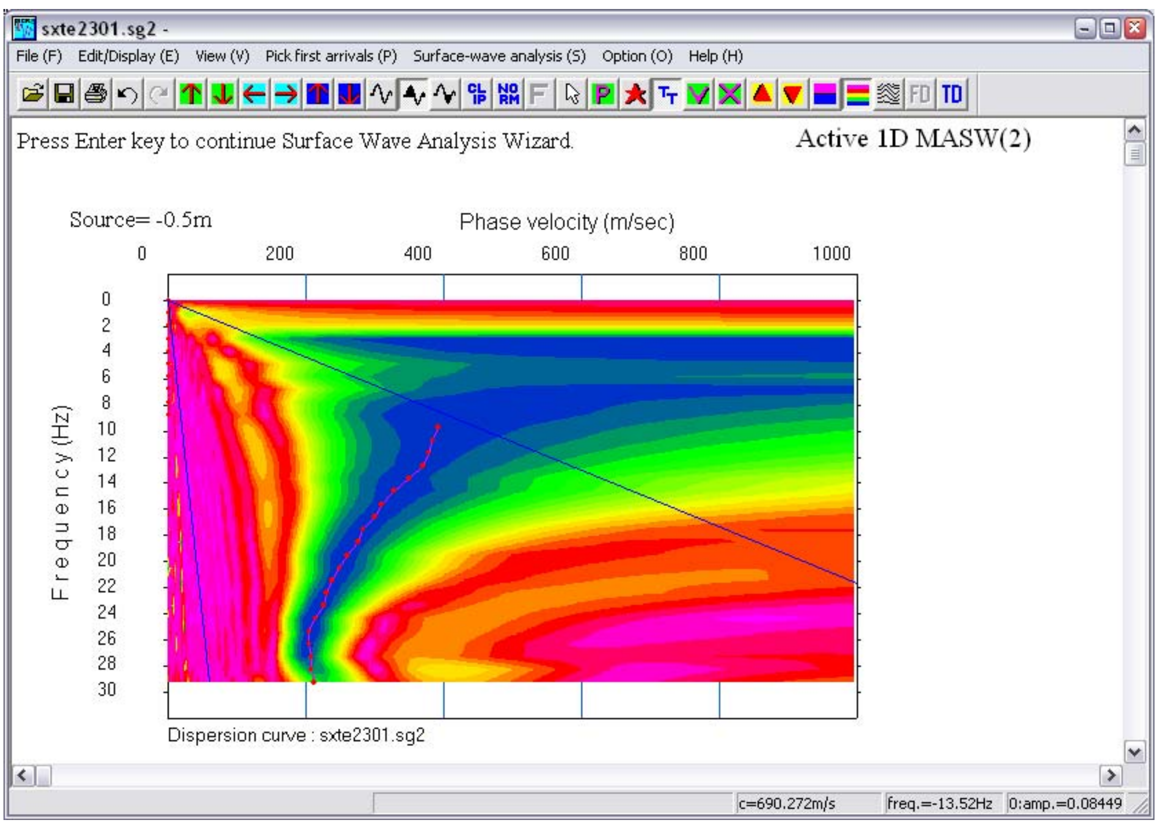


If you want to be able to input your dispersion curve picks again later and display them with the dispersion curve, you should save the picks here. Go to the *File* menu and select *Save first break pick file*.

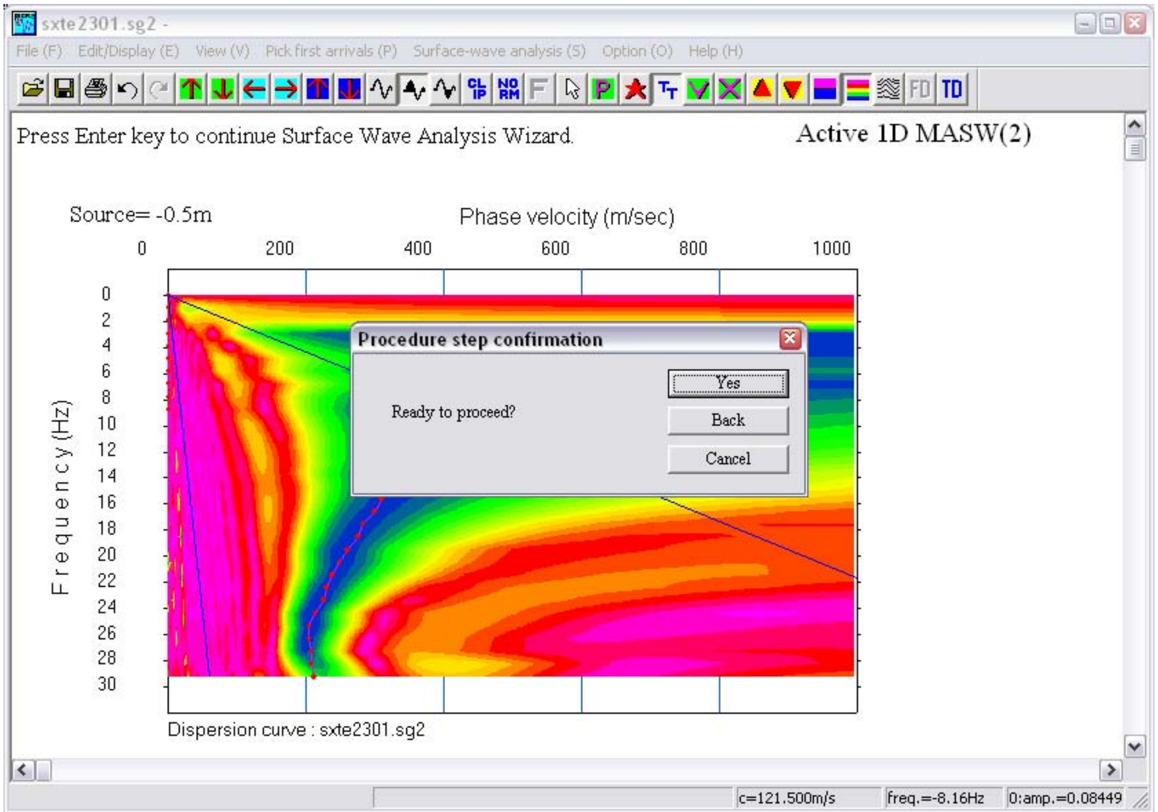




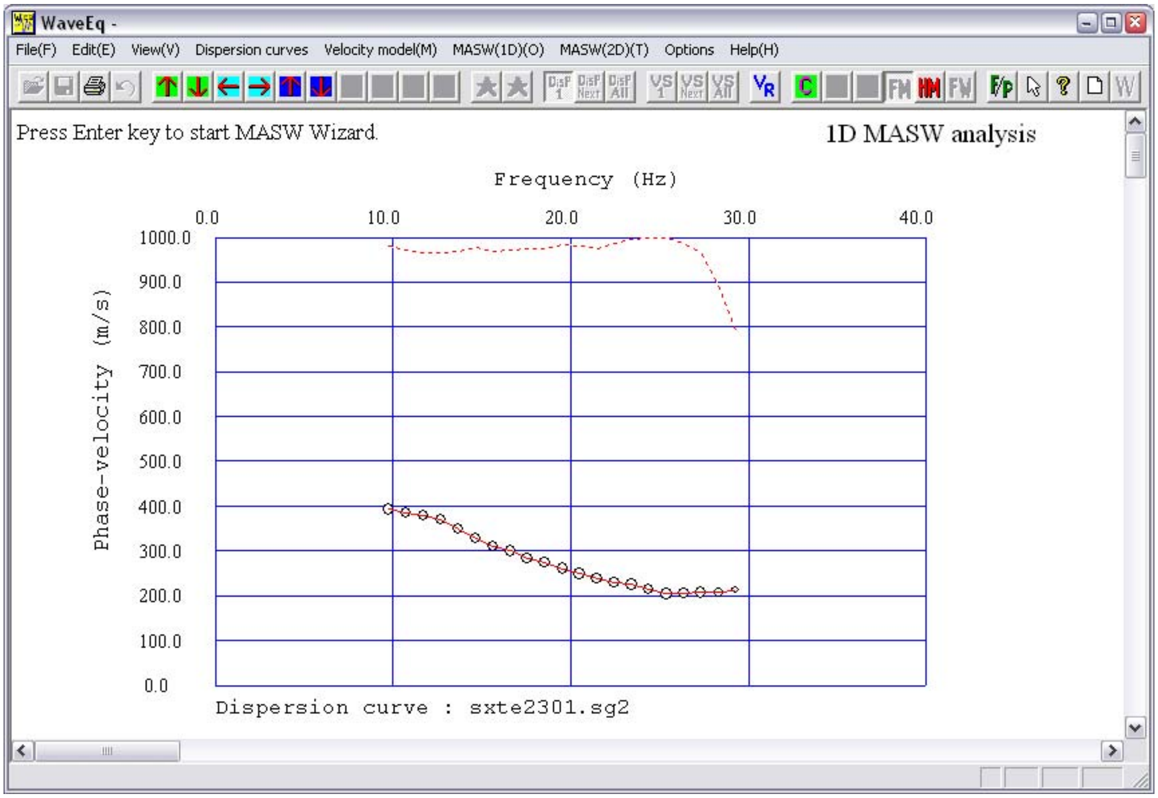
Assign a name to the file with the extension .pvs and click *Save*. Once saved you will see a pink line connecting the picks on the dispersion curve as shown below. Refer to Section 5.1.2 on how to re-input saved picks.



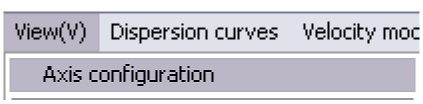
Hit the *Enter* key as instructed in the upper left-hand corner of the window and then click *Yes* when you are ready to proceed.

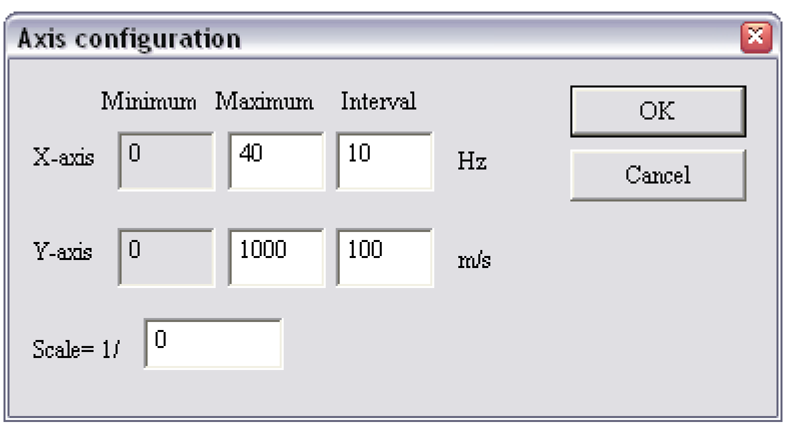


The dispersion curve will be displayed next in the WaveEq module.

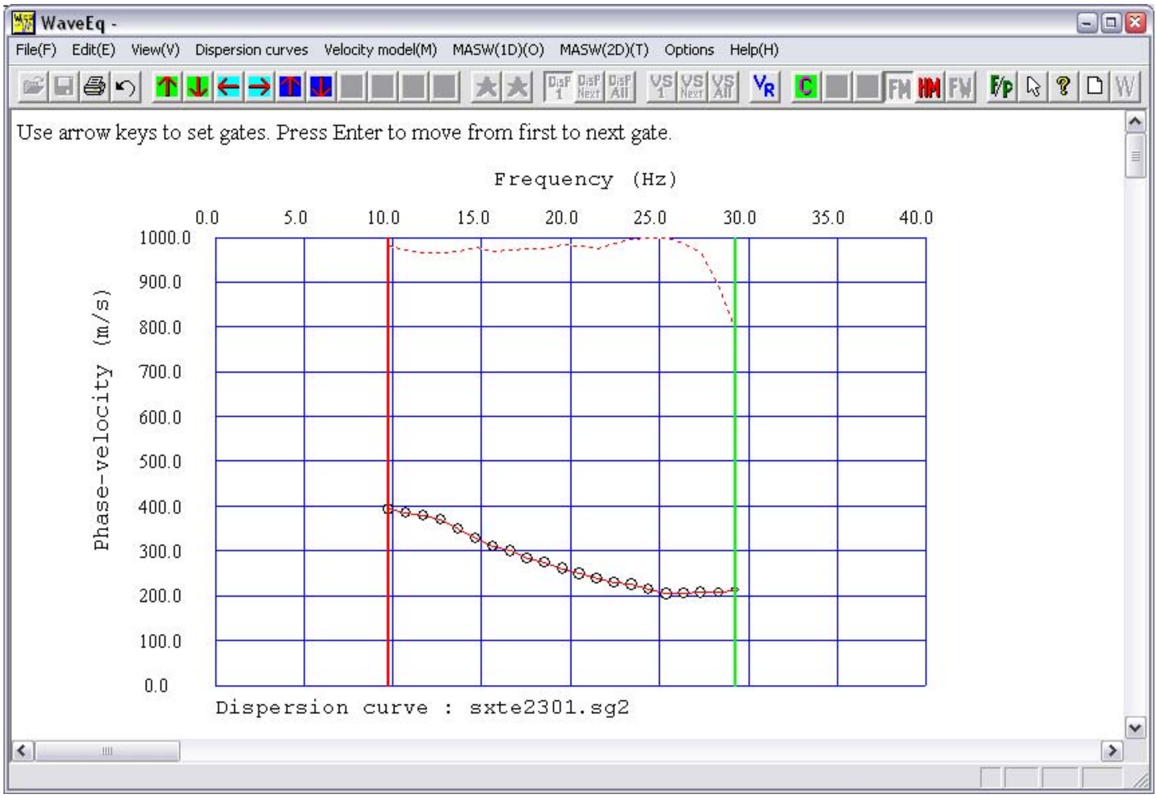


Go to the *View* menu and select *Axis configuration* to change the plotting scales if needed.





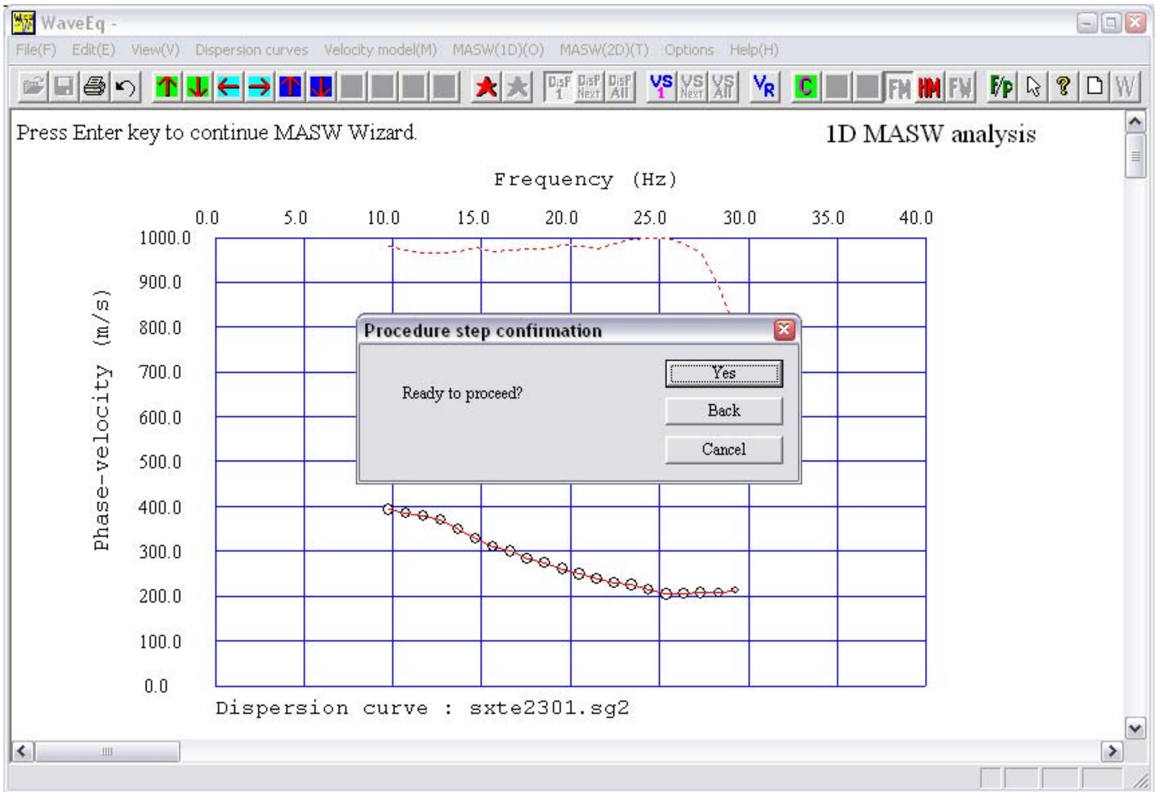
In WaveEq, you can edit the dispersion curve if needed. Commonly, there are spurious picks on the low and high frequency ends of the curve, and thus, a gate is provided for quick editing.



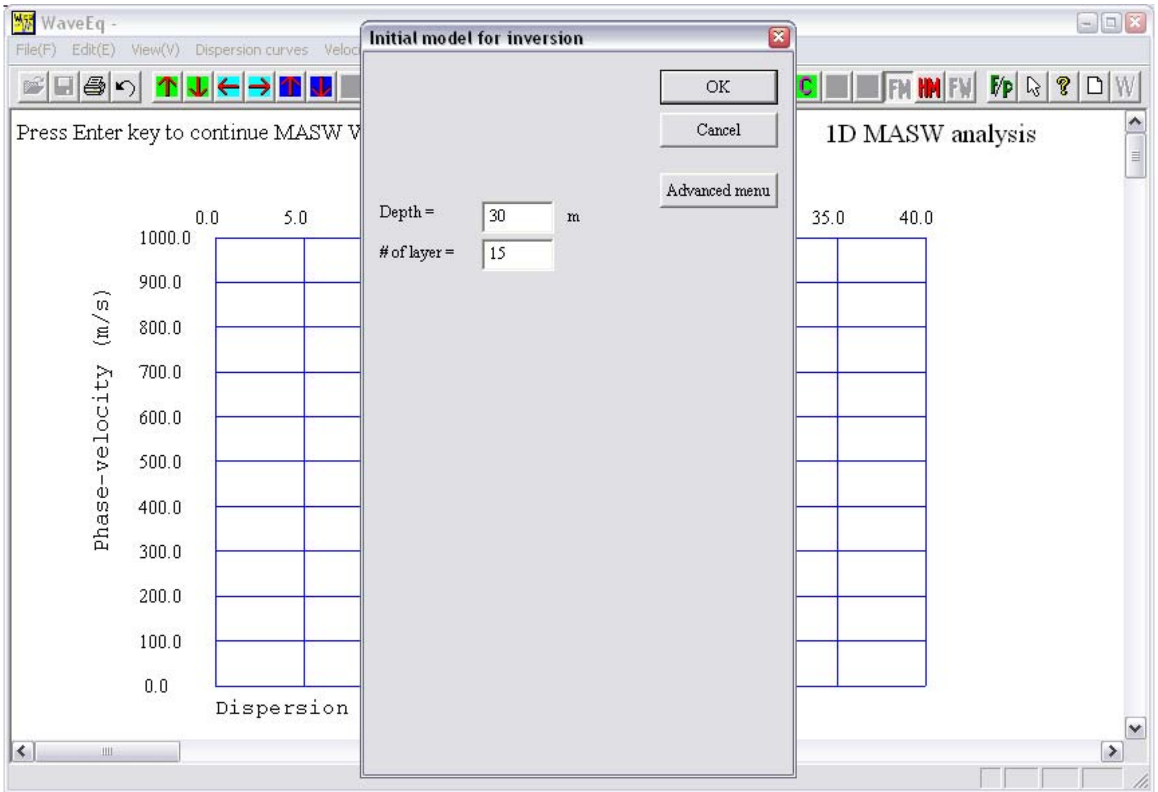
Follow the instructions in the upper left-hand corner of the window. The red-colored gate is the active gate. Use the arrow keys to position the gate at the frequency, phase velocity point to which you want to delete. Hit the *Enter* key to activate the right-hand side gate and position the same way. Hit the *Enter* key when you are done.

For this dataset, all points are retained and thus, the gates are not moved.

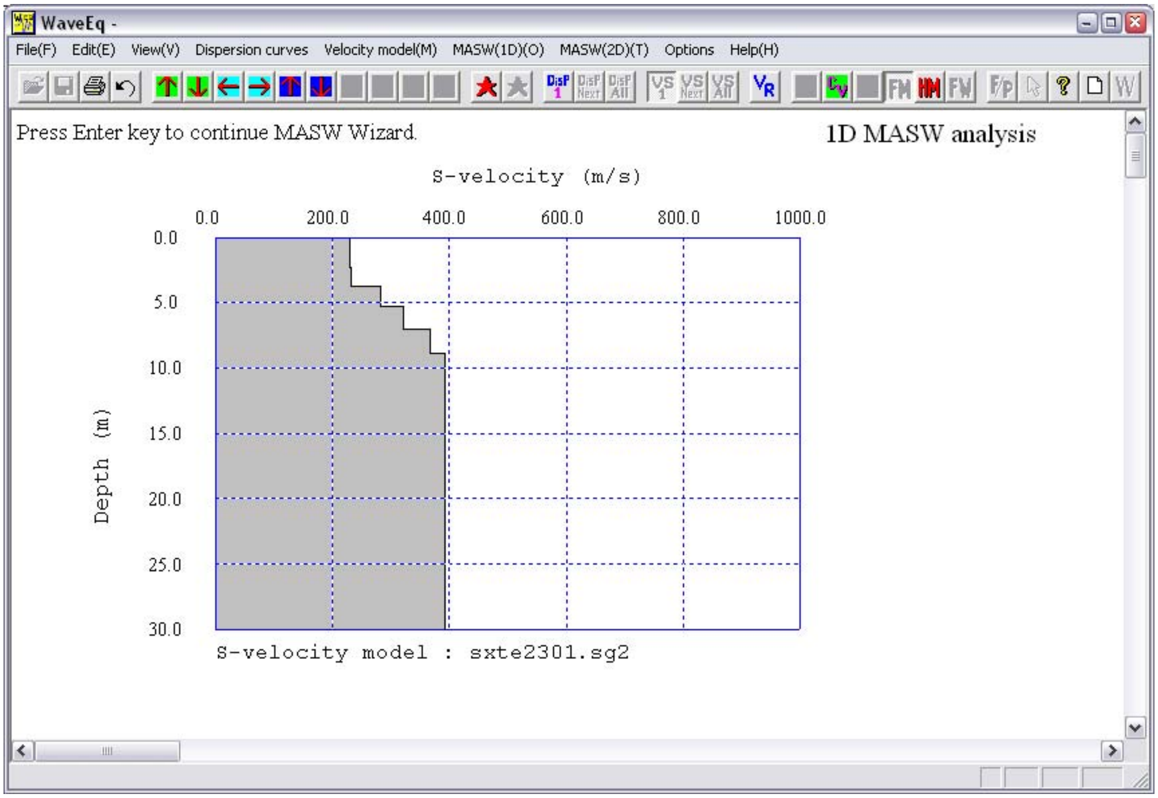
Hit the *Enter* key as instructed in the upper left-hand corner of the window and then click *Yes* when you are ready to proceed.



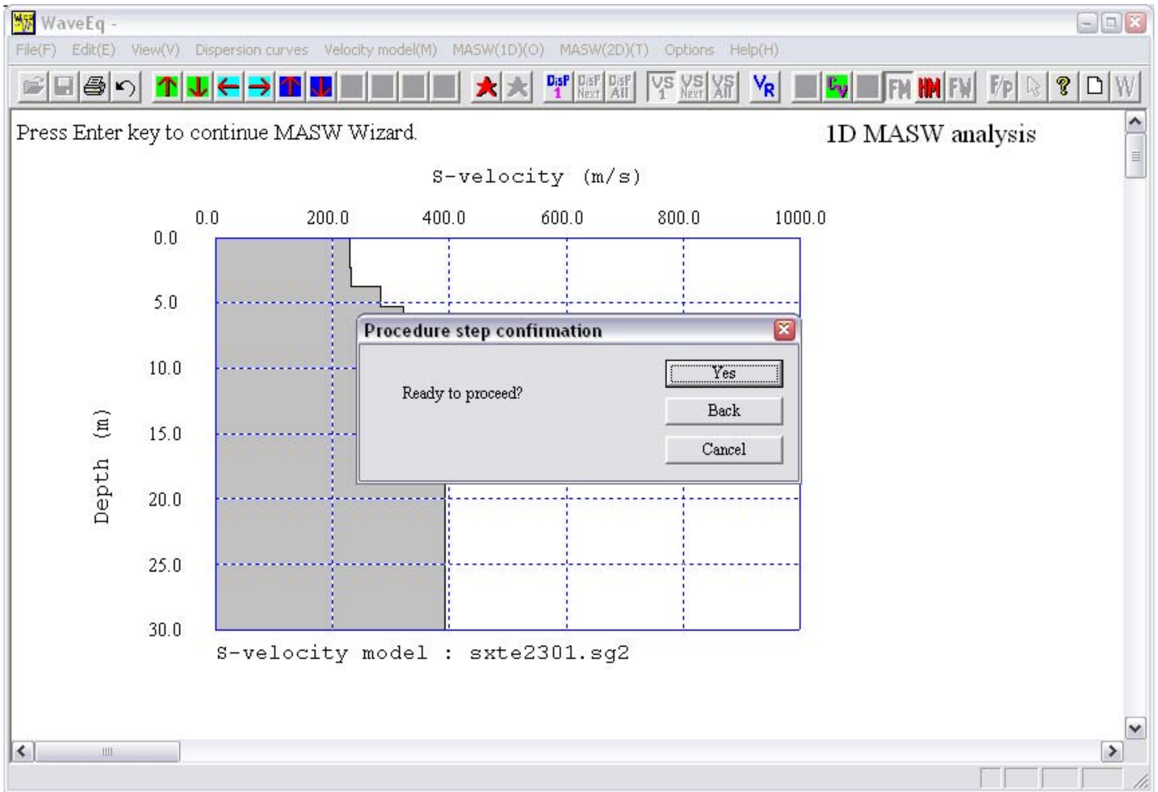
The next step is to set-up the initial model of V_s with depth. The software default is to calculate the initial model from the one-third-wavelength approximation. For *Depth*, enter the depth of penetration estimated from one-half the spread length. The default for the number of layers is fine. Click *OK* when you are done.



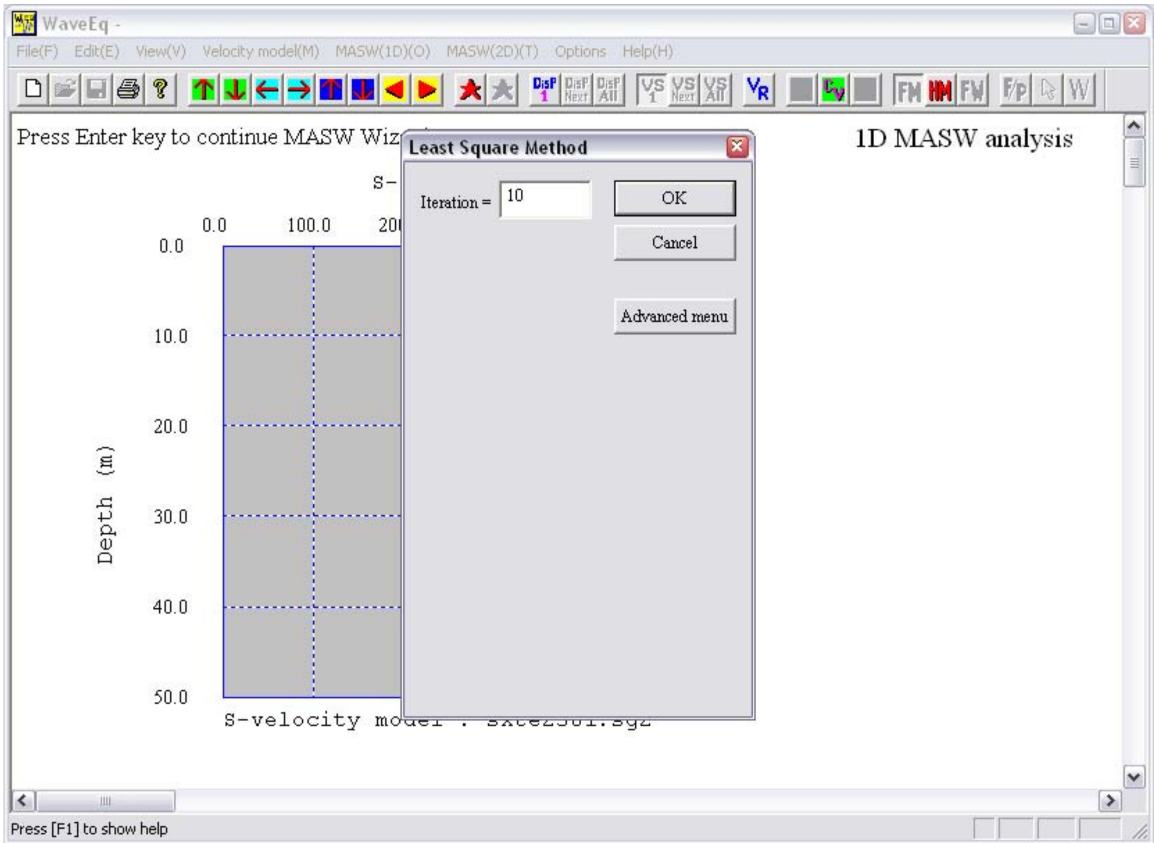
The initial model will appear.

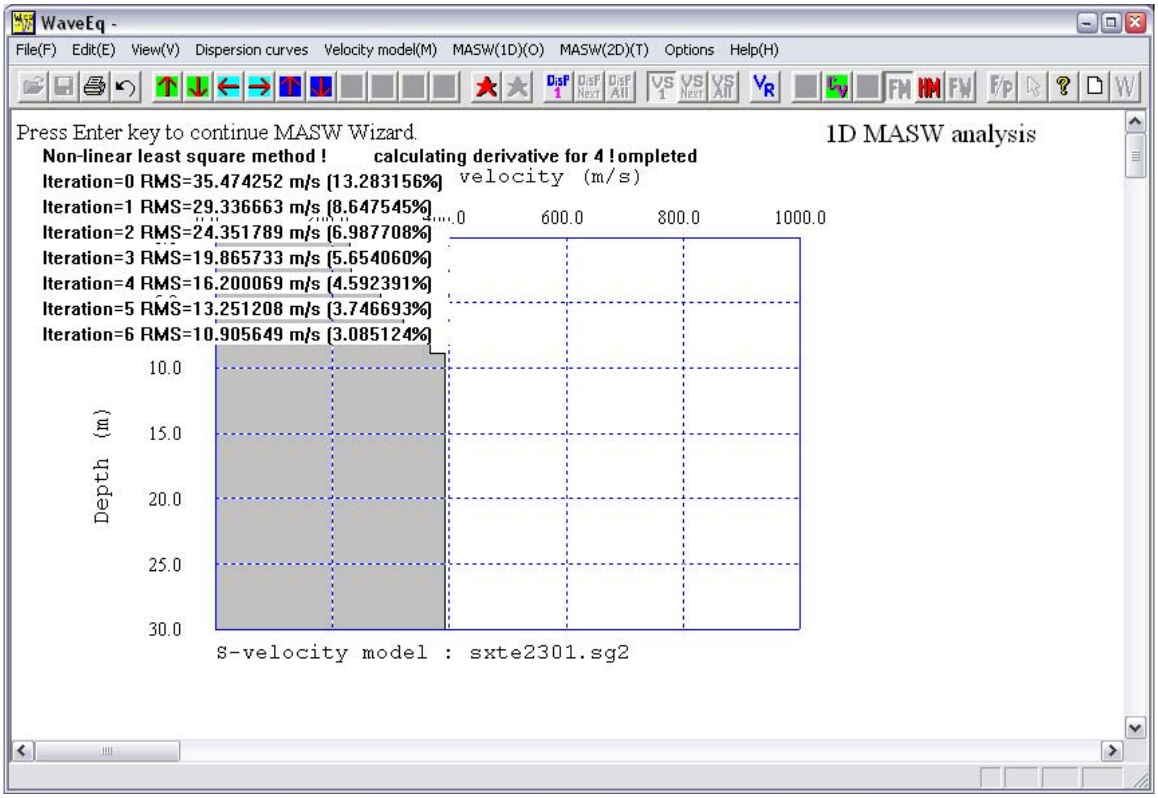


Hit the *Enter* key as instructed in the upper left-hand corner of the window and then click *Yes* when you are ready to proceed.

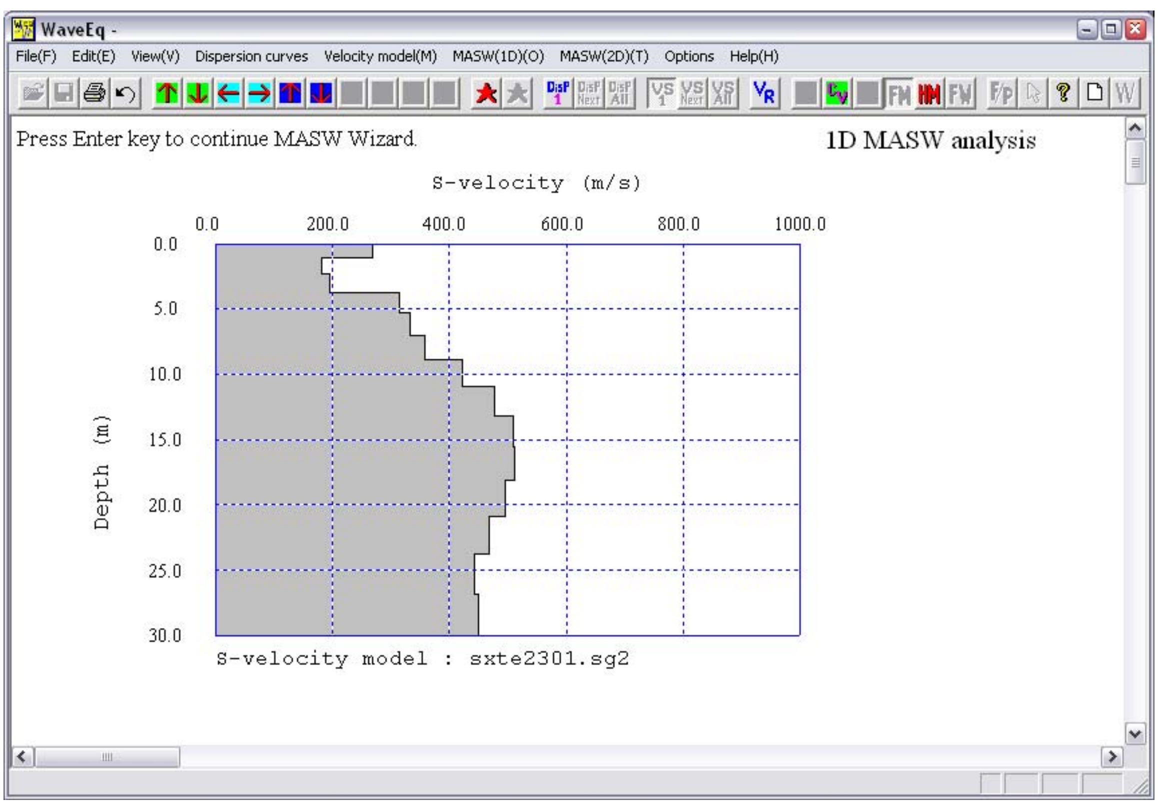


The next step is to set the number of iterations for the inversion. The software will iterate the number of times indicated to converge on the best fit of the initial model with the observed data. Accept the default of 10 iterations and click *OK*.

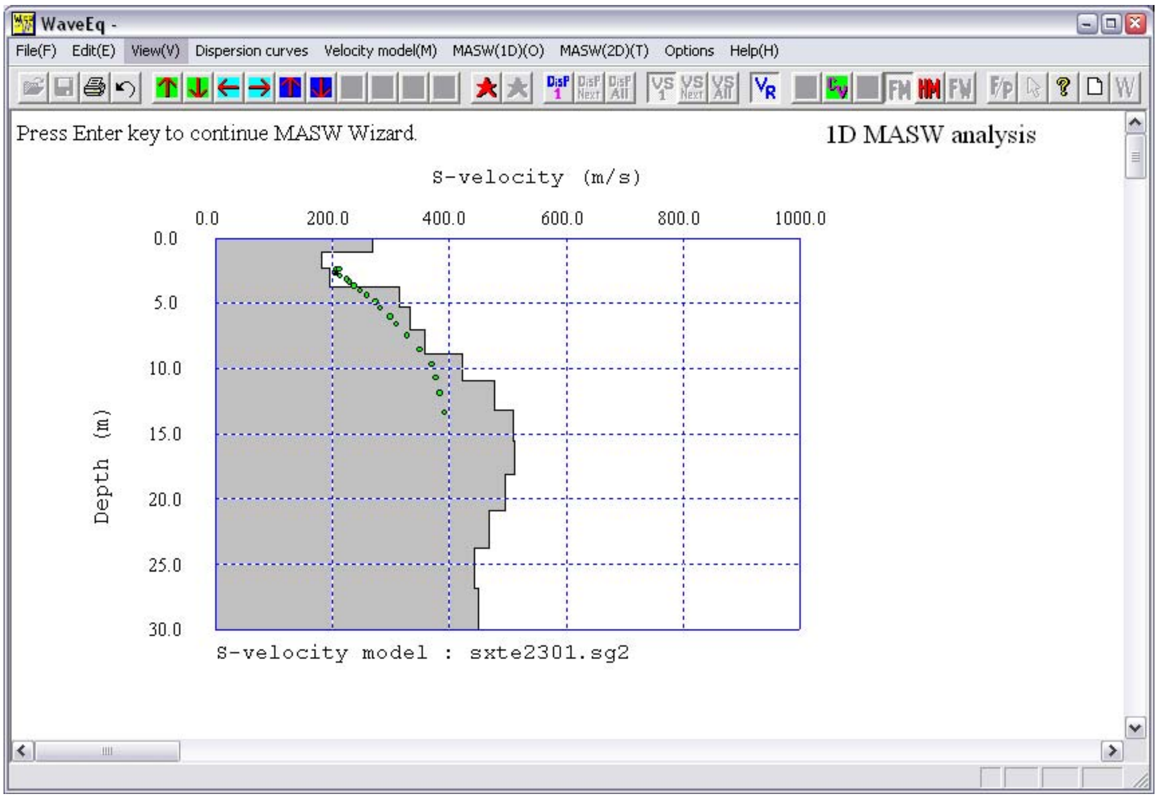




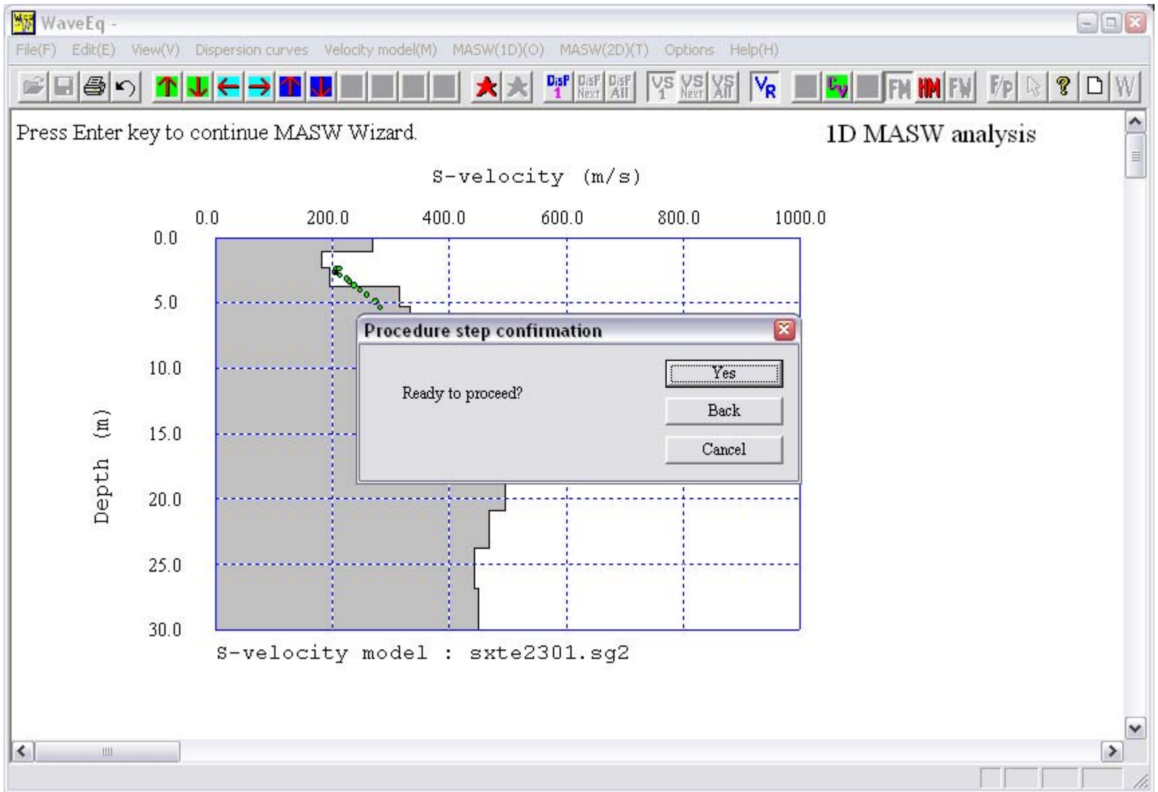
When the inversion is complete, the final V_s profile will be displayed.



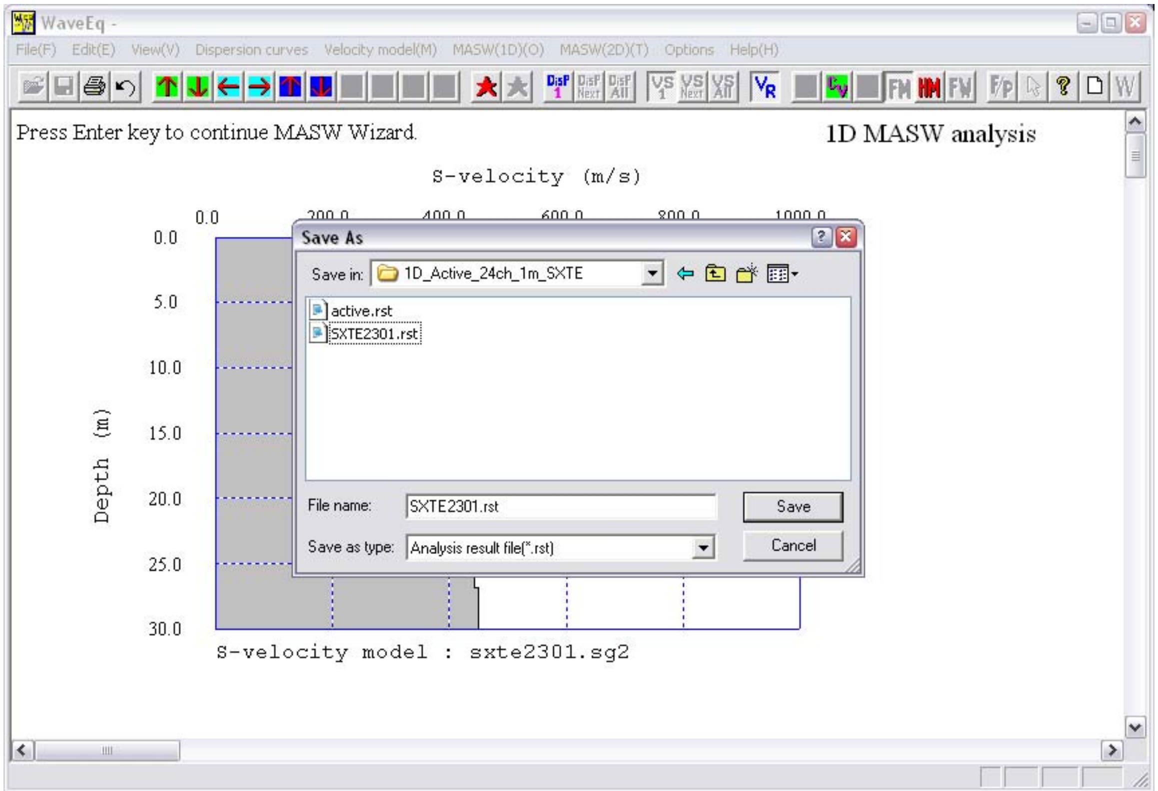
Click on the *Show apparent velocity model* button to overlay the one-third-wavelength approximation (green points), which is the best indicator of the actual depth of penetration. The model below the deepest green point should not be considered reliable.



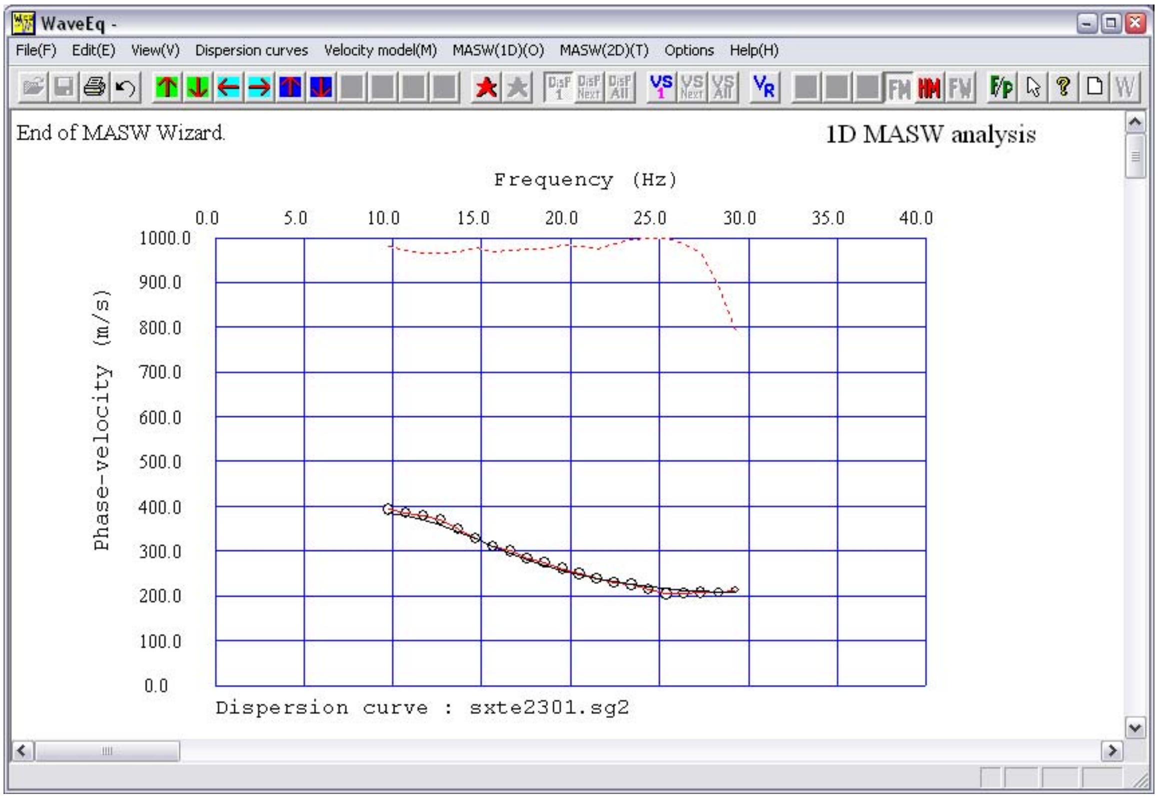
Hit the *Enter* key as instructed in the upper left-hand corner of the window and then click *Yes* when you are ready to proceed.



The last step in the wizard is to save the result. Assign a name to the file with the extension .rst and click on *Save*. The result file can be opened later in Notepad or imported into Excel for further manipulation.



After the file is saved, click on the *Show one dispersion curve*  button to view the original dispersion curve (black circles connected by red line). Click on the *Comparison*  button to overlay the calculated dispersion curve (black line) and visually assess the degree of mismatch. The matching error between the two curves is saved to a file called "RMSE.txt" in the data folder.

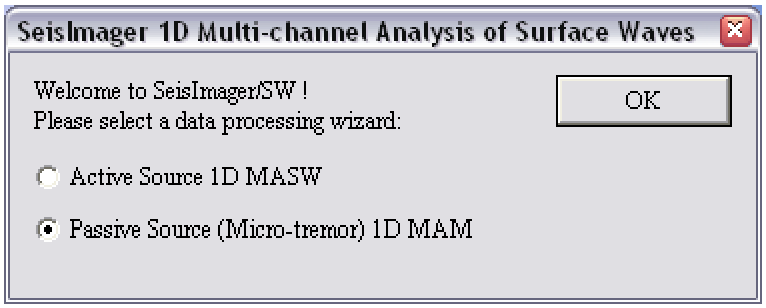


Once you are done, exit WaveEq.

