

Short Manual: Surface Wave Group Velocity Inversion.

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Surface Waves

Surface waves are waves whose motion is confined to and propagates along the surface of a body. They result from the interaction of P and S waves with the boundary conditions on the body

There are two main types of surface waves, namely, Love and Rayleigh waves.

- Love waves result from the interference of SH waves (component of S waves with purely a horizontal component of motion) trapped near the surface by total internal reflection at the free surface and at internal layers of the Earth.
- Rayleigh waves result from the interaction of P and SV waves (component of S waves with some vertical component of motion) with the free surface. Figure 1 shows the sense of particle motion during the passage of surface waves.

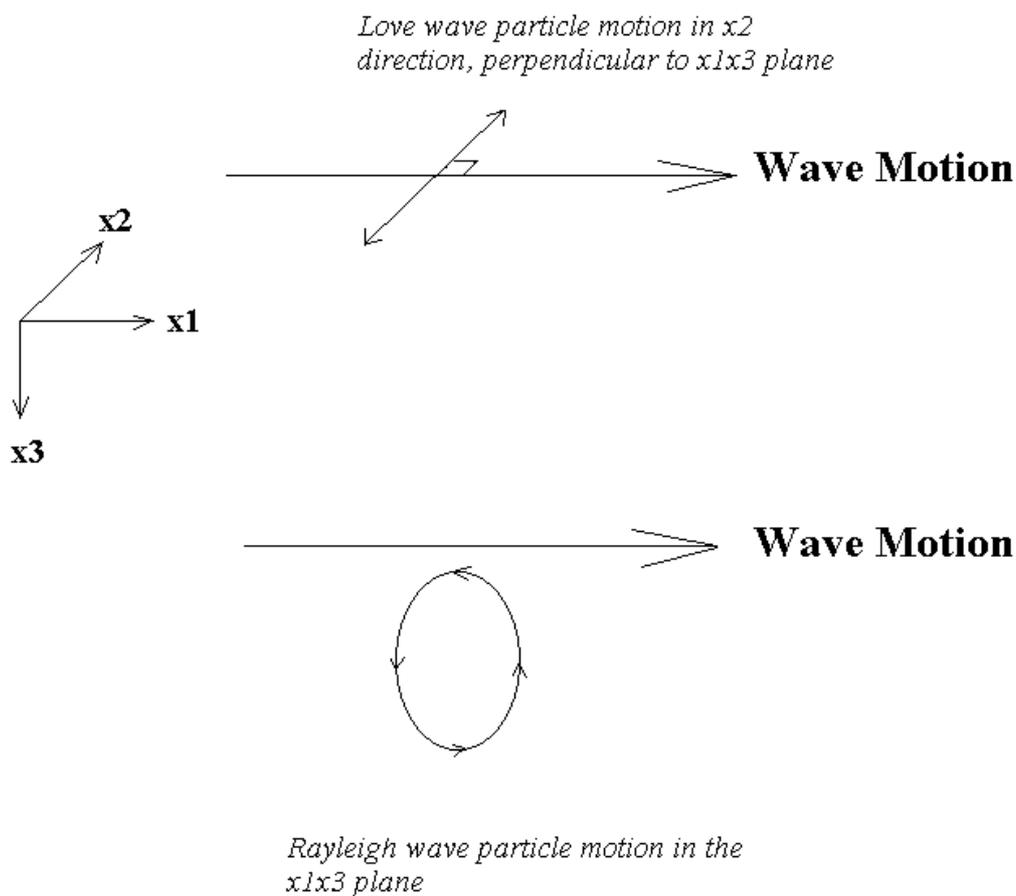


Figure1: Schematic drawing showing the sense of motion at a site during the passage of surface waves.

Dispersion

The apparent velocity of waves along the surface varies with frequency / period. This phenomenon is called (geometrical) dispersion and is commonly observed for surface waves. Since surface wave velocities vary depending on the depth range sampled by each frequency / period, surface wave dispersion is, therefore, very important for studying earth structure. Both Love and Rayleigh waves are used in such studies. Love wave dispersion depends on the shear velocity whilst Rayleigh wave dispersion depends on both compressional and shear velocities. Figure 2 and 3 illustrate this phenomenon.

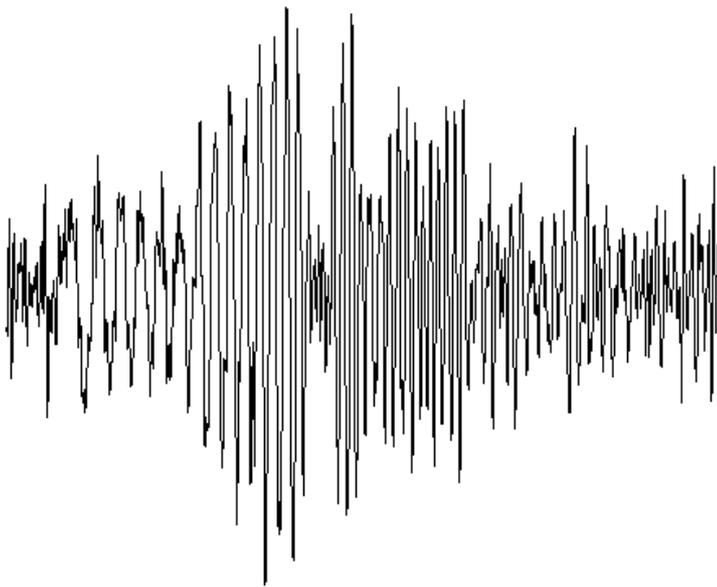


Figure 2: Long period waveform showing clear dispersion of surface waves and Love waves of longer period arriving first.

Group Velocity

The horizontal apparent velocity of surface waves is usually referred to as ‘group velocity’ and is the velocity at which a wave group apparent on a seismogram travels. The wave groups of different frequencies / periods also travel at different group velocities. The group velocities are calculated by dividing the distance between the source and receiver by the travel time of the wave group. Longer period surface waves travel faster since they sample deeper and velocity is assumed to increase with depth from the surface of the Earth. A more sophisticated method involves the filtering of the seismogram to isolate wave groups at different frequencies / periods.

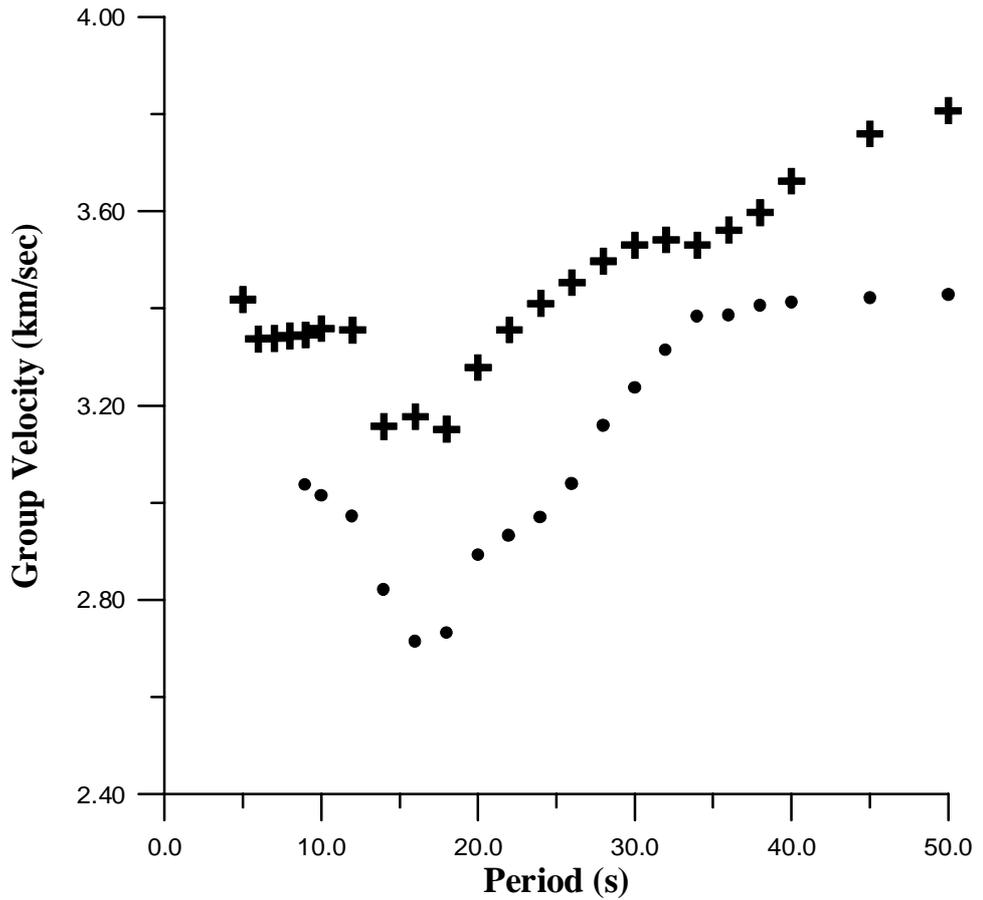


Figure 3: Surface wave dispersion observed over southern Africa. Circles represent Rayleigh wave group velocities and crosses Love waves. Note Love waves travel faster than Rayleigh waves.