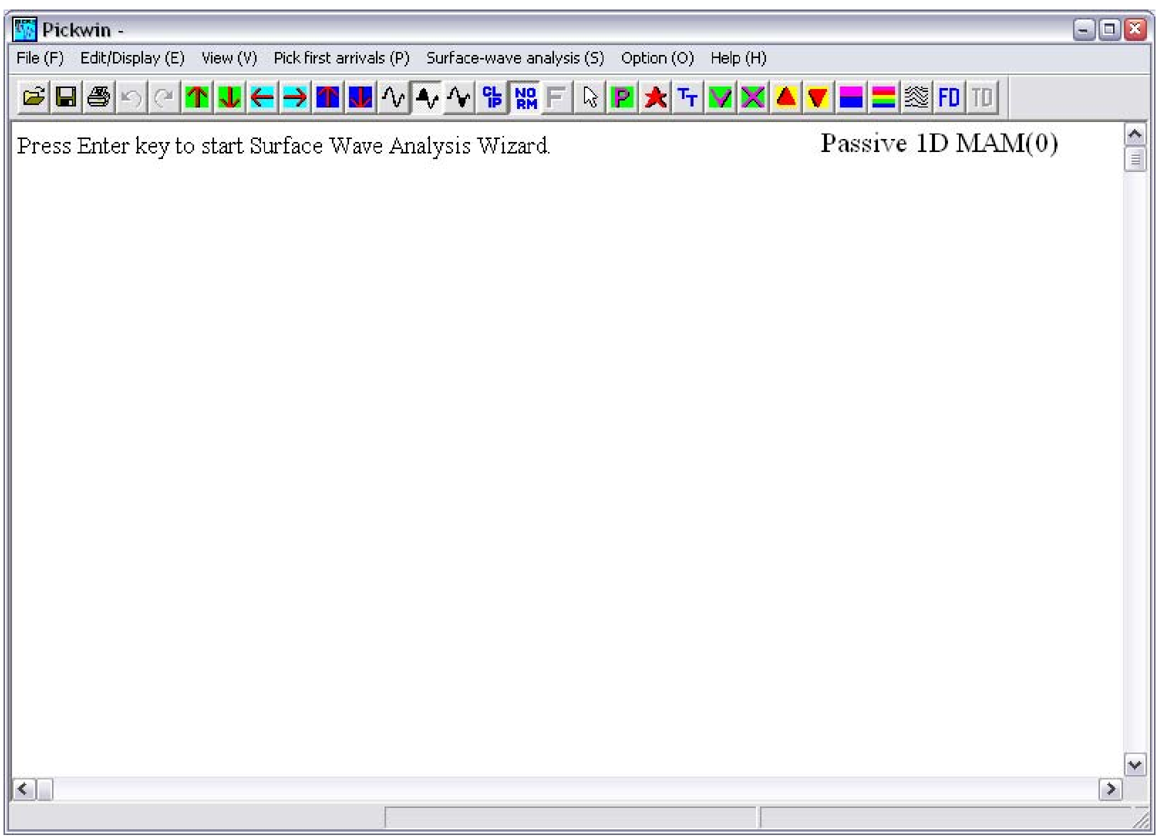
4.1.2 Passive Source 1D MAM Wizard

Most of the dialog boxes in the *Passive Source 1D MAM Wizard* you will find are the same as in the *Active Source 1D MASW Wizard* (Section 4.1.1), and this section assumes that you have already worked through the *Active Source 1D MASW Wizard*. The main difference with the passive source wizard is the number of files and how they are input.

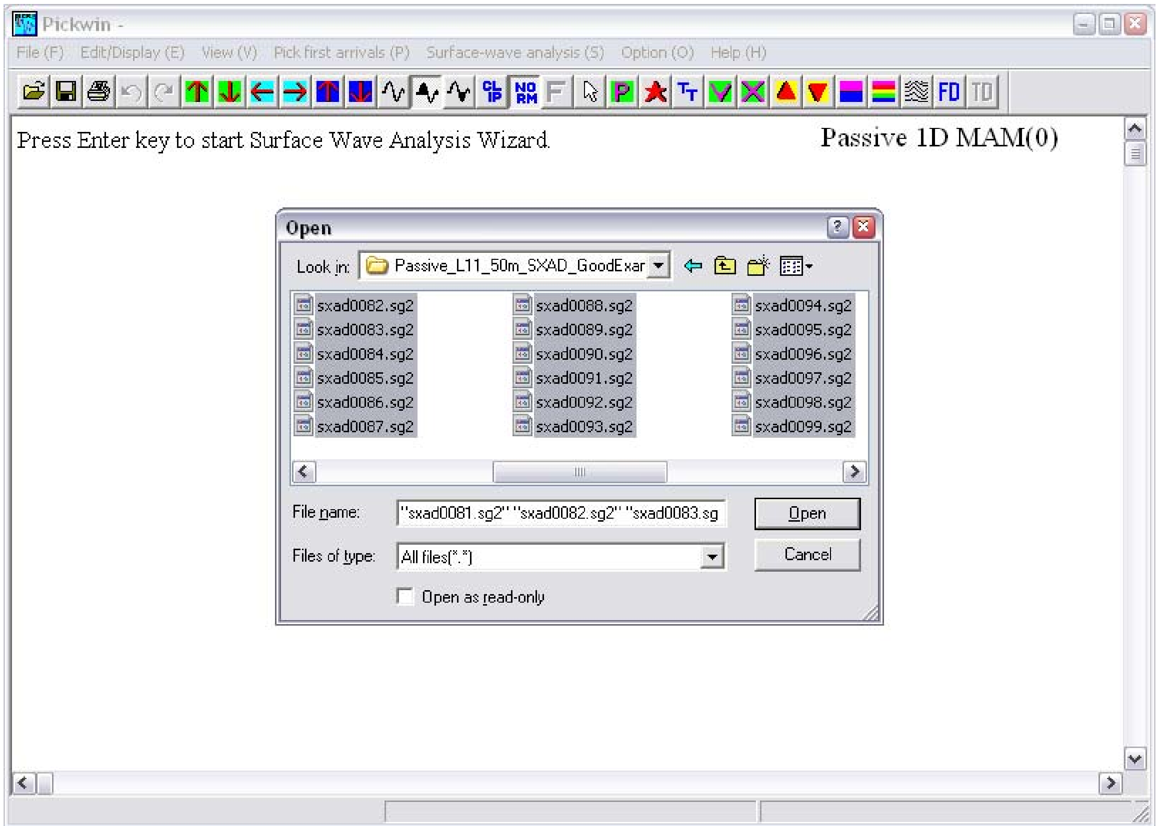
Double-click on the Surface Wave Analysis Wizard icon. The familiar dialog box appears. Select *Passive Source (Micro-tremor) 1D MAM*.



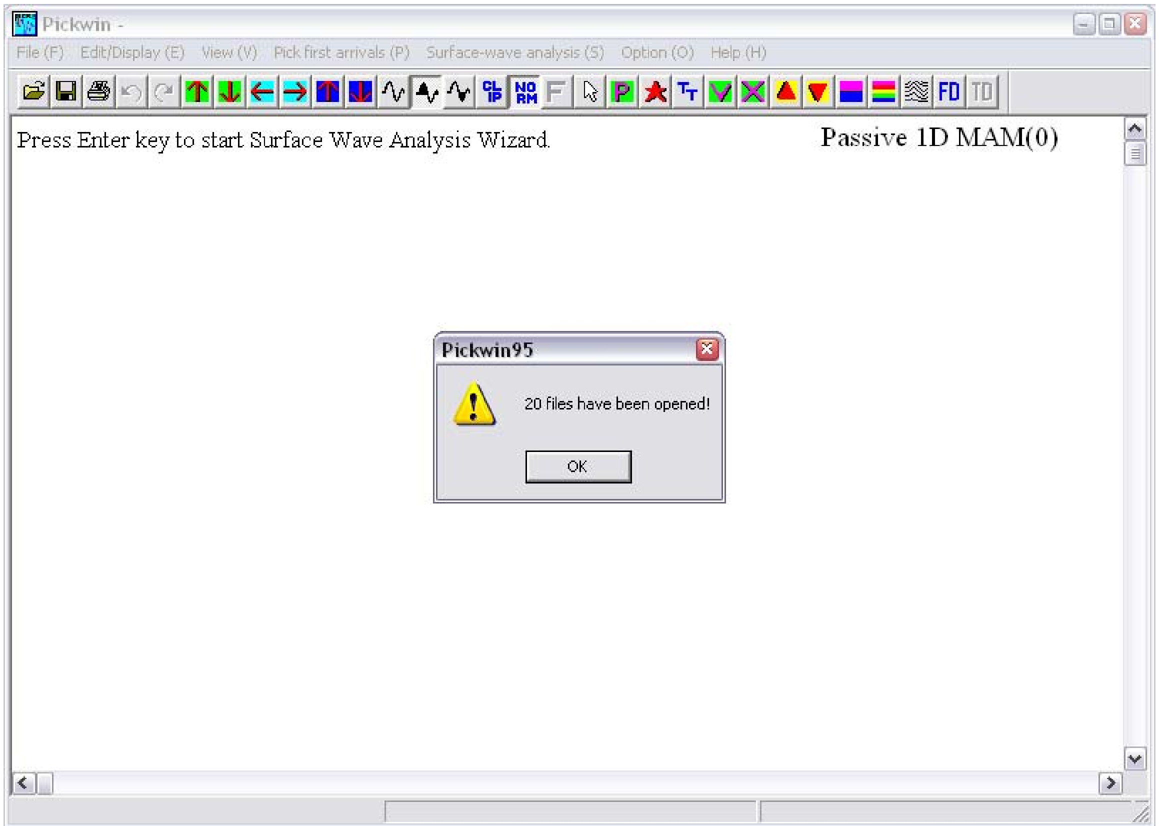
The main window will appear. The units set the last time the program was used will be recalled. As for the active source wizard, the instructions are shown in the upper left-hand corner. Hit the *Enter* key to begin.



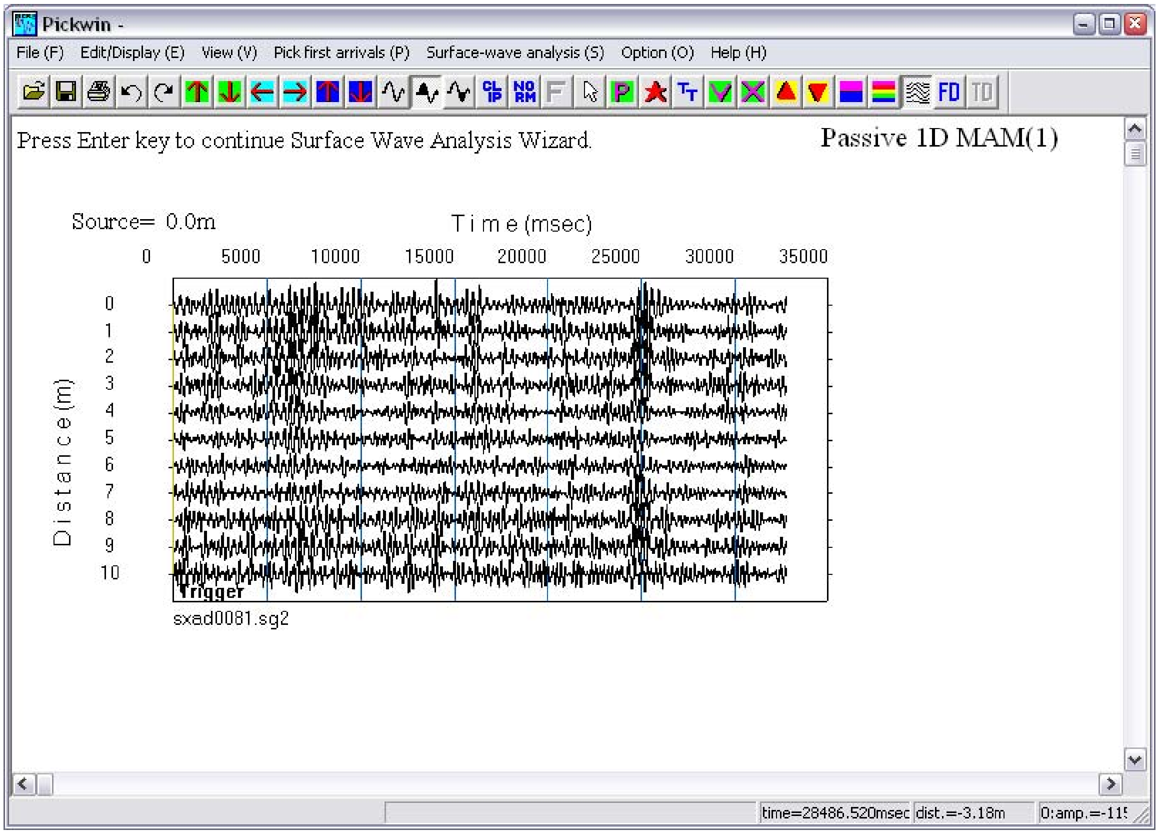
For passive data analysis, all 20 files are input at one time. Use the *Shift* key to highlight the first through last file in your dataset and click *Open*.



Click *OK* after all 20 files have been opened.



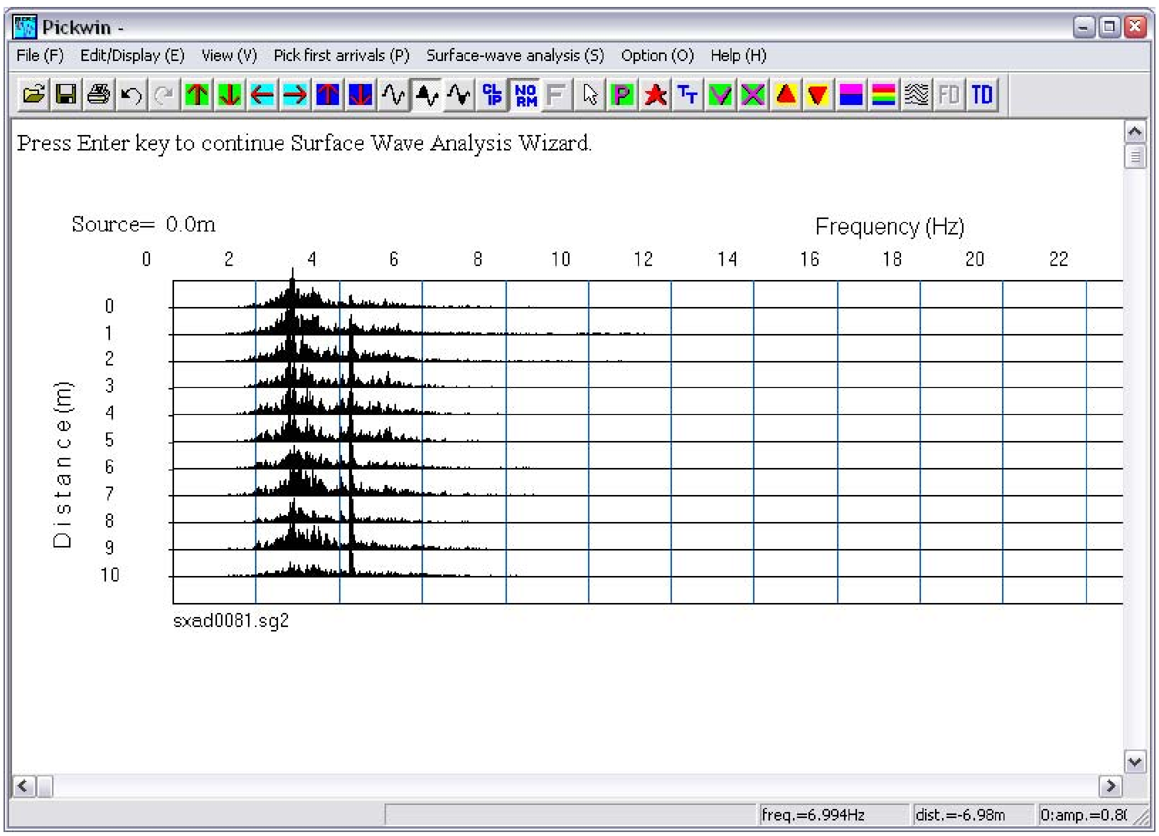
For viewing passive data, unclick the *Normalize*  button so any variation in amplitude from trace-to-trace will be visible.



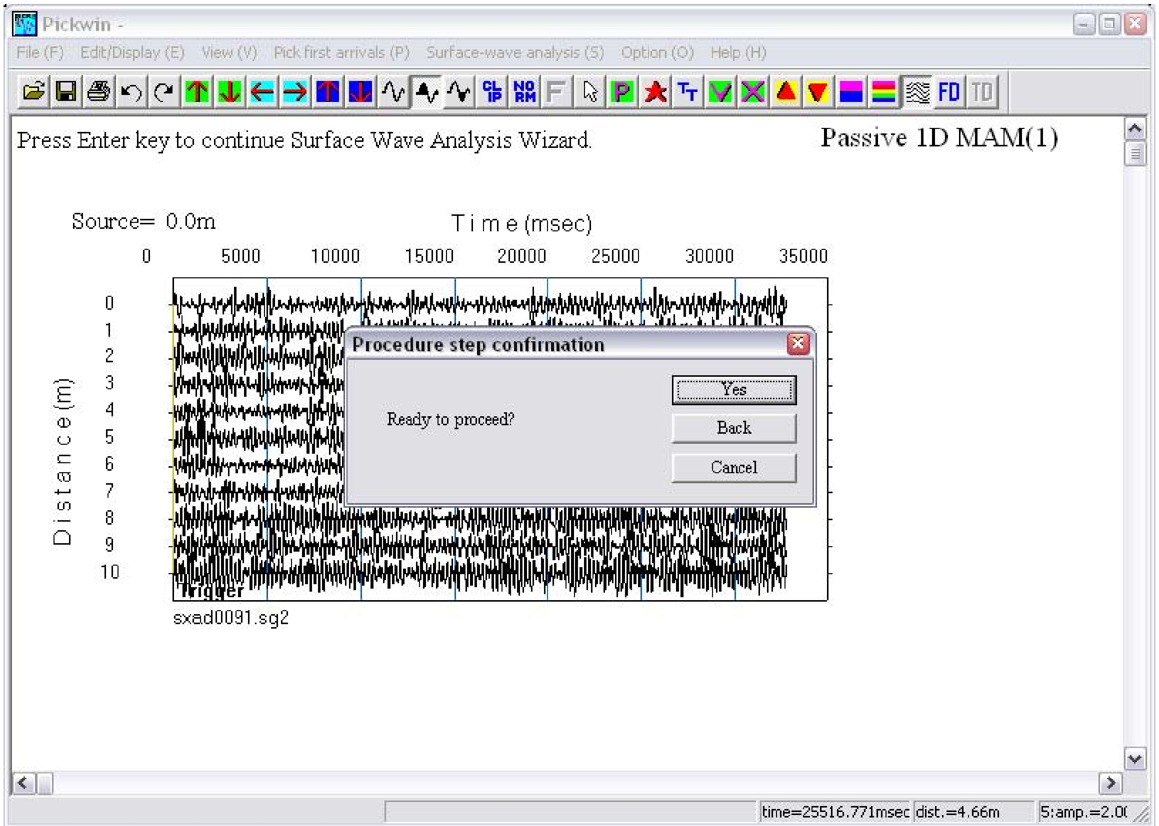
Unlike most active source data, it is usually difficult to evaluate the quality of passive source data from viewing the shot record in the time domain. You can quickly transform the data into the frequency domain by clicking on the *Frequency domain* button. The view will change to show the frequency content or spectrum for each trace.

After clicking on the *Frequency domain* button, click on the right arrow button or hit the right arrow key many times to expand the frequency scale. What you want to see is similar frequency content from trace-to-trace and dominant energy in the lower end of the frequency scale. The example spectral plot below indicates high-quality passive source data.

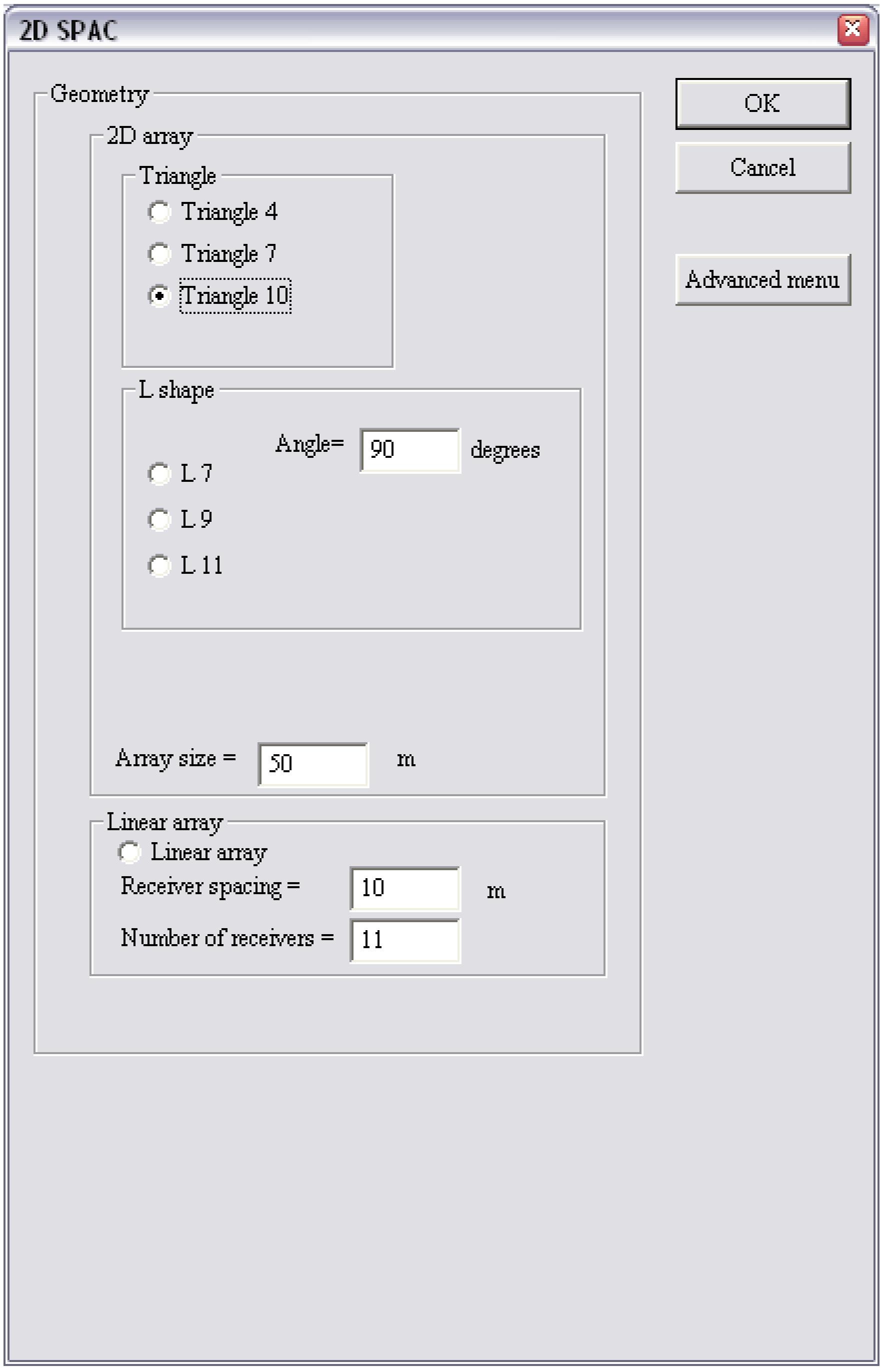
Toggle back with the *Time domain* button to proceed with the wizard.



Hit the *Enter* key as instructed in the upper left-hand corner of the window and then click *Yes* when you are ready to proceed.



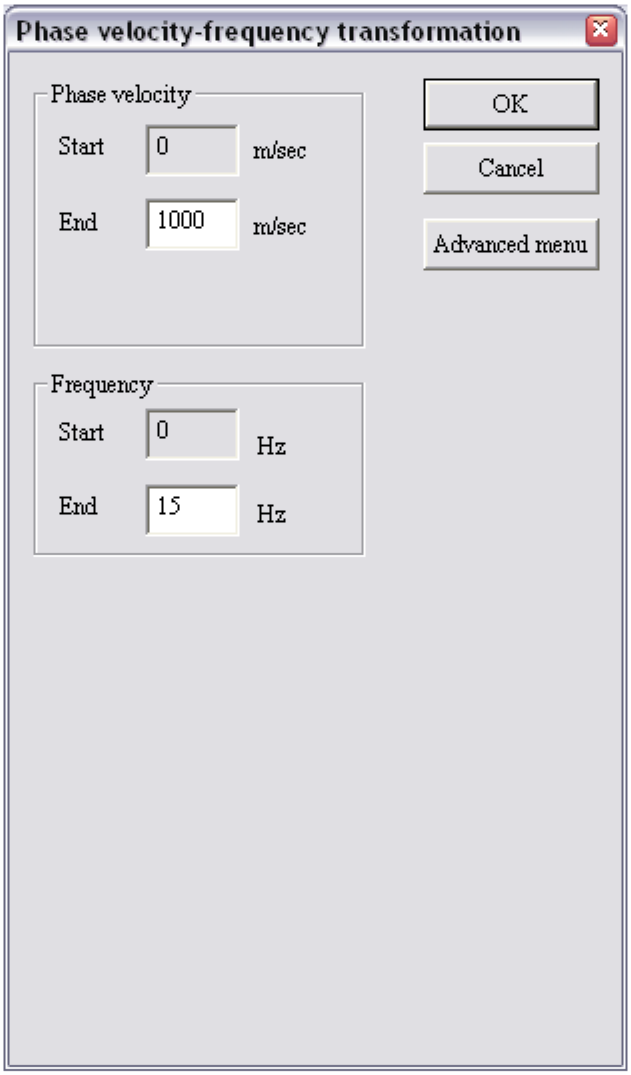
The next step is to set the array geometry. Select which *2D array* shape was used and the *Array size* or select *Linear array* and enter the *Receiver spacing* and *Number of receivers*. For this example, an L-shaped array with size of 50 meters was used.



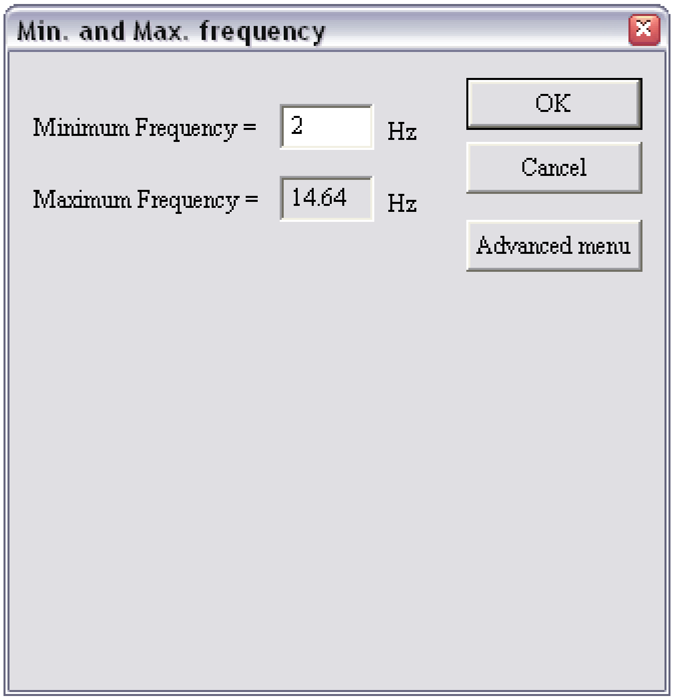
The rest of the steps are identical to the *Active Source 1D MASW Wizard*.

Set the *Phase Velocity End* to suit the maximum velocity you expect for your site. Passive source energy is generally traveling deeper and thus, at higher velocities so you will likely want to set a higher *Phase Velocity End* than what was used in the active source wizard.

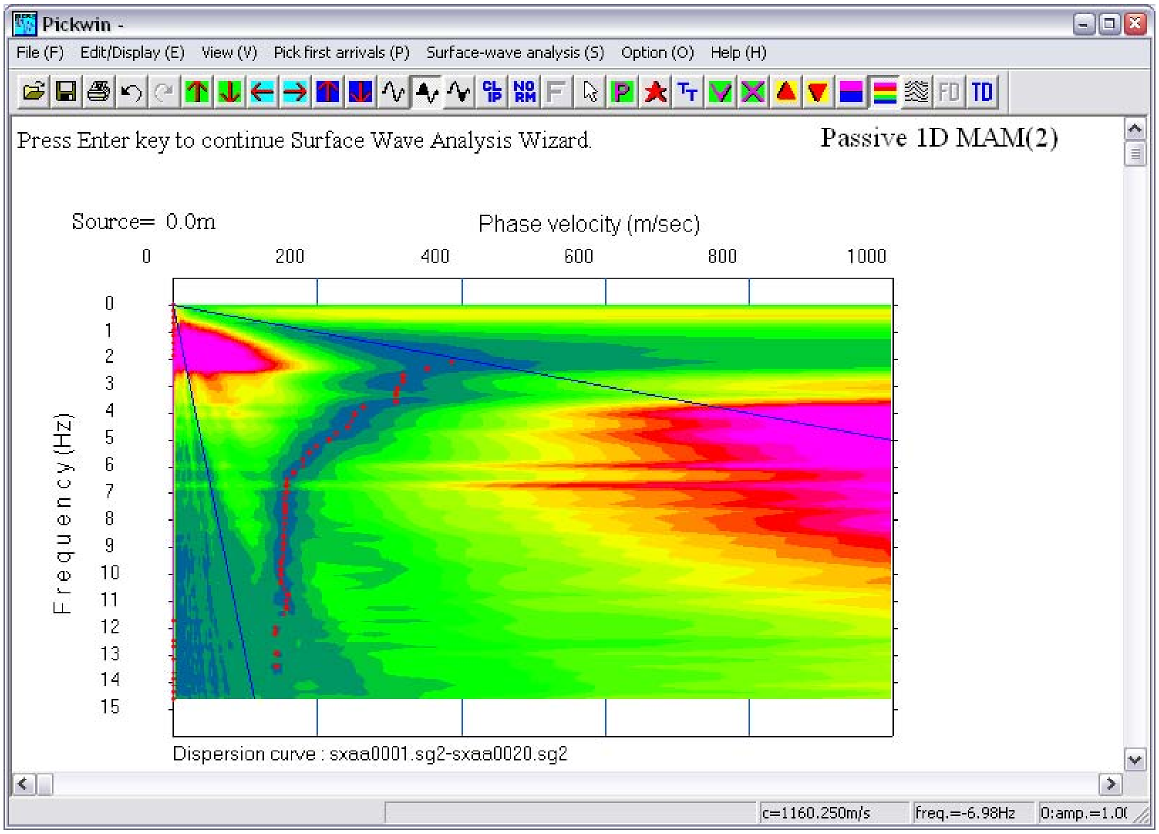
Accept the default value for *Frequency End*.



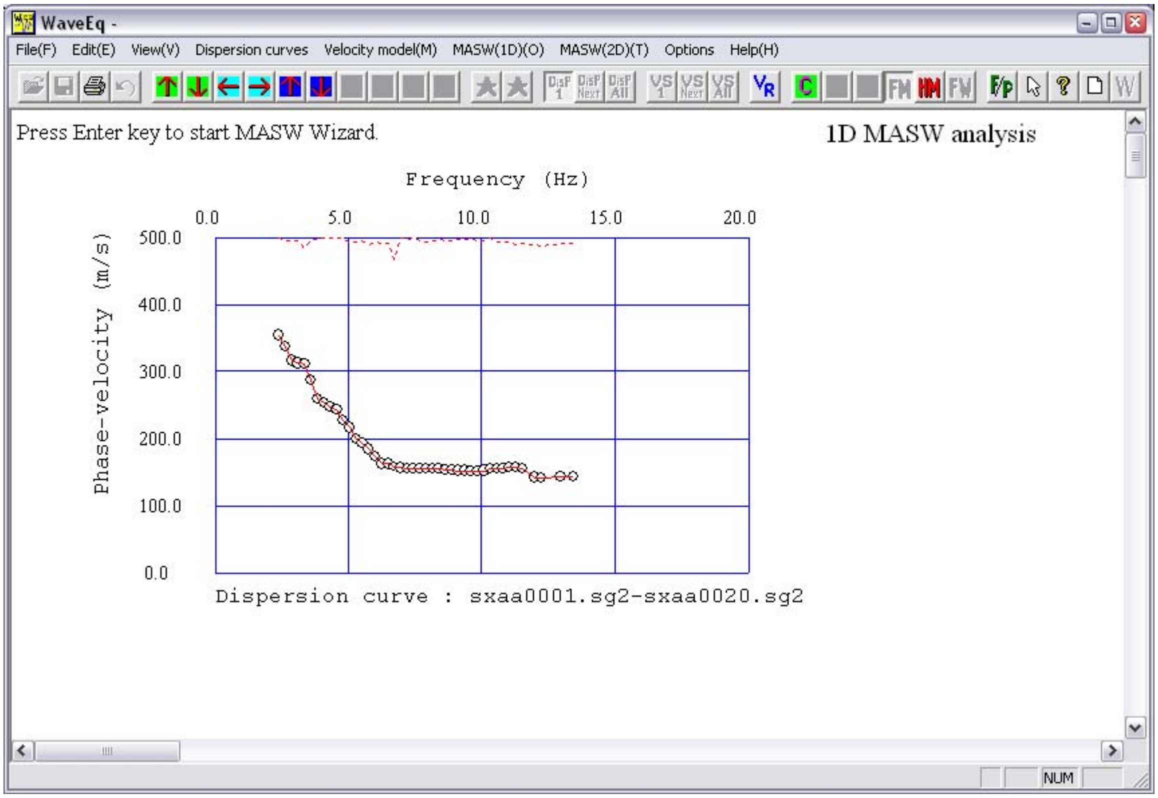
The *Minimum Frequency* default is 2 Hz. If 4.5 Hz geophones were used, energy below 4.5 Hz may have been recorded, though dampened depending on the sensitivity of the geophone. It is suggested to leave the default of 2 Hz to allow the software to attempt to pick the amplitude maxima to this end (any bad picks can be manually edited later).



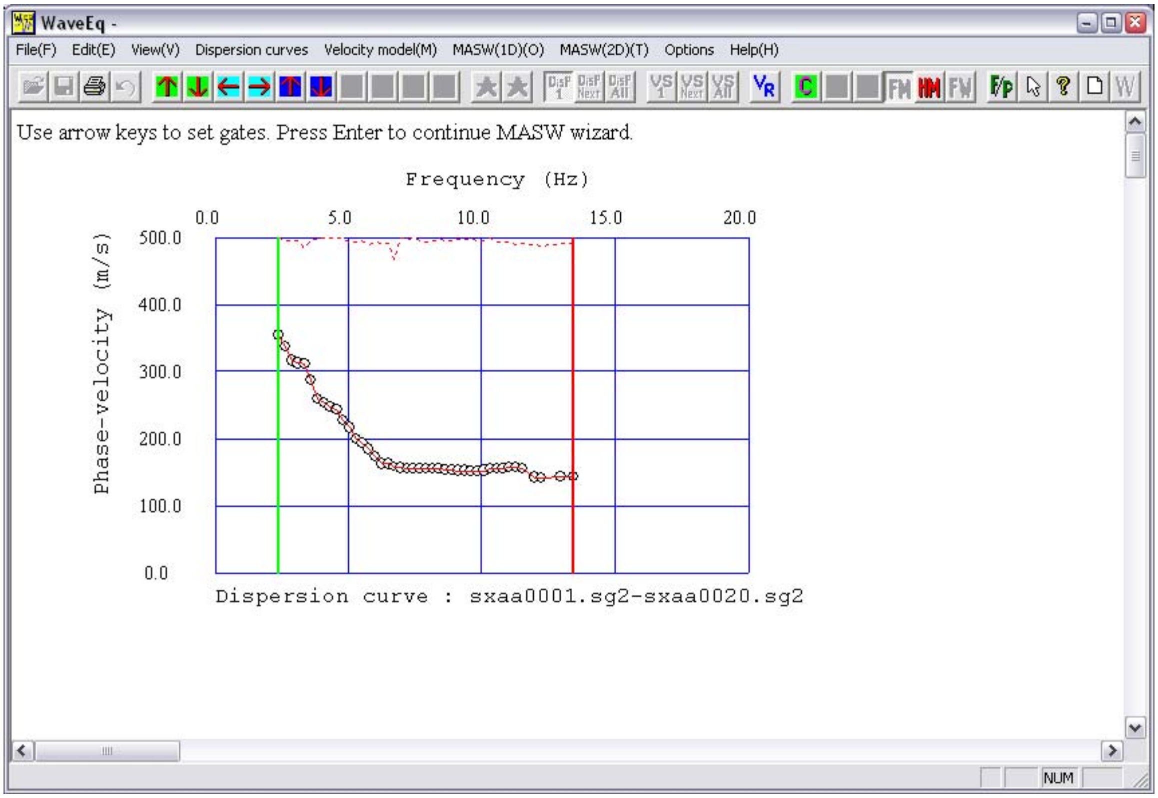
Convert the phase velocity plot to color contours and check the automatic dispersion curve picks.

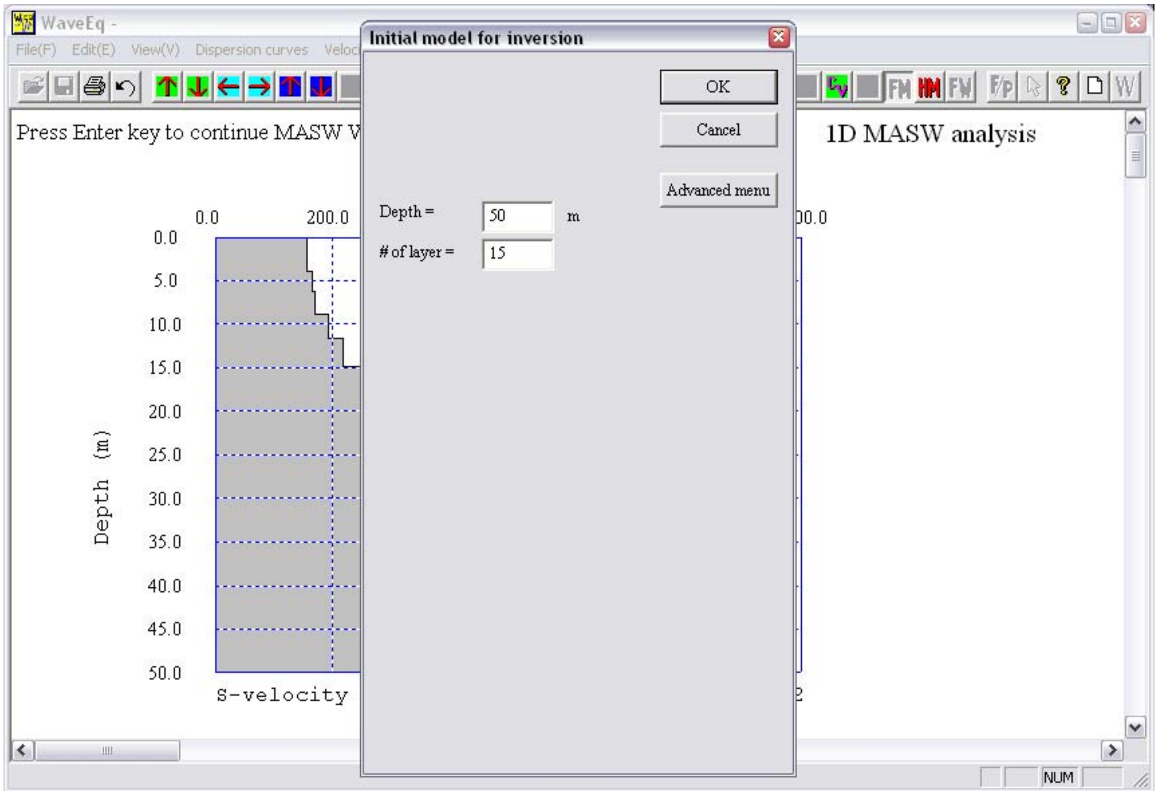


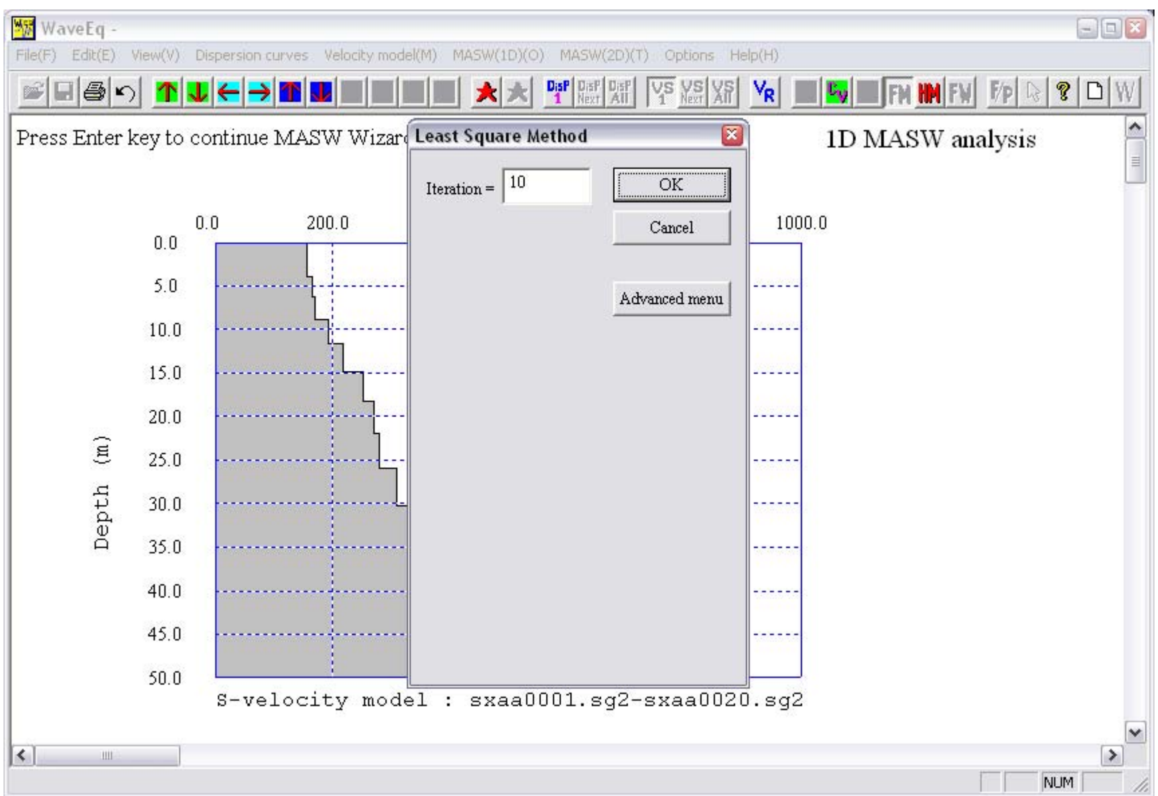
Hit the *Enter* key as instructed in the upper left-hand corner of the window and then click *Yes* when you are ready to proceed. The WaveEq module will be launched with display of the dispersion curve.

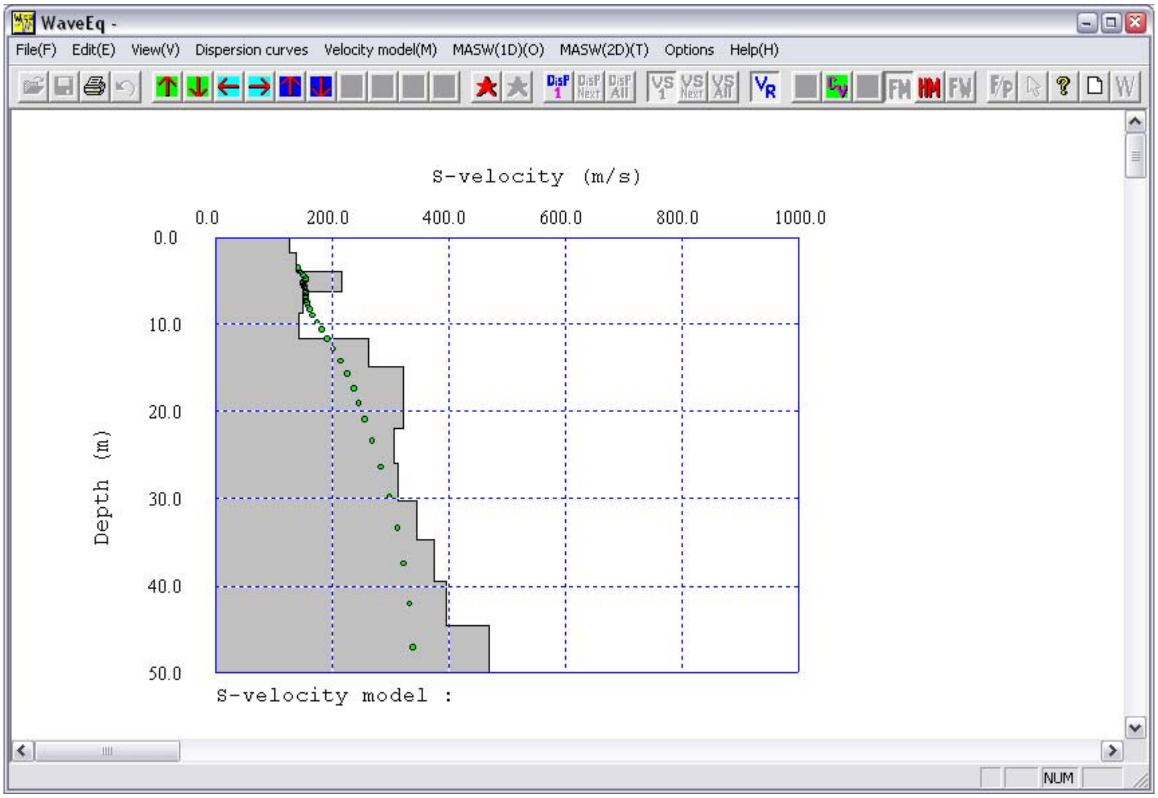


Edit the curve using the gates, set the maximum depth for the initial model, and accept 10 iterations as done previously.

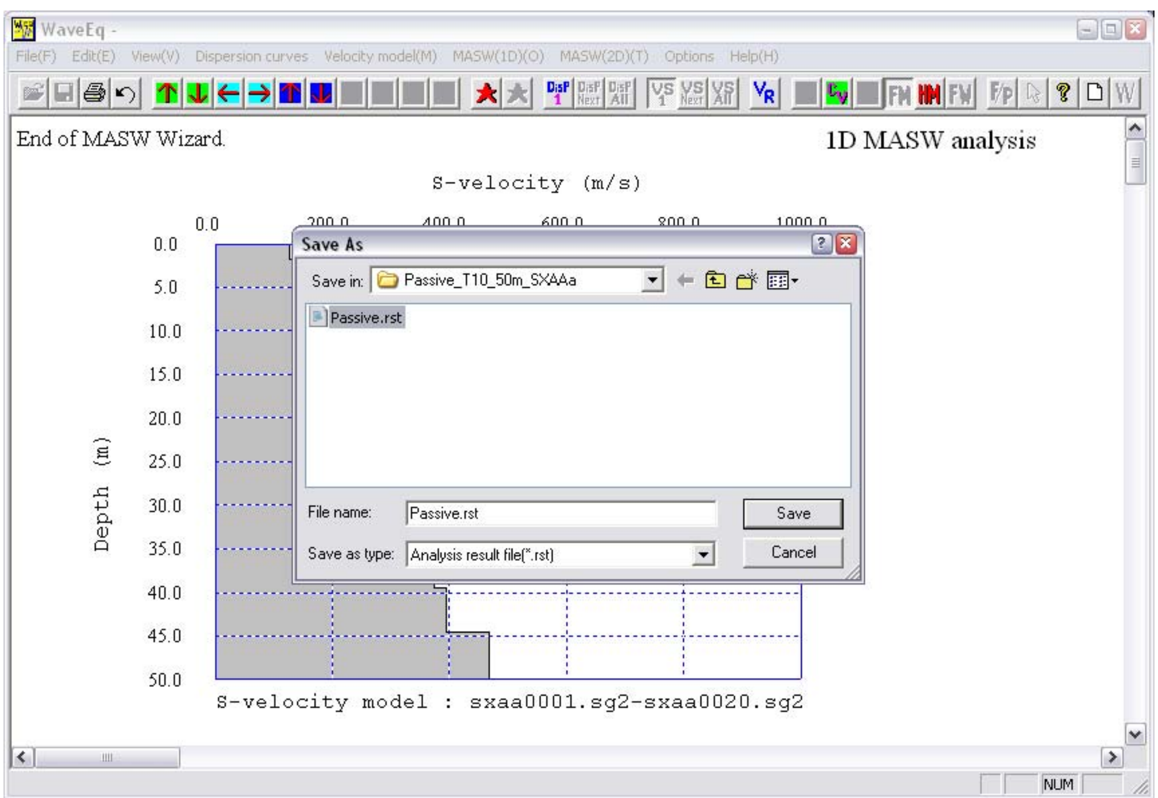



WaveEq -
File(F) Edit(E) View(V) Dispersion curves Veloc
Initial model for inversion
OK
Cancel
Advanced menu
Depth = 50 m
# of layer = 15
Press Enter key to continue MASW V
1D MASW analysis
Depth (m)
S-velocity
NUM


WaveEq -
File(F) Edit(E) View(V) Dispersion curves Velocity model(M) MASW(1D)(O) MASW(2D)(T) Options Help(H)
Press Enter key to continue MASW Wizar
Least Square Method
Iteration = 10
OK
Cancel
Advanced menu
1D MASW analysis
Depth (m)
S-velocity model : sxaa0001.sg2-sxaa0020.sg2
NUM



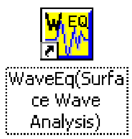
Hit the *Enter* key and when prompted, save the results.