Velocity Structure

The inversion of surface wave group velocities is a simple way used to estimate the velocity structure of the Earth. This process involves solving the equation,

$d = Gm$, where d is a data vector, whose components are changes in observed measurements such as travel time (or arrival time), Δm is the model vector, containing changes in the unknown elastic parameters of the Earth and G is partial derivative matrix,

$$\frac{\partial d_i}{\partial m_j}$$

To solve the equation, one seeks the change in the model, which when multiplied by the known matrix, G , gives the required change in the data, d .

Aim of the Overview

These notes are a brief guide to the use of computer programs to estimate the shear wave velocity of the Earth by the inversion of surface wave group velocities. Most of the codes were written by Robert Herrmann (Saint Louis University, USA) under the computer package called *Computer Programs in Seismology* and some of them are part of the SEISAN 7.0 software package by Jens Havskov (University of Bergen, Norway).

Analysis Method

Below is an outline of the analysis procedure.

- (I) Data preparation
- (II) Multiple Filter Analysis to isolate frequencies / periods and their group velocities.
- (III) Inversion of group velocities to obtain the velocity structure.

A more comprehensive description of the programs and their use can be obtained from the relevant documentation compiled by R. B. Herrmann.

The *Computer Programs in Seismology* software package is distributed with its own graphics package. The programs used here create a binary, device independent metafile of plotting commands, in a CALPLOT file. This file can be converted to the users' choice of hardware devices. A program *plotnps* is used to convert the file to postscript through a command line as will be shown below.

All the programs used for the analysis described here are included in the SEISAN 7.0 software package.

(I) Data preparation

The first step involves the identification of suitable earthquake events and waveforms.
i.e.

- Large earthquakes, preferably of $M_s > 6.0$
- Accurate hypocentral co-ordinates of the earthquakes
- Well dispersed surface wave train (*e.g. Figure 2. Love waves travel faster than Rayleigh waves and arrive on the transverse component ahead of Rayleigh waves which arrive on the vertical and radial components. Thus rotation of seismograms to transverse and radial components would clearly show the surface wave arrivals*)
- Good signal to noise ratio (*spectral analysis would show this*)

The processing mentioned in the last two points is carried out using the MULPLT program in SEISAN 7.0. Spectral analysis is applied on each rotated component. After each spectrum analysis, the program saves the amplitude spectra in a file called **com_spec.out**. Since this file is over written every time the spectral analysis is performed, it is recommended to rename it between each analysis. These output spectral files are the used as the input for the second stage. Figure 4 shows an example of the spectral analysis procedure under MULPLT, showing a good signal to

noise ratio between the frequencies 0.01Hz and 0.2Hz for the radial component of this particular recording.