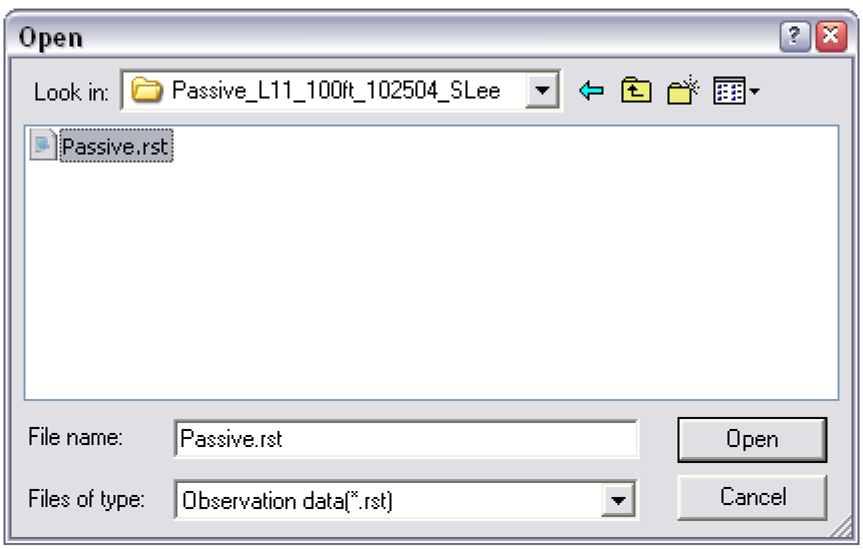
4.2 Combining Active and Passive Source Wizard Results

Once you have obtained dispersion curves for a given site's active and passive source data, it is simple to combine the curves and obtain one high-resolution plot over the entire sampled depth.

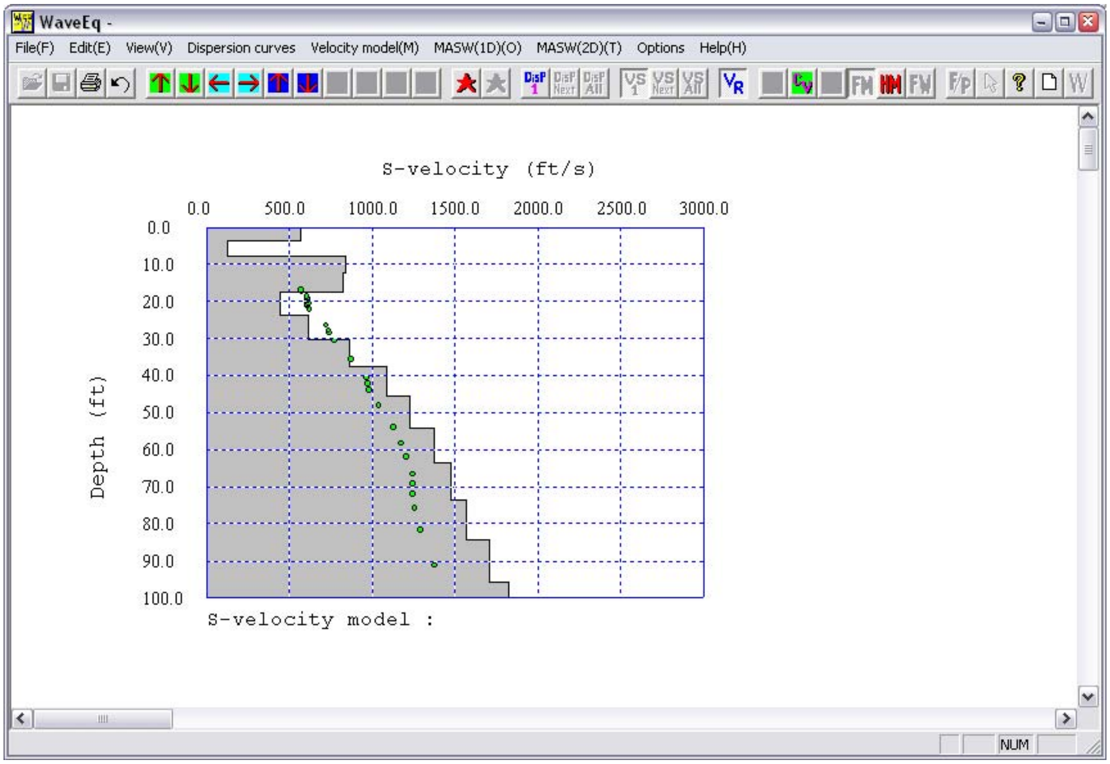
Double-click on the WaveEq icon.



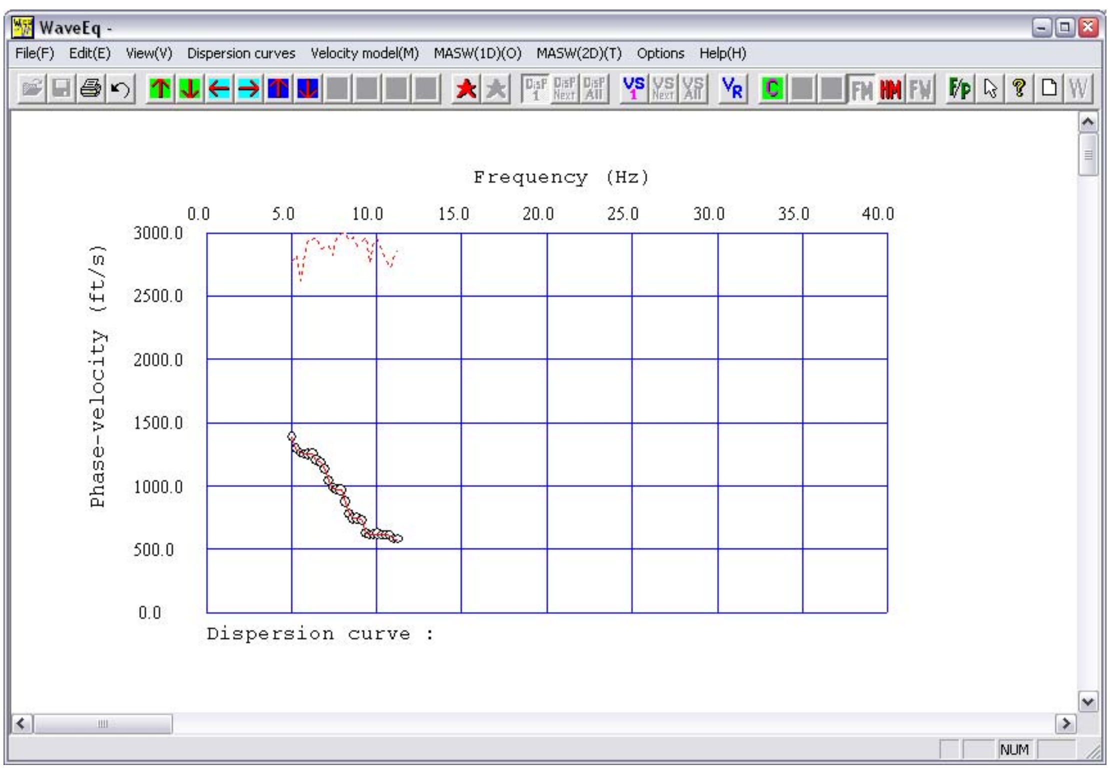
Select *Open velocity or dispersion curve file (.rst)* from the *File* menu. Open the result file for either the active or passive dataset. For this example, the passive source result file is opened first.



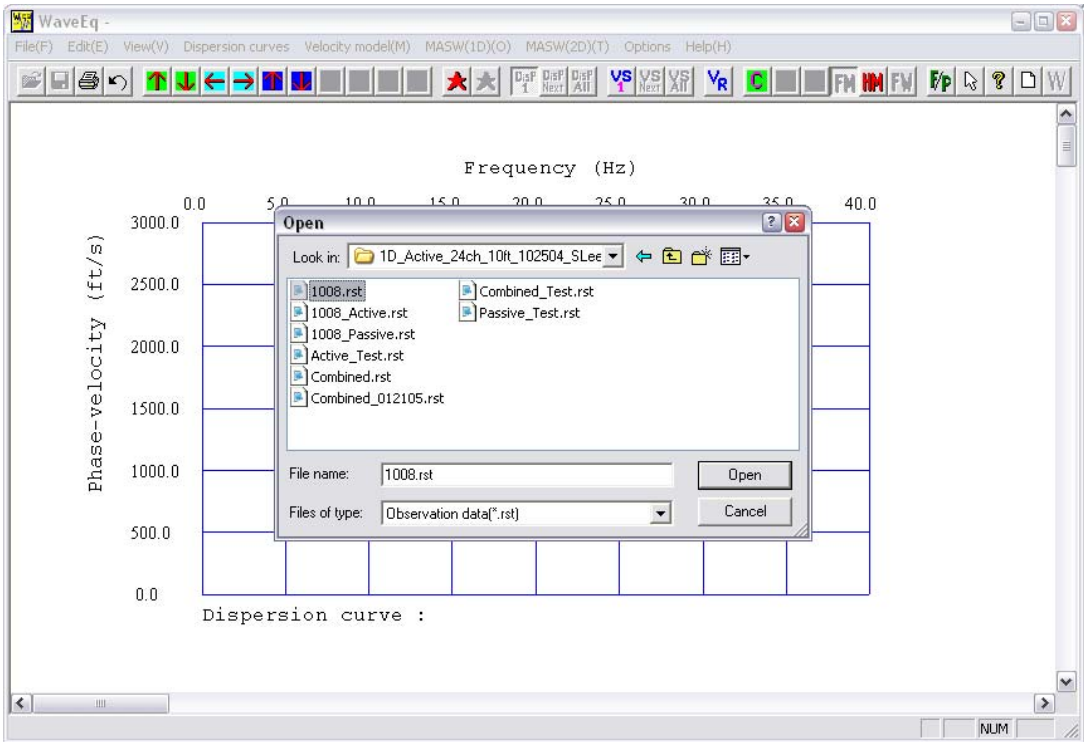
Note that the result file contains output up to the point the data was processed, so if the file was saved after the inversion, the first view you will see upon opening a result file is the final V_s profile. If the result file was saved before the inversion, the dispersion curve will be the first view upon opening the result file.



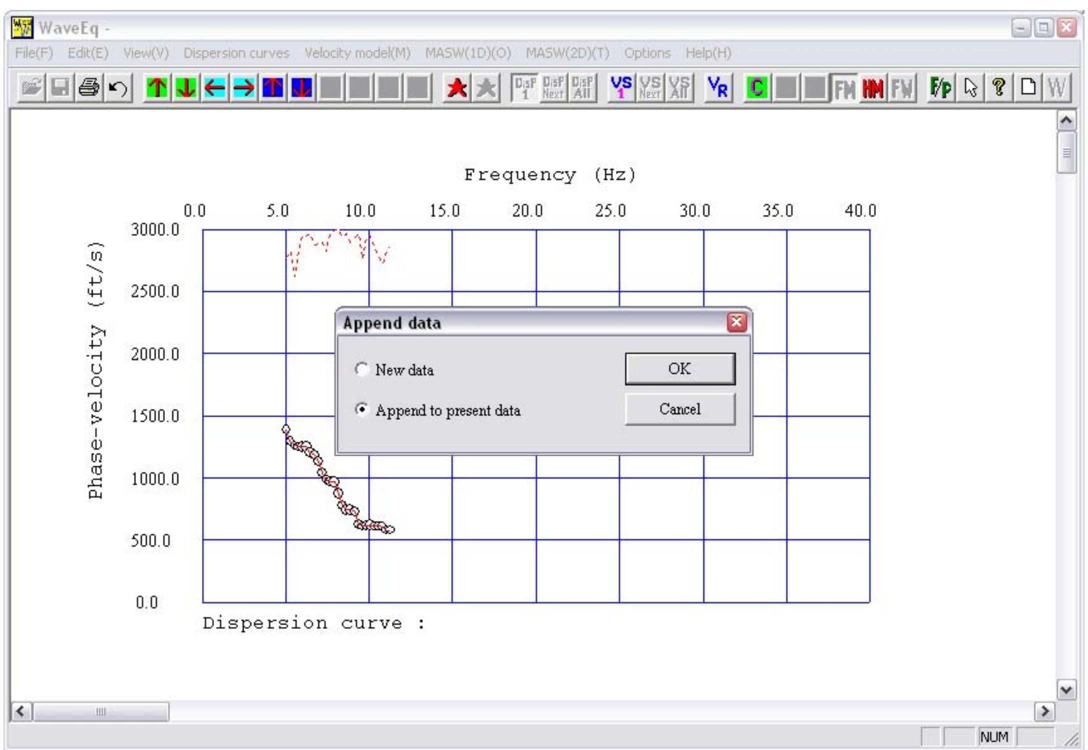
Use the *Show one dispersion curve*  button to switch over to a view of the dispersion curve.



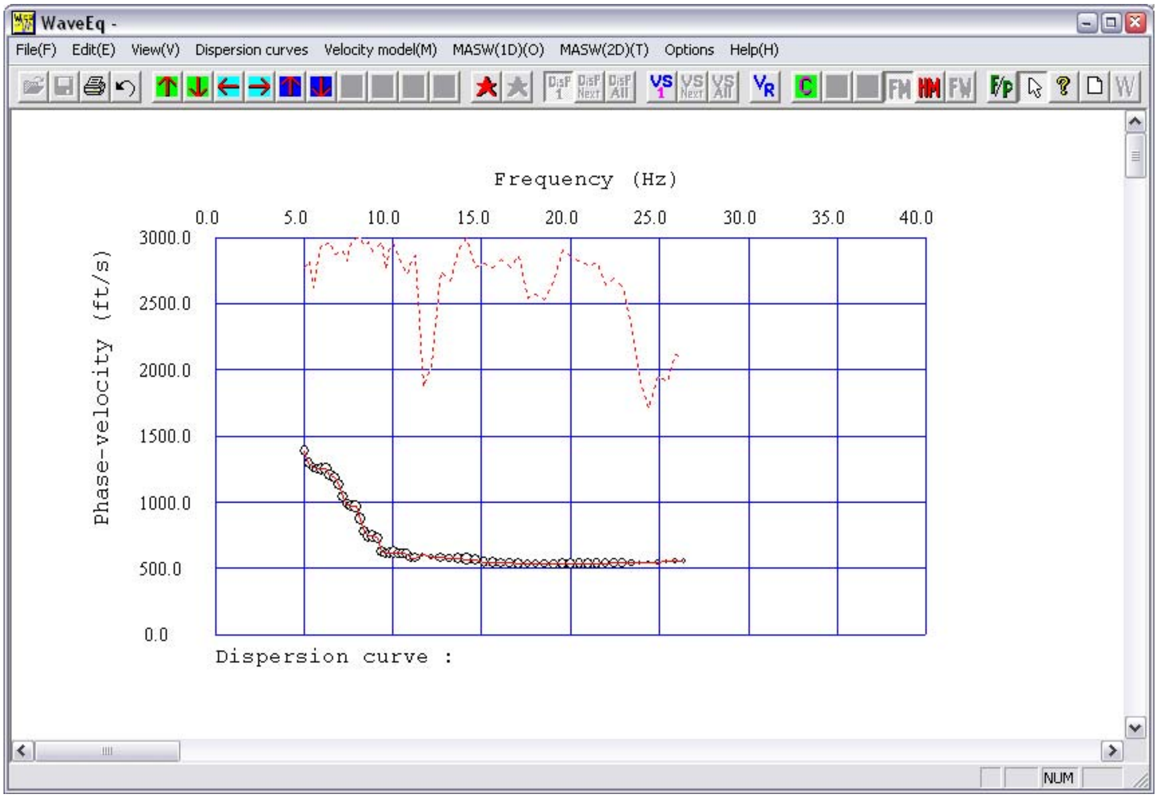
Next, open the result file from the active source survey.



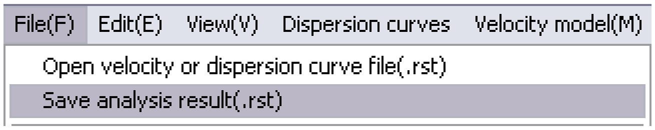
This result file should be appended to the passive source dispersion curve by choosing *Append to present data*.

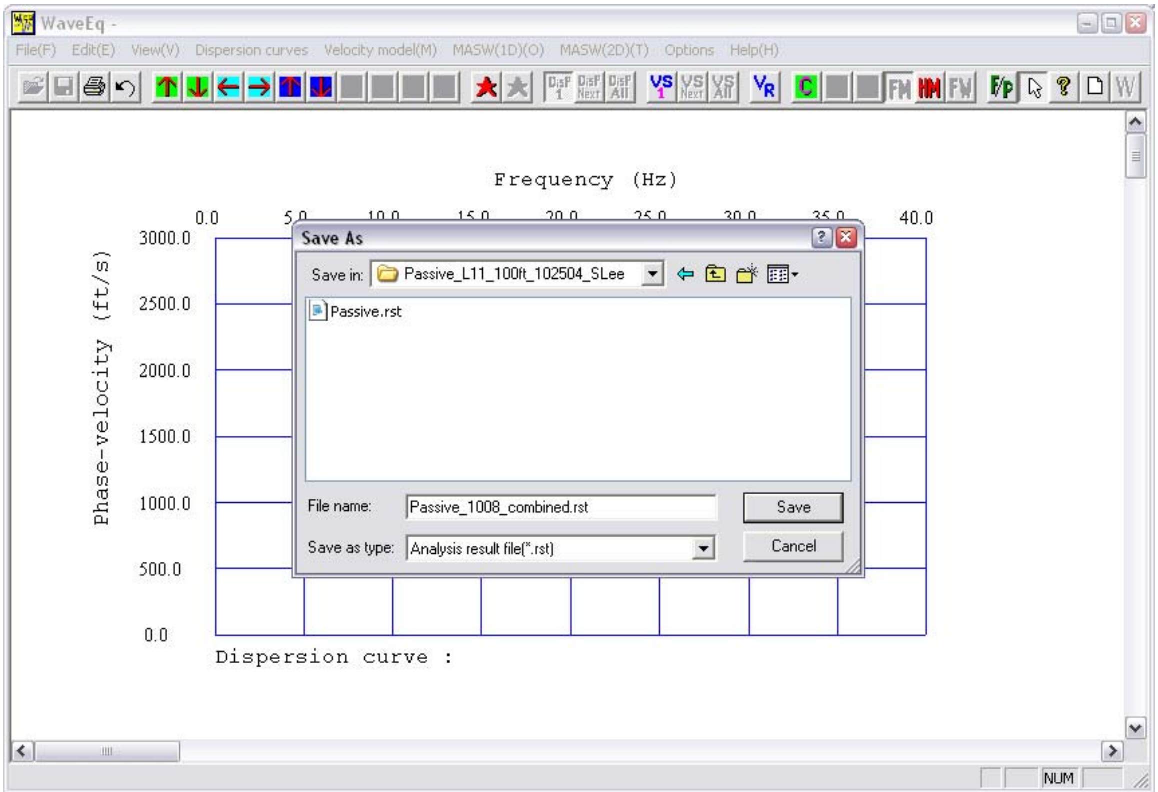


Dispersion curves from active and passive datasets should have some overlap. In this example, the overlap is between approximately 12 and 15 Hz and well matched. If the curves are not aligned, you should check your dispersion curve picks. Usually the problem lies in over-confident picks on the lower frequency end of the active source dataset and on the higher frequency end of the passive source dataset.

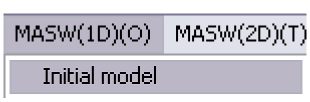


Save your combined results as a new result file.

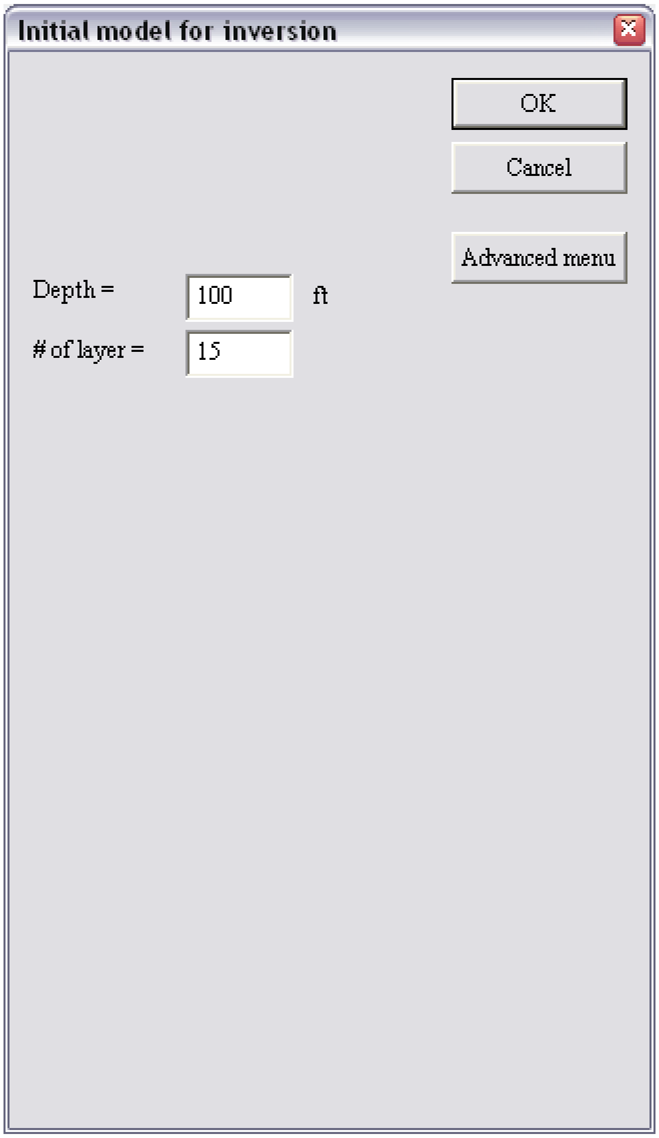




Proceed to create an initial V_s model and run the inversion for the composite dispersion curve just as done using the wizards. Since there is no wizard in use, manually select the *MASW(1D)* menu, *Initial model*.

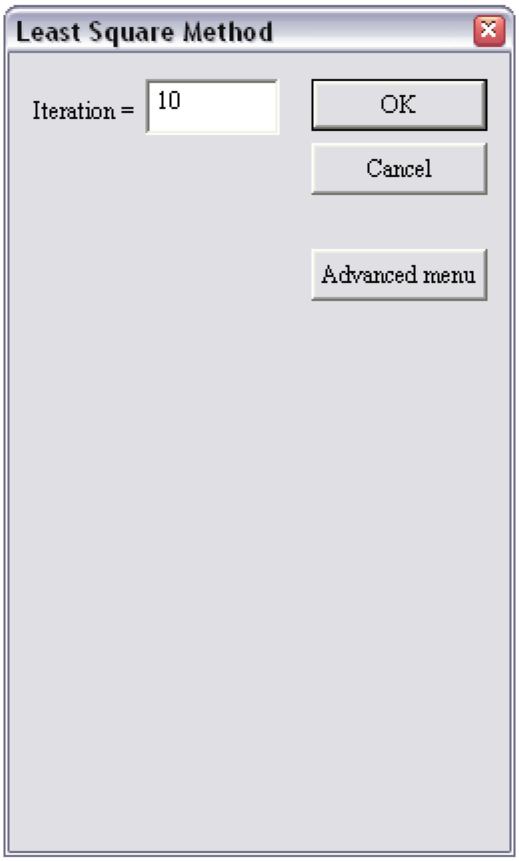


Set the maximum depth for the initial model.

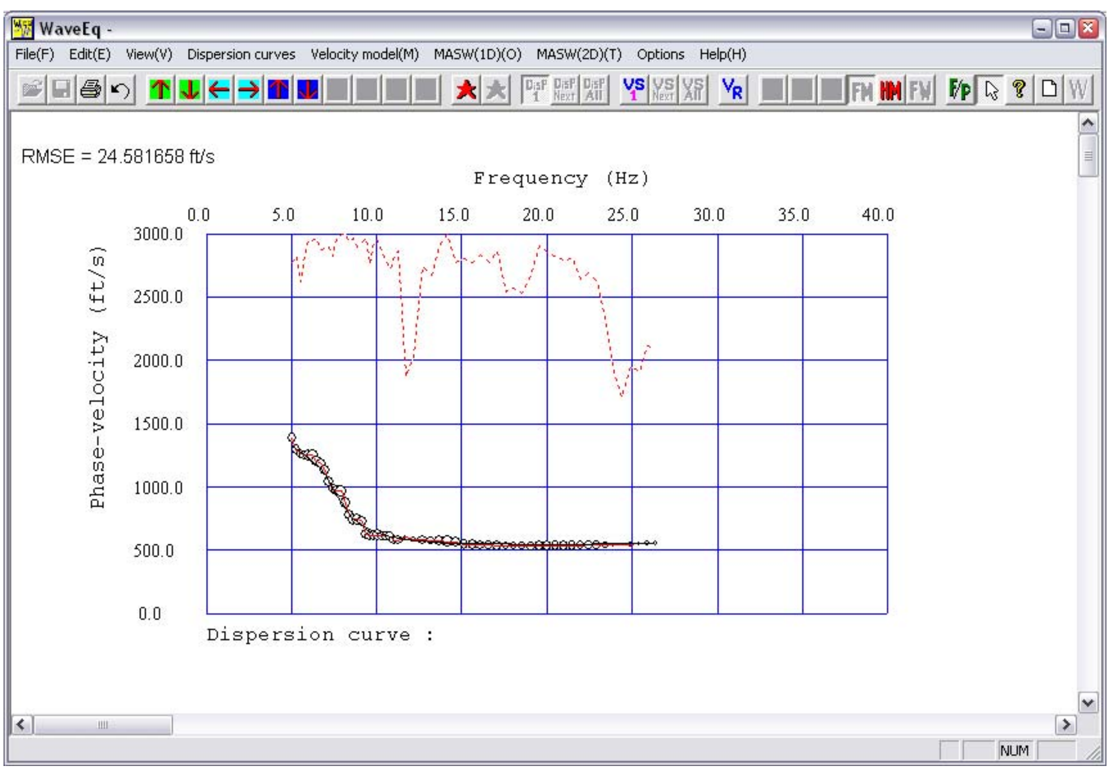


Return to the *MASW(1D)* menu and select *Inversion*.

Accept 10 iterations.



After the inversion, view the final V_s profile and compare the calculated and observed dispersion curves. A final result file can also be saved here by selecting the *File* menu, *Save analysis result (.rst)*.



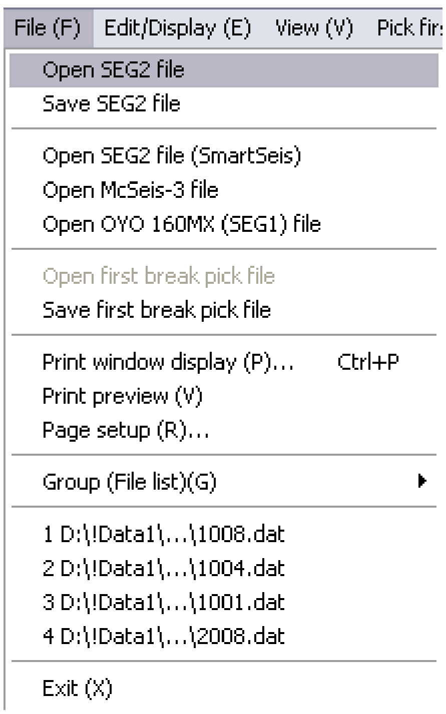
5 The Pickwin Module Surface Wave Analysis Functions

5.1 File Menu

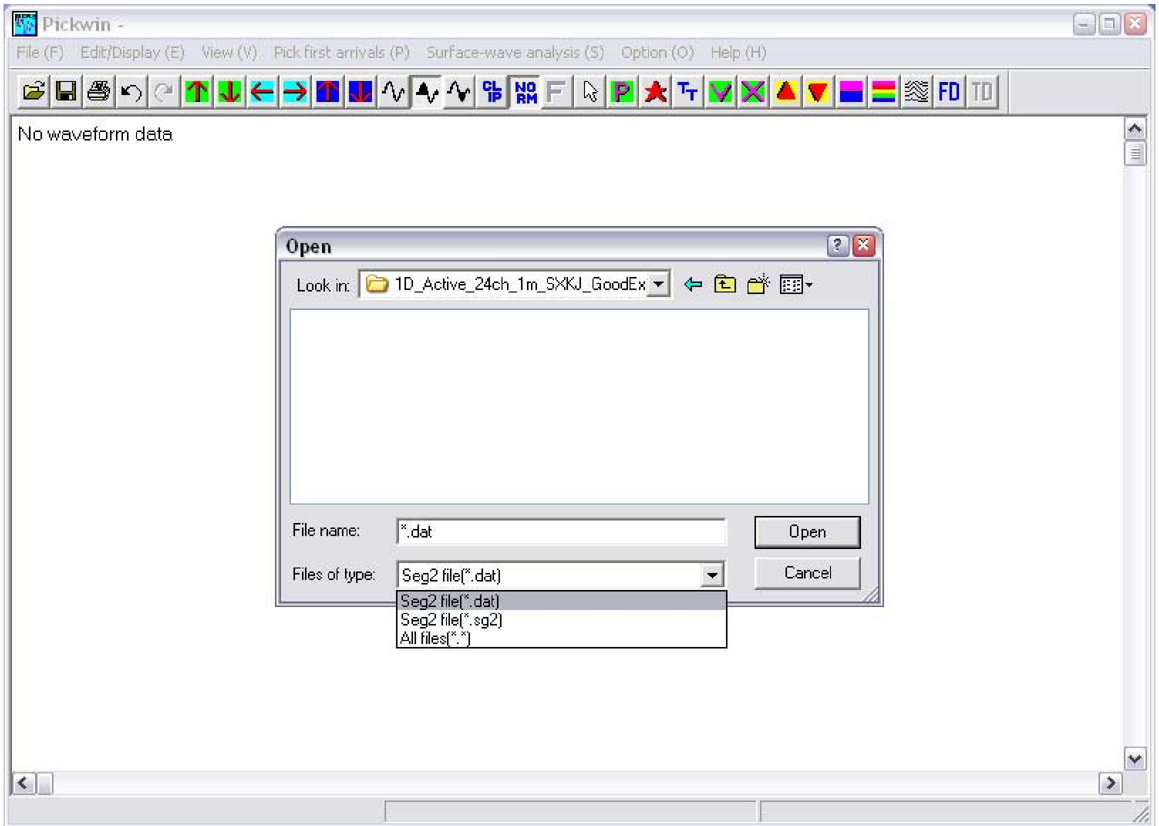
The *File* menu functions essential or uniquely used for surface wave data collected with a Geometrics seismograph are covered in this section. For complete description of the *File* menu functions common to SeisImager/SW and SeisImager/2D, please refer the separate SeisImager/2D manual, Section 3, included on the SeisImager software CD.

5.1.1 Open SEG2 File 

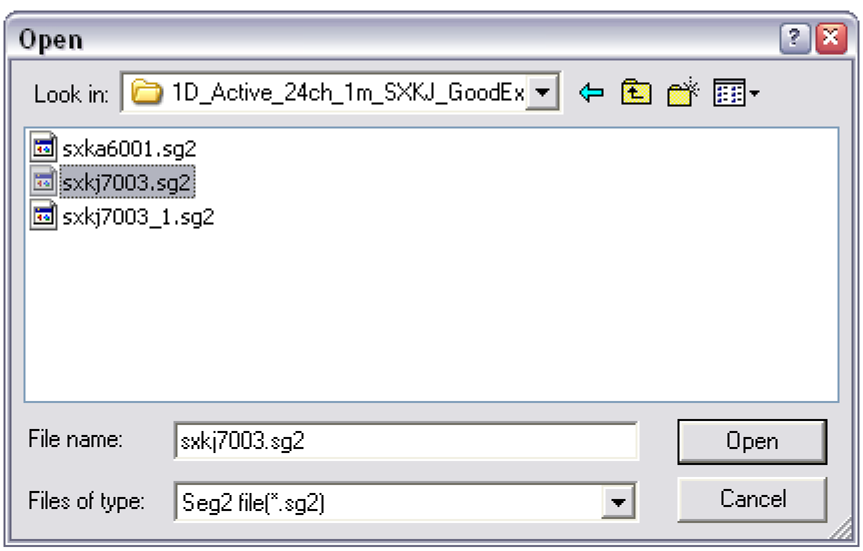
To open a SEG-2 active source record for analysis, select the *File* menu, *Open SEG2 file*.



Depending on the model of seismograph used to collect the data, you may need to adjust the *Files of type* setting. Geometrics seismographs use the file extension .dat for SEG-2 records; OYO seismographs use the extension .sg2.



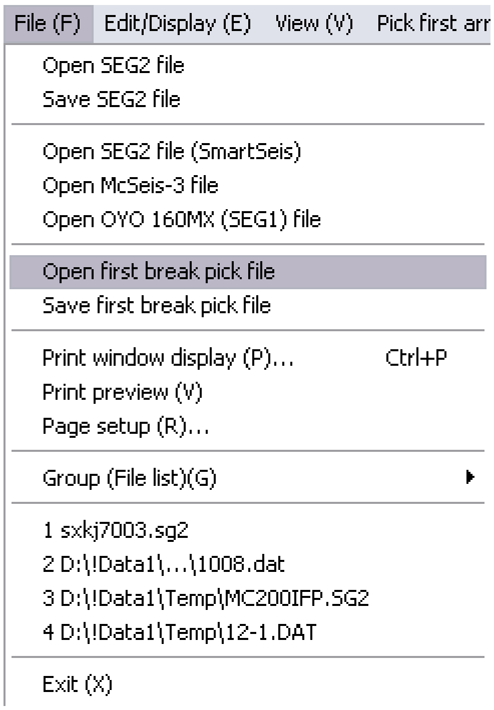
Select the file you wish to open.



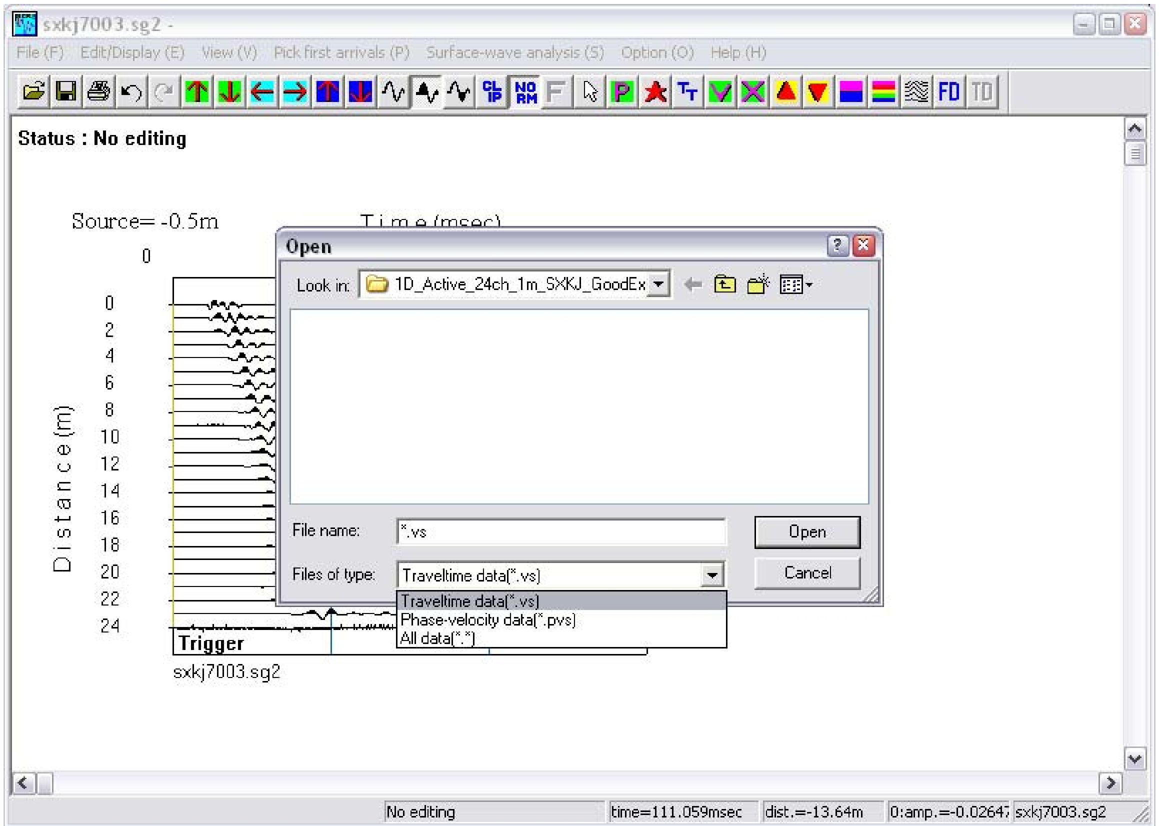
5.1.2 Open First Break Pick File

To use this function properly you should start with a fresh instance of Pickwin, not one in which you have already processed data. Double-click on the Pickwin icon to start a new instance; you need not close any other open Pickwin windows beforehand.

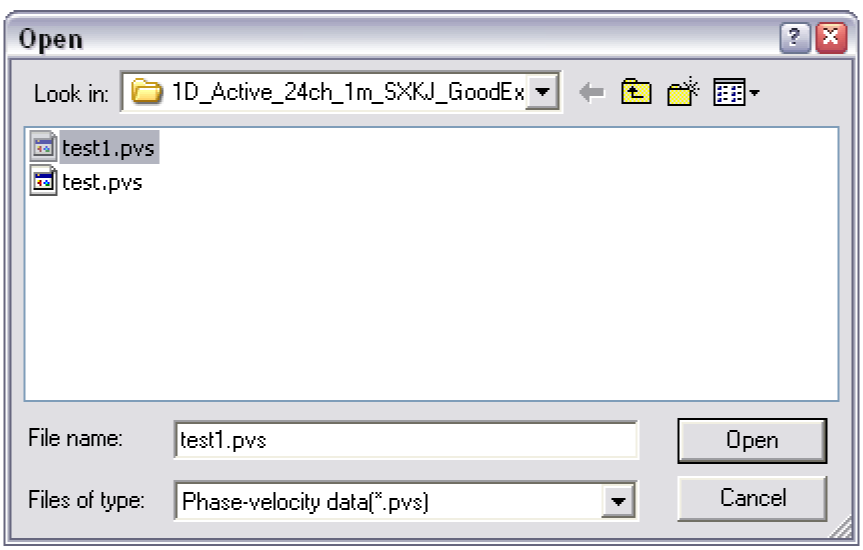
Open first break pick file can be used to open a file of saved dispersion curve picks with the file extension .pvs. First open the waveform file from which the dispersion curve picks were derived using the appropriate *Open __ file* function. Next, select the *File* menu, *Open first break pick file*.



Adjust the *Files of type* setting to show *Phase-velocity data (*.pvs)* types.



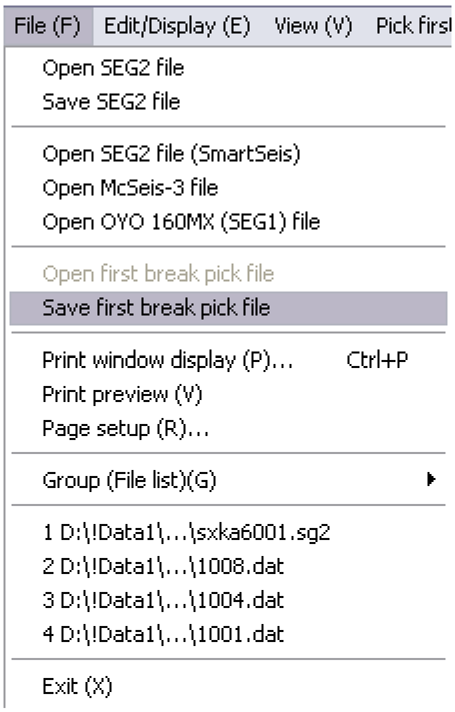
Select the file you wish to open.



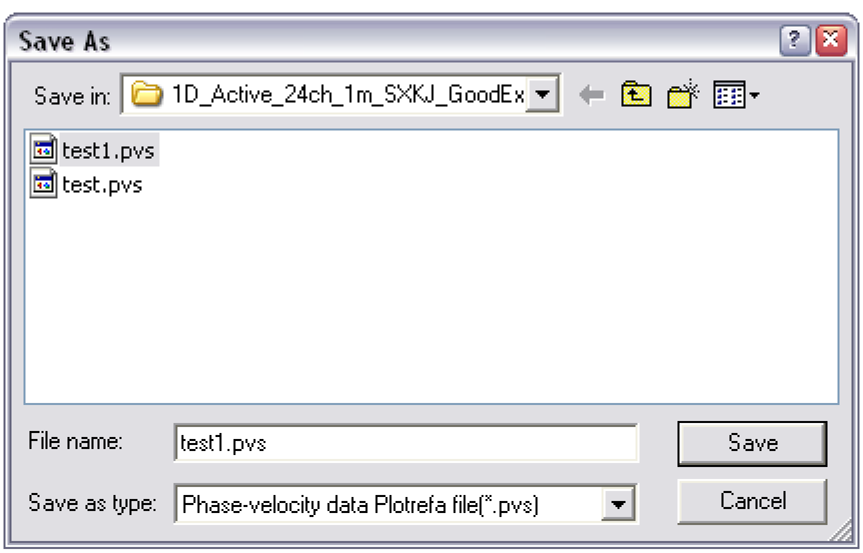
You will not see the dispersion curve picks until you run the phase velocity-frequency transformation (see Section 5.3.1).

5.1.3 Save First Break Pick File

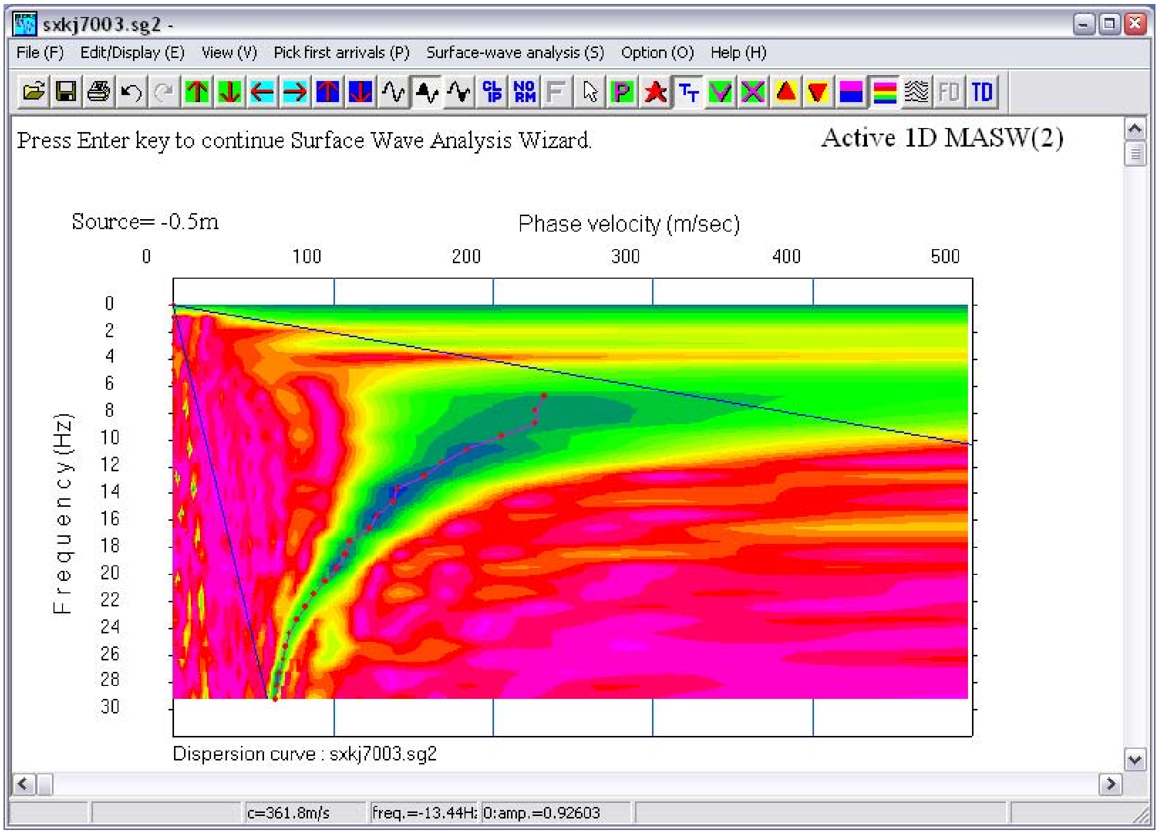
To save dispersion curve picks, select the *File* menu, *Save first break pick file*. Although the name of this function refers to (refraction) first break picks, it is also used for saving dispersion curve picks.



When prompted to name the file, use the extension .pvs.



A notice confirming that the file has been saved will appear and a pink line will now connect the dispersion curve picks.

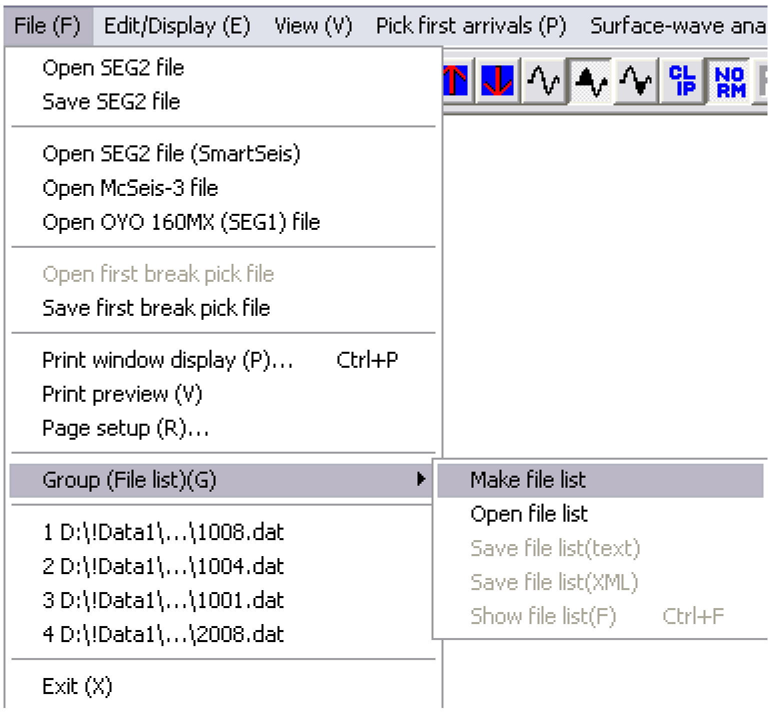


5.1.4 Group (File List)

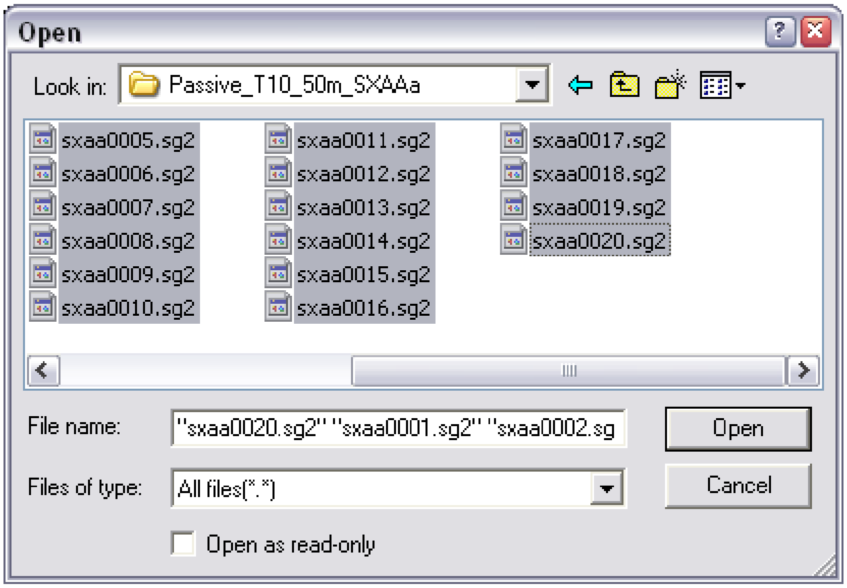
The function *Group (File List)* allows a range of records, as with a passive source dataset, to be opened.

5.1.4.1 Make File List

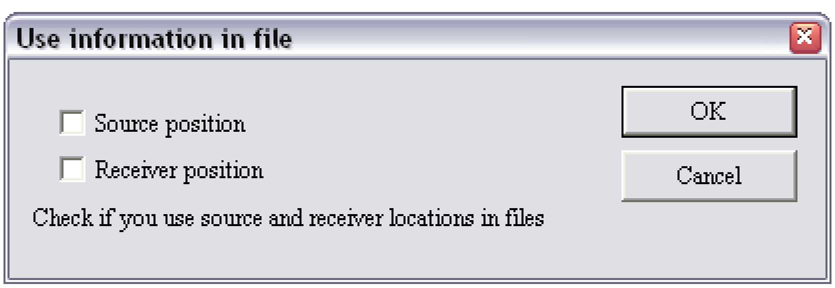
First, a list of the group of files to be opened is made. Select the *File* menu, *Group (File List), Make File List*.



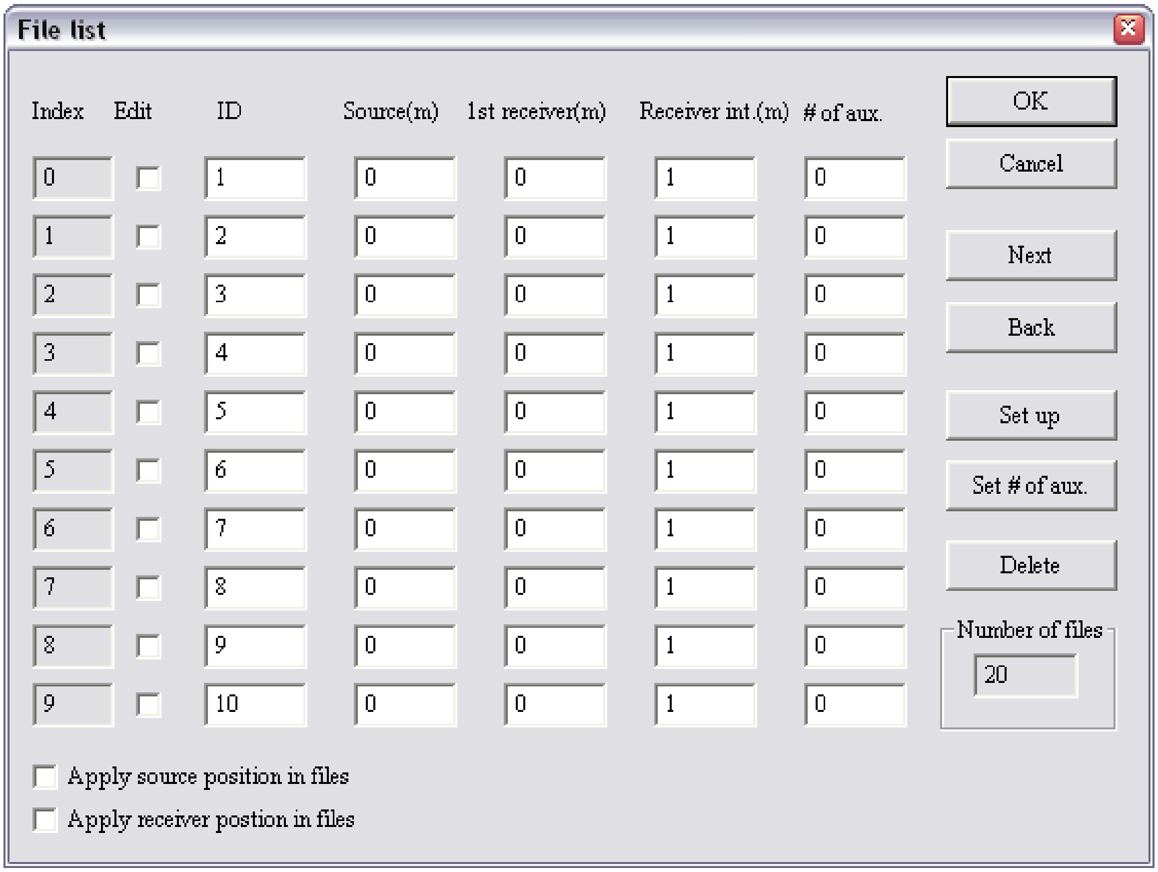
Select the set of files to be opened using the *Shift* key to select a range of files or the *Control* key to select individual files.



For passive source data, the source location is non-applicable and the geometry of the array is set in another, later dialog box. The coordinates saved in the file headers are not needed here, so leave the boxes for *Source position* and *Receiver position* unchecked.



The next *File list* dialog box presents a summary of the input files. No action is needed here; click *OK* when you are done and proceed to view the waveform files.

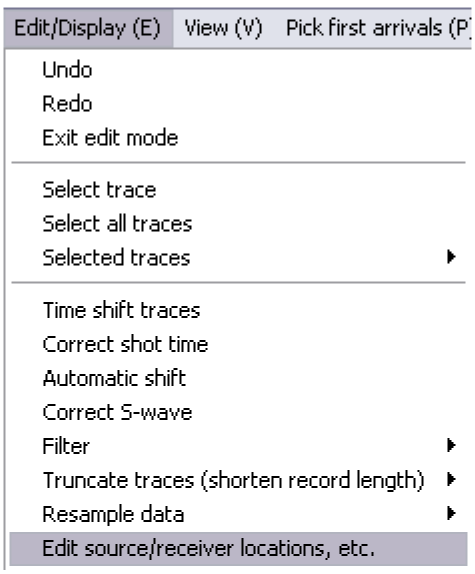


5.2 Edit/Display Menu

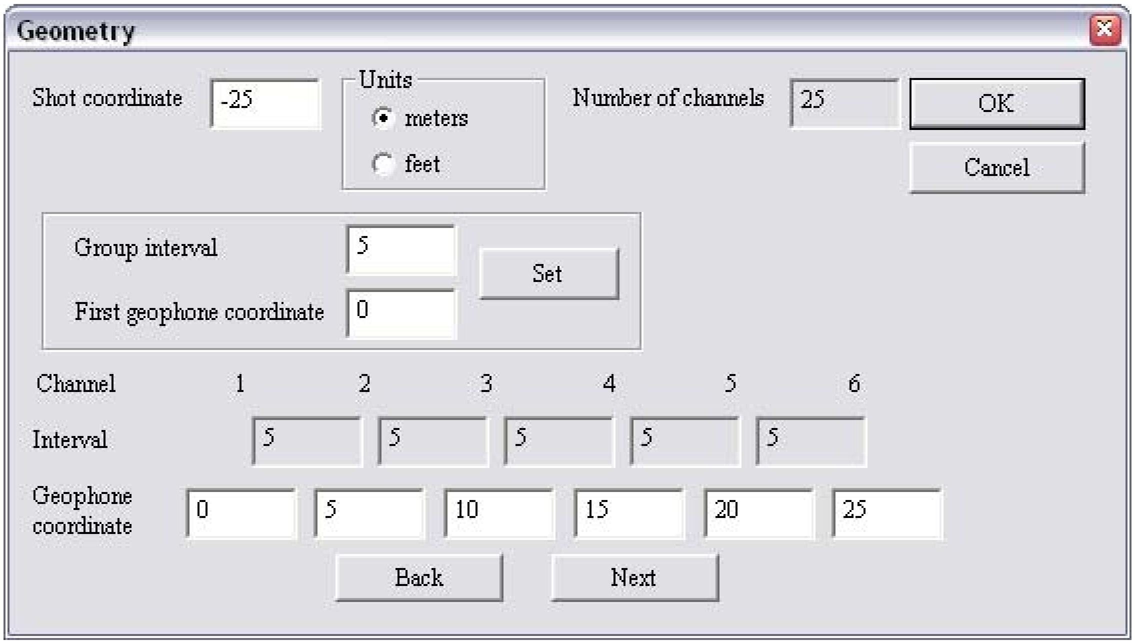
The *Edit/Display* menu functions essential or uniquely used for surface wave data are covered in this section. For complete description of the *Edit/Display* menu functions common to SeisImager/SW and SeisImager/2D, please refer the separate SeisImager/2D manual, Section 3.2, included on the SeisImager software CD.

5.2.1 Edit Source/Receiver Locations, etc.

To change the unit labeling shown in the displays and in the dialog boxes, select *Edit source/receiver locations, etc*.



The *Geometry* dialog box will appear. This dialog box allows selection of units and reports the coordinates saved in the file header at the time of acquisition. To set the units, select between *meters* and *feet*. The unit assignment also updates the minimum phase velocity default value, which is either 35 m/s or 100 ft/sec. Once set, the assigned units will be set for subsequent uses of the wizard.

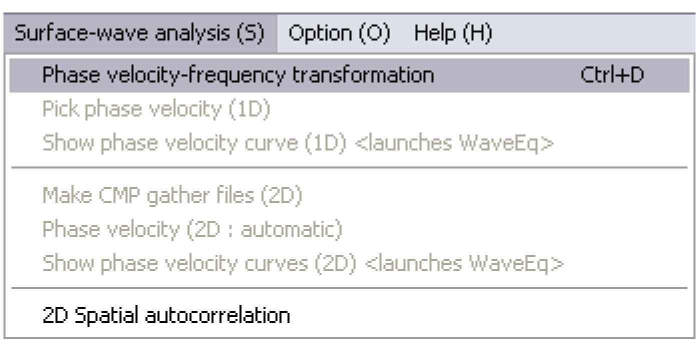


5.3 Surface-Wave Analysis Menu

This menu contains the functions needed for calculating a dispersion curve and picking the maximum amplitudes of the dispersion curve.

5.3.1 Phase Velocity-Frequency Transformation

Once a waveform file(s) is opened, select *Phase velocity-frequency transformation* to transform the time-domain waveform data to the frequency domain and calculate the phase velocity for each frequency.

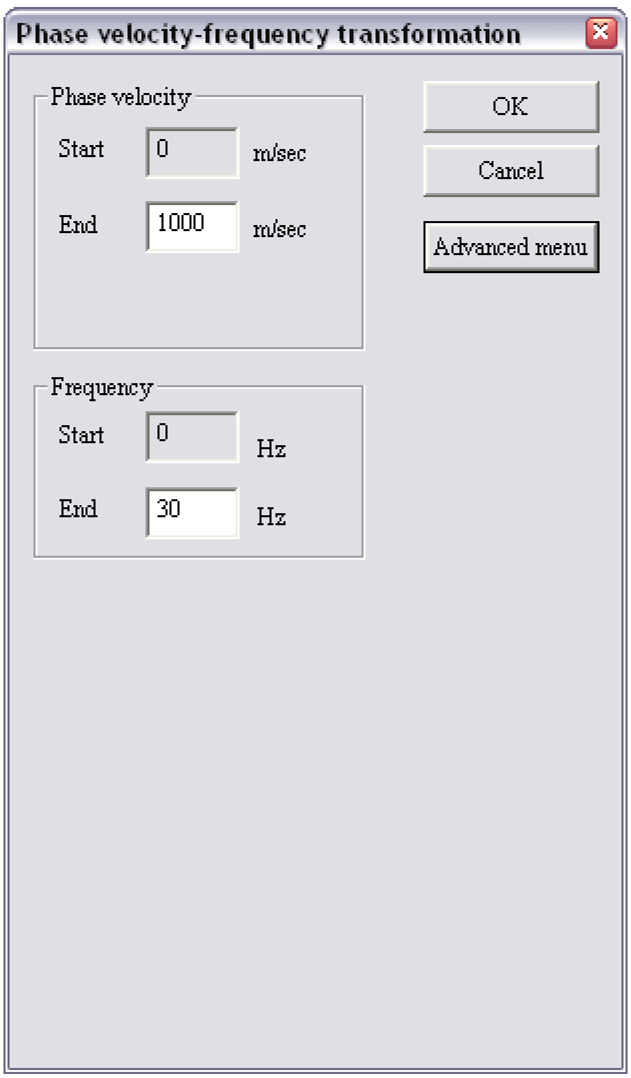


The following dialog box will appear, which you will recognize from the wizard. The bounds for the transformation are set here.

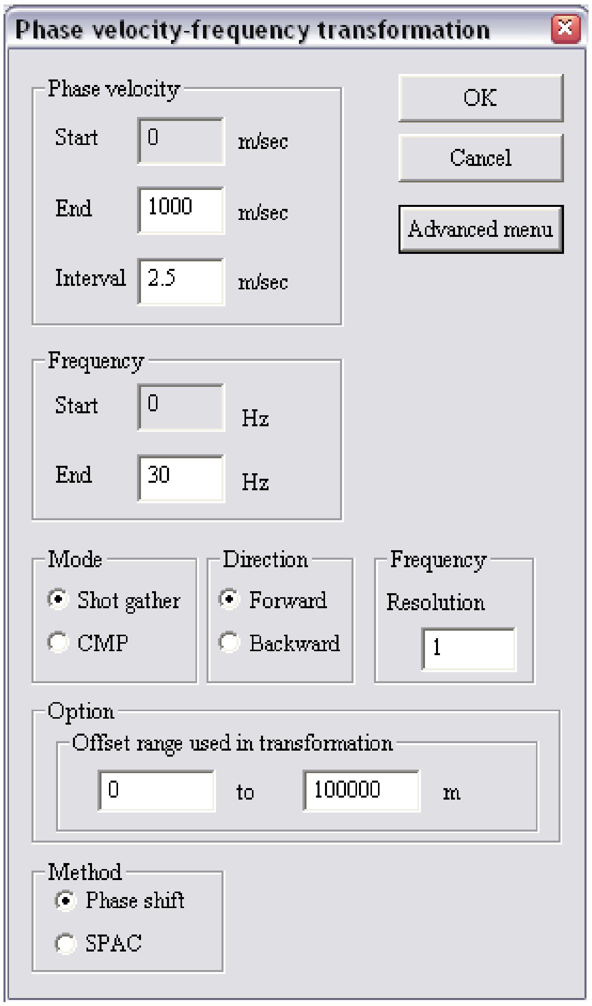
The *Start Phase Velocity* and *Start Frequency* are set fixed at 0.

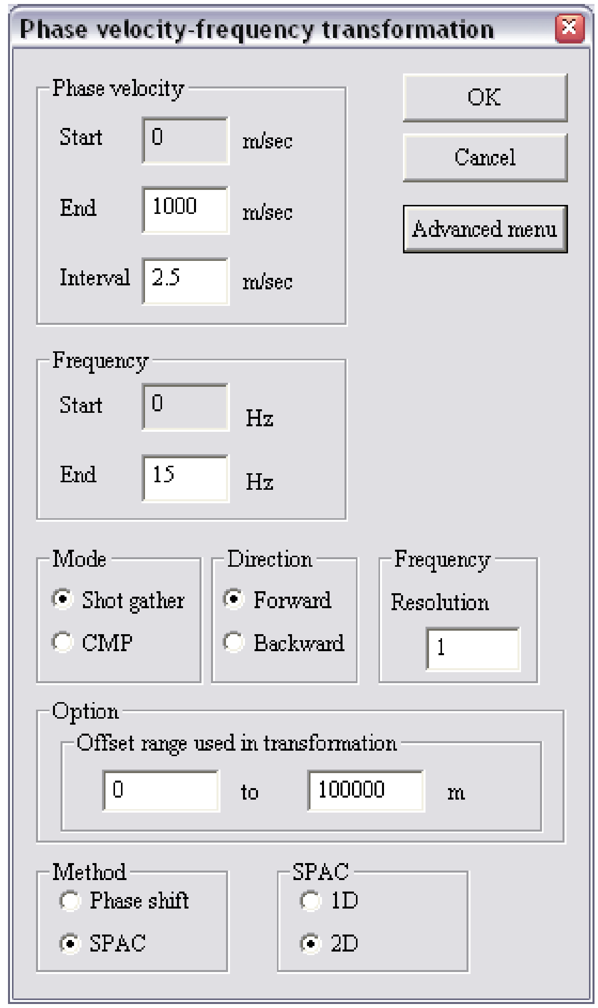
For *End Phase Velocity*, the approximate maximum velocity you expect for your site should be entered. If you see in the resulting phase velocity plot that the end velocity was too low or too high, the calculation can simply be re-run.

For *End Frequency*, adjust the default to enclose the bandwidth of fundamental mode surface wave signal. For most sites, the default of 30 Hz is fine. Again, it is simple to adjust this value and re-run the calculation if you want to experiment with this setting.



The default dialog box format hides the *Advanced menu*. If you click to show the *Advanced menu*, you will reveal the default values for active source (left) and passive source (right) processing. (Whether the passive settings are used is determined by a prior step, which is explained in Section 5.3.4.) Typically, none of these parameters need to be changed.





The *Phase Velocity Interval* defines the resolution at which the calculation steps through the range of velocities indicated. Increasing this value reduces the resolution. The default value is recommended.

Mode of *Shot gather* or *CMP gather* is used for 2D MASW processing only and is non-applicable here.

Direction of *Forward* means that the shot coordinate is less than the coordinate of the first geophone. *Backward* means the shot coordinate is greater than the coordinate of the first geophone. The software assumes that that the same gain was used on all traces and automatically attempts to determine the direction. This is done by comparison of the amplitudes of the first and last traces. If the last trace is smaller, the software assumes a

Forward direction and vice-versa for *Backward*. If you have recorded with individual gain settings, you may want to check that the software correctly determined the direction.

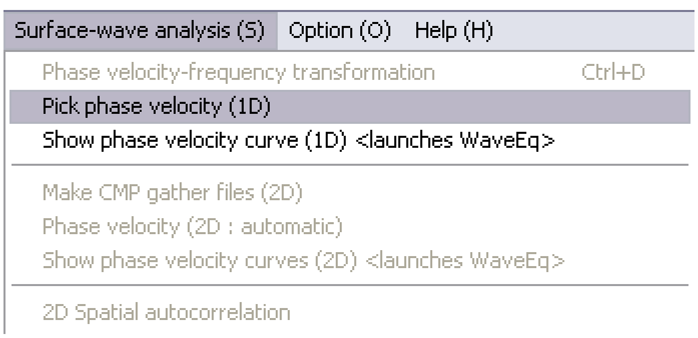
The *Frequency resolution* controls how finely the phase velocity curve is calculated. If this value is increased, the resolution will be reduced. This value cannot be less than 1 and must be an integer.

The *Offset range used in transformation* sets the range of traces used in the transformation. This is a difference, not actual coordinates. Offset is the distance from the shot to any given receiver. This is mainly used for cutting out near-source affects in 2D MASW processing and is non-applicable for 1D MASW.

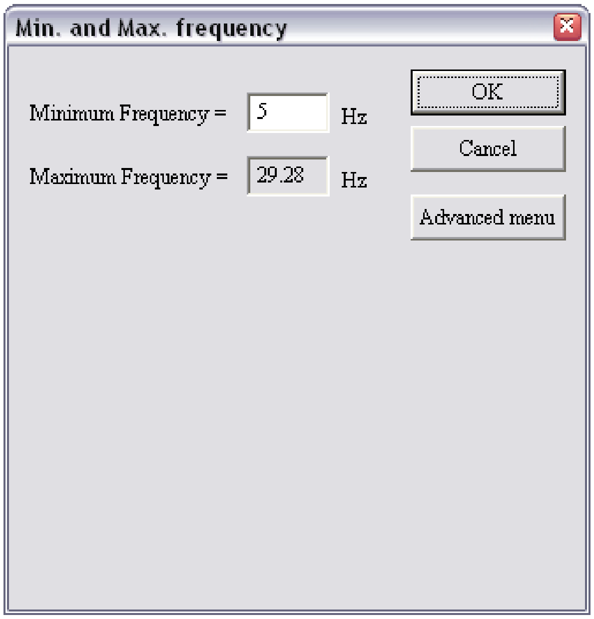
Method indicates what procedure will be used. This is the only difference between the active and passive source dialog boxes. You do not need to change these settings because they are automatically set by the software depending on the type of data being processed. For active source data processing, the *Method* is *Phase shift*. For passive source data processing, the *Method* is *2D SPAC* (Spatial Autocorrelation).

5.3.2 Pick Phase Velocity (1D)

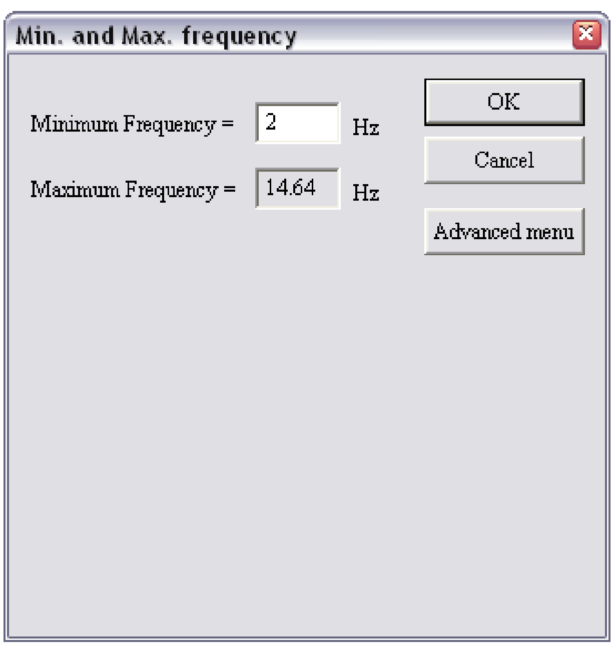
The *Pick Phase Velocity (1D)* function tells the software to automatically pick the amplitude maxima on the phase velocity plot, which defines the dispersion curve.



Upon selection, the following dialog box will appear, which you will recognize from the wizard. Here the frequency bounds for automatic picking are set. For active source data processing, the *Minimum Frequency* default is 5 assuming that 4.5 Hz geophones were used.

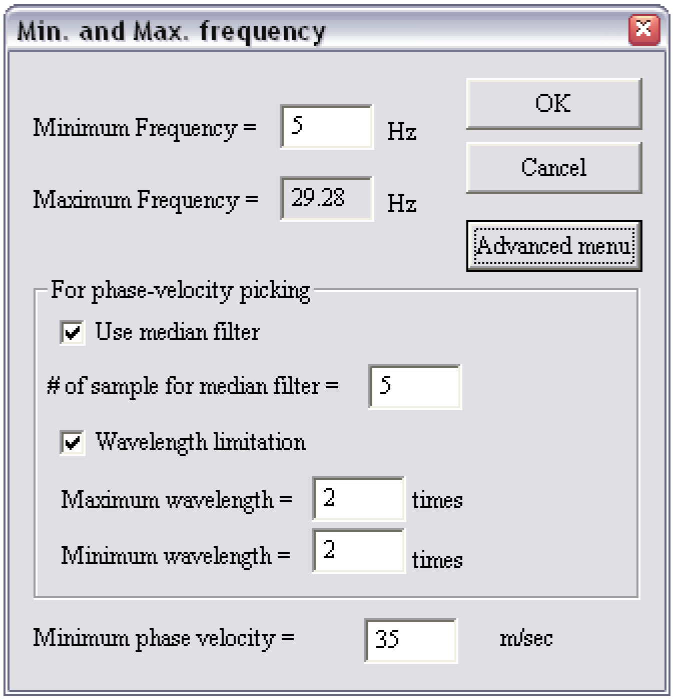


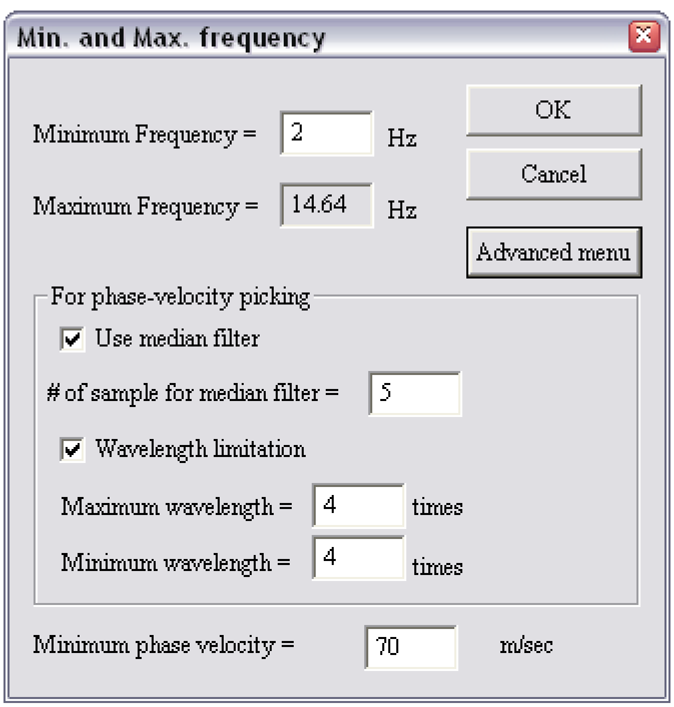
For passive source data processing, the *Minimum Frequency* default is 2 assuming that 2 Hz seismometers were used. If you have acquired your data with 4.5 Hz geophones, you can change the *Minimum Frequency* to 5 if you wish, however, any erroneous picks made between 2 and 5 Hz can easily be manually edited. It is not essential or crucial that this value be changed here.



The *Maximum Frequency* reflects in Fourier space the value closest to that set in the *Phase velocity-frequency transformation* dialog box.

The default dialog box format hides the *Advanced menu*. If you click to show the *Advanced menu*, you will reveal the default values for active source (top) and passive source (bottom) processing. Typically, none of these parameters need to be changed.





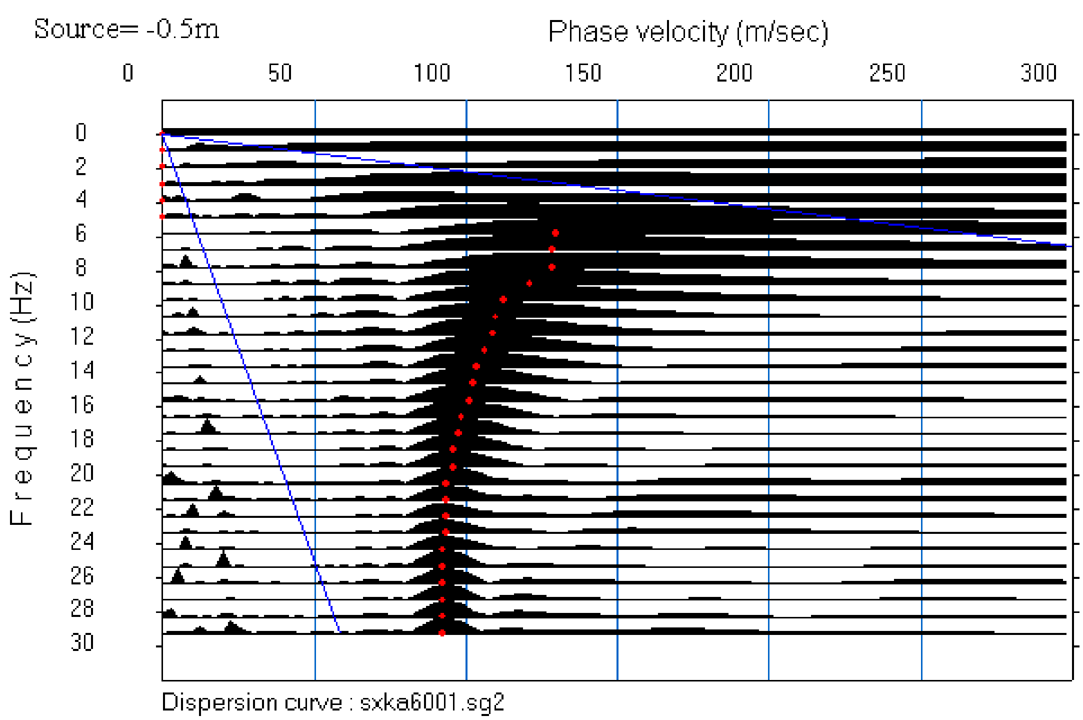
After the dispersion curve is automatically picked, if *Use Median filter* is checked (default), a median filter is applied to remove outliers. The median filter is a moving window filter sized by the number of samples. For high tolerance of outliers, a large number would be set for the number of samples. For most cases, the default value is suitable and does not need to be changed.

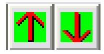
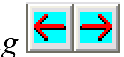
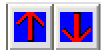
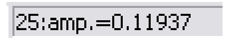
The *Wavelength limitation* defines the wavelength (phase velocity divided by frequency) boundaries for picking. If this option is checked (default), the limits as defined will be used for picking. The *Minimum wavelength* limit is calculated by the geophone interval multiplied by the scalar value entered and the *Maximum wavelength* limit is calculated by the total offset or array length multiplied by the scalar value entered. For active source processing, the default scalar value is 2 and for passive source processing the default is 4.

On the phase velocity plot, the *Maximum wavelength* setting controls the slope (x/y ratio) of the upper blue line (nearly parallel to the x-axis) and the *Minimum wavelength* controls the slope of the lower blue line (nearly parallel to the y-axis).

The *Minimum phase velocity* is the lowest velocity for which a pick should be made.

After setting these parameters and clicking *OK*, the phase velocity plot with dispersion curve picks (red points) is presented.



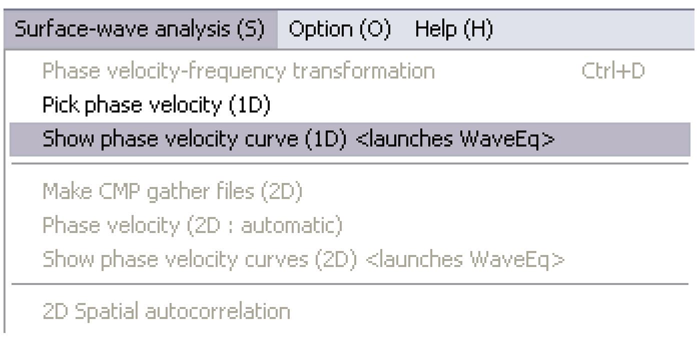
The actual picks are the maximum amplitude at each frequency, which define the dispersion curve. The automatic picks can be manually edited with the mouse by individually clicking on a new pick or dragging the mouse over a range of picks. Manual picking is facilitated by using the *Fine color contour*  button to switch to a color plot and the *Amplitude gain*  buttons, the *Horizontal axis sizing*  buttons, and the *Vertical axis sizing*  buttons to optimize the gain and scale. The actual amplitude values can also be checked on the bottom bar 

where the value preceding the colon is the frequency and the following value the amplitude.

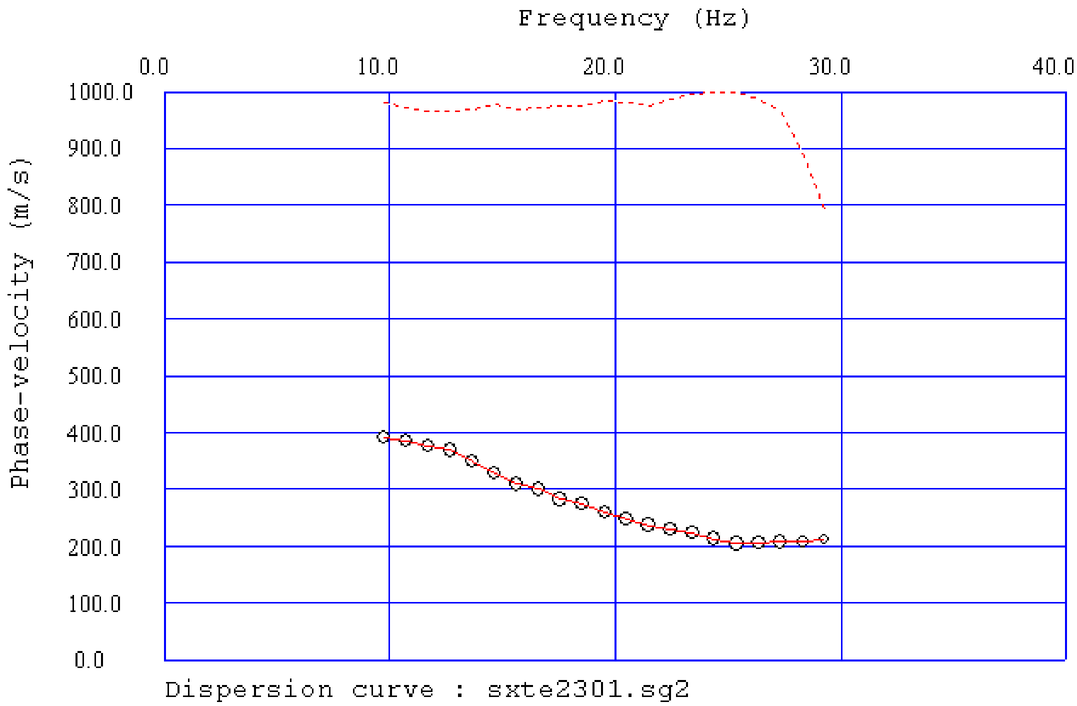
Any picks lying on the y-axis have a value of zero (Phase velocity = 0) and are automatically excluded from further analysis.

5.3.3 Show Phase Velocity Curve (1D)

Once the dispersion curve is picked in Pickwin, WaveEq is used for detailed editing, inversion to back-calculate the V_s structure, and additional analysis. The function *Show phase velocity curve (1D)* automatically launches WaveEq and imports the dispersion curve from Pickwin. This step is necessary to import a new dispersion curve into WaveEq. WaveEq can be launched separately, but only WaveEq dispersion curve result files (.rst files, not Pickwin .pvs files) can be input.



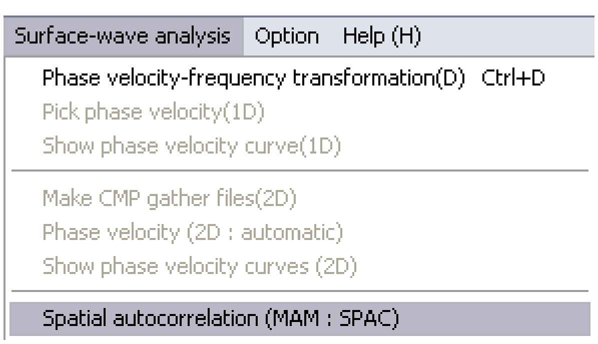
Upon selection of *Show phase velocity curve (1D)*, WaveEq is launched and the dispersion curve plot is presented. Refer to Section 6 for a complete explanation of this plot.



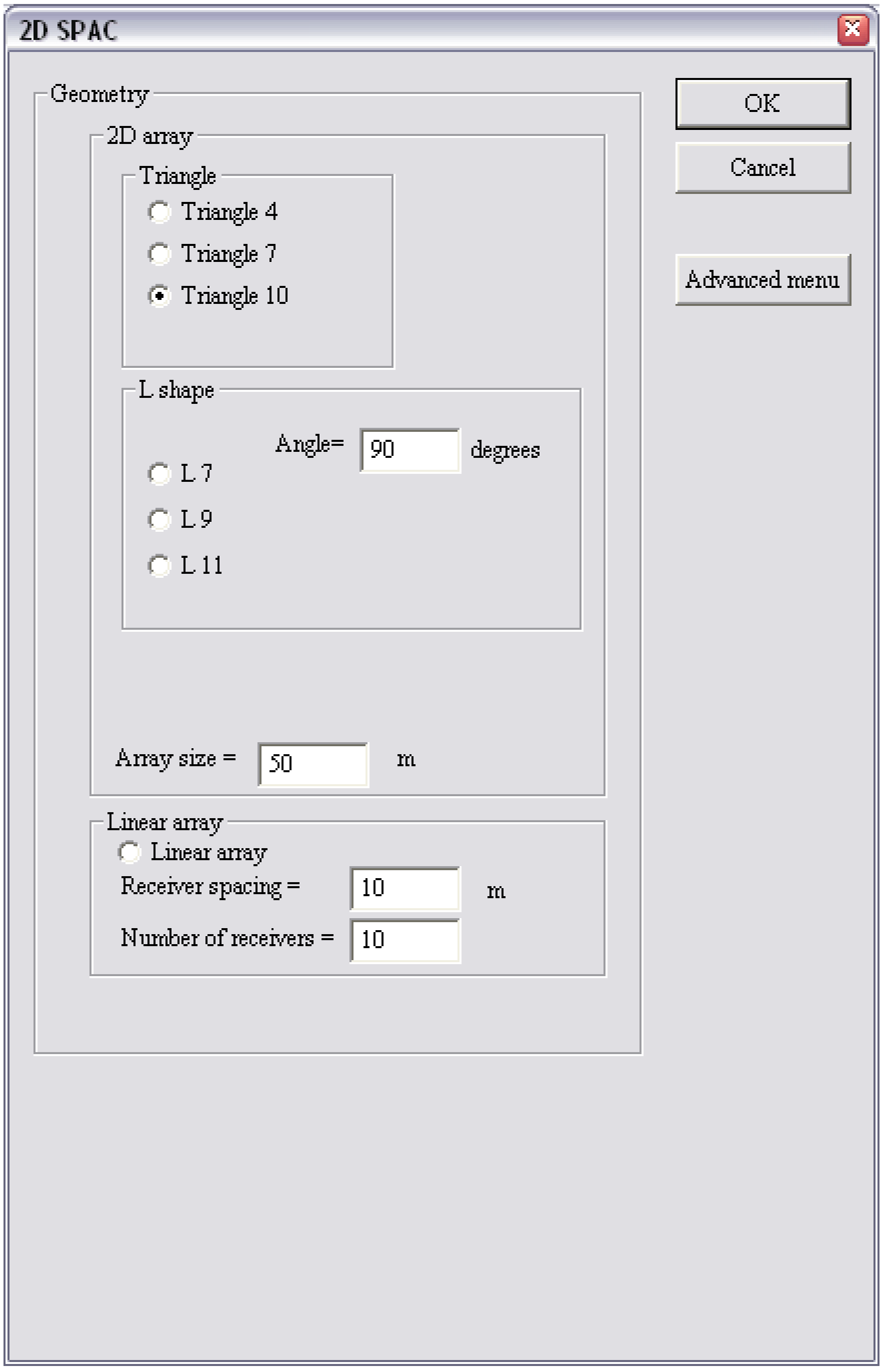
5.3.4 Spatial Autocorrelation (MAM : SPAC)

For passive source datasets (MAM or micro-tremor array measurements), the function *Spatial Autocorrelation (MAM : SPAC)* transforms all of the associated files using the Spatial Autocorrelation (SPAC) method. A phase velocity is calculated from the SPAC function for each frequency. By this method, data from sources at various distances can be unified.

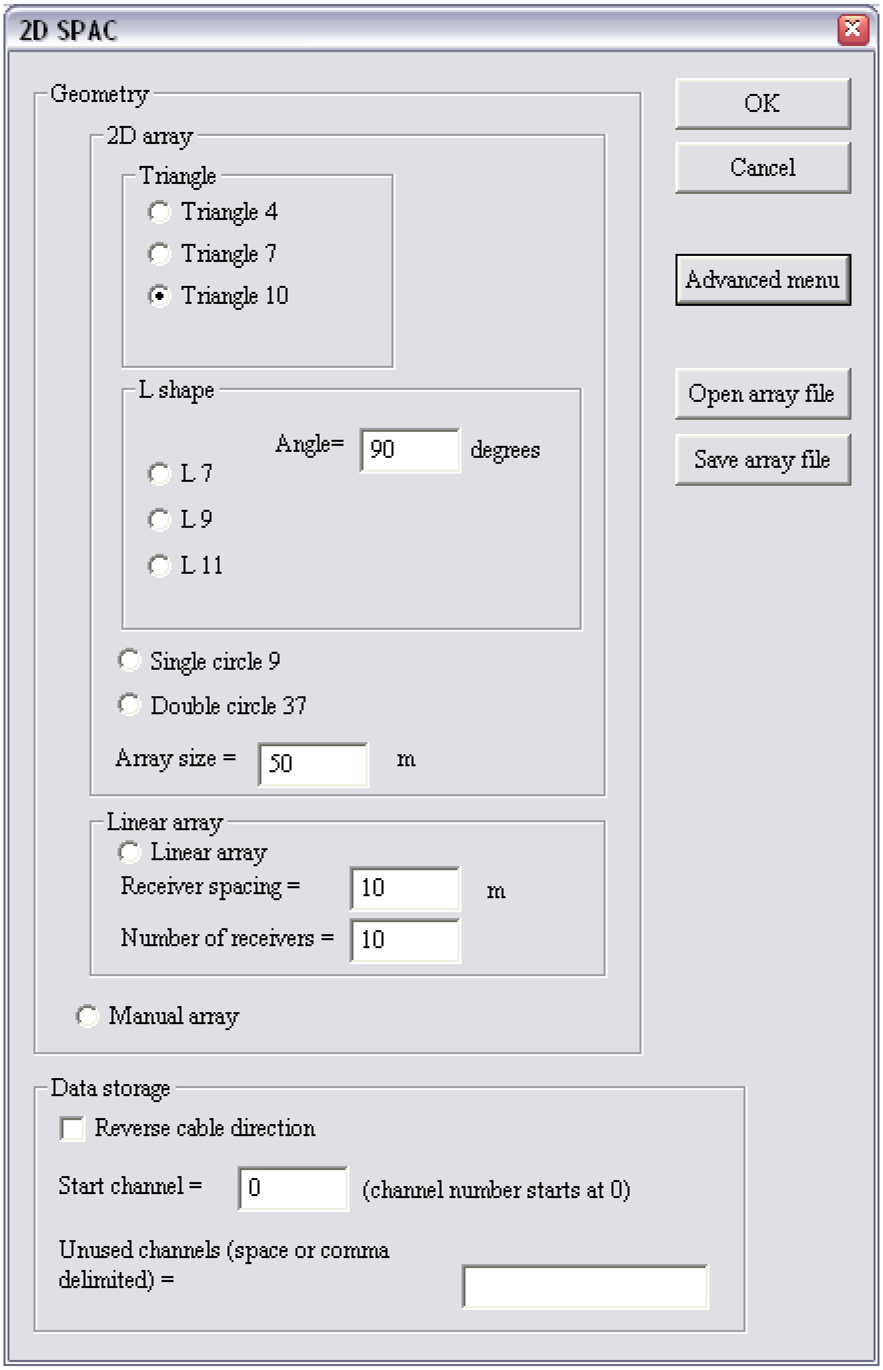
If you are doing analysis manually instead of using the *Passive Source 1D MAM* wizard, note that *Spatial Autocorrelation (MAM : SPAC)* must be run before the *Phase velocity-frequency transformation*. Refer to Section 7.2 for the processing order.



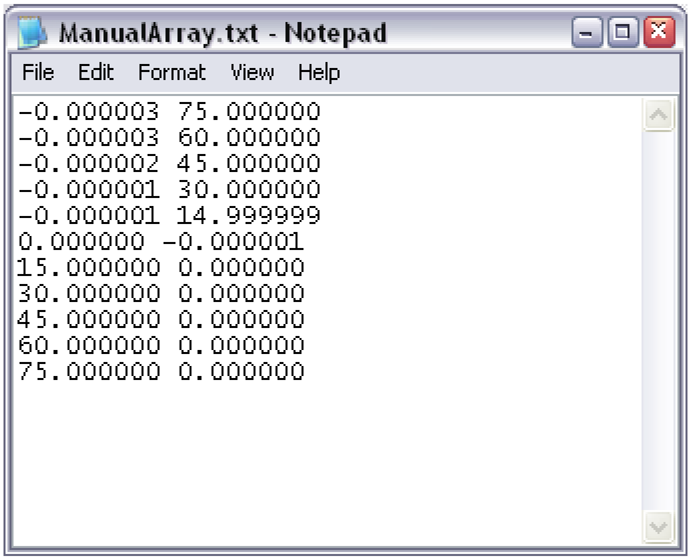
Upon selection of *Spatial Autocorrelation (MAM : SPAC)*, the following dialog box on the geometry of the passive array will appear. Refer to Section 3.2.1 for explanation of the different arrays and *Array size*.



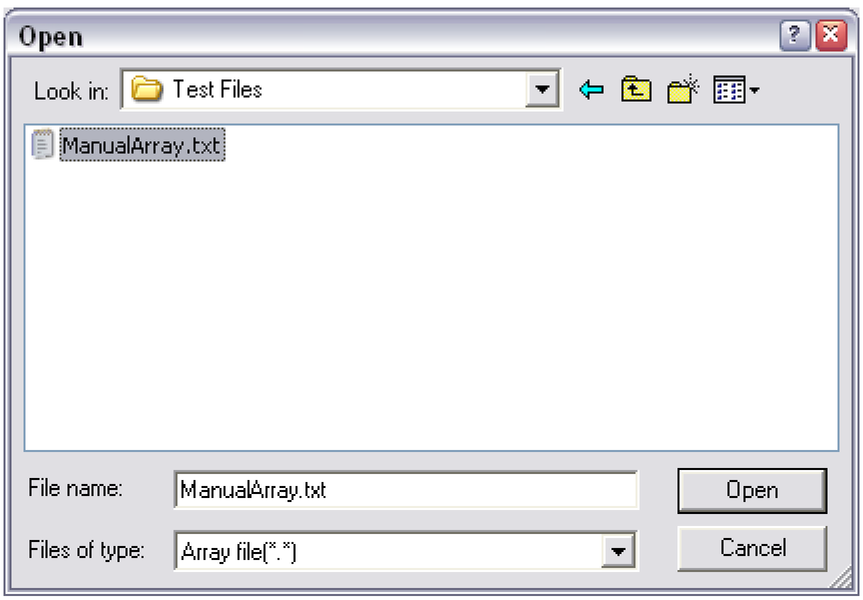
The default dialog box format hides the *Advanced menu*. If you click to show the *Advanced menu*, you will reveal an option to define a *Manual array* and *Data storage* parameters.



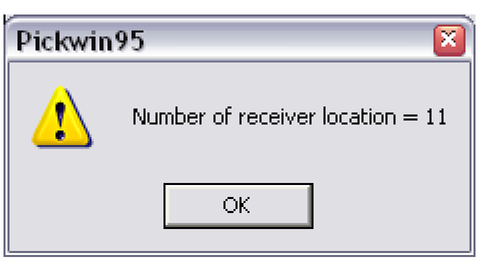
If your array does not conform to one of the standard geometries, a *Manual array* can be defined in a simple space-delimited text file as shown below where each row is a pair of x- and y-coordinates.



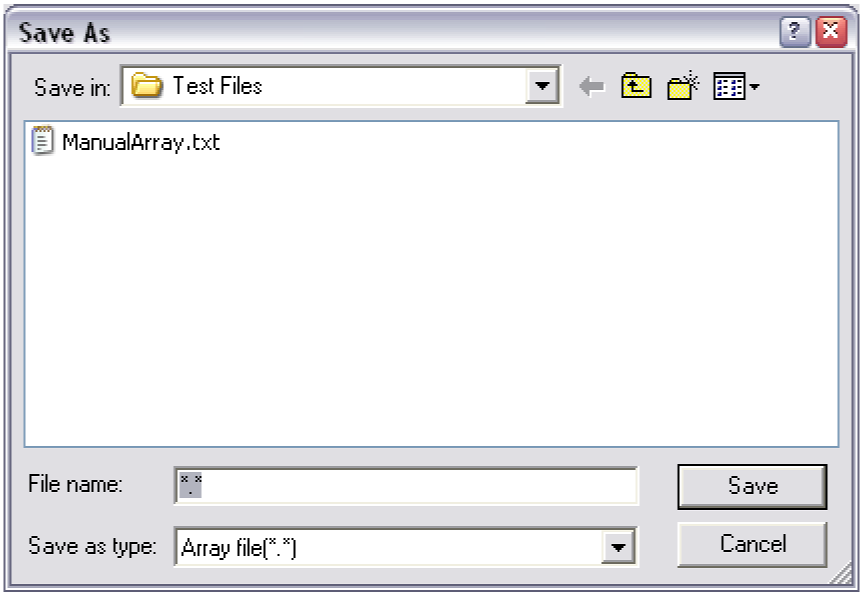
Once the *Array file* is created, click on *Open array file* to input the file.



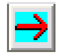
After clicking *Open*, a confirmation of the number of receiver locations read from the file is displayed.