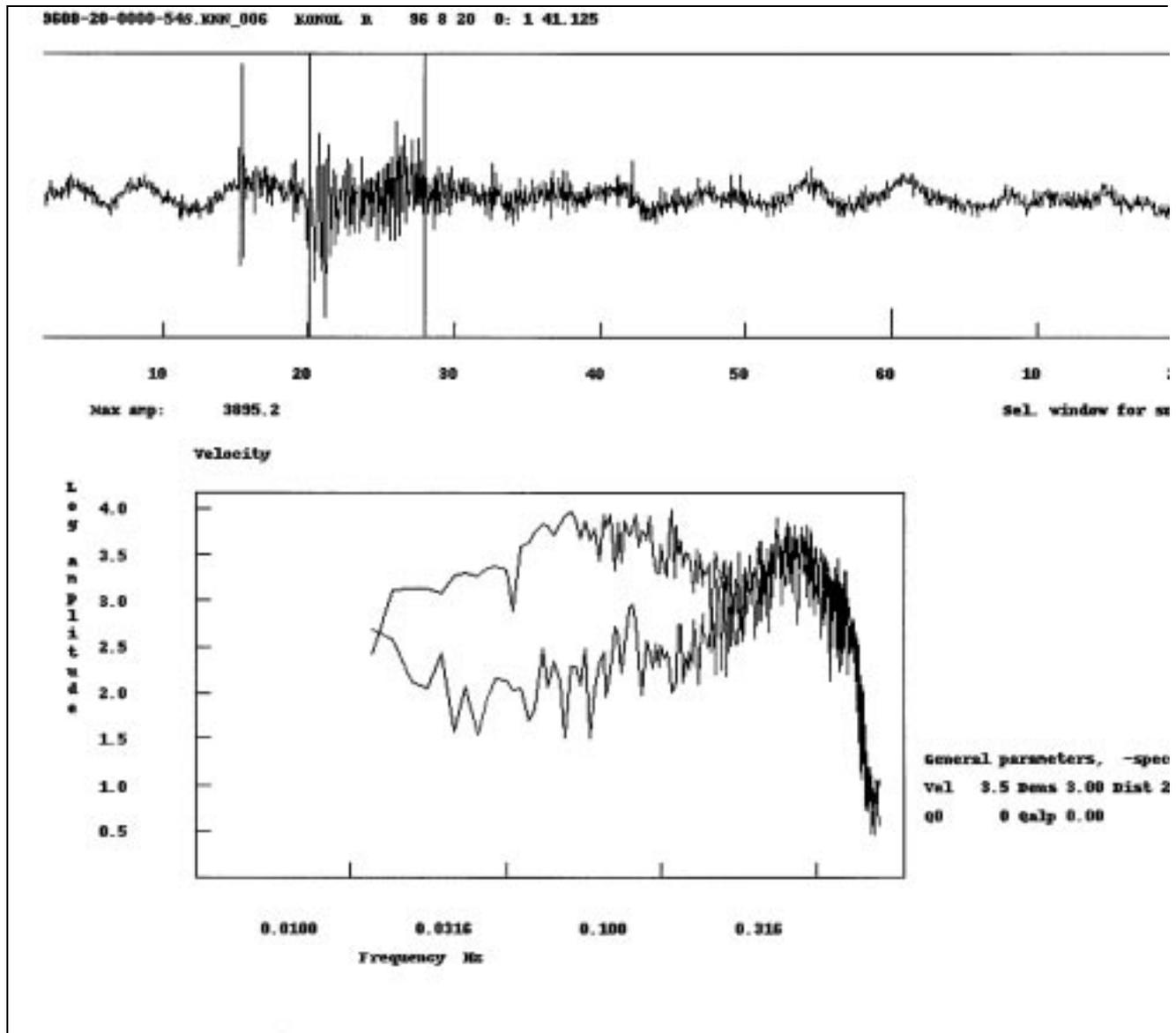


Figure 4: Typical velocity spectrum obtained when running the SPEC program in SEISAN. On top is the original trace with the window chosen and at the bottom, the corrected spectrum.

(II) Multiple Filter Analysis

One of the methods available for calculating group velocities is the Multiple Filter Technique (MFT). This technique is applied on multiply dispersed signals to isolate group velocities as a function of time. There exist numerous computer programs to accomplish this. Here, the program called *xspmft* written by R. B. Herrmann is used. The program is controlled from a command line with several options. Of the available options, only three are used here (A description of other options can be found in the full manual written by R. B. Herrmann)

To run the program, two input files are required. One contains the waveform file (spectral amplitudes) prepared in stage (I), and the second contains the frequencies / periods for which the group velocities will be calculated (i.e. filter centre frequencies / periods). An example of the command to run the program is given below.

```
xspmft -v -V -C xspm.d < com_spec.out
```

where,

- xspm.d* is an input file containing the filter centre frequencies
- com_spec.out* is the file containing the spectral amplitude data from stage (I)
- v* is an option to have the spectral amplitudes annotated
- V* is an option to create an ASCII output file containing the dispersion data
- C xxxx* is an instruction to read the filter centre frequencies from the file *xxxx* (where *xxxx* is *xspm.d* in the example given above)

Input Files Format

Examples of these files are found in SEISAN 7.0.

Input file 1 (centre frequency file, e.g. *xspm.d*)

Contains filter centre frequencies or periods in the following format,

ifrper (i.e. flag to show whether file contains frequencies or periods, **0** for period and **1** for frequency)

value (frequency or period values to the end of file in one column)

.....

EOF

There is a limit of 512 different frequencies / periods.

Input file 2 (spectrum file)

This file contains the spectral amplitudes from stage (I). The file can be edited to change the epicentral distance and travel time, when the values obtained from SEISAN are questionable.

The *first line* has the code where the signal was recorded, the component and date of earthquake event (STAT, COMP, DATE)

The *second line* contains:

- the number of points in FFT (**n**, it should be a power of 2).
- the number of frequencies (**n21** where $n21 = n/2 + 1$)
- the number of points in original time series (**npts**, where $npts \leq n$)
- epicentral distance in kilometers (**dist**)
- epicentral distance in degrees (**deg**)
- source – receiver azimuth in degrees (**az**)

In the *third line* are the following

- receiver – source back azimuth in degrees (baz)
- travel time of first sample in seconds (to)
- sample interval (dt, e.g. 1.0 sps for LP and 20 sps for BB)

Following the first three lines are complex spectral amplitudes.

Output Files

Two files are created after running the MFT program.

- (1) An ASCII type file (if option `-V` is included) containing the dispersion data (default file name is **vel.dat**). Be sure to rename the ASCII file before running the program again.
- (2). A Calplot file saved in a file whose name is written as **plotxxxx**, where xxxx is an arbitrary number chosen by the program. The plot is the dispersion data contained in the vel.dat file mentioned above.

To view the plot file, it is first converted to postscript using the conversion program *plotnps*

i.e. *plotnps <plotxxxx > tt.ps*

where, tt.ps is the postscript file that can be viewed on any postscript friendly software or printed directly. Two plots are produced. The first is a plot of amplitude as function of period. The second is a plot of group velocity as a function of period and spectral amplitude, with amplitude isolines drawn (Figure 5).

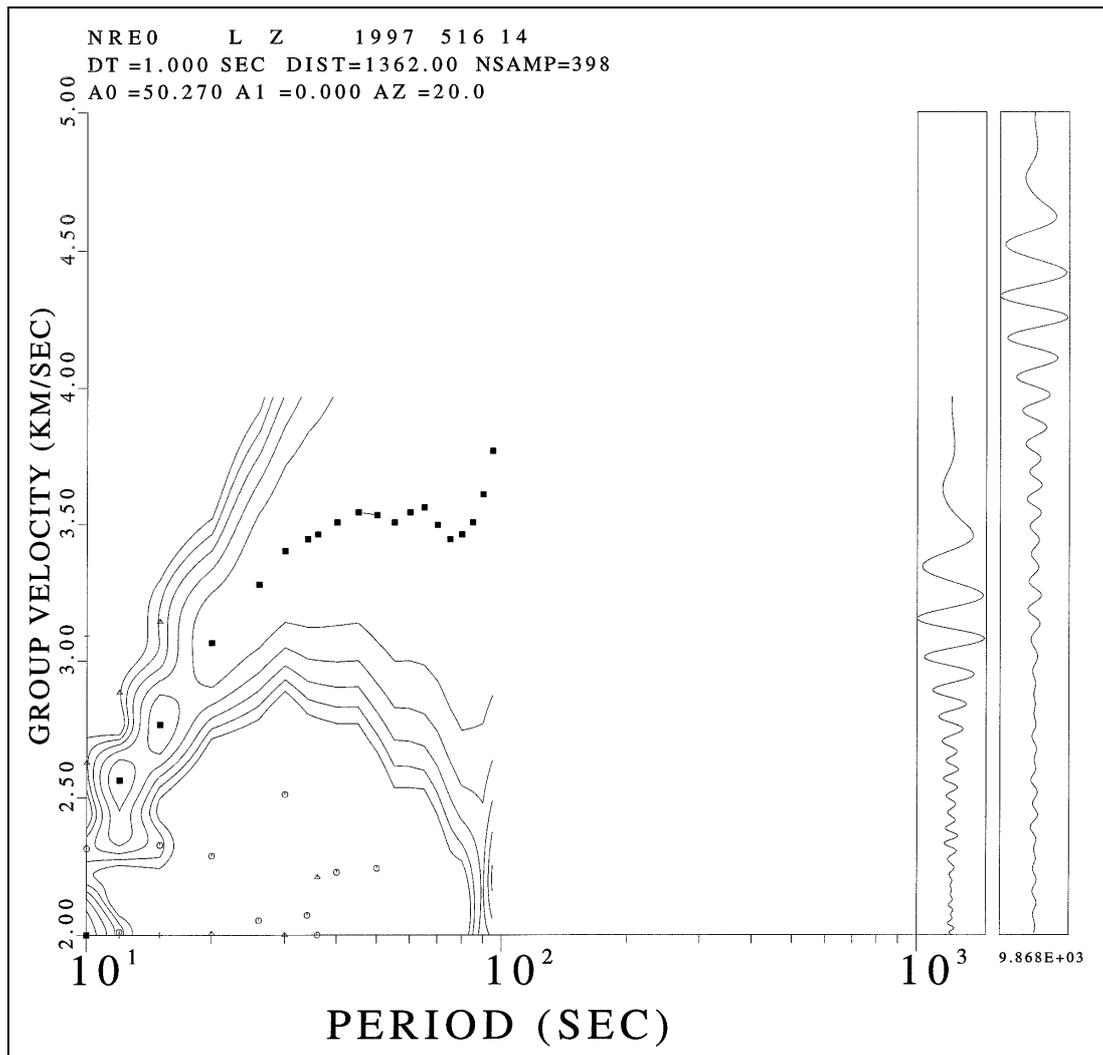


Figure 5. A typical contoured dispersion curve obtained from Multiple Filter Analysis of the vertical component of an event recorded at the NRS array. Black squares represent the maximum spectral amplitude at each period and correspond to the fundamental mode. (Circles and triangles scattered on the diagram represent high modes) The trace to the far right is that obtained after band-pass filtering of the original signal using a Gaussian filter and immediately to the left, the same trace is plotted as amplitude versus apparent velocity (Herrmann 1987).

An example of the ASCII output file (vel.dat) is found in SEISAN 7.0.

From the vel.dat file, one can select the periods, and group velocities for whatever modes are of interest to the user. These are the values that are inverted for the velocity structure.