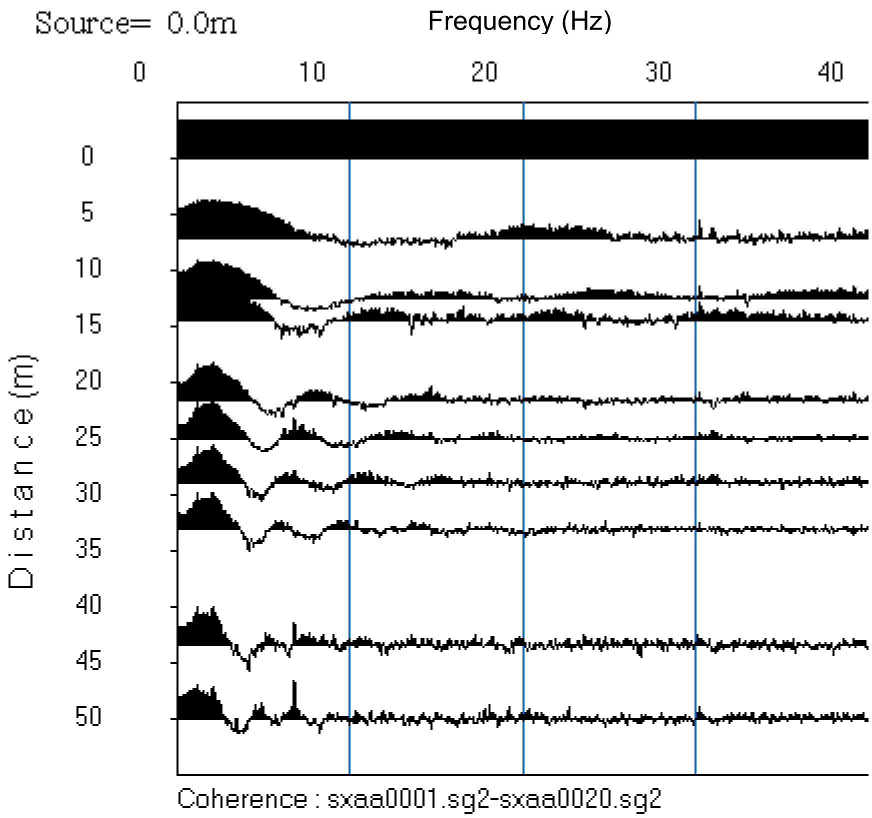


If changes are made to the existing *Array file*, click on *Save array file* to revise the file or save a new file with a different name.



Data storage pertains to 2D MASW. The *Data storage* settings allow you to apply particular array geometry to other data. *Reverse cable direction* will flip the channel order, *Start channel* sets the new start channel number, and *Unused channels* allows you to delete dead or unused channels.

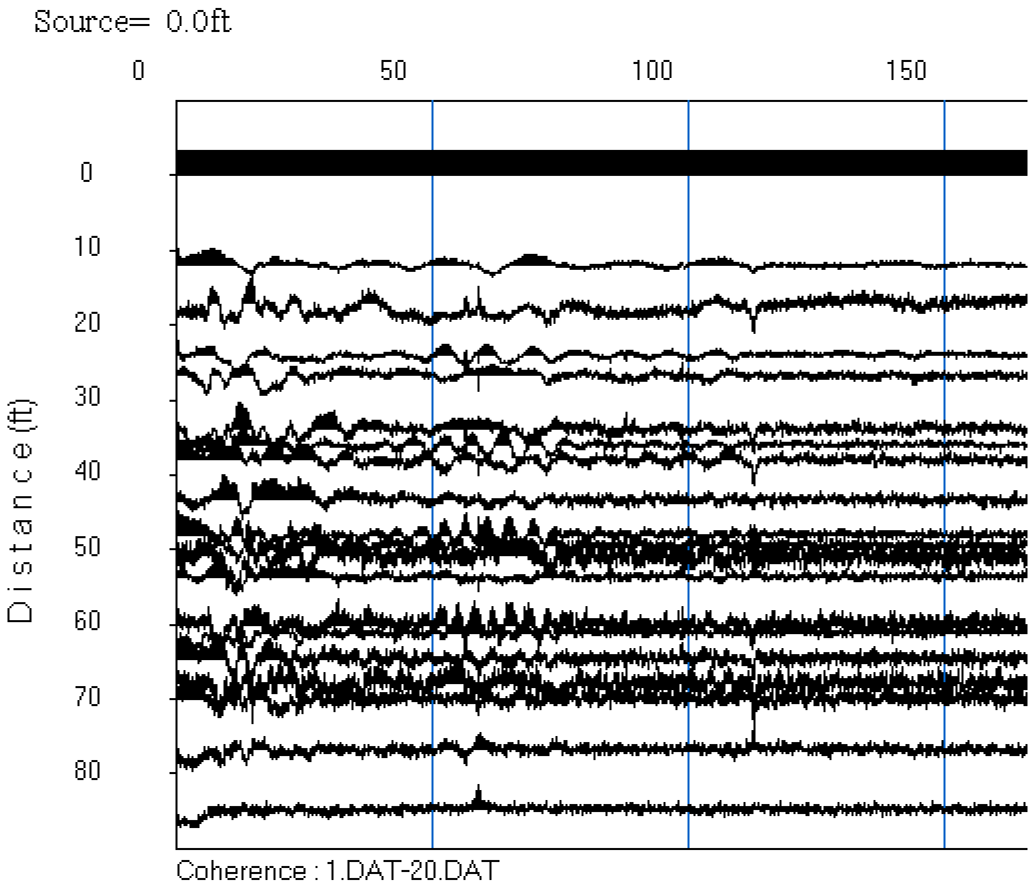
After clicking *OK* on the *Spatial Autocorrelation (MAM : SPAC)* or *2D SPAC* dialog box, a coherence plot like that shown below will appear. It will be necessary to press the right arrow key or the right arrow  button to expand the scale and zoom in on the low-frequency end of the plot. Coherence plots are symmetrical, but you need only focus on the low-frequency end.



This plot displays the coherence, or similarity, between all possible pairs of geophones, in this case in a triangle array with 10 geophones, with an array size of 50 m. The separation between each geophone pair is plotted on the y-axis as *Distance* and the coherence between each of those two traces is plotted as a function of *Frequency* on the x-axis.

Consider the geophone separation of zero, the coherence is 1 shown by a bar, or horizontal line with shaded fill, across all frequencies. At a distance of zero, a trace is compared with itself and there is 100% similarity or coherence of 1. Generally, as geophone separation increases, coherence decreases. Coherence also tends to be higher at lower frequencies and goes down with increase in frequency.

The shape of a coherence curve by nature is a Cosine function with 1D arrays and a Bessel function with 2D arrays (as shown above). You can see in the above plot that at each separation the coherence curve is well shaped (calculated from what is considered an ideal dataset). Compare this with the following plot for an L-shaped array with 11 geophones and array size of 60 feet that shows poor coherency for all separations greater than zero.



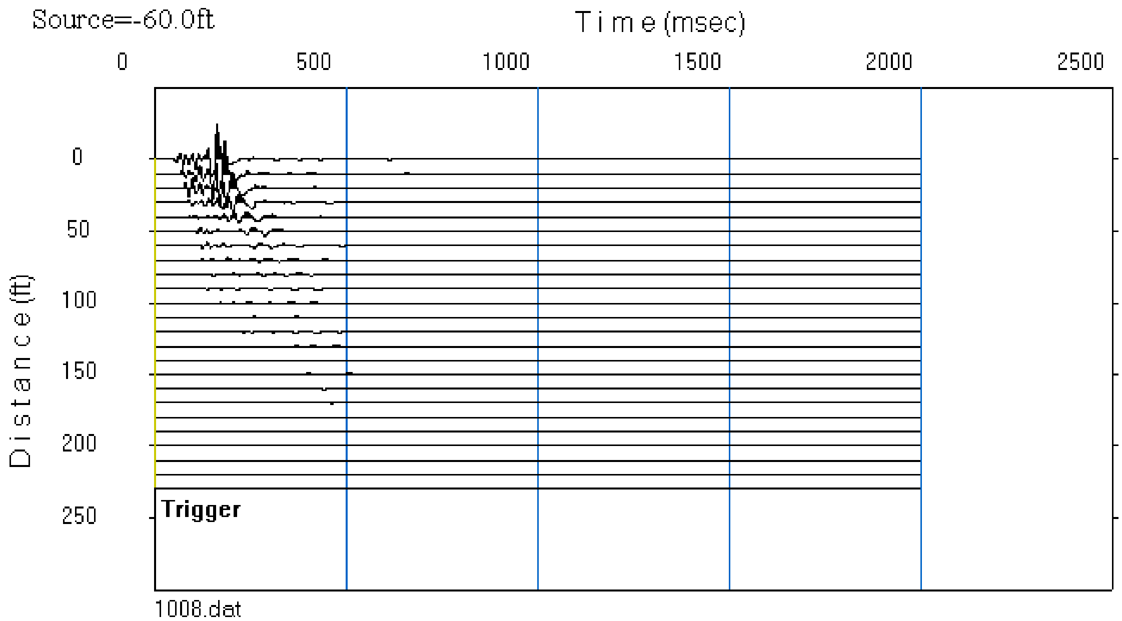
Checking coherence is a quick calculation and can be readily performed in the field to confirm that passive source datasets will yield good results.

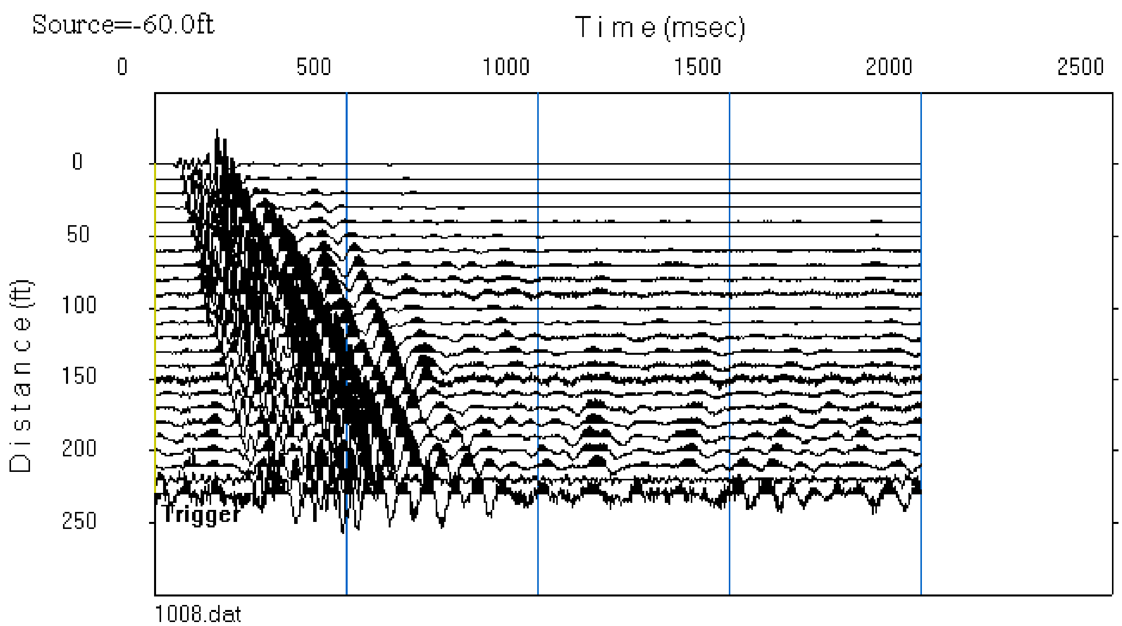
5.4 Button Bar Functions

The button bar functions essential or uniquely used for surface wave data processing are covered in this section. For complete description of the button bar functions common to SeisImager/SW and SeisImager/2D, please refer the separate SeisImager/2D manual included on the SeisImager software CD.

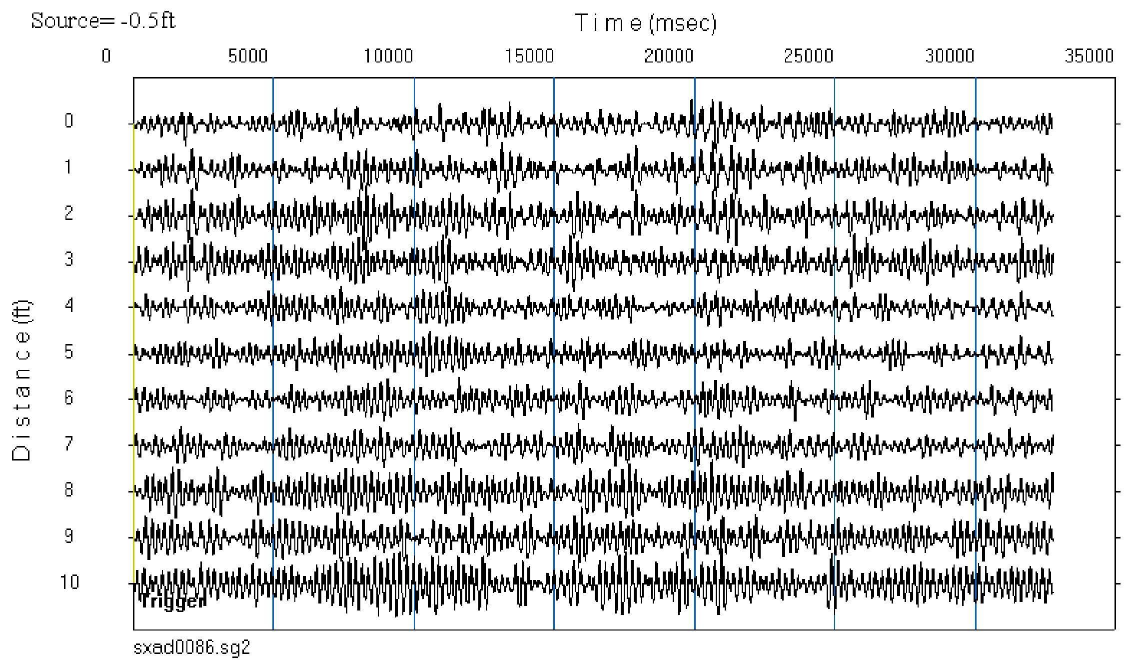
5.4.1 Normalize 

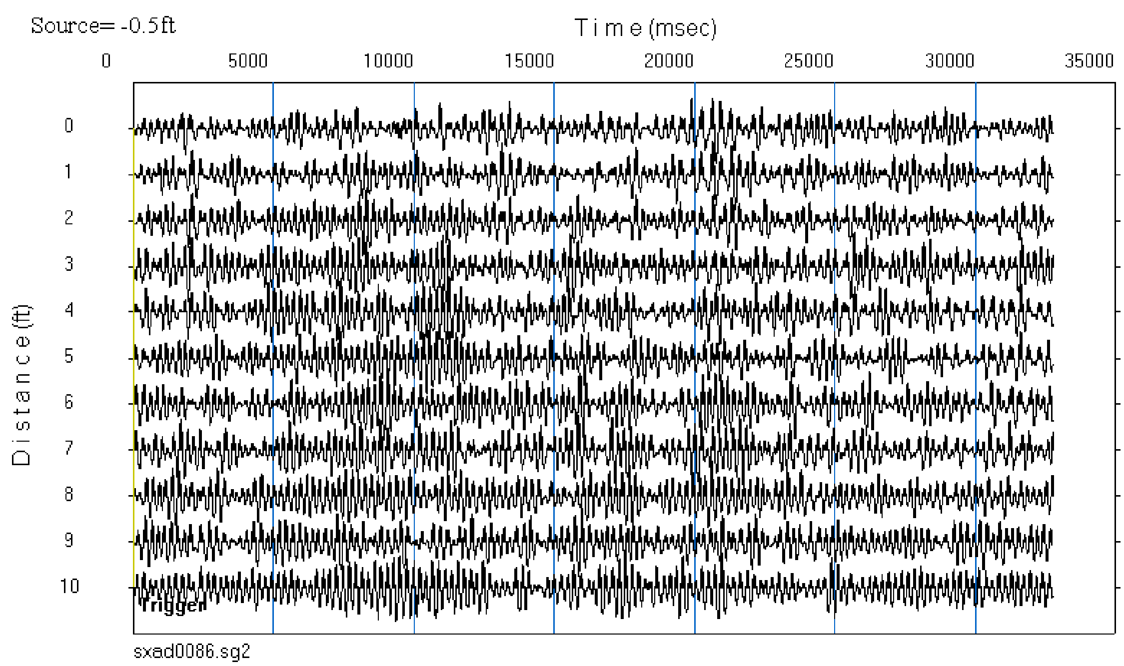
When traces are normalized, the maximum amplitude of each trace will be equalized. Lower amplitude traces (those farther from the source) will be “turned up” so that their maximum amplitude is equal to that of higher-amplitude traces. This has the effect of equalizing the appearance of all the traces across the record and allows viewing of the active source surface wave package. The example below shows an active source shot record with *Normalize* off (top) and *Normalize* on (bottom).





With passive source surface wave data, it is important to be able to observe trace-to-trace variations, and thus, *Normalize* should be turned off. The example below shows how subtle amplitude changes seen on traces 4 through 7 in the un-normalized view (top) can be swamped by application of *Normalize* (bottom).

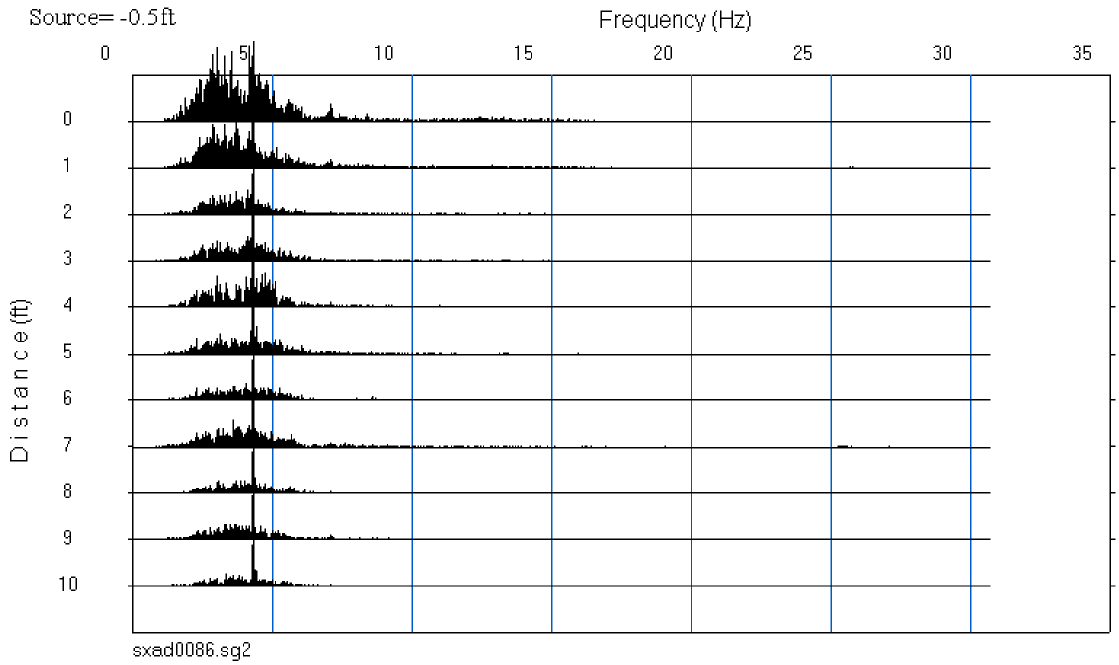




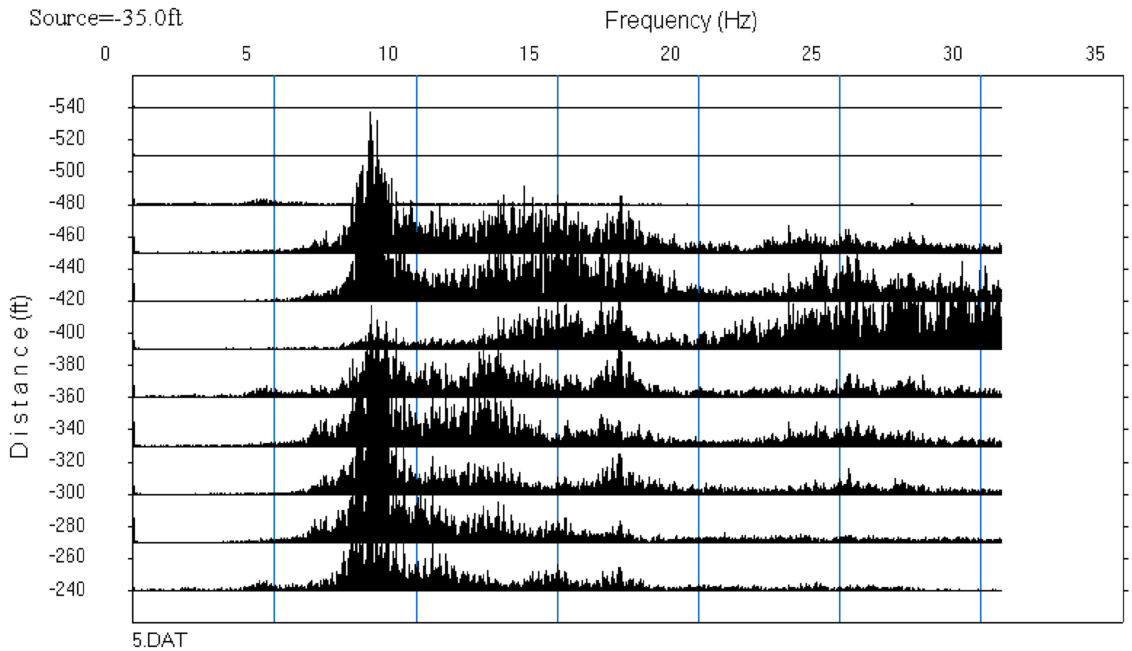
5.4.2 Frequency Domain 

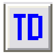
The *Frequency domain* button transforms a time-domain waveform record to the frequency domain. Clicking on the 

button will change the view from the waveforms to a plot of the frequency content or spectrum for each trace. It will be necessary to press the right arrow key or the right arrow button to expand the frequency scale and zoom in on the lower end of the frequency scale. The example below shows the spectrum for the above passive source record.



Unlike most active source data, it is usually difficult to evaluate the quality of passive source data from viewing the waveform record in the time domain. Similar frequency bandwidth from trace-to-trace like that shown above, and unlike that shown below, indicates high-quality data.



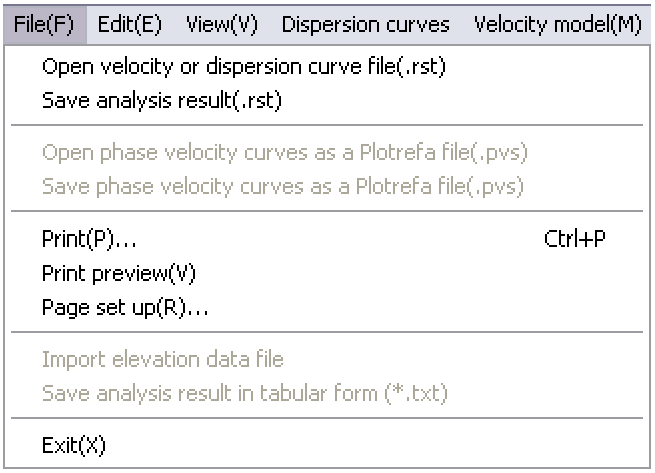
5.4.3 Time Domain 

The *Time Domain* button allows you to toggle out of the frequency domain.

6 The WaveEq Module Functions

6.1 File Menu

The *File* menu includes functions for opening WaveEq result files, importing and exporting various files, and printing.



6.1.1 Open Velocity or Dispersion Curve File (.rst)

To open a dispersion curve and/or V_s profile previously saved as a result file with the extension .rst, select *Open velocity or dispersion curve file (.rst)*.

6.1.2 Save Analysis Result (.rst)

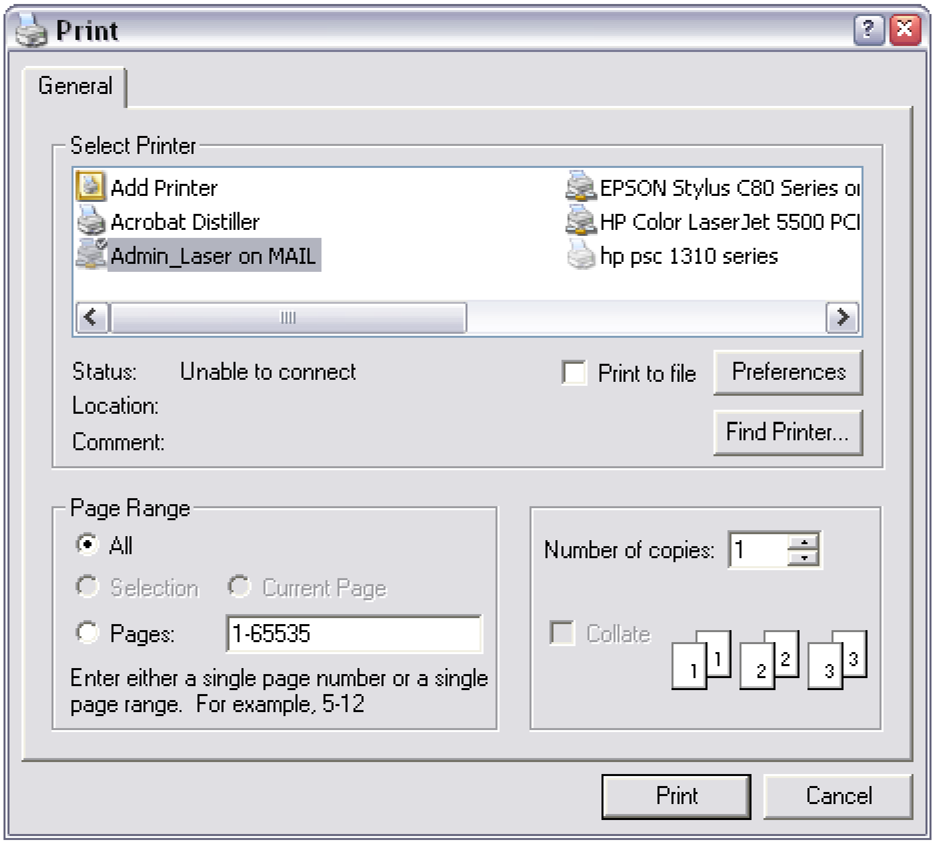
To save a dispersion curve and/or V_s profile, select *Save analysis result (.rst)*. A result file can be saved at any time in the processing flow and will reflect the extent of results at the time of save. You might like to save your "raw" dispersion curve before any processing. To do so, save the result file before creating the initial model and running the inversion. After the inversion, save the final result with a file name different than that used for the unprocessed dispersion curve.

6.1.3 Open Phase Velocity Curves as a Plotrefa File (.pvs)  *and Save Phase Velocity Curves as a Plotrefa File (.pvs)* 

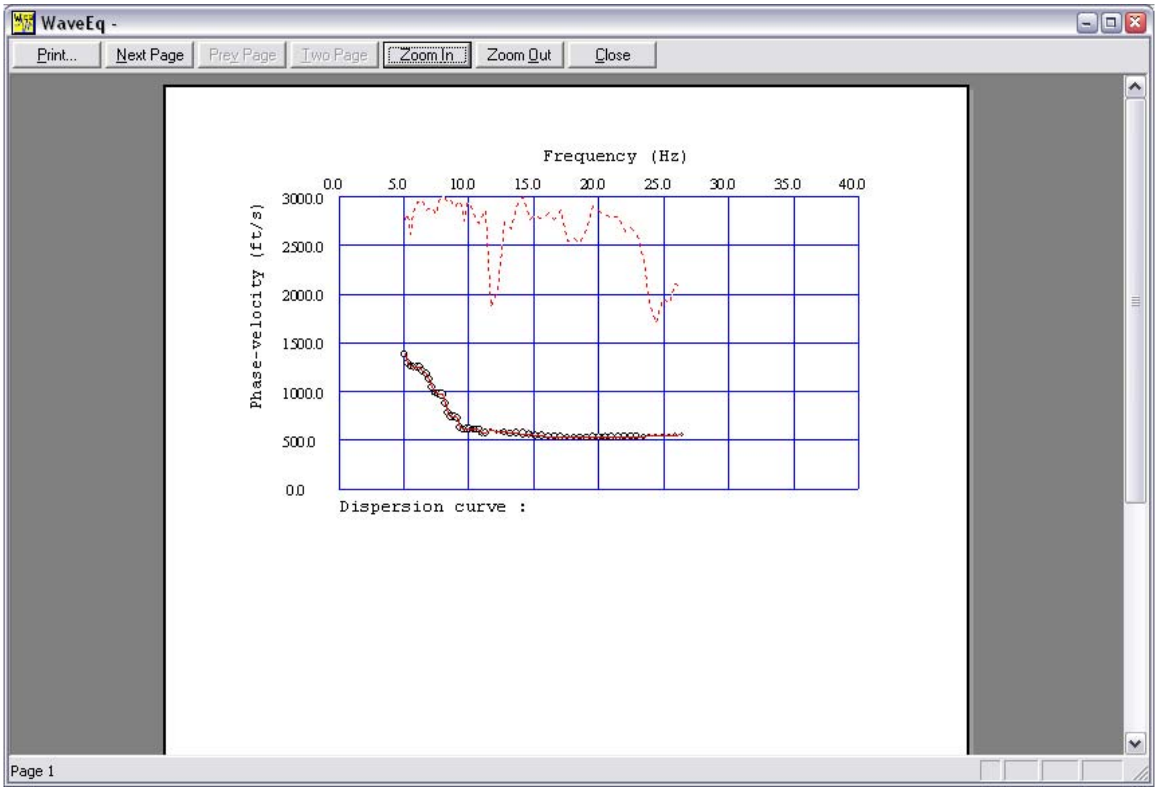
These functions are not active for this version of SeisImager/SW.

6.1.4 Print, Print Preview, and Page Set-up

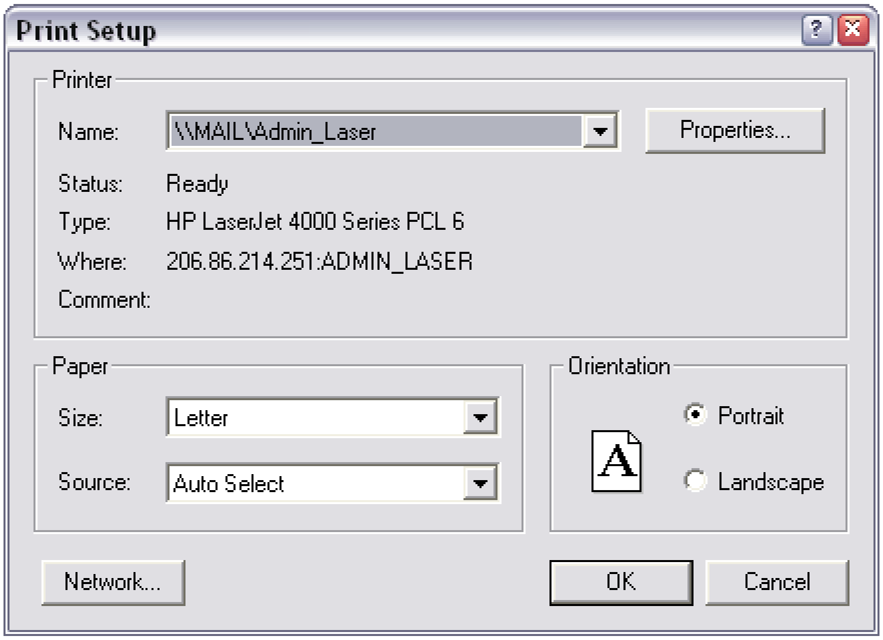
To print the current window display of WaveEq, choose *Print*, press Ctrl-P, or press the *Print* button. The following dialog box common to Windows will appear. Click *OK* to print.



To preview the window display of WaveEq for printing, choose *Print preview(V)*. A preview of the window display to be printed will appear.



To set up a page for printing, choose *Page set up(R)*. The print dialog box for your computer will appear.



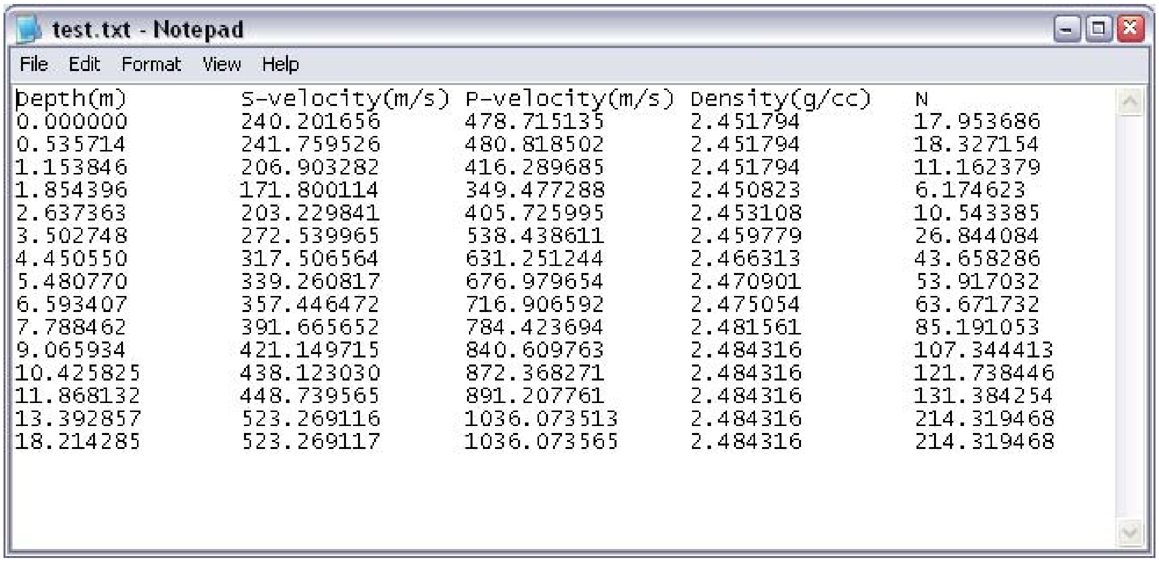
Adjust the properties for printing and then click *OK* to print the current WaveEq window display.

6.1.5 Import Elevation Data File

The function *Import Elevation Data File* is not active for SeisImager/SW. It is recommended that surface wave surveys be conducted on flat, planar ground. Some variation in elevation can be tolerated and would be averaged, especially for the passive source surveys, but flat ground is best.

6.1.6 Save Analysis Result in Tabular Format (.txt)

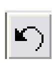
To save the final results of an analysis, select *Save analysis result in tabular format (.txt)*. The file saved is a simple text file with *Depth*, *S-wave velocity*, *P-wave velocity*, *Density*, and *N* (or blow counts). Refer to Section 6.5.4 for discussion of the relationships used for calculating the equivalent *P-wave velocity*, *Density*, and *N*.



Depth(m)	S-velocity(m/s)	P-velocity(m/s)	Density(g/cc)	N
0.000000	240.201656	478.715135	2.451794	17.953686
0.535714	241.759526	480.818502	2.451794	18.327154
1.153846	206.903282	416.289685	2.451794	11.162379
1.854396	171.800114	349.477288	2.450823	6.174623
2.637363	203.229841	405.725995	2.453108	10.543385
3.502748	272.539965	538.438611	2.459779	26.844084
4.450550	317.506564	631.251244	2.466313	43.658286
5.480770	339.260817	676.979654	2.470901	53.917032
6.593407	357.446472	716.906592	2.475054	63.671732
7.788462	391.665652	784.423694	2.481561	85.191053
9.065934	421.149715	840.609763	2.484316	107.344413
10.425825	438.123030	872.368271	2.484316	121.738446
11.868132	448.739565	891.207761	2.484316	131.384254
13.392857	523.269116	1036.073513	2.484316	214.319468
18.214285	523.269117	1036.073565	2.484316	214.319468

6.2 Edit Menu

The *Edit* menu contains functions for making and reversing edits and copying graphical displays to the clipboard.

6.2.1 *Undo* 

The *Undo* function becomes active when you are in editing mode with the *Select dispersion curve*  button. *Undo* can be used to undo the deletion of a point on a dispersion curve. It does not apply to all functions.

6.2.2 *Delete*

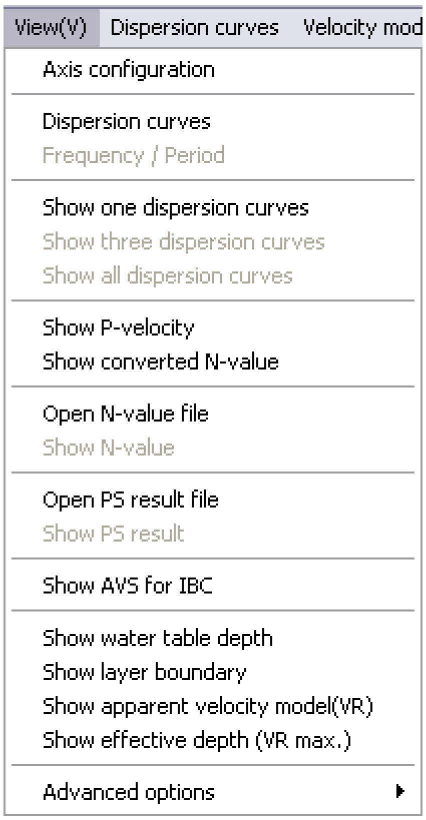
Delete becomes active when a point on the dispersion curve has been selected using the *Select dispersion curve*  button. To delete a point on a dispersion curve, you would activate editing with the white arrow button and then select the point(s) on the dispersion curve to be deleted with a mouse click. The selected points will turn red, and the *Delete* menu item can be selected or the *Delete* key can be pressed to remove the selected points.

6.2.3 Copy to Clipboard

To copy the current view to the clipboard for pasting in Microsoft Word or other program, select *Copy to clipboard,* then paste.

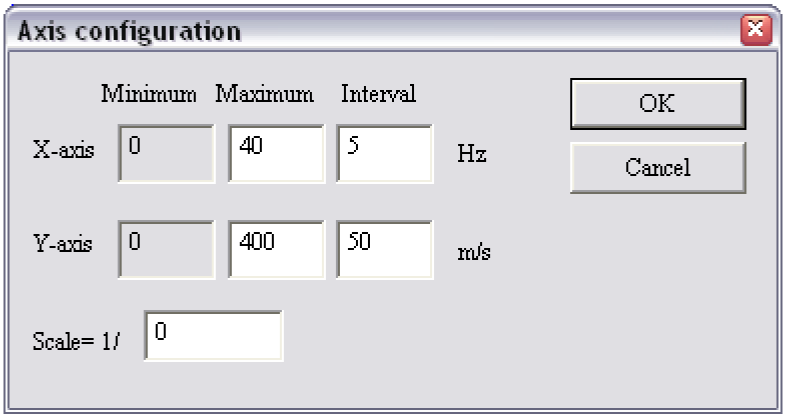
6.3 View Menu

The *View* menu includes functions to configure scales, alter displays, and overlay or import other types of data.



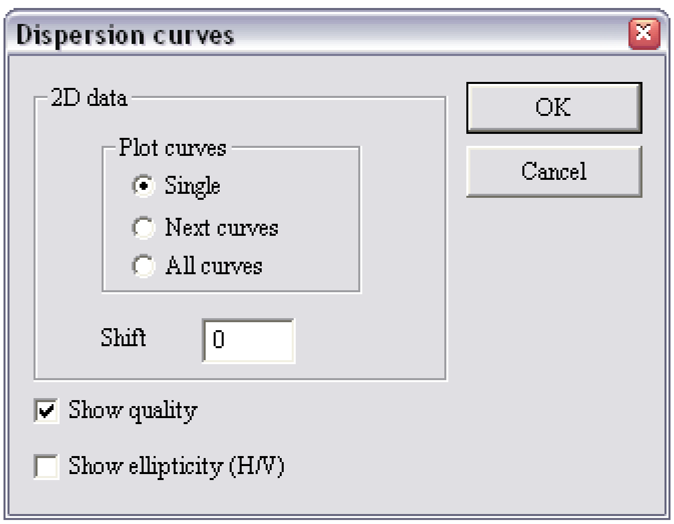
6.3.1 Axis Configuration

To configure the axis scales of the dispersion curve or velocity profile plot, select *Axis configuration*. The minimum values for the x-axis and y-axis are fixed at zero. *Scale* is not active for this version.



6.3.2 Dispersion Curves

The *Dispersion curves* dialog box allows you to control how dispersion curves are displayed. *2D data* is only applicable for 2D MASW, not for 1D analysis.

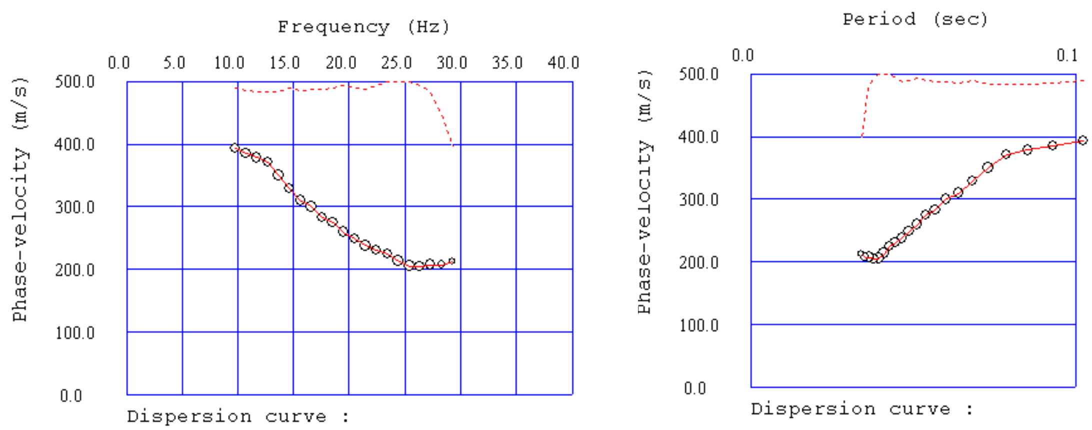


Unchecking *Show quality* will remove the dashed red quality line that plots by default on all dispersion curves. The quality line is a relative indicator of the quality of the points that define the dispersion curve. If all data points were high quality, the line would be flat. High quality points will correlate with peaks and low-quality points with valleys on the quality line. Usually the quality decreases at the ends of the curve and thus, the line will dip down.

Show ellipticity (H/V) allows you to plot the horizontal over vertical amplitude ratio for three-component passive source data.

6.3.3 *Frequency/Period* 

Frequency/period allows you to toggle the view of the dispersion curve between frequency (cycles per second) and the inverse of frequency, or period (seconds).



Some workers find it more straightforward to think in terms of seconds, which directly relates to the natural period of buildings, etc.

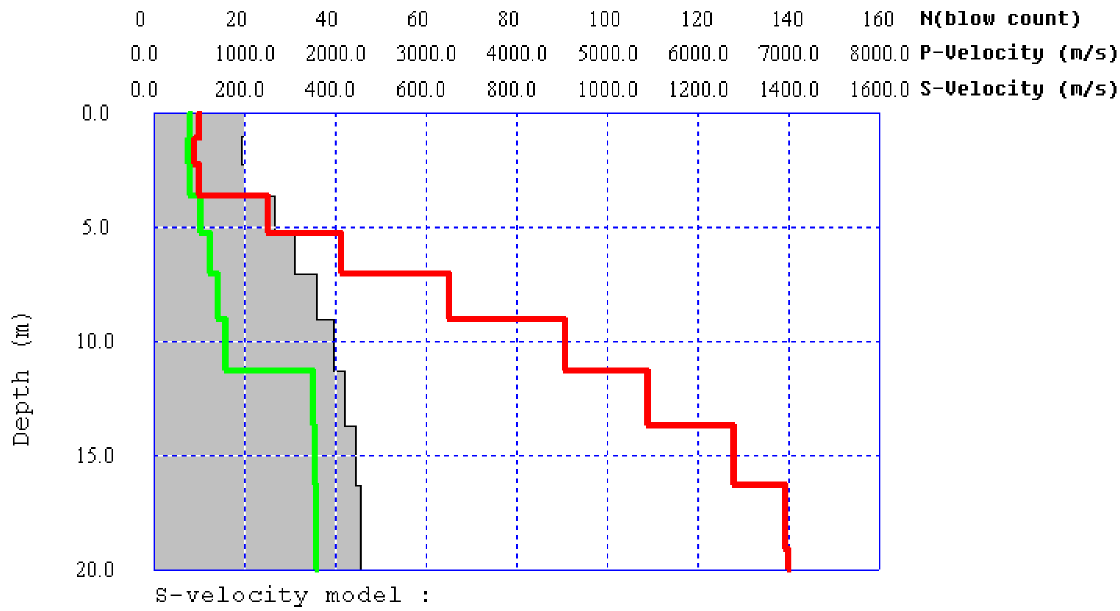
6.3.4 *Show One* *, Three, and All Dispersion Curves*

Show one dispersion curve or clicking on the  button presents the current dispersion curve.

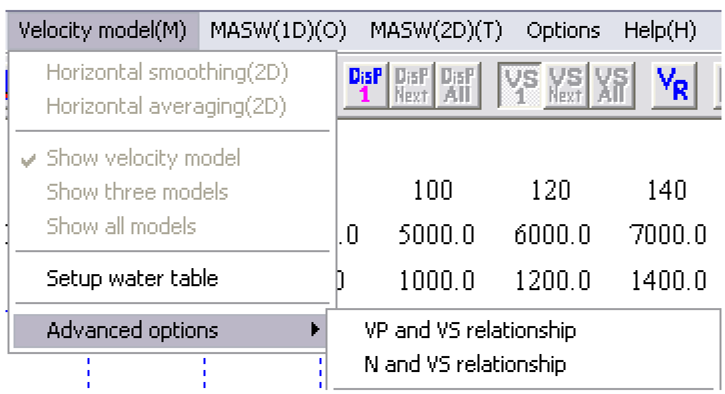
Show three dispersion curves and *Show all dispersion curves* are only applicable for 2D MASW.

6.3.5 *Show P-Velocity and Show Converted N-Value*

Calculated P-wave velocities (V_p) and N-values can be overlaid on the S-wave velocity profile be selecting *Show P-velocity* and *Show converted N-value*. A green curve will appear for V_p and the horizontal axis will include a second scale corresponding to the V_p values. A red curve is used for N-values and the horizontal axis will include a third scale.

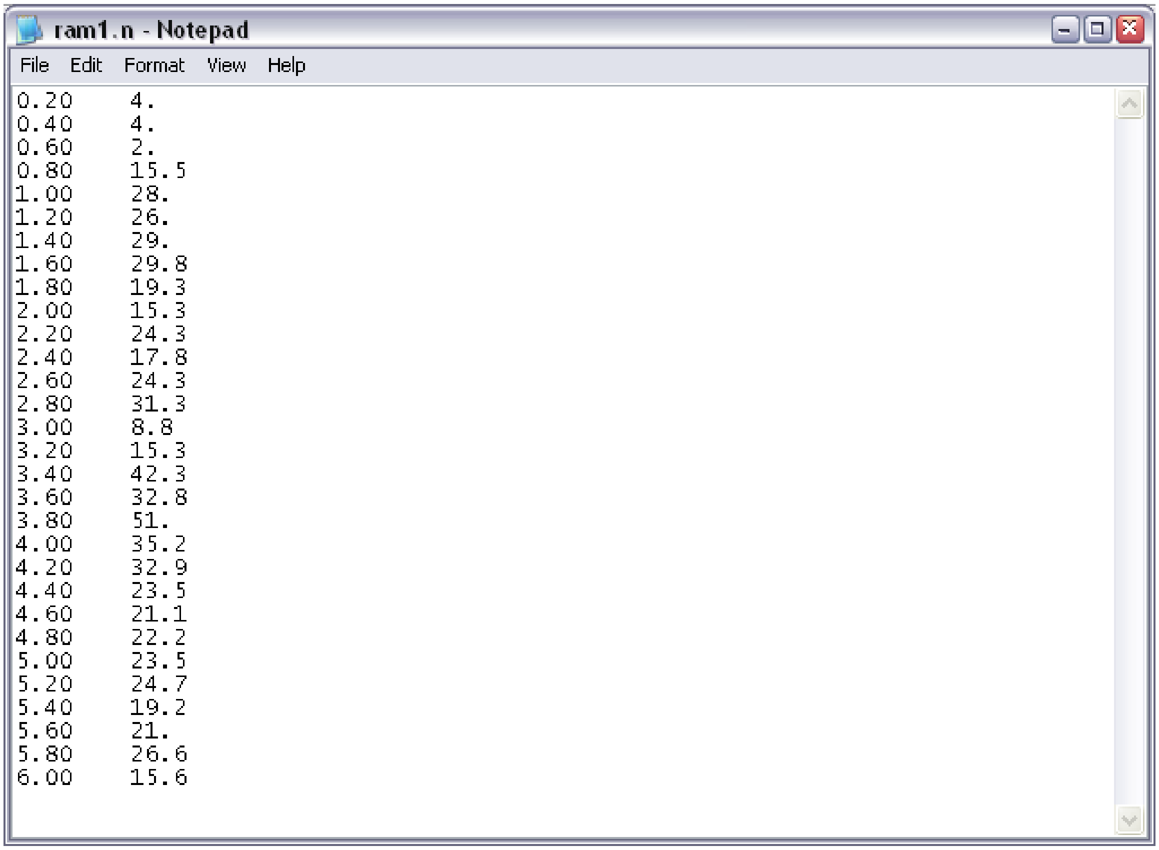


The V_p values and N-values are calculated based on the equations defined in the following menu. See Section 6.5.4 for a complete explanation.