(III) Inversion

The inversion of the surface wave dispersion data (e.g. group velocities) for plane layered shear velocity earth structure is accomplished by a sequence of programs driven by the main driver program *surf*. This is an interactive process with a menu explaining all the steps shown.

Three input files are required to run the *surf* program. The control file, *obs.d*, which contains control flags used in running the inversion programs, and two data files, *modl.d*, which contains the initial model parameters used in the inversion, and *disp.d* containing the observed dispersion data. (Examples of the input files are found in SEISAN)

Below is an explanation of the parameters found in the files. All parameters should be entered.

Control file (obs.d)

LINE 1: **h,dcl,onel,dcr,oner**

- h** controls the dispersion calculations. The first parameter, **h**, controls the group velocity partial derivative computation which is performed numerically by choosing periods $(1+h)T$ and $(1-h)T$, where T is the desired period, to obtain a necessary partial derivative with respect to period. A value of 0.005 is reasonable.
- dcl** controls the search for the Love wave phase velocity. A zero crossing is scanned for by evaluating the period equation at increments of **dcl** units of phase velocity. When the zero crossing is found, the root is refined. Too small a value causes an excessively lengthy search, while too large a value may cause mode jumping and hence improper mode identification.
- onel** is important in situations in which phase velocity decreases with increasing period, which can occur for low velocity zones. To avoid losing a mode, the search backs up by 'onel*dc' velocity units from the estimate at the previous period. In no case will the previous mode at the same period be latched onto. (2.0 is the default).
- dcr** is the search increment for the Rayleigh wave phase velocity.
- oner** permits the backing up for Rayleigh waves (2.0 is the default).

LINE 2: **nf(i), i=1,8,nf(11),nf(12)**

These are control flags used in running the programs. Those specified here are defined by the model and dispersion files.

- nf(1)** = 1 estimated stdev computed from residuals
= 0 no scaling by residuals
*(The dispersion data input requires the specification of an observed velocity and an error estimate of the observation, or a specification of the spatial attenuation factor gamma and its error. If **nf(1) = 0** then the estimated model error obtained from the covariance matrix is based solely upon these errors. This is a standard technique in regression analysis. On the other hand if **nf(1) = 1** the error estimate is based solely on the fit between the observed and predicted dispersion data. In this case, the observation error estimate can be set to 1.0 irrespective of the size of the observation.)*
- nf(2)** = Total number of Love Wave Gamma Modes
= 0 DO NOT PROCESS Love Wave Gamma Data for Q
- nf(3)** = Maximum Number of Love Wave Phase Velocity Modes

- = 0 DO NOT PROCESS Love Wave Phase Velocity
- nf(4)** = Maximum Number of Love Wave Group Velocity Modes
 - = 0 DO NOT PROCESS Love Wave Group Velocity
- nf(5)** = Maximum Number of Rayleigh Wave Gamma Modes
 - = 0 DO NOT PROCESS Rayleigh Wave Gamma Data for Q
- nf(6)** = Maximum Number of Rayleigh Wave Phase Velocity Modes
 - = 0 DO NOT PROCESS Rayleigh Wave Phase Velocity
- nf(7)** = Maximum Number Rayleigh Wave Group Velocity Modes
 - = 0 DO NOT PROCESS Rayleigh Wave Group Velocity
- nf(8)** = Model Weighting
 - = 0 No Weighting
 - = 1 Read In Layer Velocity Weights
- nf(11)** = Type of Damping
 - = 0 Stochastic (*A damping value lam is introduced to control the size of the change in model vector*)
 - = 1 Differential (*A damping value lam is introduced to control the size of the difference in model values in adjacent layers. This will lead to a smoother model*)
- nf(12)** = Earth Flattening
 - = 0 No Earth Flattening – Model is Flat Earth Model
 - = 1 Earth Flattening – Model is Spherical Earth Model

LINE 3: nmmodl

nmmodl is the name of the file containing earth model information

LINE 4: nmdisp

nmdisp is the name of the file containing the observed dispersion information

LINE 5 (optional): (dd(i), i=1,m)

If **nf(8)** = 1, read in preassigned layer velocity weights here, one for each layer (including the halfspace). This can be used to fix the velocity of certain layers during the inversion. A value of **dd(i)** = 0 indicates that the *i*'th layer parameter does not change, whereas larger values will change more. Positive values are required. The *m* values refer to the corresponding layers of the model. If **dd(8)** = 0, all the **dd(i)** are set equal to 1.0. During the operation of the program, the **dd(i)** can be changed using MENU OPTION 31 from within the program. The purpose of this is to keep an unstable layer or a well-known layer from changing. When a damping value is used, the fixed layer will not change unless the damping value is much less than the **dd(ival)** = *fval*, unless all are alike.

Initial Earth Model File (e.g. modl.d)

Including the half space, the earth model file is allowed a maximum of 50 layers. The file consists of the following lines:

LINE 1: iunit, nf(10)

- iunit** = 0 km,km/sec,gm/cc (model units)
- = 1 ft,ft/sec,gm/cc
- = 2 m,m/sec,gm/cc

nf(10) = Input Format of Earth Model
 = 0 Input d,a,b,rho,qbinv – Inversion for b: a, rho fixed
 = 1 Input d,a,b,rhi,qbinv – Inversion for b: Poisson Ratio Fixed
 = 2 Input d,b,ratio,qbinv – Inversion for b: Poisson Ratio Fixed
 = 3 Input d,a,ratio,qbinv – Inversion for b: Poisson Ratio Fixed
 (**d** is layer thickness, **a** is layer P-wave velocity, **b** is layer S-wave velocity (0.0 for surface water layer), **rho** is layer density, **ratio** is Poisson ratio, **qbinv** is Q^{-1}_β)

LINE 2 (to end): the model information according to nf(10). The end of the model is indicated by d(halfspace) = 0.0

Dispersion Data File (e.g. disp.d)

The final input file to be described is the velocity dispersion file. This file can be made by entering the parameters manually following the format shown below, or especially in the case of averaging dispersion data from several paths, one can write a small program to do the averaging and putting the results in the required file format. Note a maximum of 1024 velocity observations can be used with a maximum of 512 different frequencies / periods.

LINE 1: iunit, ifrper

iunit as above for the earth model. These must agree!

ifrper = 0 input abscissa are period
 = 1 input abscissa are frequency.
 (If input is frequency, it is converted to period and henceforth period is displayed, and output).

LINE 2 (to the end): ilvry,iporg,imode,frper,val,dval

ilvry = 1 for Love
 = 2 for Rayleigh data
iporg = 1 for phase velocity
 = 2 for group velocity
 = 3 for gamma
imode = mode number with the convention that imode = 1 corresponds to the fundamental model, etc.
frper = abscissa
 = period if ifrper = 0
 = frequency if ifrper = 1
val = velocity value for iporg = 1,2
 = gamma value for iporg = 3
dval = velocity error estimate for iporg = 1,2
 = gamma error estimate for iporg = 3
 (Must be specified. If set to 0.0, will be internally set to 1.0)

With the three input files discussed above, the program surf can then proceed. Below is a discussion of all the menu options associated with surf. To invert group velocity for shear wave velocity earth structure, only a few of these options are used as shown in the tutorial following this discussion. (The stars show these options).

0 - relist menu

1 - Run Dispersion*

This can be run at any time. This is the most time consuming part of the program. This must be run if the velocity model is updated before using other options, except saving current state on ASCII file. After this, OPTIONS 2, 3, 4, 5, 11,12, 16, 17, 22 or 27 may be run.

2 – Run Velocity Inversion*

This makes use of the previous run of OPTION 1. This sets up the data file for the program srfinv, which creates the data file for OPTIONS 13, 14, 18, 19, 23, 24, 28 and 29. If the velocity model has been updated, OPTION 1 must be rerun first.

3 – Run Q (beta) Inversion

This makes use of the previous run of OPTION 1. This acts as OPTION 2, but just for the Q (beta) inverse problem.

4 – Run Simultaneous Veloc-Q Inversion

Set up data files for simultaneous inversion of velocity dispersion and anelastic attenuation dispersion.

5 – Run Depth Inversion*

Set up data files for inversion of velocity dispersion for layer thickness.
OPTIONS 2, 3, 4, 5 must be run before OPTIONS 13, 14, 18, 19, 23, 24, 28 or 29 can be run.
If OPTIONS 35 or 36 are changed, then OPTIONS 2, 3, 4 or 5 must be rerun before running any of the subsequent OPTIONS.

6 – Update Model (needs lam)*

Update the model. Unless OPTIONS 23 or 28 are invoked, OPTION 1 must be run next. If OPTION 4 is invoked and OPTION 35 is 2, then both the Q and velocity models are updated, and OPTION 1 must be run next.

7 – Call Plot Dispersion

Invoke the program srfphv, which will plot the observed and predicted velocity, and gamma dispersion for the current, previously updated model.

8 – Call Plot Model

Invoke the program srfphm, which will show the effect of a particular damping value on the inversion step. This is useful to avoid placing too many velocity inversions in the initial model.

10 – List Singular Values*

List the singular values in decreasing order. For m layers, $2m$ values will be listed corresponding to the velocity and Q (beta) inverse combined model. If one of these is not inverted, OPTION 2, 3 or 5, then second m eigenvalues will be equal to zero.

11 – Gamma Data Partial Derivatives

Mostly useful for diagnostics.

12 – Gamma Data Dispersion

Useful to see how well the model fits the data.

13 – List Q Model (needs lam)

Gives results.