6.3.6 Open N-Value File and Show N-Value File

Measured N-values can be used to define the initial V_s model used for inversion. The values need to be formatted in a space- or tab-delimited text file with a depth and corresponding N-value in each row as shown below. The file can have the extension .n or .txt.

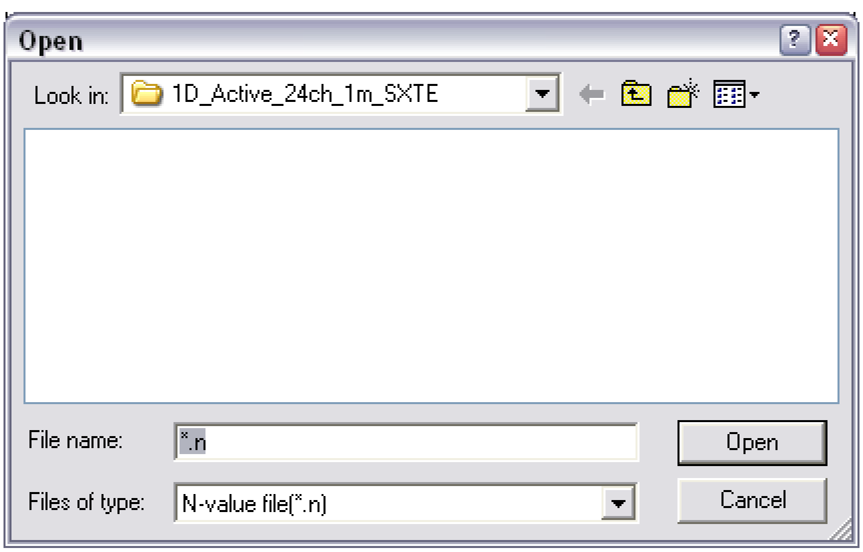


ram1.n - Notepad

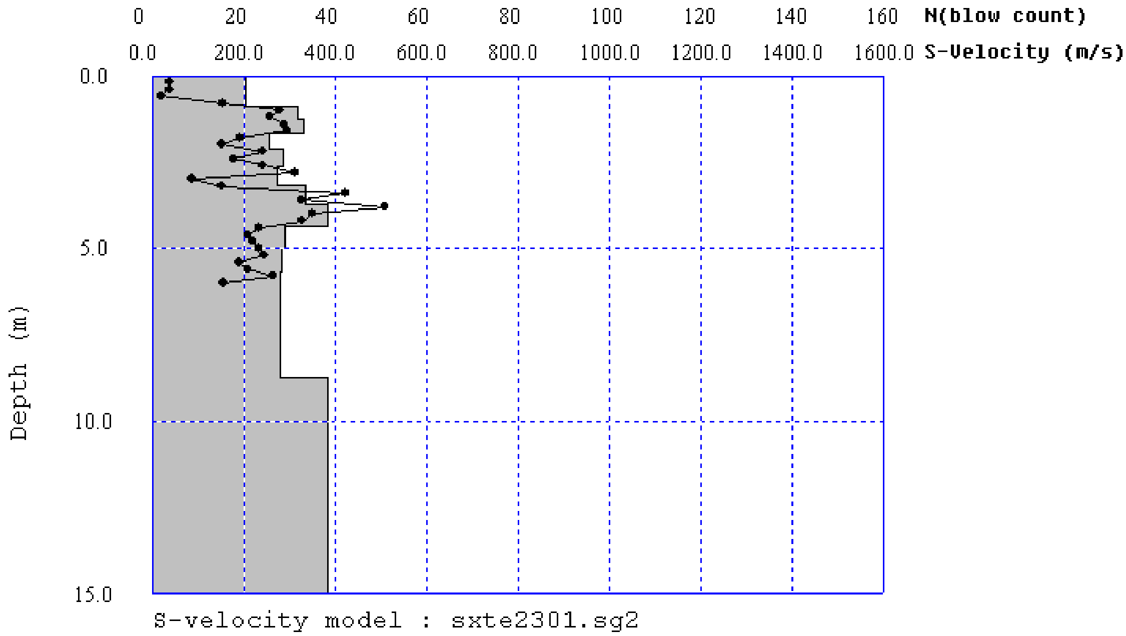
File Edit Format View Help

0.20	4.
0.40	4.
0.60	2.
0.80	15.5
1.00	28.
1.20	26.
1.40	29.
1.60	29.8
1.80	19.3
2.00	15.3
2.20	24.3
2.40	17.8
2.60	24.3
2.80	31.3
3.00	8.8
3.20	15.3
3.40	42.3
3.60	32.8
3.80	51.
4.00	35.2
4.20	32.9
4.40	23.5
4.60	21.1
4.80	22.2
5.00	23.5
5.20	24.7
5.40	19.2
5.60	21.
5.80	26.6
6.00	15.6

Once the file is prepared, select *Open N-value file* and highlight the file. If it has the extension .txt, you will need to choose *All files* under *Files of type* so it is shown in the list.



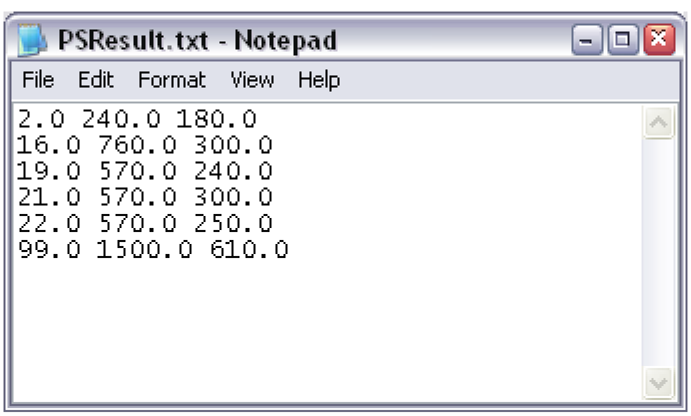
The N-values will now be stored in a buffer until the initial V_s model is created, at which time the initial model will be displayed with the N-values as shown below. When an N-value file has been opened, by default the initial model will be based on the N-values. Refer to Section 6.6.1 for more information.



To toggle between viewing the V_s profile with and without N-values, select *Show N-value*. When the values are showing this menu item is checked.

6.3.7 Open PS Result File and Show PS Result

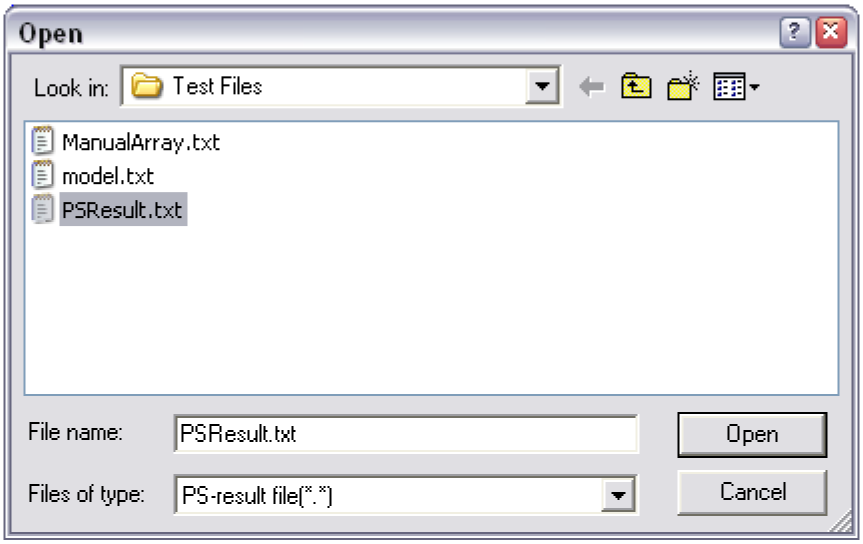
Once a velocity model exists (required), measured V_p and V_s values can be input for comparison or to refine the model. The values need to be formatted in a space- or tab-delimited text file with a depth and corresponding V_p and V_s value in each row as shown below. The file can have any extension.


PSResult.txt - Notepad

File Edit Format View Help

```
2.0 240.0 180.0
16.0 760.0 300.0
19.0 570.0 240.0
21.0 570.0 300.0
22.0 570.0 250.0
99.0 1500.0 610.0
```

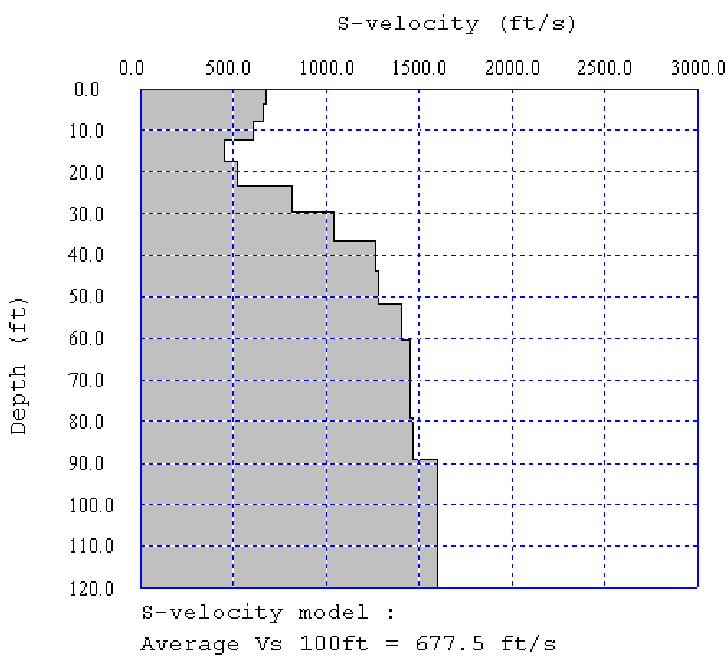
Once the file is prepared, select *Open PS result file* and highlight the file.



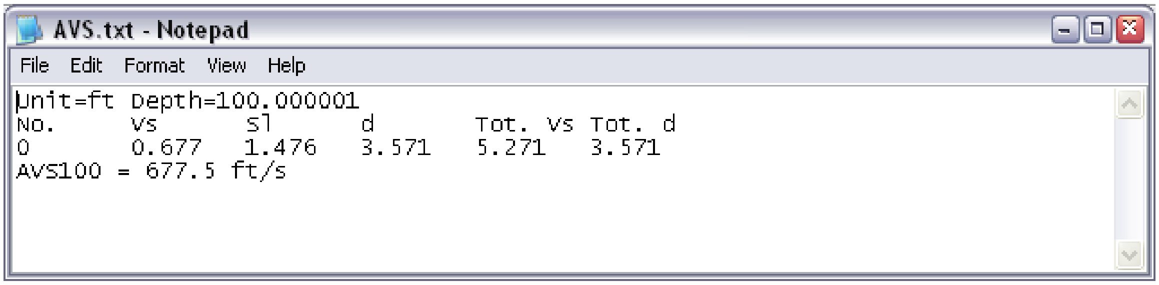
To toggle between viewing the model with and without the measured V_p and V_s data, select *Show PS result*. When the values are showing this menu item is checked.

6.3.8 Show AVS for IBC

The average V_s as defined by the 2000 and 2003 International Building Code (IBC) in Section 1615.1.5, Equations 16-22 and 16-44, respectively, can be calculated by selecting *Show AVS for IBC*. The calculated average V_s for the V_s profile will be shown at the bottom of the plot.

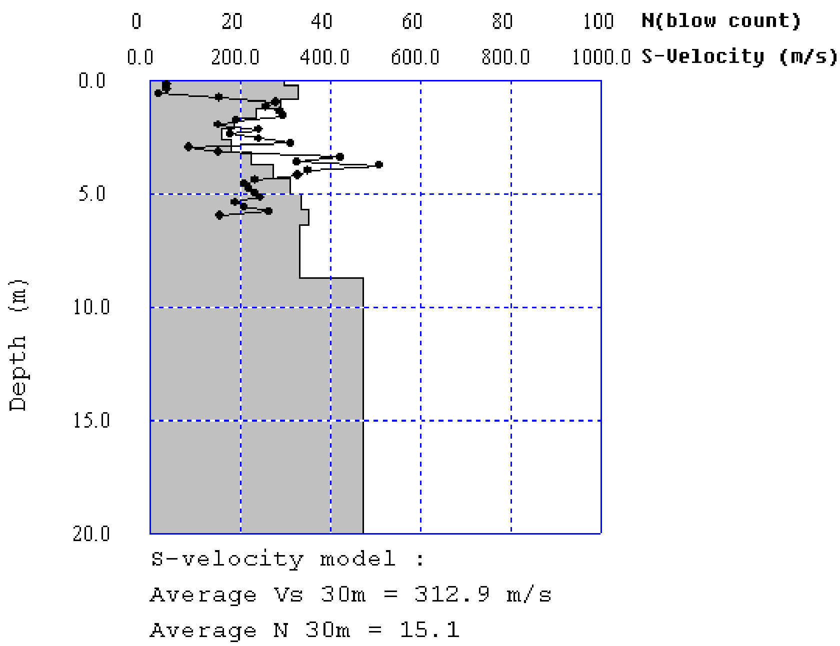


The result is saved to a text file with the name AVS.txt in the same directory where the subject profile is stored.




```
Unit=ft  Depth=100.000001
No.      Vs       Sl       d        Tot. Vs  Tot. d
0        0.677    1.476    3.571    5.271    3.571
AVS100 = 677.5 ft/s
```

The average N as defined by the 2000 and 2003 International Building Code (IBC) in Section 1615.1.5, Equations 16-23 and 16-45, respectively, will also be calculated if you have opened an N-value file.



The result is saved to a text file with the name AN.txt in the same directory where the subject profile is stored.

AN.txt - Notepad

File Edit Format View Help

No.	N	d	Tot. d	Tot. d/n
0	4.000	0.200	0.200	0.050
1	4.000	0.200	0.400	0.100
2	2.000	0.200	0.600	0.200
3	15.500	0.200	0.800	0.213
4	28.000	0.200	1.000	0.220
5	26.000	0.200	1.200	0.228
6	29.000	0.200	1.400	0.235
7	29.800	0.200	1.600	0.241
8	19.300	0.200	1.800	0.252
9	15.300	0.200	2.000	0.265
10	24.300	0.200	2.200	0.273
11	17.800	0.200	2.400	0.284
12	24.300	0.200	2.600	0.292
13	31.300	0.200	2.800	0.299
14	8.800	0.200	3.000	0.322
15	15.300	0.200	3.200	0.335
16	42.300	0.200	3.400	0.339
17	32.800	0.200	3.600	0.345
18	51.000	0.200	3.800	0.349
19	35.200	0.200	4.000	0.355
20	32.900	0.200	4.200	0.361
21	23.500	0.200	4.400	0.370
22	21.100	0.200	4.600	0.379
23	22.200	0.200	4.800	0.388
24	23.500	0.200	5.000	0.397
25	24.700	0.200	5.200	0.405
26	19.200	0.200	5.400	0.415
27	21.000	0.200	5.600	0.425
28	26.600	0.200	5.800	0.432
29	15.600	24.200	30.000	1.984

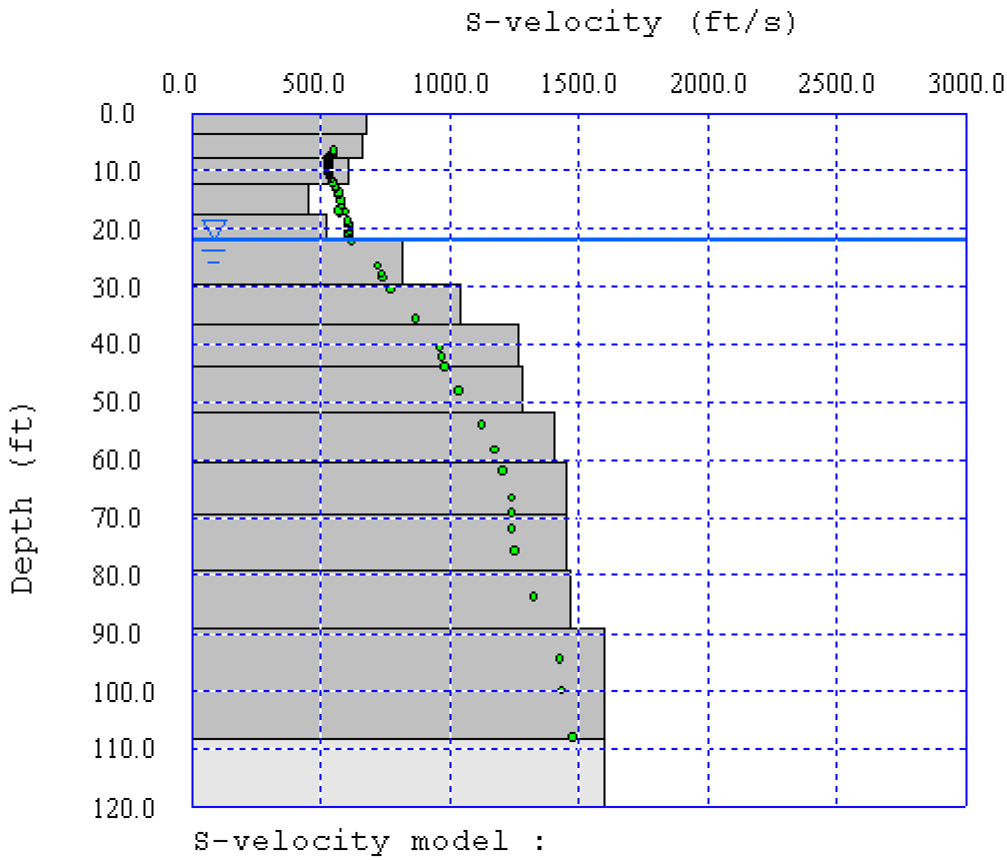
AN30 = 15.1

Note that the average calculations of V_s and N should only be done if you have reliable information to 30 m or 100 ft. Although the V_s profile may extend to 100 ft or 30 m, the recorded seismic waves may not have sampled to that depth. Refer to the following section on how to estimate the approximate depth of penetration.

6.3.9 Show Water Table Depth, Show Layer Boundary , Show Apparent Velocity Model (VR) , and Show Effective Depth (VR Max)

To show the depth of the water table on your profile, select *Show water table depth*. A blue line with standard water table symbol will appear as shown below. If there is no water table depth established, the line will plot at a depth of zero. The depth of the water table is set in a separate menu. Refer to Section 6.5.3 for details.

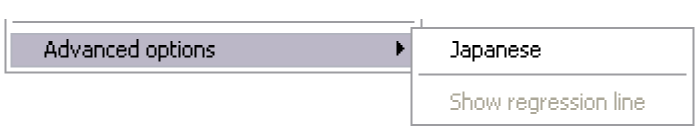
Selecting *Show layer boundary* or clicking the button will outline the layers in the profile with horizontal black lines as shown below.



Selecting *Show apparent velocity model (VR)* or clicking the  button will plot in green points the one-third wavelength V_s profile determined from the dispersion curve picks. Using each set of points (phase velocity, frequency), the wavelength is calculated (phase velocity divided by frequency) and then multiplied by one-third from the empirically determined estimate of depth of penetration. This is a good indicator of actual depth of penetration and limit of the V_s profile.

Show effective depth (VR max) shades the profile light gray from the deepest green point downward. This setting is on by default to call attention to the limit of the profile and to help prevent erroneous interpretation.

6.3.10 Advanced Options: Japanese, Show Regression Line

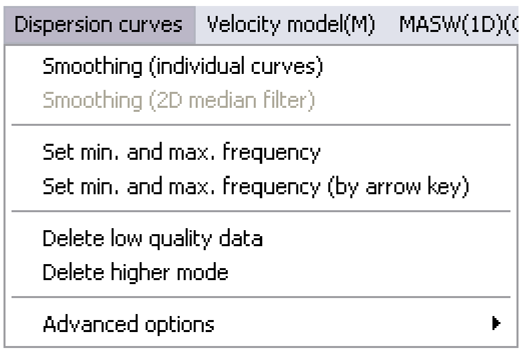


The *Advanced options* menu includes the option to convert the program from the English to Japanese language. If you select this, you will need to re-start the program to see the change take effect. Obviously, this is not recommended unless you want to use the software in Japanese.

Show regression line is not an active function for this version.

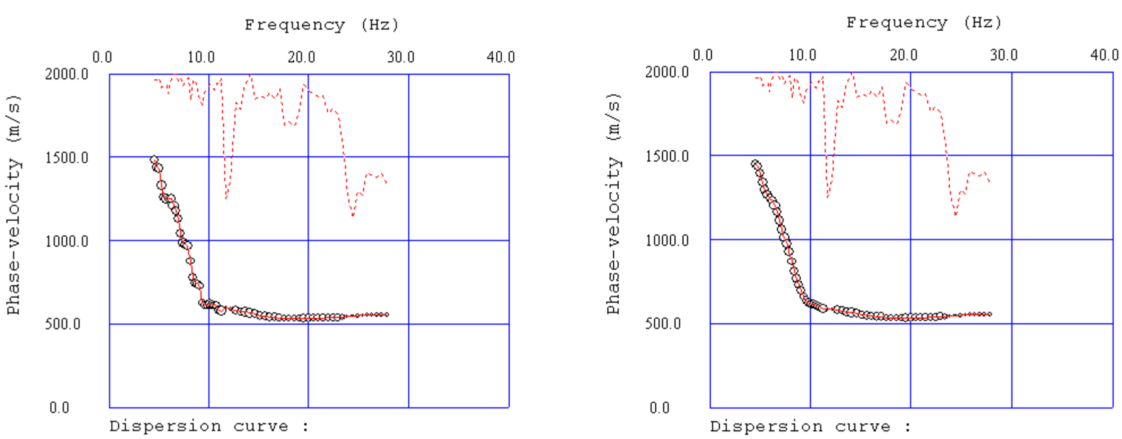
6.4 Dispersion Curves Menu

The *Dispersion curves* menu allows various editing of dispersion curves.



6.4.1 Smoothing (Individual Curves)

To smooth, or align the points along the overall trend of a dispersion curve, select *Smoothing (individual curves)*. You will see the original dispersion curve (left) be converted to a smoother curve (right). Smoothing maintains the trend of the original dispersion curve but evenly distributes the points and removes localized jitter that may cause unrealistic anomalies in the V_s profile.



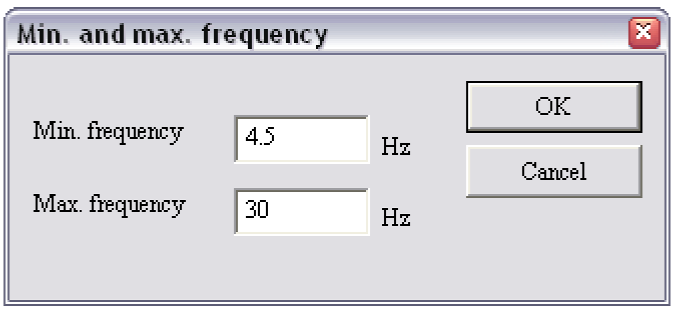
6.4.2 Smoothing (2D Median Filter)

Smoothing (2D Median Filter) is not active for the 1D analysis version.

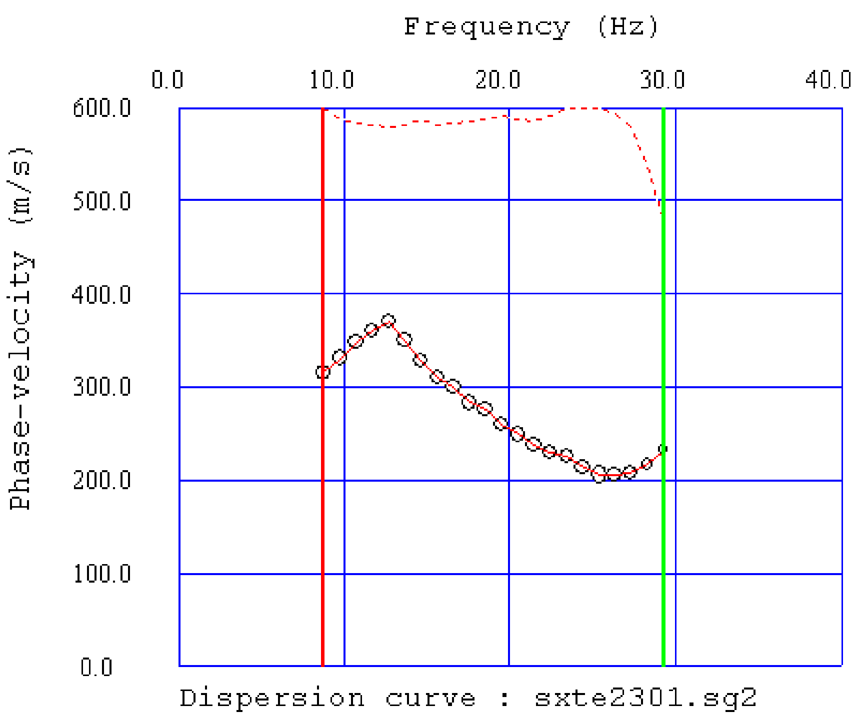
6.4.3 Set Min and Max Frequency and Set Min and Max Frequency (by Arrow Key)

Setting the minimum and maximum frequencies is the main step for editing the dispersion curve. This sets the range of points on the dispersion curve to retain, deleting the points that are less than the minimum and those that are greater than the maximum. You will find that in most cases trimming the ends of the dispersion curve will be the only editing needed. If you have already zeroed out unusable end picks in Pickwin, this step may not be necessary at all.

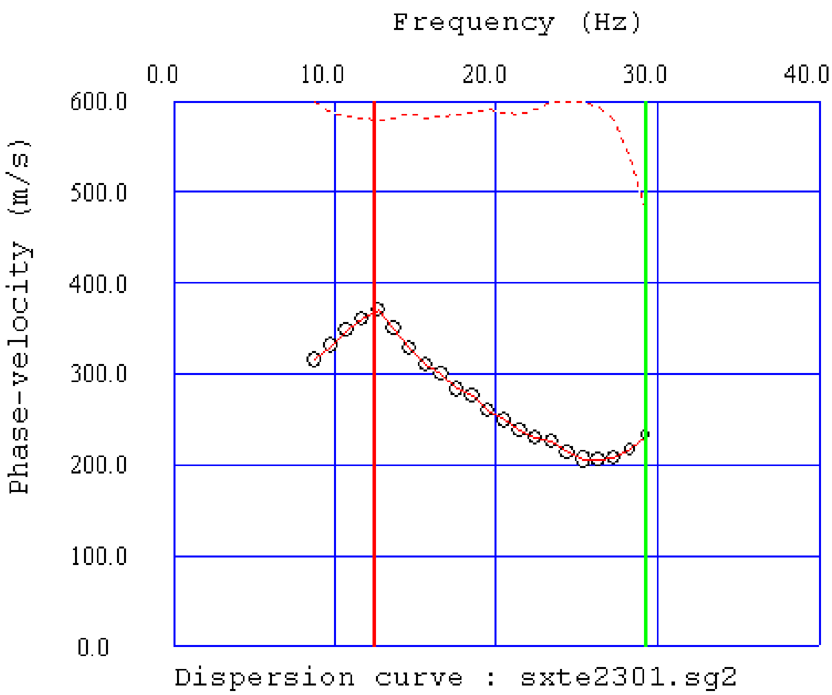
There are two ways to set the frequency range. Selecting *Set min and max frequency* presents the following dialog box. Simply enter the values and click *OK*.



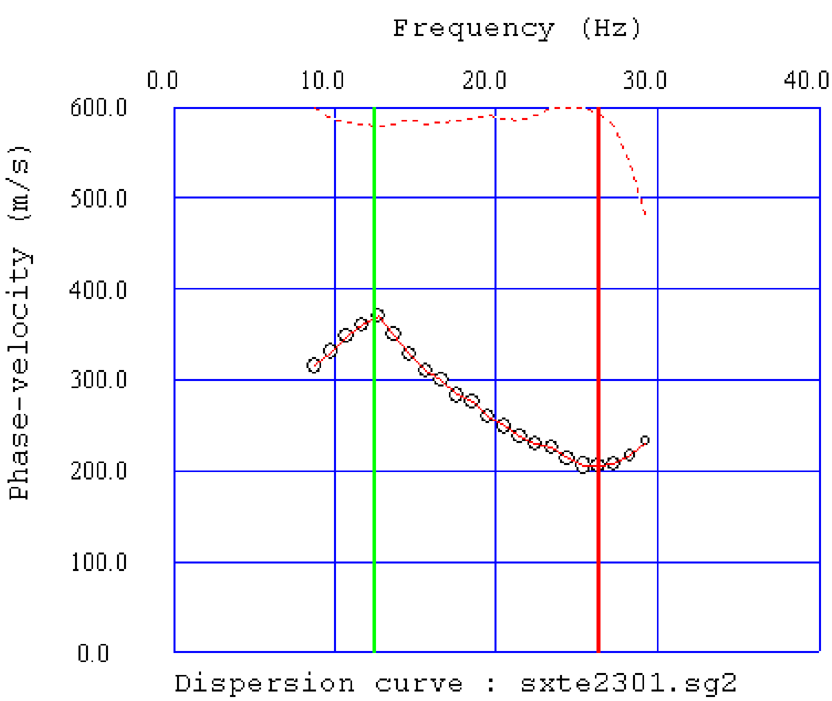
As an alternative, the frequency range can be set visually using gates. Select *Set min and max frequency (by arrow key)* and two gates will appear on the dispersion curve plot.



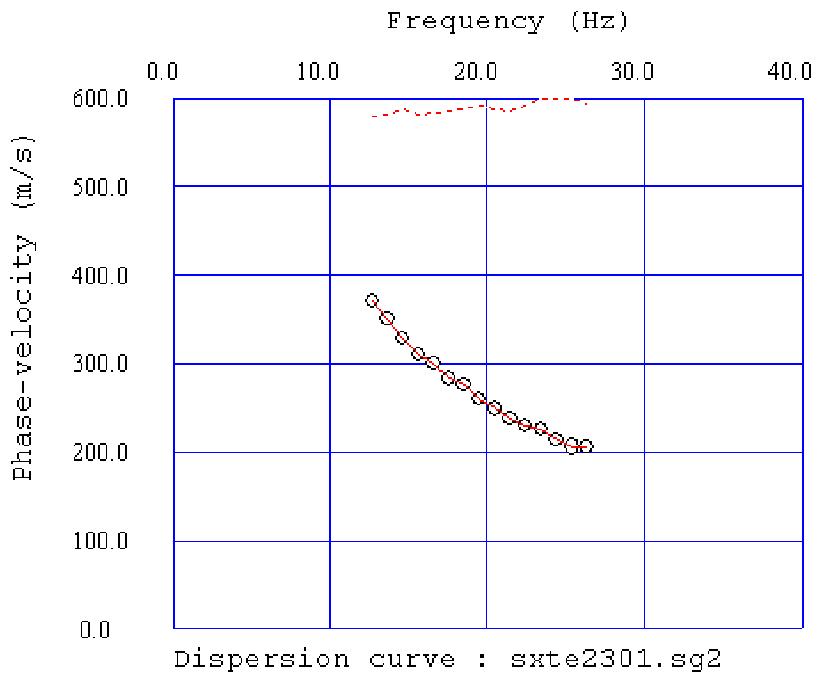
The red color indicates which is the active gate, where green indicates the inactive gate. Use the right arrow key to move the red gate to the new minimum frequency.



After the first gate is positioned, hit the *Enter* key and the next gate will become active. Use the left arrow key to move the gate to the new maximum frequency.



Hit the *Enter* key when done and the trimmed dispersion curve will be displayed.

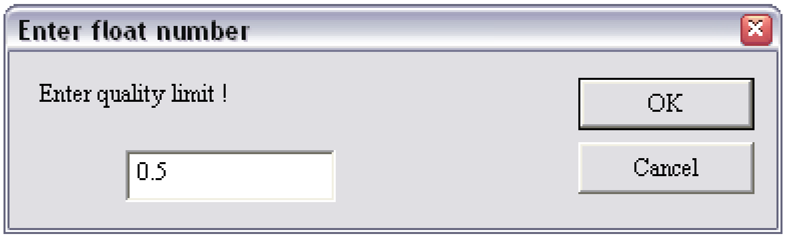


In setting the gates, exclude only the points that are poor-quality or spurious. Commonly, on the low-frequency end, the phase velocity will start to decrease and the dispersion curve will slope downward (when phase velocity is plotted on the y-axis). This decrease in phase velocity is usually an artifact of difficult picking because the peak amplitudes become less distinct.

To determine where to set the new maximum frequency on the high-frequency end, use the quality line to assess where the quality starts to decrease (usually due to weak amplitudes at higher frequencies). In addition to quality, if the phase velocity starts to increase that is likely related to higher mode energy and those points should also be deleted.

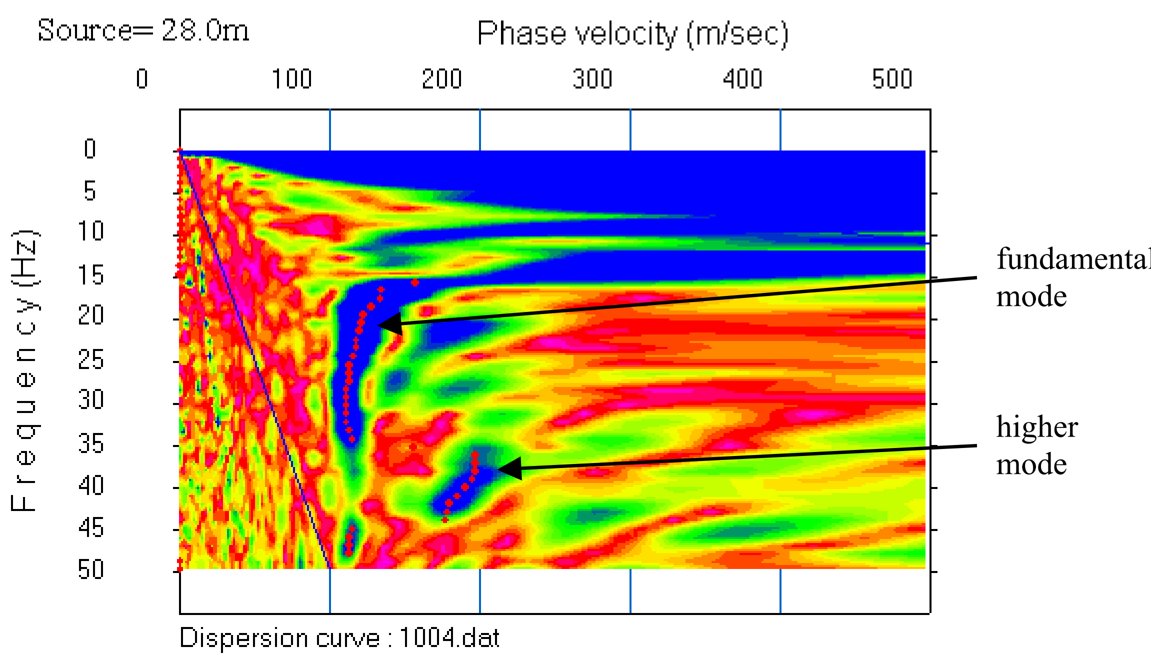
6.4.4 Delete Low Quality Data and Delete Higher Mode

The definition of low quality and low quality picks can be automatically deleted by selecting *Delete low quality data*. The following dialog box will appear.

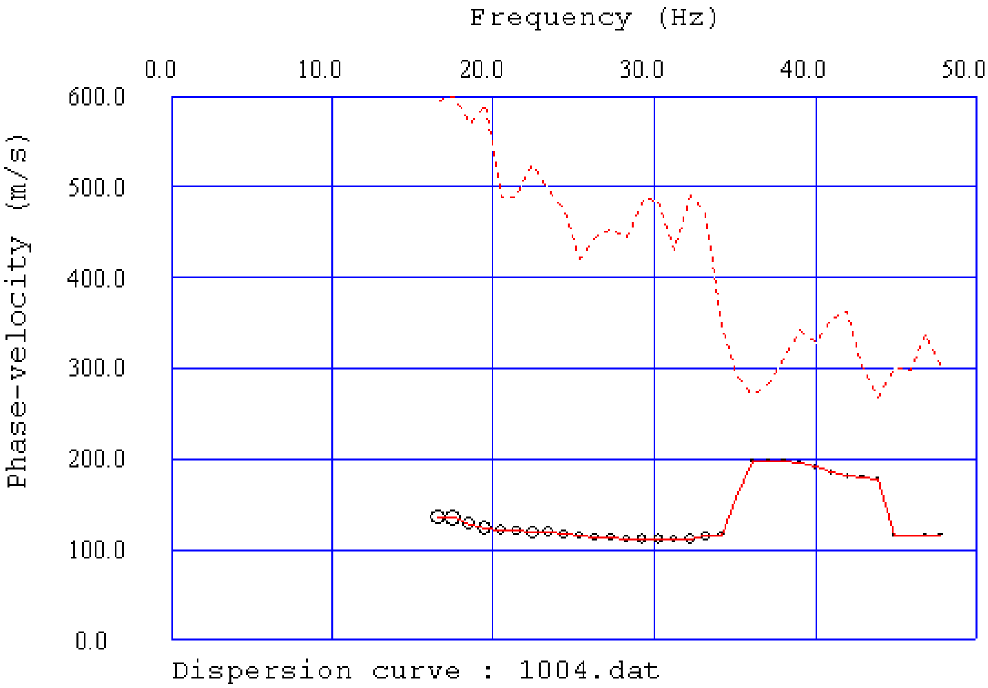


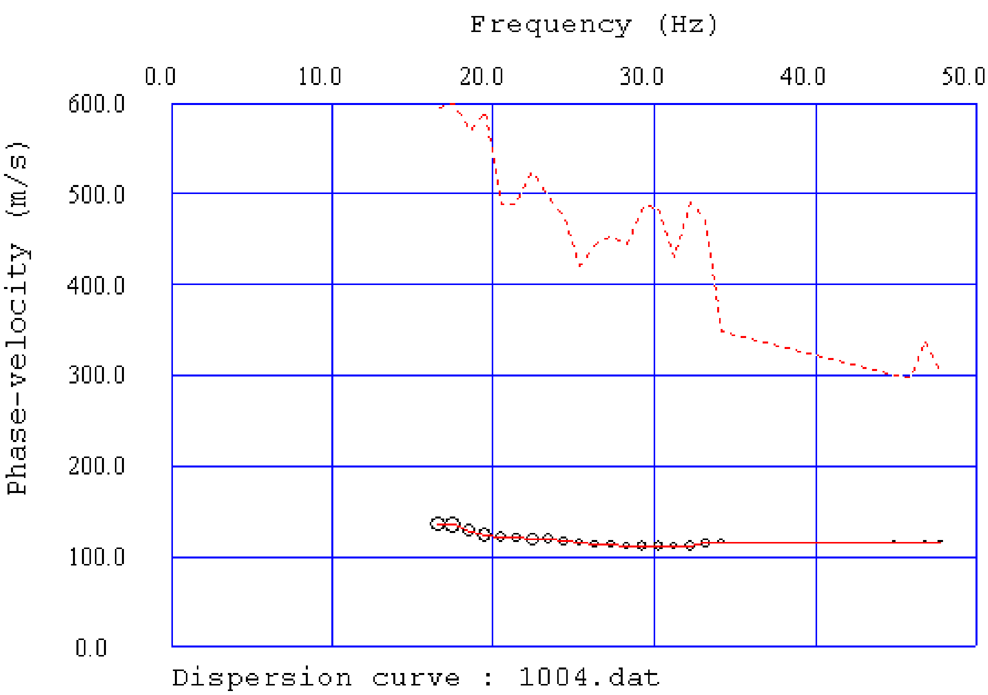
The largest circle possible on the dispersion curve plot is equal to 1.0 and the smallest circle possible is a dot, which is equal to zero. The default limit is 0.5, but you can enter your own value. When you click *OK* the points that fall below the quality limit will be deleted. If you want to reverse the changes, click on the *Undo*  button.

If higher mode picks are present on the dispersion curve (as shown in the Pickwin plot below), and you have not zeroed them out in Pickwin, the function *Delete higher mode* can be selected in WaveEq to automatically delete those picks.



Select *Delete higher mode*, and the higher mode points will be deleted.

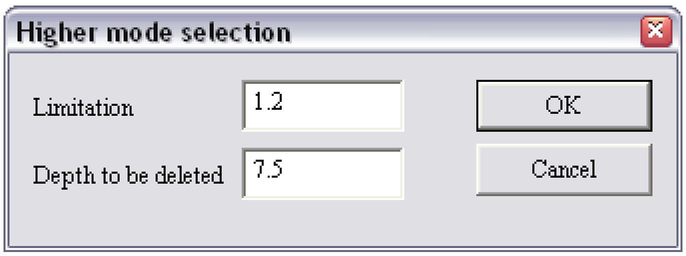

Frequency (Hz)
0.0
10.0
20.0
30.0
40.0
50.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
Phase-velocity (m/s)
Dispersion curve : 1004.dat


Frequency (Hz)
0.0
10.0
20.0
30.0
40.0
50.0
600.0
500.0
400.0
300.0
200.0
100.0
0.0
Phase-velocity (m/s)
Dispersion curve : 1004.dat

6.4.5 *Advanced Options: Smoothing (Multiple Curves), Resampling (Every Other), and Setup Higher Mode Selection*

The functions *Smoothing (multiple curves)* and *Resampling (every other)* are not active for the 1D analysis version.

Selecting the function *Setup higher mode selection* displays the following dialog box used for setting the criteria for higher-mode pick deletion via the *Delete higher mode* function.

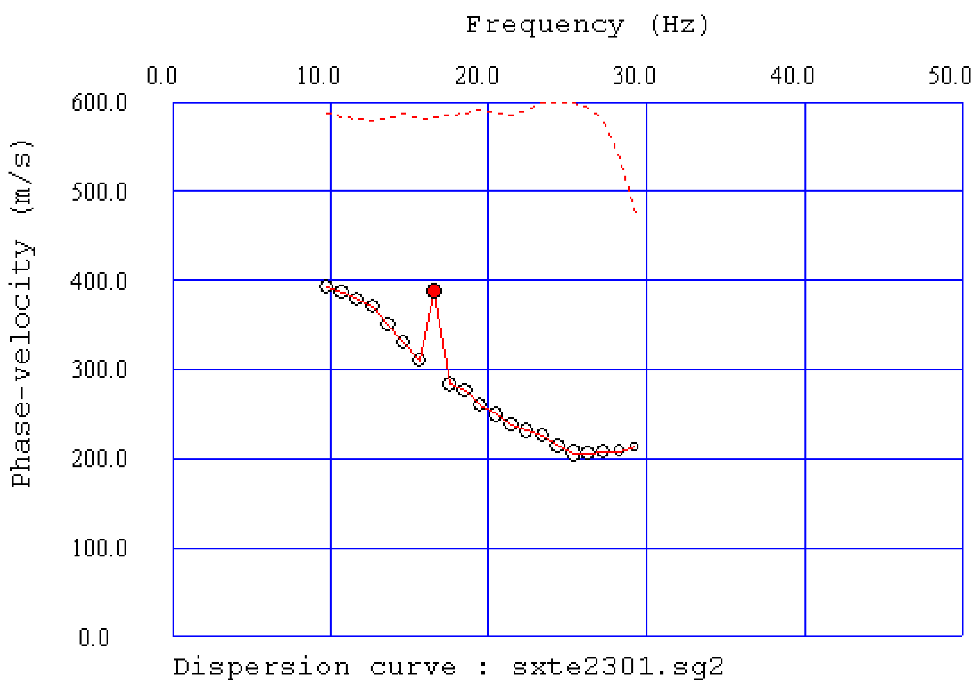


The *Limitation* default value is 1.2, but can be set between 1.0 and 5.0. The *Depth to be deleted* is the maximum depth determined by the one-third-wavelength calculation.

6.4.6 *Button Bar Editing Functions: Select Dispersion Curve*  *and Correct Dispersion Curve* 

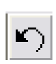
In addition to the aforementioned editing functions, the *Select dispersion curve*  button and the *Correct dispersion curve*  button can be used for point-based editing.

Click on the  button and click on any point on the dispersion curve that you wish to delete. The point will turn red to indicate it is selected. Click on just one or multiple points.



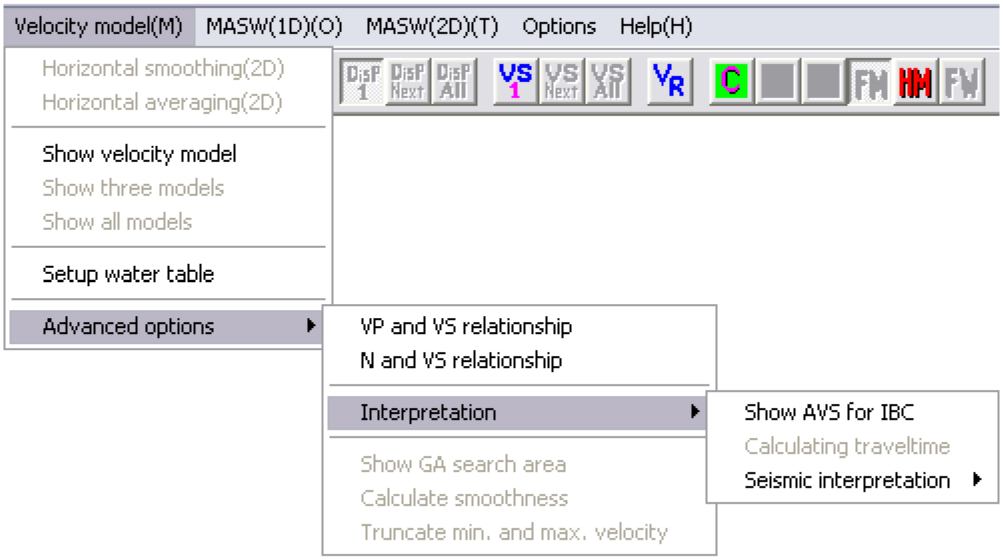
When done selecting points, hit the *Delete* key or select *Delete* under the *Edit* menu. If you change your mind and do not want to delete the selected points, hit the  button to deselect the points and exit editing mode.

To edit the dispersion curve by dragging points, click on the  button. Click and hold the mouse button on the point to adjust, it will turn red and then return to white at the new location when the mouse button is released.

The *Undo*  button can be clicked in between any deletion to reverse the effect.

6.5 Velocity Model Menu

The *Velocity model* menu allows you to set the parameters of how your velocity model is calculated.



6.5.1 Horizontal Smoothing (2D) and Horizontal Averaging (2D)

Horizontal smoothing (2D) and *Horizontal averaging (2D)* are not active for the 1D analysis version.

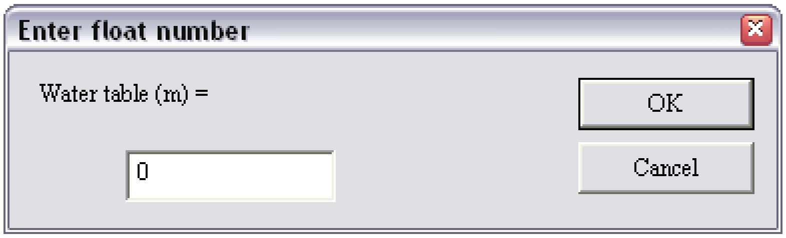
6.5.2 Show Velocity Model , Show Three Models, Show All Models

Once a velocity model exists, *Show velocity model* or  button, will display the model. The  button is useful for toggling between the dispersion curve and the velocity model displays.

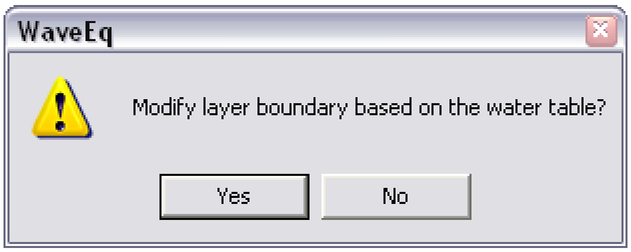
Show three models and *show all models* are used for 2D MASW and are not active for the 1D analysis version.

6.5.3 Setup Water Table

Once a velocity model exists, the depth of the water table can be set with *Setup water table*. When selected the following dialog box will appear. The default is zero; enter the value for your site. If you have water table measurements along the geophone spread, you could use the average value.



After clicking *OK*, you will be prompted to confirm the change.

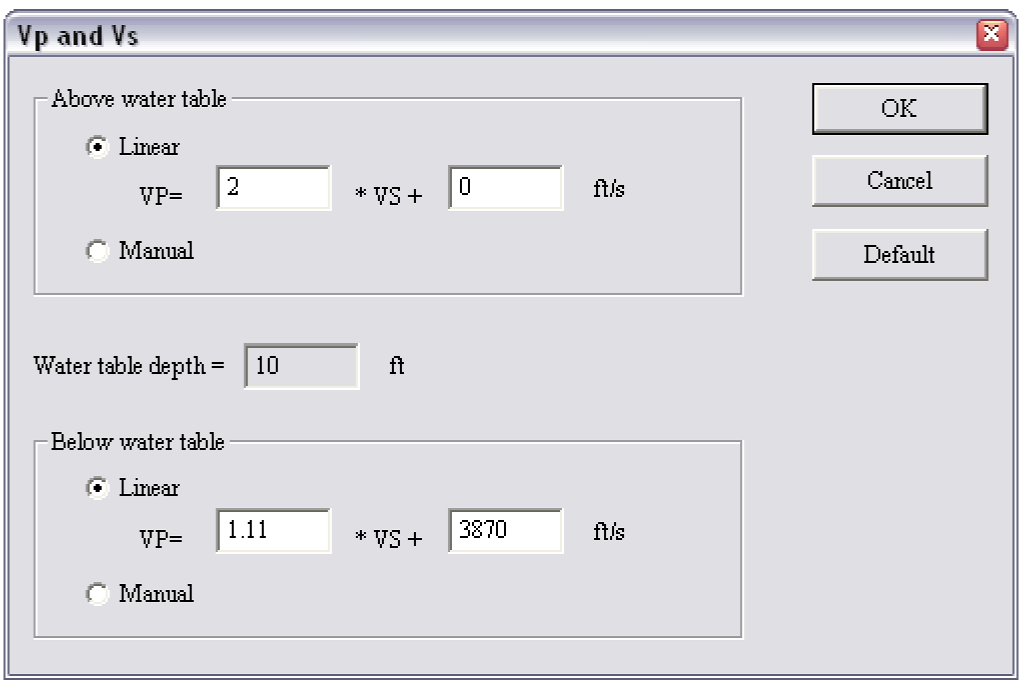


Now the depth of the water table is set. To show a blue line with standard water table symbol at the depth you indicated, you must also select *Show water table depth* under the *View* menu.

6.5.4 Advanced Options: V_p and V_s Relationship and N and V_s Relationship

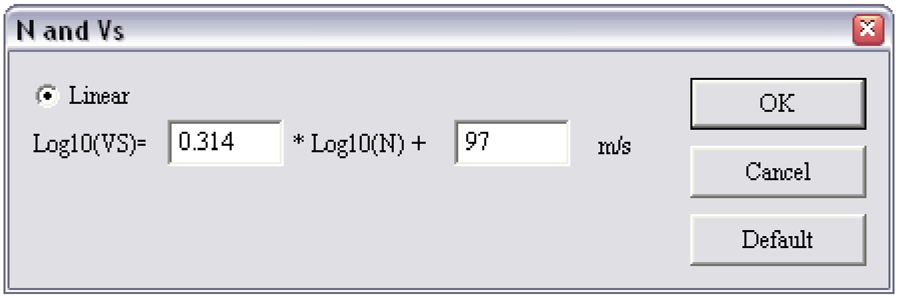
The *V_p and V_s relationship* and *N and V_s relationship* dialog boxes allow you to customize the equations used for calculating V_p from V_s and N from V_s.

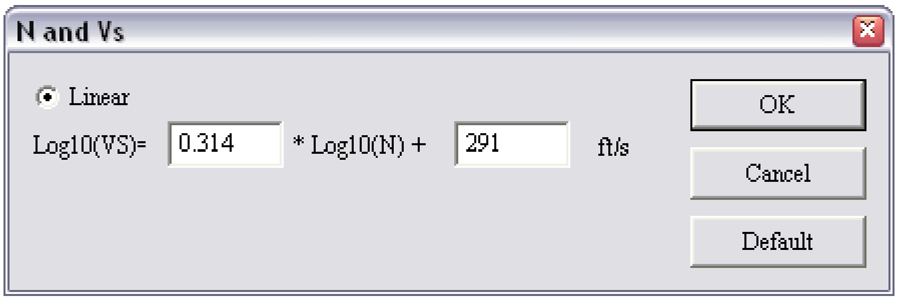
Upon selecting *V_p and V_s relationship*, the following dialog box will appear (if you are working in metric units, see next dialog box for English units). An equation may be defined for above and below the water table, with the water table depth set in the *Velocity model* menu, *Setup water table* dialog box. The default equation for above the water table is simply two times V_s. The default equation for below the water table is from Kitsunezaki (1990). The effect of V_p on phase velocity is minimal; these relationships work fine for most models.



Relationships can also be manually set by choosing *Manual* and inputting V_p values through the *View* menu, *Open PS result file*.

Upon selecting *N and V_s relationship*, the following dialog box will appear (if you are working in metric units, see next dialog box for English units). The default equations are from Imai and Tonouchi (1982). This relationship works fine for most models.





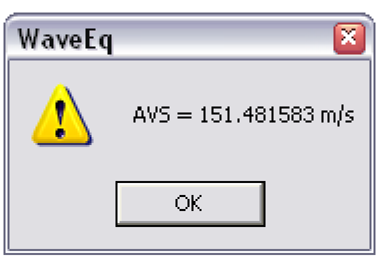
Where applicable, the equation for density is from Ludwig *et al.* (1970):

$$\rho = 1.2475 + 0.399V_p - 0.026V_p^2$$

If you make changes but want to revert to the default values, click on *Default*.

6.5.5 Advanced Options: Interpretation, Show AVS for IBC

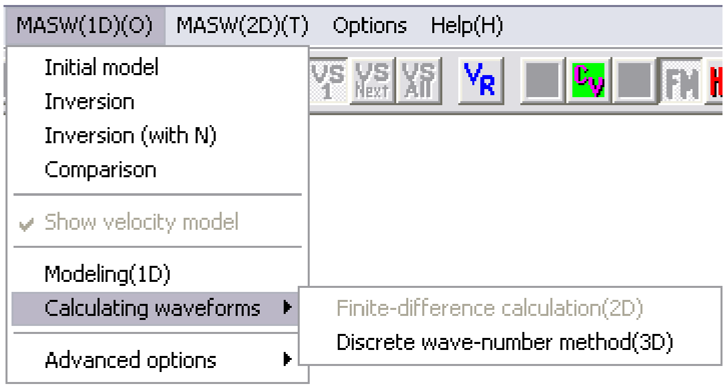
Show AVS for IBC calculates and displays the average V_s as defined by the 2000 and 2003 International Building Code (IBC) in Section 1615.1.5, Equations 16-22 and 16-44, respectively.



This is one of two ways the average V_s can be calculated. Selecting the *Show AVS for IBC* function in the *View* menu calculates and displays the average V_s at the bottom of the velocity model.

6.6 MASW (1D) Menu

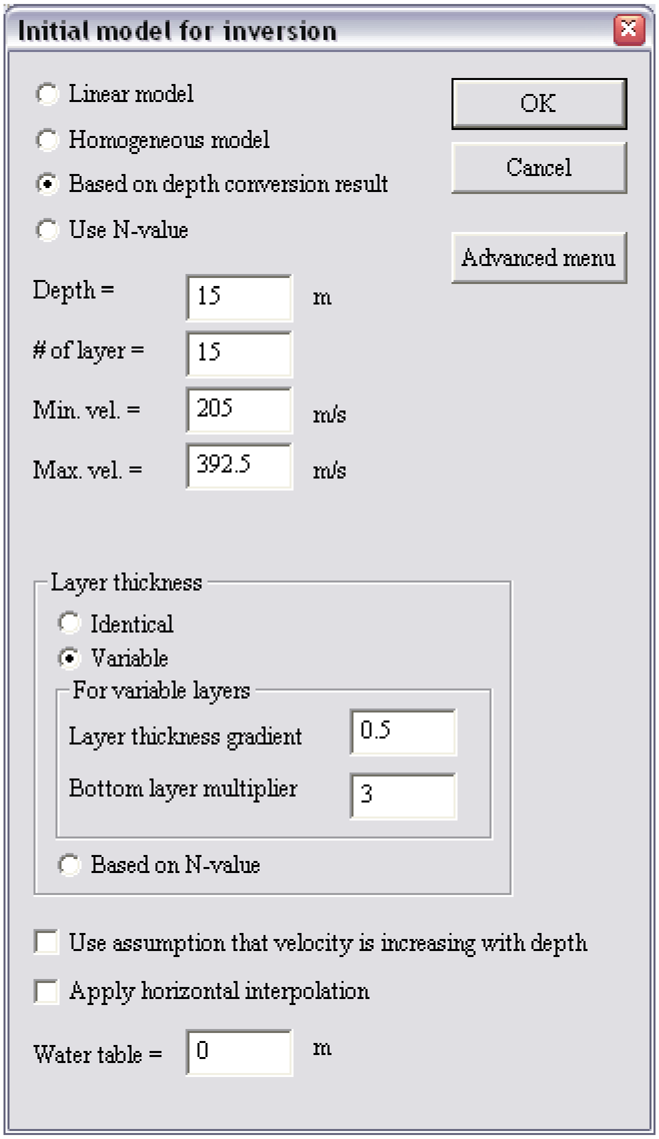
The *MASW (1D)* menu mainly includes the functions for calculating an initial model and running the inversion or back-calculation, to find the best fit of the initial model with the observed data. Other modeling functions are also included. Although MASW refers to active source surveys, the same functions are used for analysis of MAM data.



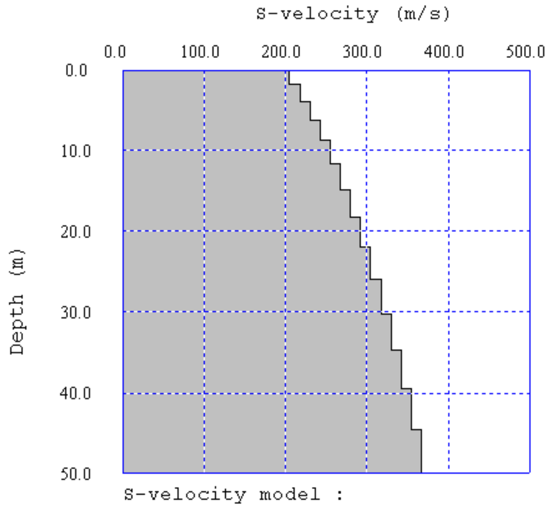
6.6.1 Initial Model

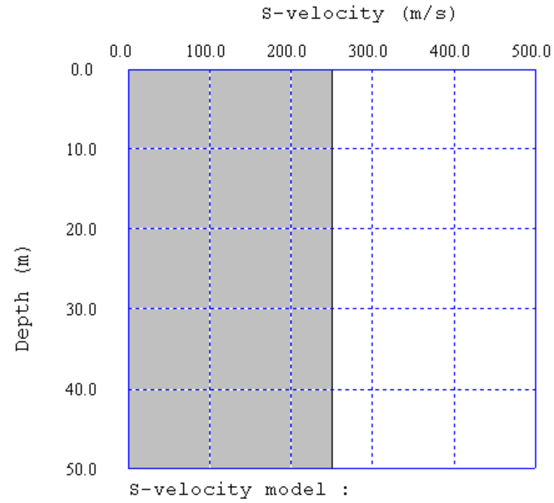
The initial model of V_s with depth is the starting point for the inversion. All of the initial model parameters except *Depth* and *Number of layers* are not visible by default. Expose all of the parameters by clicking on the *Advanced menu* button. Also note that the basic and advanced menu parameters are always reset to the defaults in between closing and re-opening an instance of WaveEq.

The default is for the model to be *Based on depth conversion result* as shown below, which is the one-third-wavelength approximation of depth for each associated phase velocity. The *Minimum* and *Maximum* (phase) *velocities* are automatically assigned corresponding directly to the low and high values observed on the dispersion curve. The *Maximum velocity* is automatically assigned to the deepest layer.

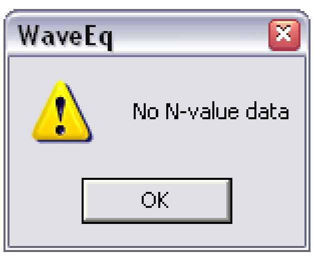


Alternatives are *Linear model*, *Homogeneous model*, and *Use N-value*. A *Linear model* (left example below) is constructed following a straight line starting at the *Minimum velocity* and ending at approximately the *Maximum velocity* (the model may not extend to exactly the *Maximum velocity* depending on the number and configuration of the layers). A *Homogeneous model* (right example below) has no velocity variation with depth; the *Minimum* and *Maximum velocity* are entered as the same value.





To base the initial model on N-values, select *Use N-value*. The model *Depth* will be automatically set to the deepest N-value. Note that the N-value file must already be open through the *View* menu, *Open N-value* file. If it has not already been opened, you will be prompted as shown below.



Layer thickness applies to all models. The layer thickness automatically increases with depth; to override and set all layers to equal thickness select *Identical*. For *Variable*, the gradient controls how the layer thickness increases with depth. A value of 1 means there is no gradient and the layer thickness is identical. A smaller number equals a steeper gradient. The default value of 0.5 is usually fine for most models.

The *Bottom layer multiplier* controls the thickness of the bottom layer relative to overlying layers. The thickness of the bottom layer or layer just above the model half-space, can have a large impact on the dispersion curve. Setting it thicker than the overlying layers stabilizes the inversion. After the *Layer thickness gradient* is applied, the thickness of the bottom layer will be multiplied by the multiplier value. The multiplier value default is 3 and is usually fine for most models.

To set layer thickness based on N-values select *Based on N-value*.

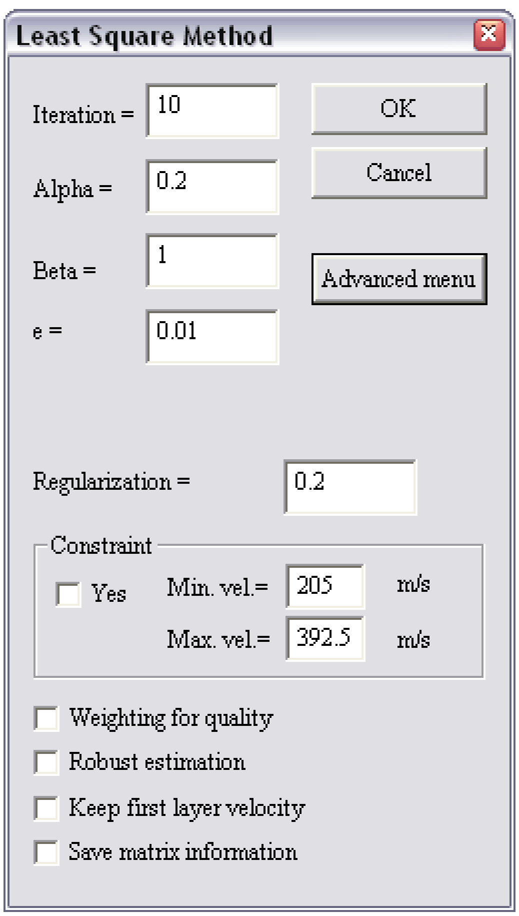
To disallow velocity inversions in the resultant V_s profile, check *Use assumption that velocity is increasing with depth*. It is common to see small V_s inversions near the surface (especially at paved sites) and at the water table due to a pore pressure increase, and thus, you probably want to leave this setting unchecked. This setting can be useful when you detect higher modes and want to suppress their influence on the final result.

Apply horizontal interpolation does not apply to 1D analysis and is not active for the 1D analysis version.

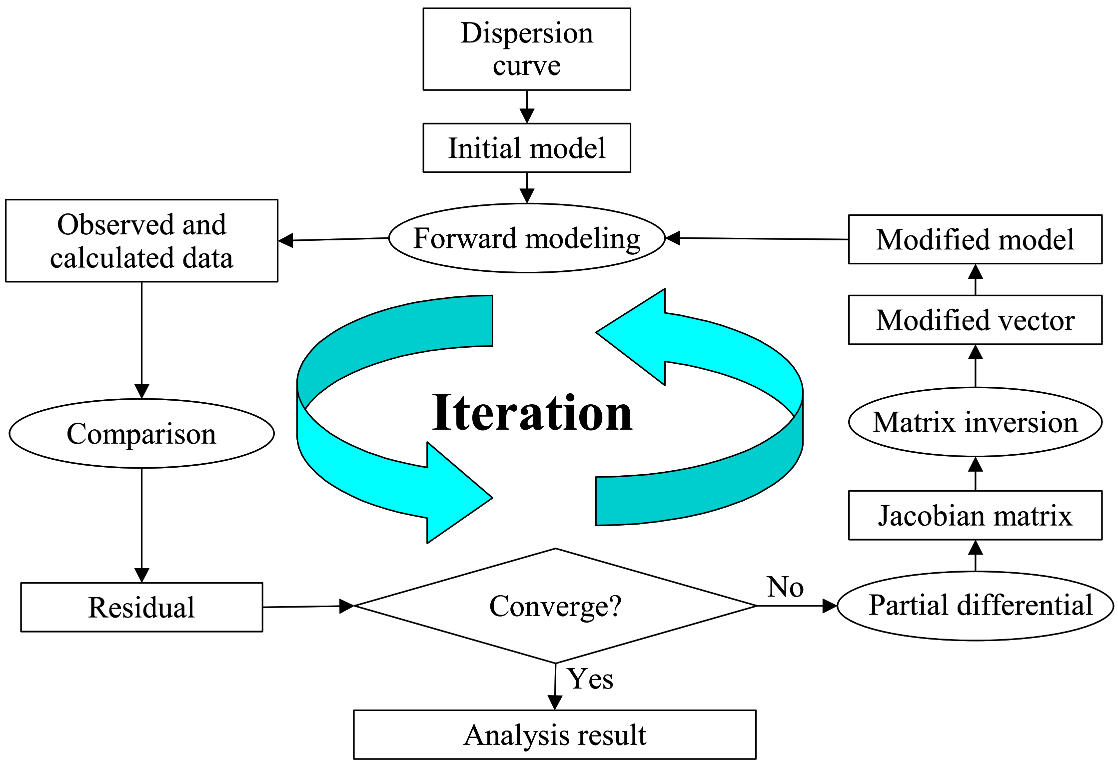
6.6.2 Inversion and Inversion with N

6.6.2.1 Inversion

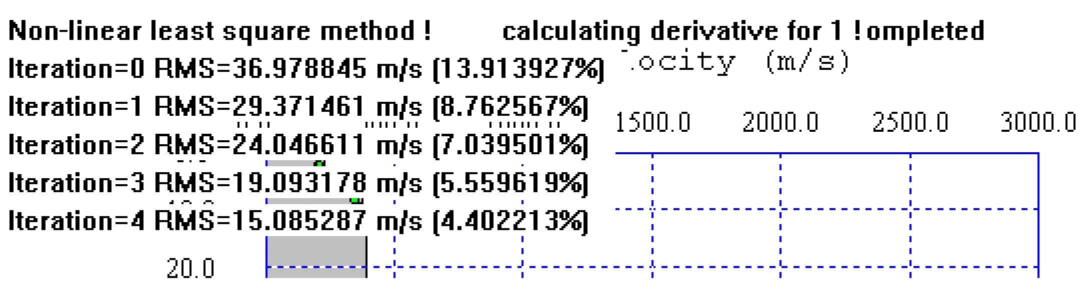
Inversion is selected to calculate the V_s profile that best matches the observed data through iterative modification of the initial model. In the *Inversion* dialog box, all of the parameters except *Iteration* are hidden by default. All of the parameters can be exposed by clicking on the *Advanced menu* button. Also note that the basic and advanced menu parameters are always reset to the defaults in between closing and re-opening an instance of WaveEq.



Iteration is the number of times the software will run the calculation and iteratively seek the best match between the initial V_s model and the observed data. Before the next iteration the improved model is used as the new starting point so the error or mismatch should decrease. The iteration concept is conveyed in the following flowchart.



After setting *Iteration* to the desired value, and no other changes are made, the process will run and the error in velocity (m/s or ft/s) and percent (%) will be displayed as shown below. The error should decrease with each iteration.



When complete, the final error value is saved to a file called RMSE.txt.

If the error increases, the inversion process will be interrupted and terminated. The initial model settings, inversion parameters, and units in the *Option* menu should be checked and corrected if necessary before running the process again.

The *Alpha* and *Beta* settings optimize the non-linear least square matrix inversion through deceleration and acceleration, respectively. An *Alpha* multiplier of the maximum logical value of 1 provides the least stabilization. Values less than 1 provide increasing stability but are more computationally intensive, and thus, cause the process to run more slowly. A value of zero cancels the *Alpha* correction factor.

Alpha is used in the first iteration because the matrix is least stable in the beginning. As the process stabilizes, *Alpha* is multiplied by *Beta* to increase the inversion speed. A *Beta* value of 1 causes no acceleration; values greater than 1 are used for acceleration.

E is a dumping parameter also with the effect of stabilization. *E* would be increased to increase stability.

Regularization is a type of matrix smoothing, working to control wild differences in V_s in between layers. The higher the *Regularization* value, the higher will be the degree of smoothing. All of the layers would be artificially similar if an extremely large value was used and a value of zero would apply no smoothing.

Alpha, Beta, *e*, and *Regularization* rarely need to be changed and the default values are recommended. Illogical values for these parameters will cause erroneous and unrealistic results.

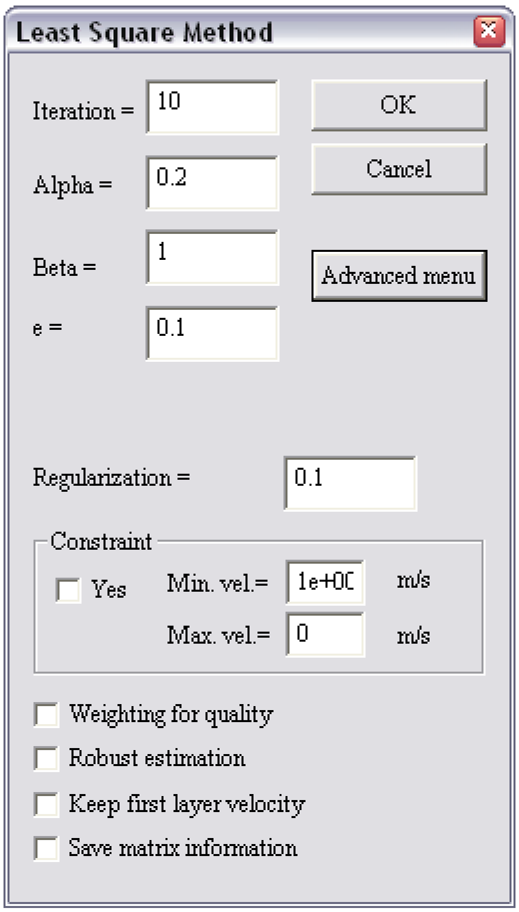
Saying *Yes* to *Contraint* will use the indicated *Minimum* and *Maximum* (phase) *velocities* to limit the lower and upper bounds of the inversion. This can be useful if you have accurate knowledge of velocity, otherwise the defaults are automatically assigned corresponding directly to the low and high values observed on the dispersion curve. .

Weighting for quality incorporates dispersion curve pick quality into the inversion. *Robust estimation* puts less weight on data with large error. *Keep first layer velocity* prevents the velocity of the shallowest layer from changing. This is useful if the first layer has a high known velocity, like pavement.

If *Save matrix information* is checked, the Jacobian matrix from each iteration is saved to a file called Matrix.txt in the data folder.

6.6.2.2 Inversion with N

Inversion with N is an option when an N-value file has been opened and the initial model has been set-up using N-values. The parameters and defaults in the *Inversion with N* dialog box are the same as in the in the *Inversion* dialog box, except for the *Minimum* and *Maximum velocities* under *Constraint*. If you have accurate knowledge of velocity, you may want to enable *Constraint* and set velocity limits, otherwise no velocity constraint is applied.



6.6.3 Comparison 

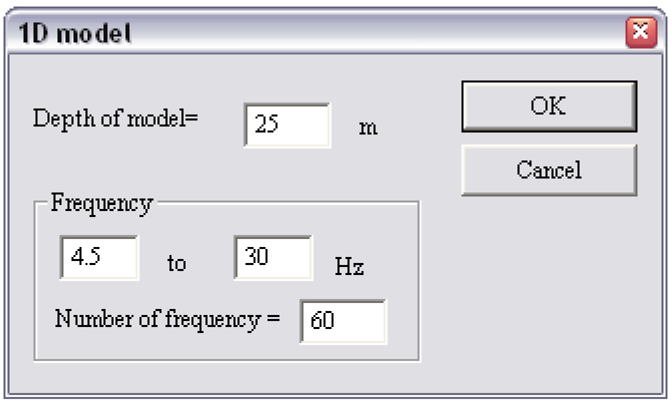
Comparison or the  button allows the calculated dispersion curve to be overlaid on the observed dispersion curve. The calculated curve is shown as a black line as seen below. To remove the calculated dispersion curve, select *MASW(1D)* menu, *Comparison* or click the button again.

6.6.4 Show Velocity Model

To toggle to the velocity model display from the dispersion curve display, select *Show velocity model* or click the button.

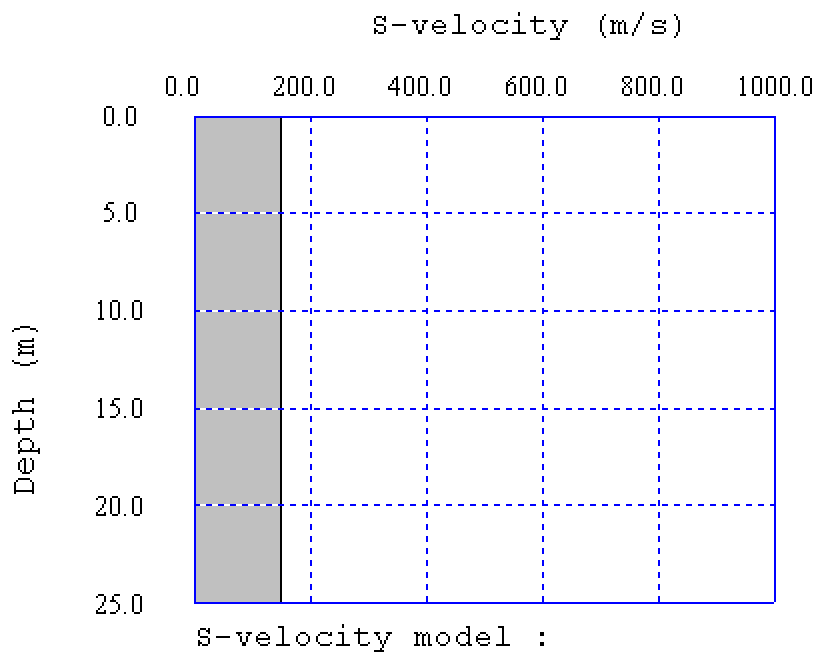
6.6.5 Modeling (1D) or Creating a New Velocity Model

Velocity models can easily be created independent of waveform data acquired in the field. Modeling can be useful for planning a survey, modeling borehole data, or testing and comparing various results. Selecting *Modeling (1D)* or the *Creating a new velocity model* button, presents the following dialog box.

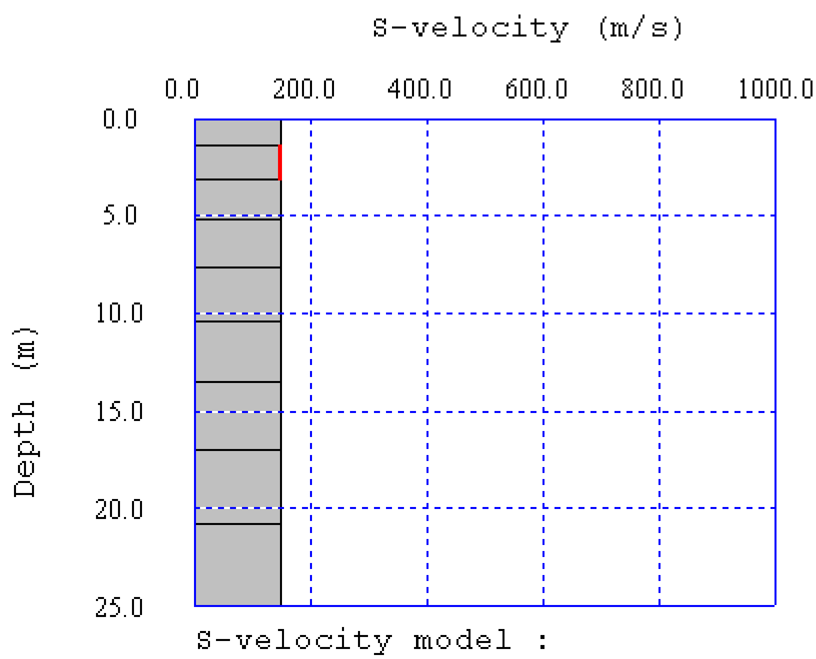


Enter the desired *Depth of model*. The default *Frequency* range is suitable to simulate depth of penetration from an active source. If the *Depth of model* is greater than 30 m or 100 ft, correspondingly, the lower end frequency should be set to 2 Hz to simulate a greater depth of penetration.

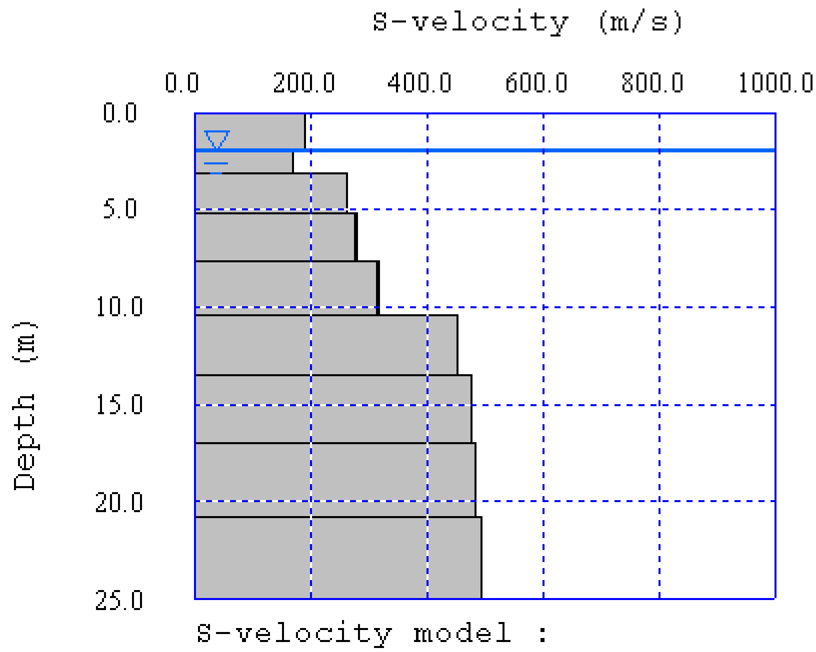
The frequency range is divided by the *Number of frequency* and sets the resolution of the upcoming dispersion curve. The *Number of frequency* default of 60 is fine for this frequency range. If the frequency range is widened significantly, the *Number of frequency* should also be scaled up accordingly. Upon clicking *OK*, the following homogeneous model will appear. An associated dispersion curve will not yet exist.



To modify the velocity model, click on the *Correct velocity model* button. Horizontal lines defining the model layers will appear. Use the mouse to click on the vertical edge of a layer and the selected layer edge will turn red. Drag the edge to the desired velocity.



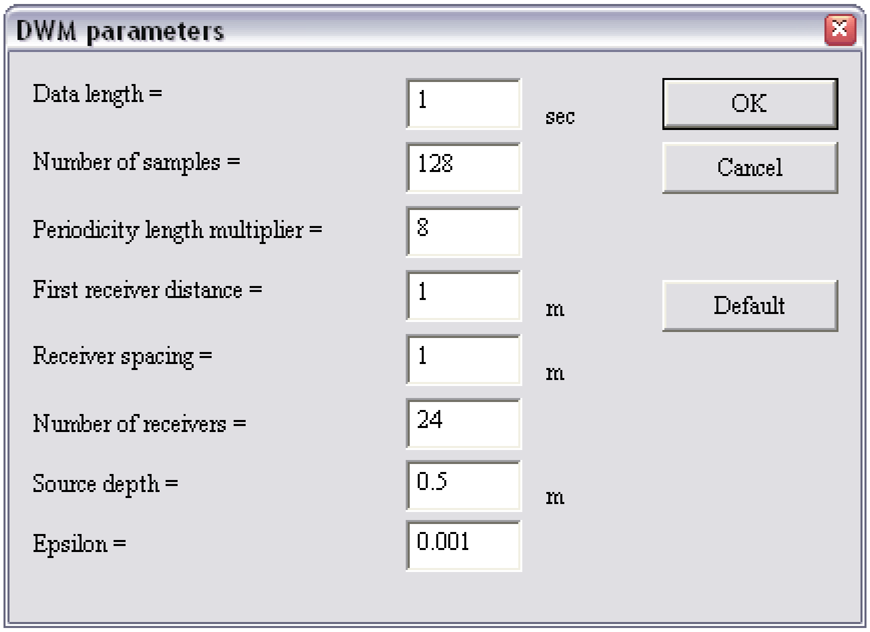
Position the rest of the layers and set the water table, if applicable or desired.



Refer to Section 6.6.6 for instructions on how to continue modeling by simulating a survey.

6.6.6 Calculating Waveforms, Discrete Wave-number Method (3D)

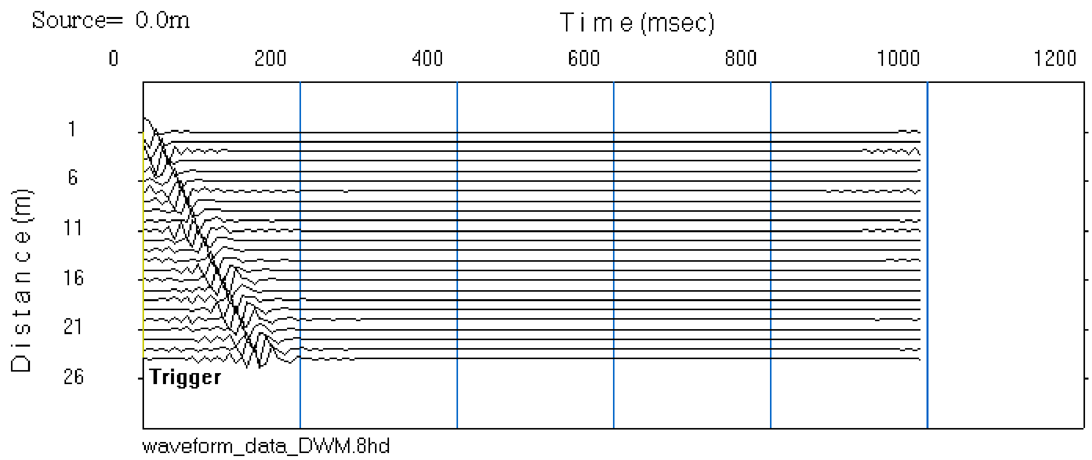
Once a model is created as shown above, to calculate the dispersion curve, first a time-domain waveform file must be generated. Only active source waveform files are simulated; passive source waveform files are not generated. Select the function *Calculating waveforms*, *Discrete wave-number method (3D)* and the following dialog box will appear. *DWM parameters* determine how the time-domain record will be calculated.



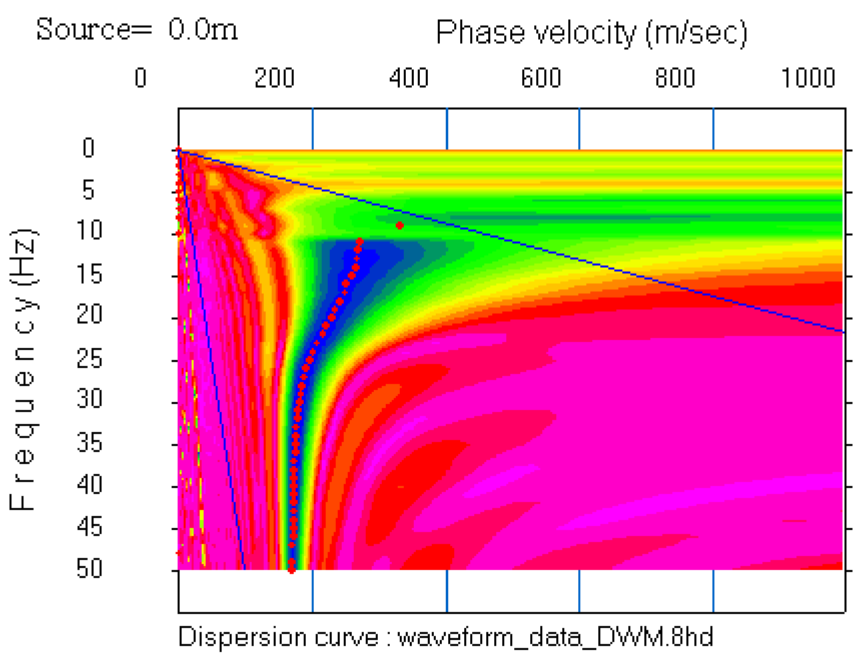
The *Data length* is the record length in time. *Number of samples* relates to the sample interval used in field acquisition; 1 second divided by 128 samples equals a sample interval of 7.8 milliseconds. Although this is much larger than what is commonly used in the field for a 1D MASW survey, a value of 128 is sufficient and makes the calculation less CPU-intensive.

The *Periodicity length multiplier* defines the size of the calculation and the default is fine for most cases. *First receiver distance* is the near offset, the *Receiver spacing* is simply the geophone interval, and the *Number of receivers* is the number of channels. To set values similar to what would be used in the field for a 1D MASW survey, refer to Section 3 for guidelines. The *Source depth* is the depth below surface of the source; for a surface source enter zero. *Epsilon* controls the accuracy of the calculation and the default is fine for most cases.

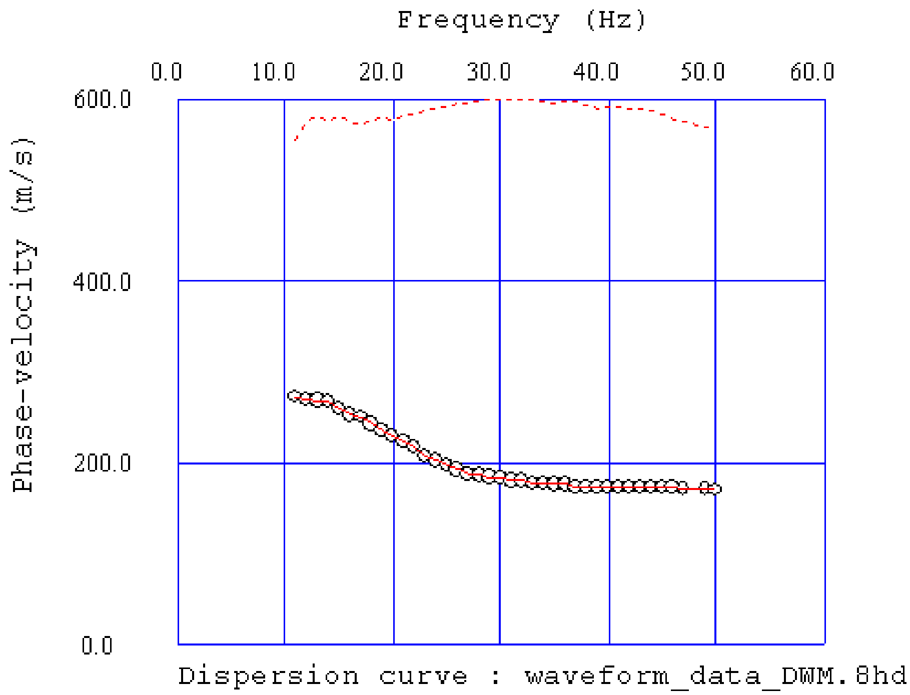
After clicking *OK*, WaveEq will calculate the corresponding waveform file and automatically launch Pickwin to display the result. The waveform file is automatically saved to the current directory with the extension .8hd. Note that the function to re-open .8hd files is not currently activated in Pickwin, but this will be corrected in a future release. As a work-around, complete your waveform analysis before closing Pickwin or re-run *Calculating waveforms*, *Discrete wave-number method (3D)* again with the same parameters.



At this stage, analysis proceeds from Pickwin as if the calculated waveform file was a field record. Proceed to calculate the phase velocity plot.

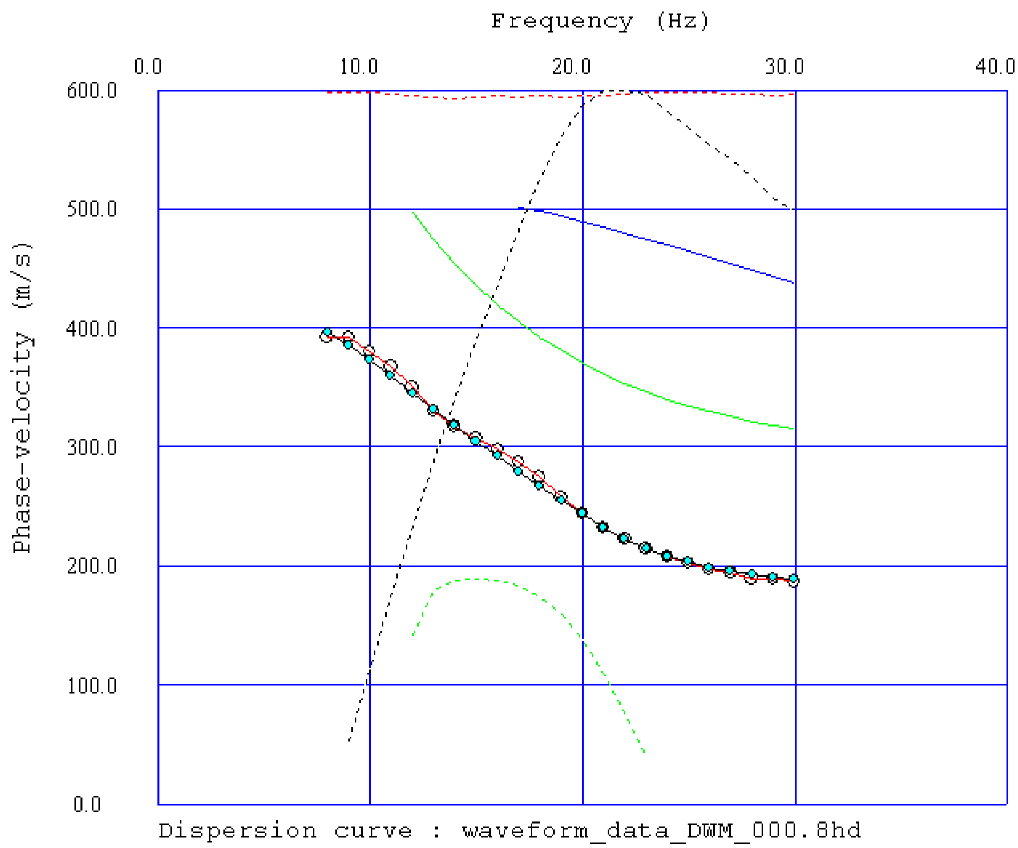


After picking the dispersion curve, import the picks into WaveEq and proceed with the standard analysis.



Set-up an initial model, run the inversion, and view the dispersion curve. At this point in the dispersion curve view, you can also model higher modes by first clicking on the *Calculating a theoretical higher mode dispersion curve* 

button, then clicking on the  button. The dispersion curve view will now display a set of curves. The curves with connected open circles are fundamental mode dispersion curves and the solid lines are the higher mode dispersion curves, associated with each fundamental mode curves by color. The dashed lines are the relative amplitudes of the higher modes, again associated by color.



To toggle off the higher mode dispersion curves, click on the  button again. To return to the fundamental mode, click on the 

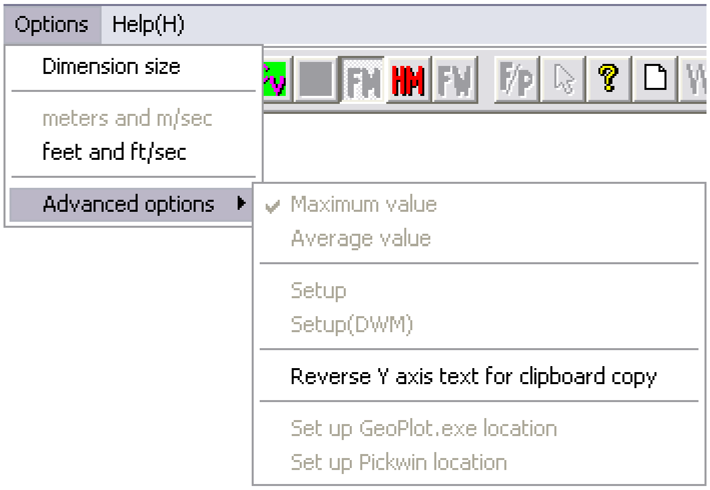
button.

6.7 MASW (2D) Menu

The *MASW(2D)* menu applies to 2D MASW and is not active for the 1D analysis version.

6.8 Options

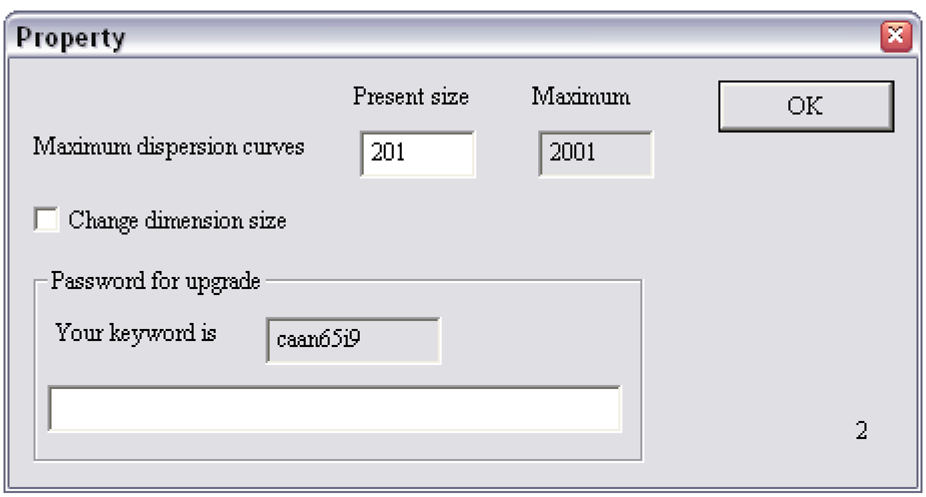
The *Options* menu includes general display and program controls.



6.8.1 Dimension Size

Select *Dimension size* to look-up data input allowances for the current software registration and the keyword for upgrade if applicable. At the time of publishing, no upgrades were available.

Check *Change dimension size* to increase the *Present size* or the maximum allowable number of dispersion curves. Only with 2D MASW do you need to input more than one dispersion curve; there is no need to adjust this setting for 1D MASW. If you do select to change the dimension size, enter a new *Present size* and click *OK*.



You will be prompted to restart the program to work with the new dimension size.

6.8.2 Meters and M/Second and Feet and Ft/Second

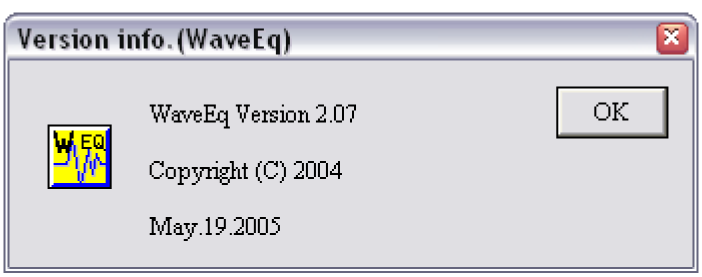
Select the units that apply to your dataset by choosing *meters and m/sec* or *feet and ft/sec*. This setting is reflected in the display labels, dialog box labels, and default values where applicable.

6.8.3 Advanced Options: Reverse Y-Axis Text for Clipboard Copy

If *Copy to clipboard* from the *Edit* menu is selected, the label for the vertical axis will appear horizontal if *Reverse Y-axis text for clipboard copy* is not selected. Reverse Y-axis text for clipboard copy corrects the horizontal orientation of the label. It is enabled as the default setting.

6.8.4 Help

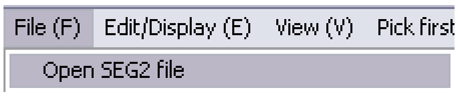
The Help menu or button presents the version information. When requesting customer support, please provide the version information.



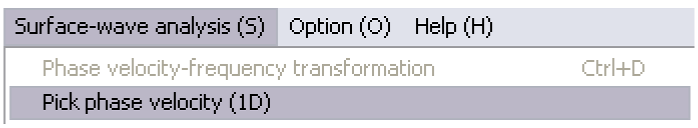
7 Summary of Basic Processing Flows

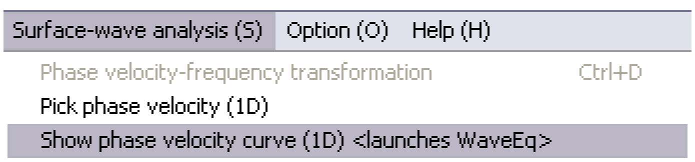
The Pickwin and WaveEq menu functions and their processing order are summarized below. The wizards automatically run these functions in the same order.

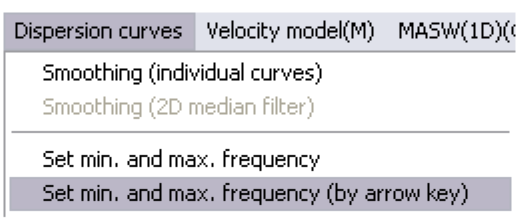
7.1 Active Source 1D MASW

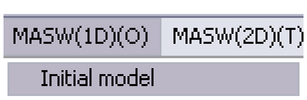
1.


2.


3.


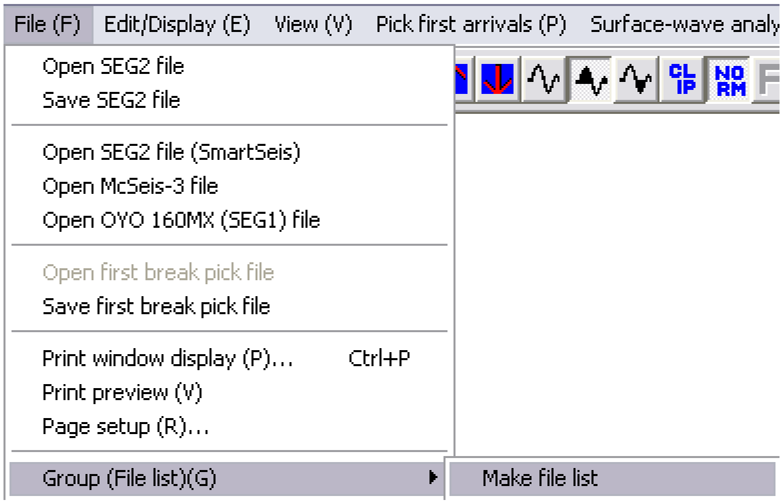
4.


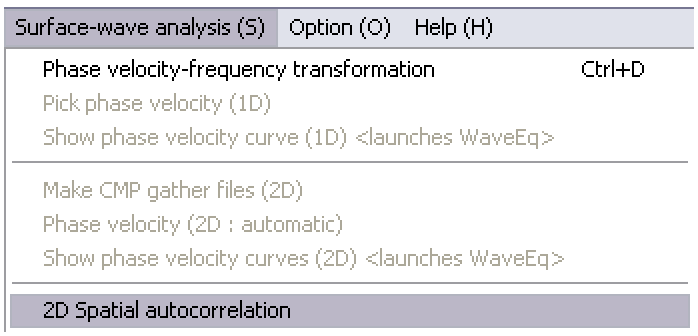
5.


6.


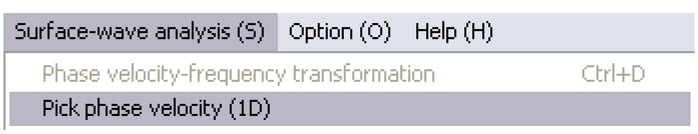
7.

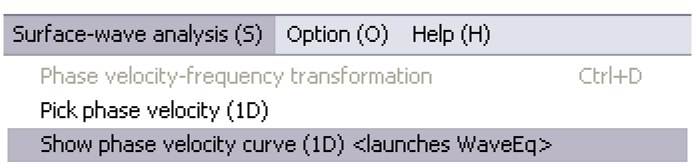

7.2 Passive Source 1D MAM

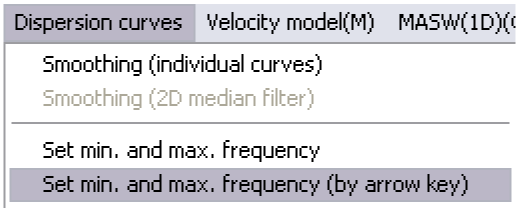
1. 

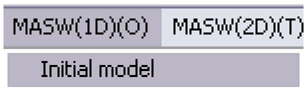
2. 

3. 

4. 

5. 

6. 
Dispersion curves
Velocity model(M)
MASW(1D)(
Smoothing (individual curves)
Smoothing (2D median filter)
Set min. and max. frequency
Set min. and max. frequency (by arrow key)

7. 
MASW(1D)(O)
MASW(2D)(T)
Initial model

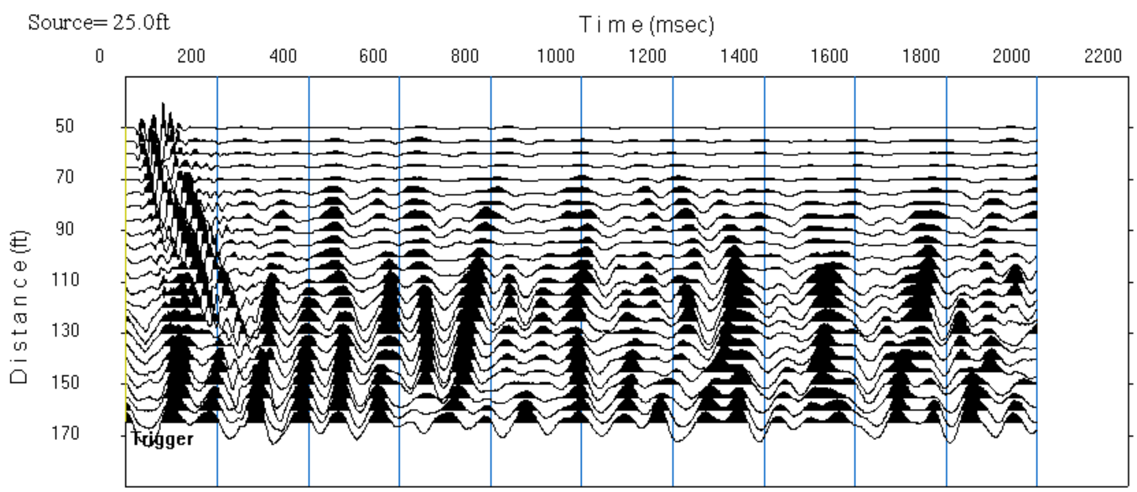
8. 
MASW(1D)(O)
MASW(2D)(T)
Initial model
Inversion

8 Examples

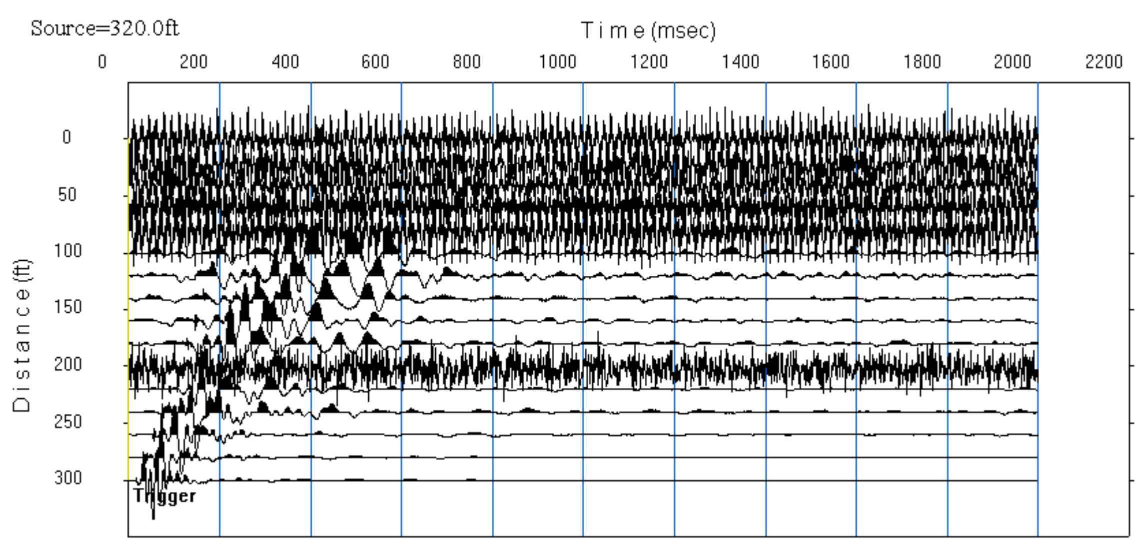
8.1 Active Source Waveform Data

8.1.1 Low Quality

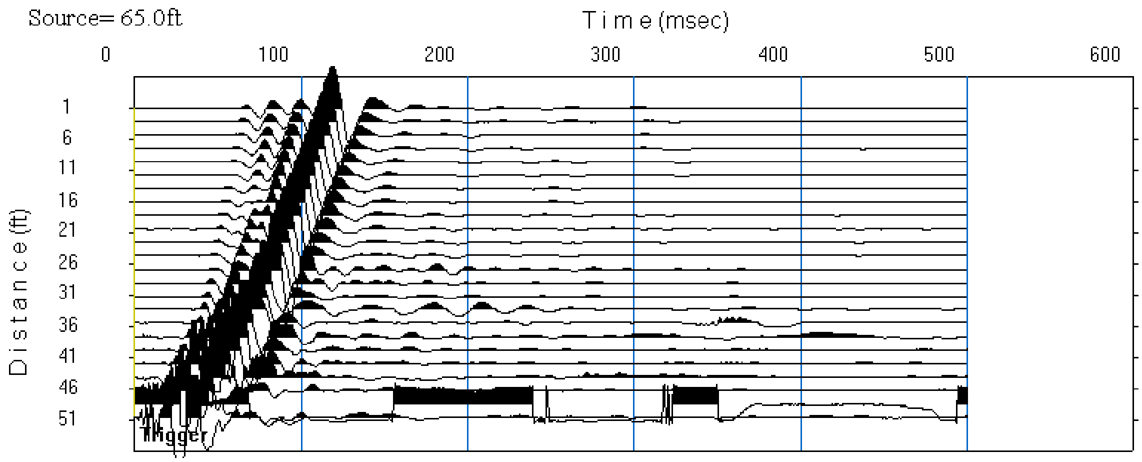
The example below lacks coherent signal from the near to far traces and is heavily contaminated with relatively lower frequency noise, particularly from 75 to 170 feet. Shot stacking or a larger source, and also waiting for a quieter recording period, may help.



In the example below, the takeouts for channels 6, and 12 through 16 were left open with no geophone connected. No signal was recorded on these channels, giving up 100 ft of offset on the far end of the spread and creating a 40-foot gap in between traces 5 and 7.

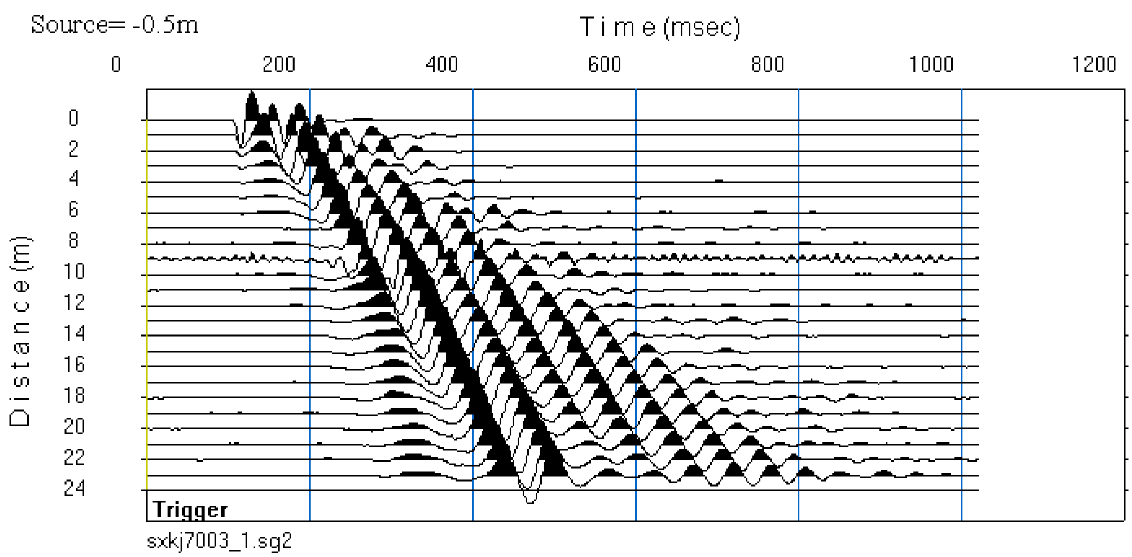


Due to a small near offset, the signal on the nearest geophone was clipped in the example below. A few saturated traces can be tolerated but it is best practice to not overdrive channels.



8.1.2 High Quality

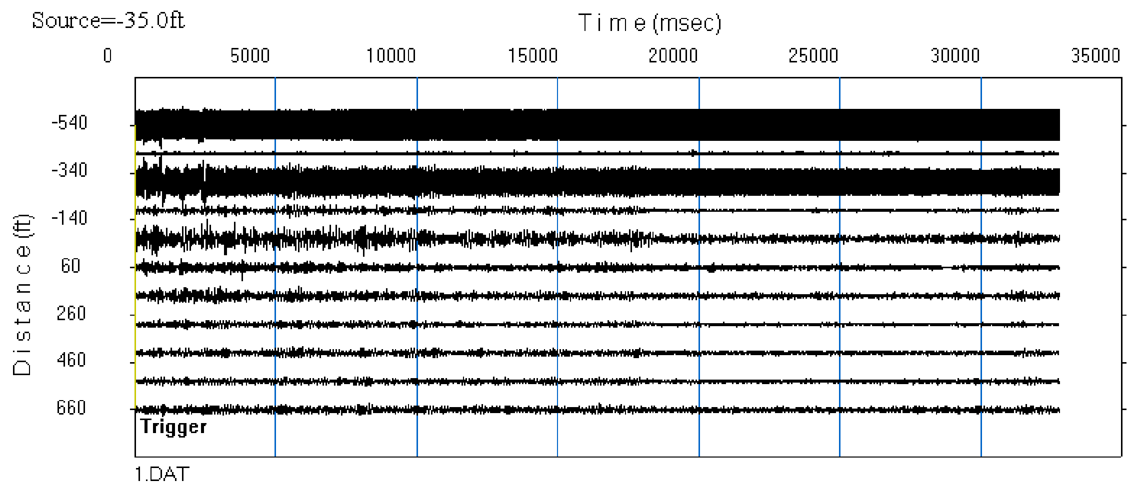
The shot record below displays high signal-to-noise ratio, no clipped traces, and coherency from trace-to-trace.



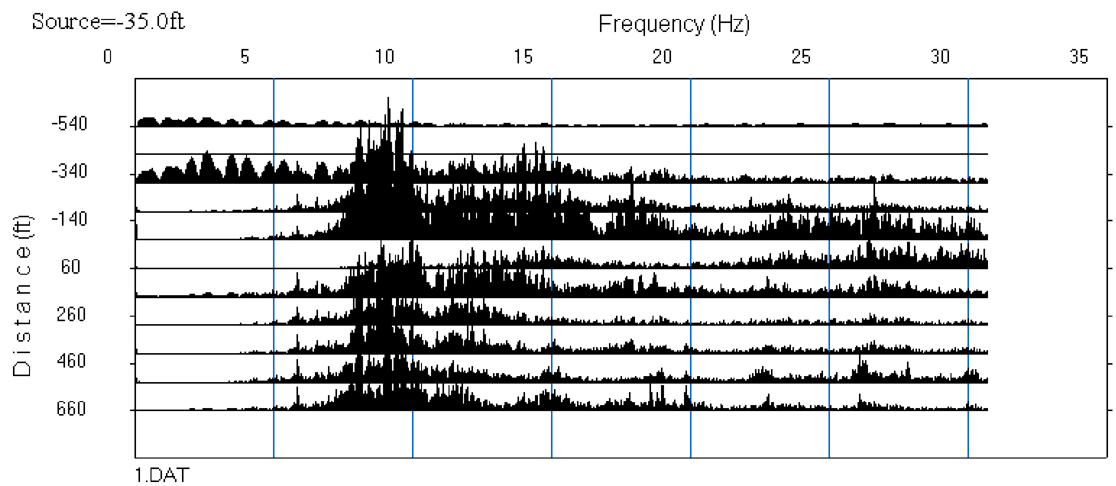
8.2 Passive Source Waveform Data

8.2.1 Low Quality

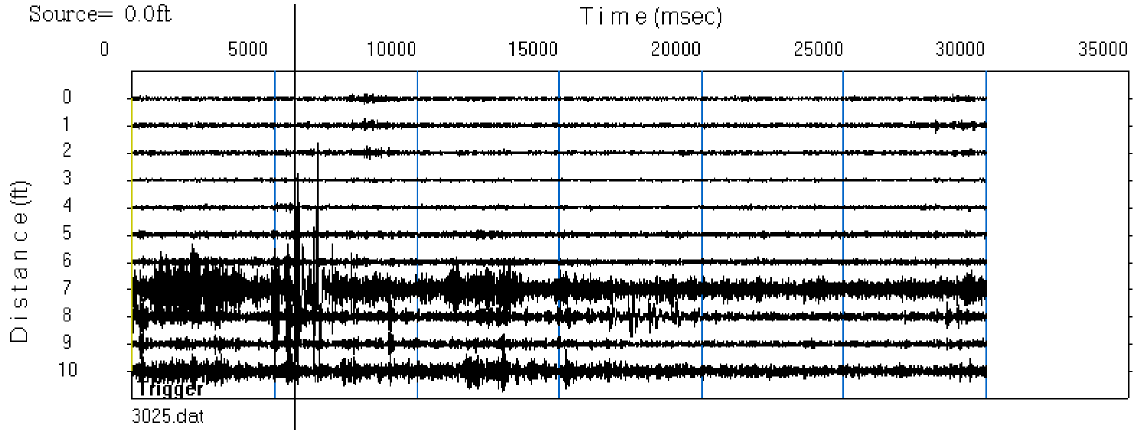
Trace-to-trace, there is wide variation in trace amplitude in the example below.

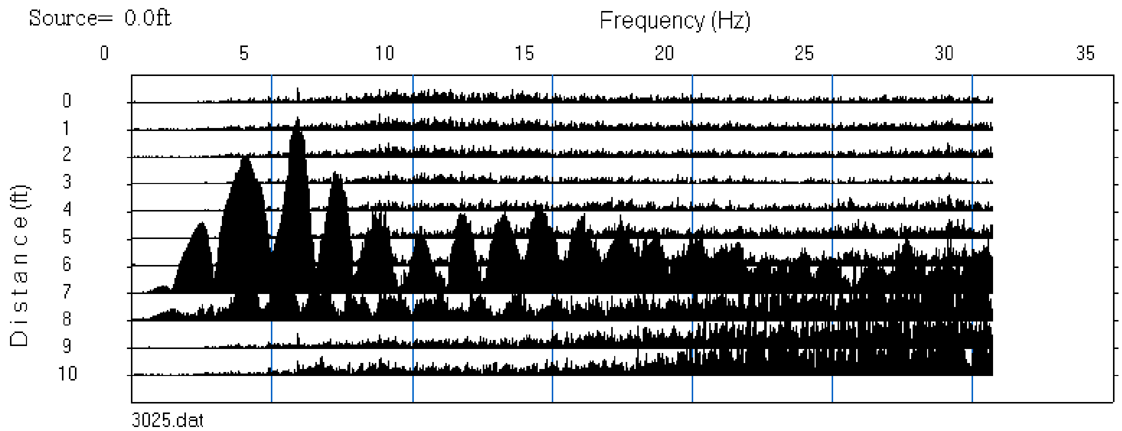


Upon viewing the spectrum, it is clear that the frequency content is uneven.

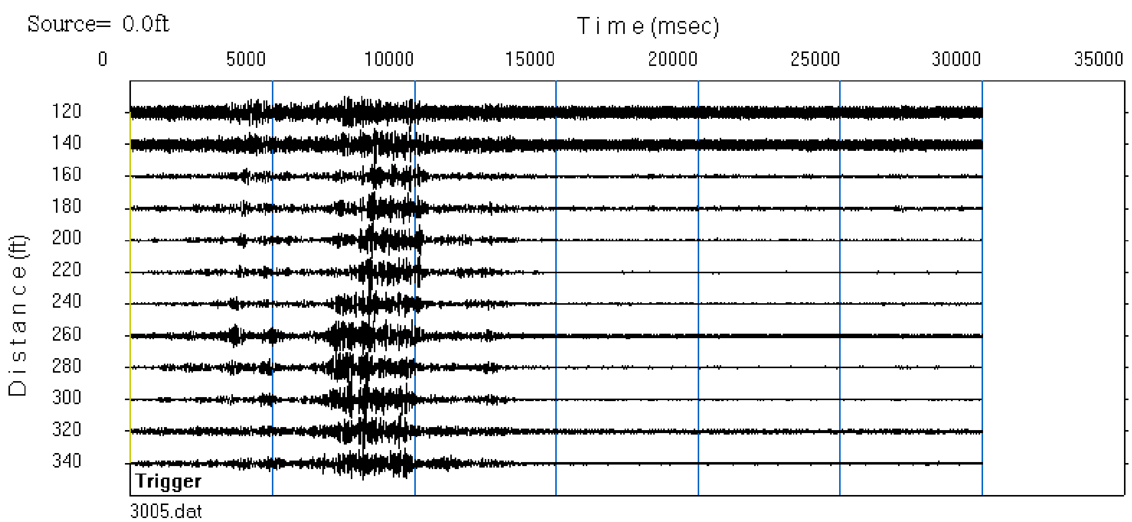


A similar condition is evident in the below shot record and associated spectrum.

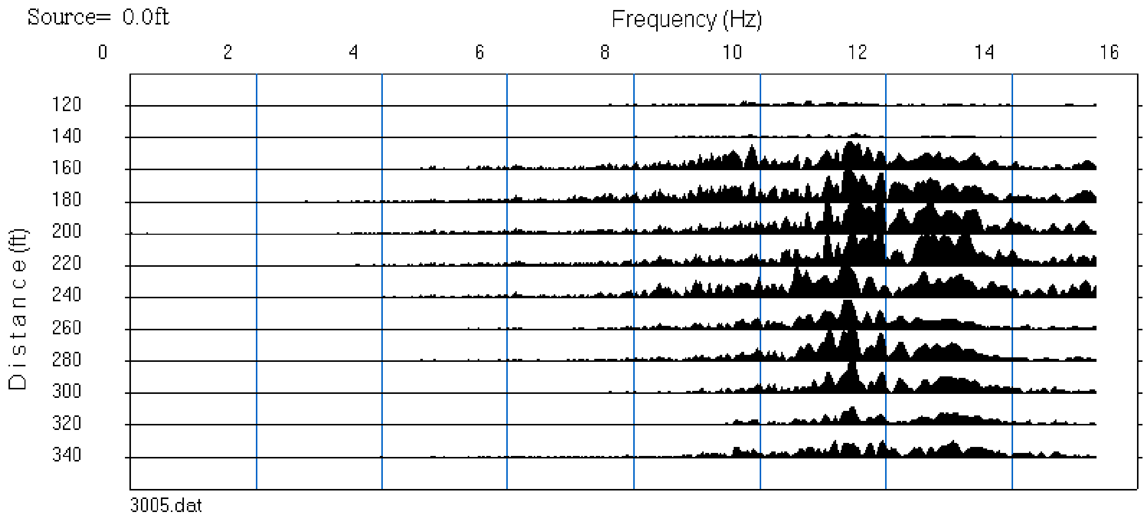




In this example, from the traces are similar to each other, but over time, there is wide range in amplitude.

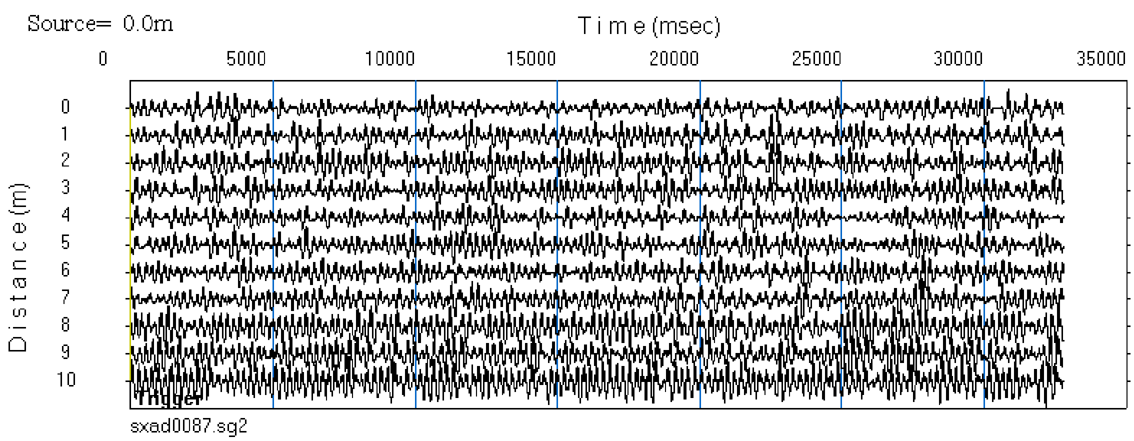


The spectrum shows fairly consistent frequency content from trace-to-trace, but not as tight as it could be.

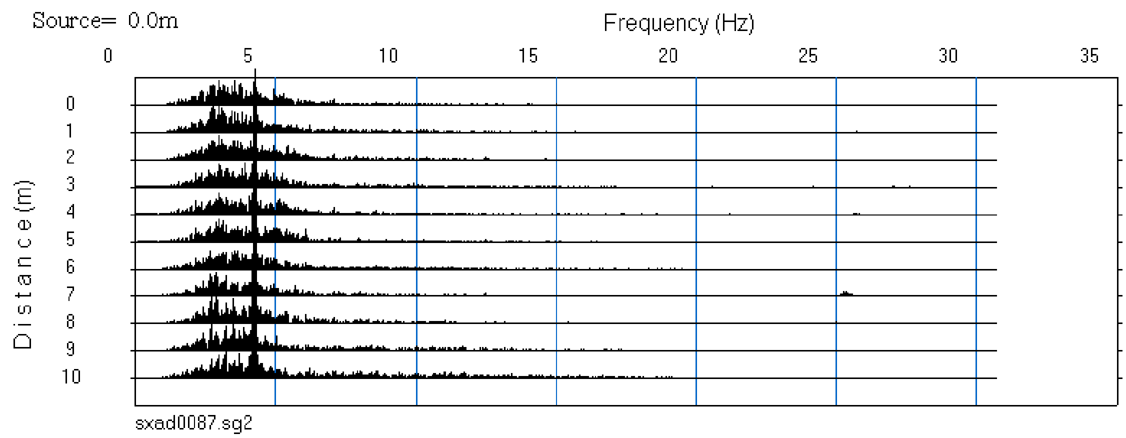


8.2.2 High Quality

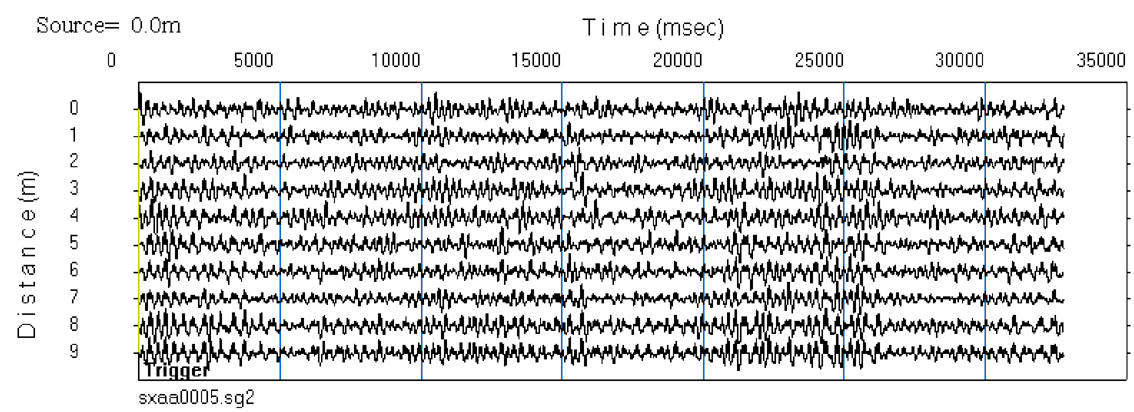
This example of an ideal record shows even signal amplitude from trace-to-trace and over time.



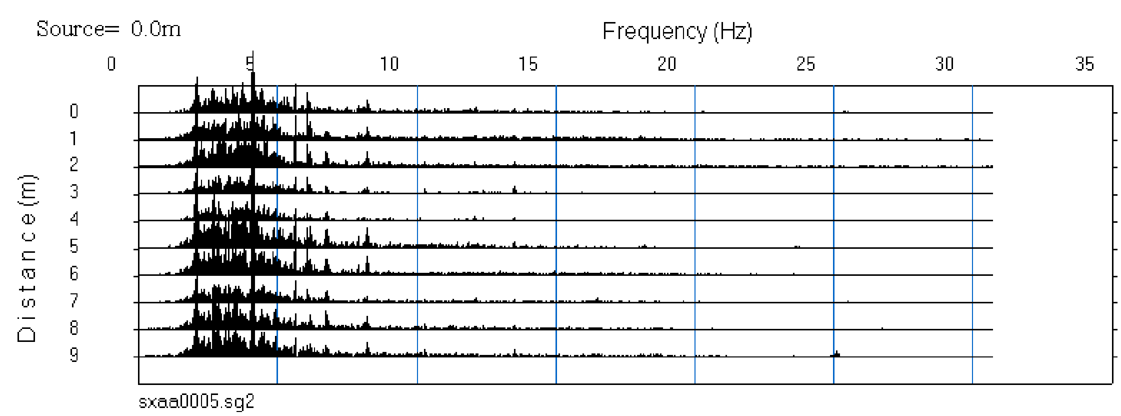
The corresponding spectrum shows the energy contained in a neat envelope from approximately 2 to 7 Hz.



The record below has intermittent higher-amplitude noise from passing cars (between 20 and 26 seconds).



The spectrum shows the car noise had relatively little impact on the record quality since it comprised a relatively short period compared to the total recording time.



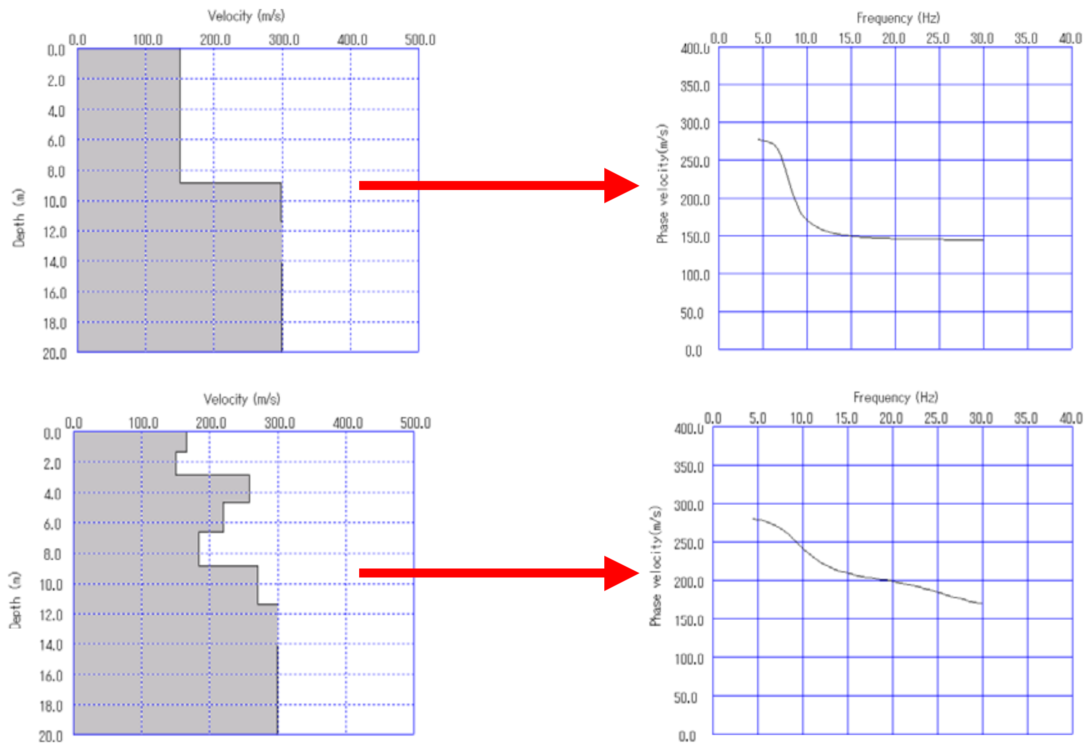
8.3 Dispersion Curves

8.3.1 Characteristics

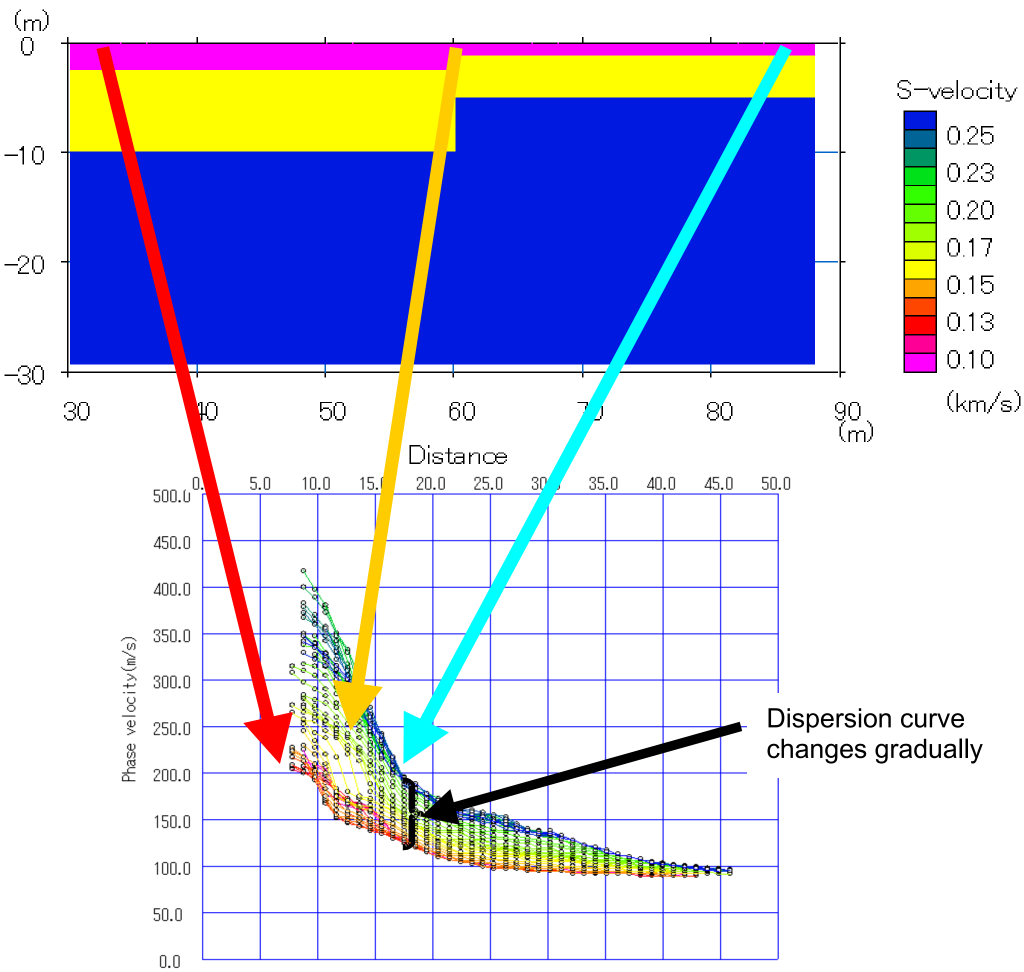
Dispersion curves are smooth, curved or straight lines.

S-wave velocity structure

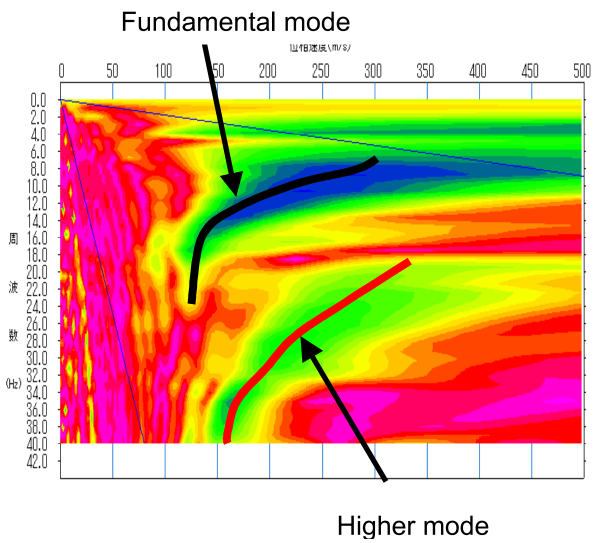
Dispersion curve

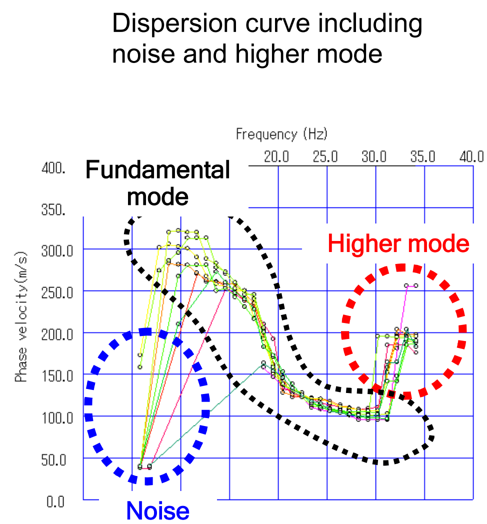


Dispersion curves reflect the *average* velocity model beneath the geophone spread and for 1D analysis, the resultant V_s profile is representative of the center of the geophone spread.



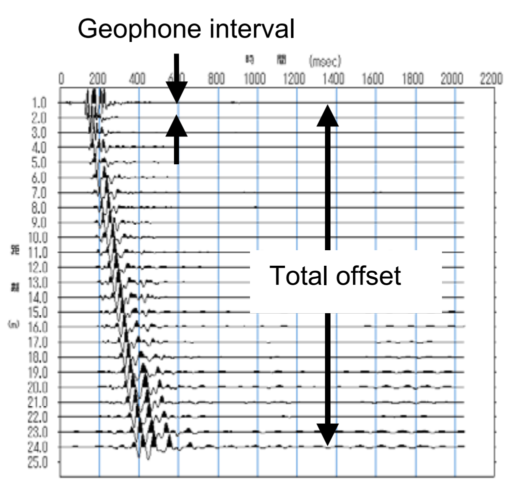
Only the Rayleigh wave fundamental mode is used for analysis, though higher mode(s) are present and often visible.

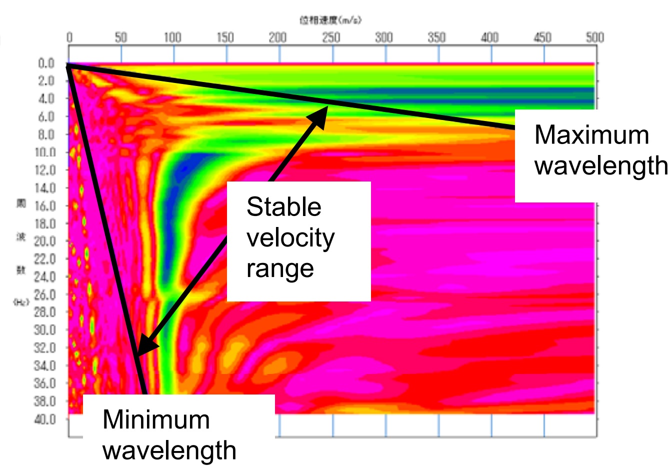




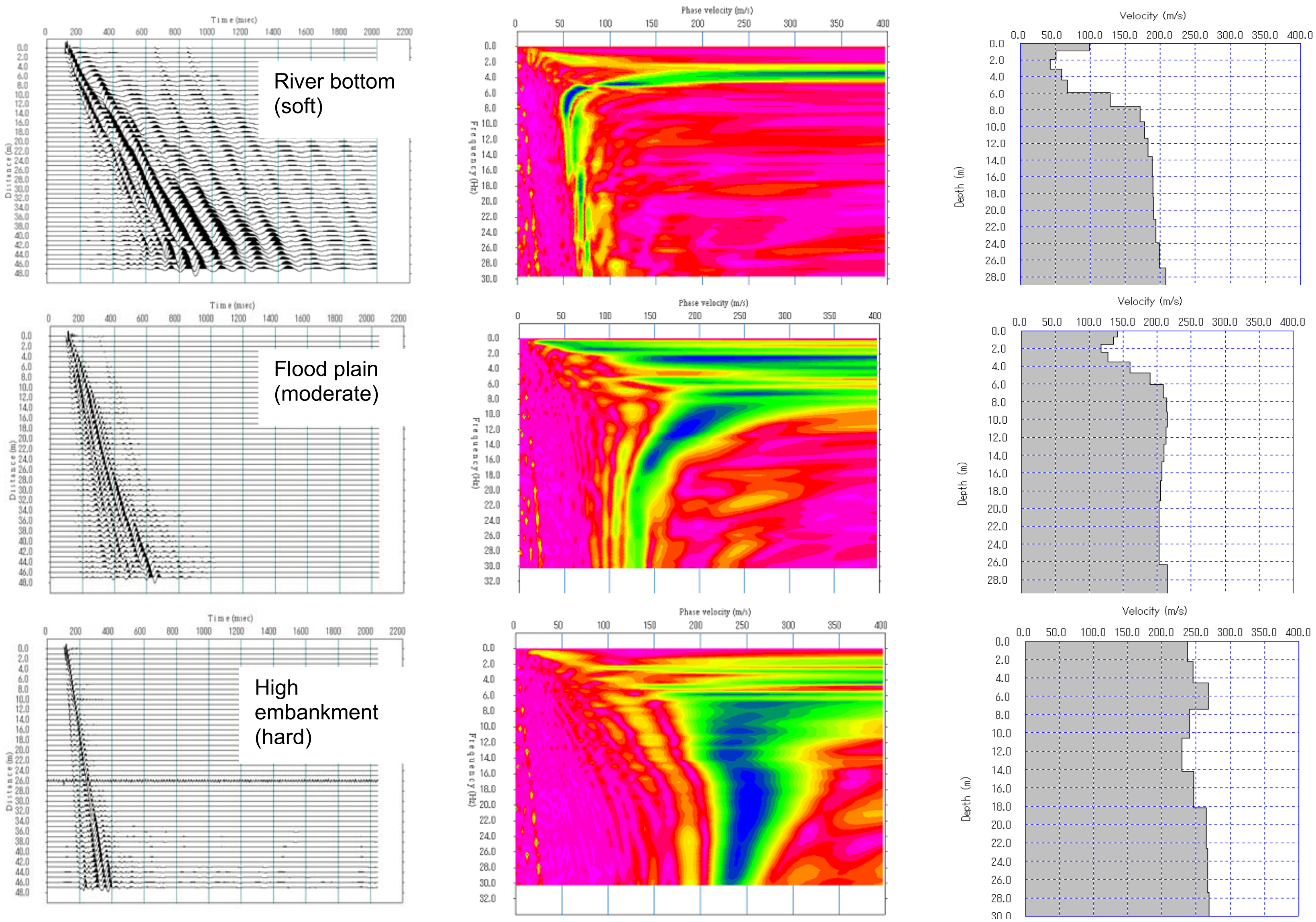
The frequency range within which the phase velocity is considered stable corresponds to the receiver or geophone interval and total offset for active source surveys (and array length for passive source surveys). The geophone interval and total offset generally relate to wavelength by one-half, meaning that the minimum wavelength sampled for any given survey is approximately two times the geophone interval and the maximum wavelength sampled is approximately two times the total offset.

The frequency range is depicted on the phase velocity plot by black lines (shown on right) with slopes that correspond to the minimum and maximum wavelengths.





8.3.2 *Comparison of data from ground with variable stiffness*



9 References

Aki, K. and Richards, P.G. (1980), *Quantitative seismology*, W.H. Freeman and Co.

Crice, D. (2002), Borehole shear-wave surveys for engineering site investigations, 14 pgs.

Dorman, J. and Ewing, M. (1962), Numerical inversion of seismic surface wave dispersion data and crust-mantle structure in the New York-Pennsylvania area, *Journal of Geophysical Research*, 67: 5227-5241.

Fowler, C.M.R. (1990), *The Solid Earth: an Introduction to Global Geophysics*, Cambridge University Press.

Hayashi, K. and Suzuki, H. (2004), CMP cross-correlation analysis of multi-channel surface-wave data, *Exploration Geophysics*, 35: 7-13.

Hayashi, K., Inazaki, T. and Suzuki, H. (2004), Buried channel delineation using a passive surface wave method, *Proceedings of the 7th SEGJ International Symposium*, 395-400.

Heisey, J.S., Stokoe II, K.H., Meyer, A.H. (?), Moduli of pavement systems from spectral analysis of surface waves, *Transportation Research Record*, 852: 22-31.

Imai, T. and Tonouchi, K. (1982), Correlation of N-value with S-wave velocity and shear modulus, *Proceedings of the Second European Symposium on Penetration Testing*, Amsterdam, 67-72.

International Code Council (2000, 2003), *International Building Code (IBC)*.

Kitsunezaki, C., Goto, N., Kobayashi, Y., Ikawa, T., Horike, M., Saito, T., Kurota, T., Yamane, K., and Okuzumi, K. (1990), Estimation of P- and S-wave velocities in deep soil deposits for evaluating ground vibrations in earthquakes, *SIZEN-SAIGAI-KAGAKU*, 9(3): 1-17 (in Japanese).

Lay, T. and Wallace, T.C. (1995), *Modern Global Seismology*, Academic Press.

Louie, J.N. (2001), Faster, better: shear-wave velocity to 100 meters depth from refraction microtremor arrays, *Bulletin of the Seismological Society of America*, 91(2): 347-364.

Ludwig, W.J., Nafe, J.E. and Drake, C.L. (1970), Seismic Refraction, *The Sea*, 4: 53-84.

Mari, J.L. (1984), Estimation of static correction for shear-wave profiling using the dispersion properties of Love waves, *Geophysics*, 49: 1169-1179.

Marosi, K.T. and Hiltunen, D.R. (2004), Characterization of spectral analysis of surface waves and shear wave velocity measurement uncertainty, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 130(10): 1034-1041.

Martin, A.J. and Diehl, J.G. (2004), Practical experience using a simplified procedure to measure average shear-wave velocity to a depth of 30 m (V_s30), 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada.

Mayne, P.W. and Rix, G.J. (1995), Correlations between shear wave velocity and cone tip resistance in natural clays, *Soils and Foundations*, 35(2): 107-110.

Menzies, B. (?), Near-surface site characterization by ground stiffness profiling using surface wave geophysics, unpublished, 14 pgs.

Nazarian, S. (1989), *Applicability of spectral-analysis-of-surface-waves method in determining moduli of pavements*, Symposium on the State of the Art of Pavement Respons Monitoring Systems for Roads and Airfields, 16 pgs.

Nazarian, S., Stokoe II, K.H., and Hudson, W.R. (?), Use of spectral analysis of surface waves method for determination of moduli and thicknesses of pavement systems, *Transportation Research Record*, 930: 38-45.

Park, C.B., Miller, R.D., and Miura, H. (?), Optimum field parameters of an MASW survey, unpublished, 6 pgs.

Park, C.B., Miller, R.D. and Xia, J. (1999), Multichannel analysis of surface waves, *Geophysics*, 64(3): 800-803.

Schneider, J.A., Hoyos Jr., L., Mayne, P.W., Macari, E.J., Rix, G.J. (1999), Field and laboratory measurement of dynamic shear modulus of Piedmont residual soils, *Behavioral Characteristics of Residual Soils*, GSP 92, ASCE, Reston, VA, 12-25.

Sheriff, R.E. (1994), *Encyclopedic Dictionary of Exploration Geophysics*, 3rd ed., Society of Exploration Geophysicists.

Xia, J., Miller, R.D. and Park, C.B. (1999), Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves, *Geophysics*, 64(3): 691-700.