14 – Q(beta) Resolving Kernel (needs lam)

16 – Velocity Data Partial Derivatives

17 – Velocity Data Dispersion*

18 – List Velocity Model (needs lam)*

If the inversion was for layer thickness changes, OPTION 5, then the output will show the change in later thickness. Otherwise it will show the change in the layer shear velocity.

19 – Velocity Resolving Kernels (needs lam)*

22 – ASCII Gamma Dispersion (file name)

23 – ASCII Q(beta) File (file name, lam)

24 – ASCII Q Resolving (file name, lam)

27 – ASCII Veloc Dispersion (file name)*

28 – ASCII Veloc File (file name, lam)*

29 – ASCII Vel Resolving (file name, lam)*

The OPTIONS in the twenty series, make use of the information of the previously saved model, e.g., the corresponding dispersion, resolving kernels. A proper sequence is to save the model, and rerun OPTIONS 2, 3, 4 or 5. It is done this way, since the model depends upon the damping value lam and is not finalised until the model is saved.

30 – Change Q(beta) inv

31 – Change dd(i), enter i, dd(i)*

Model parameter weighting is introduced according to the choice of nf(8) in obs.d. This OPTION permits a change in this value during program operation. A dd(i) = 0 will fix the model parameter. OPTIONS 2, 3, 4 or 5 must be run after changing this value. Initially, unless stated otherwise in the initial setup under **srfp**, all dd(i) = 1.0. Thus a dd(i) = 10.0 in a layer will force the inversion to emphasize that layer value.

32 – Enter Damping Factor (lam)*

This controls the change in the model at any iteration step. A value of 0 will yield large model changes. A value of 10 will yield a reasonably small model at any iteration step. If lam is changed, it affects the results of the MENU OPTIONS requiring a value of **lam**. (It is recommended to reduce damping to about 0.1 as convergence is approached)

33 – Reset Ref. Freq Causal Q (1.0 = def)

34 – Reset Q_a/Q_b (2.25 = default)*

If positive, the ratio is constant for all layers. It only influences the Rayleigh part of the inversion. If this number is negative, then a model with no bulk loss is assumed, and the ratio is given by $Q_a/Q_b = (3/4)(a/b)^{**2}$ where the ratio can now vary in each layer according to the ratio of layer compressed to shear velocity. This is not as general as permitting fixed values of the Q_a/Q_b ratio in each layer, but may be more realistic in some cases. If the ratio is negative, and the layer shear velocity is 0.0, e.g., a water layer, the ratio is internally set at a large number. In no case can the ratio b equal to 0.0. If it is, it is internally set to 2.25 to avoid division by zero!

35 – Inversion:*

0 – Non-causal (default), (1) Decoupled Causal, (2) Coupled Causal.

36 – Reset Inversion smoothing:*

0 – Damped inversion, no smoothing, 1 – damped differential smoothing inversion.

37 – Reset Number of Iterations

For a command line controlled run, this provides a shorthand way to repeat a sequence of operations.

38 – Temporary End*

Exit surf, but leave the temporary files unchanged so that **surf** can be restarted where it left off. One use of this might be to run **surf** from the command line in the background, and then run it online for final computations, rather than tie up the terminal for the dispersion to run.

39 – Permanent End*

Permanently terminate, by removing all the temporary files.

Inversion Tutorial

Below is an actual sample run to give an idea of how the program works. The sample shows the inversion process for shear velocity. The program is started off by typing the command, *surf*. It will proceed to list the control file, initial model file, name the dispersion data file and list the menu. (The program prompts by showing the word **ready**, upon which the user enters the option of choice)

```

akvamarin{vunganai}45: surf
  1.00000E-03  1.00000E-02  0.  1.00000E-02  0.
  0 0 0 1 0 0 1 0 0 0
modl.d
  3.10000  6.20000  3.02000  2.74000  5.00000E-02
  6.10000  6.20000  3.47000  2.81000  5.00000E-02
  4.00000  6.35000  3.67000  3.00000  5.00000E-02
  2.50000  6.30000  3.17000  3.10000  5.00000E-02
  3.10000  6.60000  3.48000  3.10000  5.00000E-02
  7.20000  7.10000  3.67000  3.20000  5.00000E-02
  4.00000  7.10000  3.76000  3.30000  5.00000E-02
  3.00000  7.10000  3.86000  3.30000  5.00000E-02
  39.8000  8.10000  4.25000  3.45000  5.00000E-02
  59.4000  8.30000  4.45000  3.50000  5.00000E-02
  14.9000  8.40000  4.15000  3.60000  5.00000E-02
  49.7000  8.50000  4.55000  3.60000  5.00000E-02
  0.  8.70000  4.76000  3.66000  5.00000E-02
disp.d
          SURF MENU
0- relist menu                22- ASCII Gamma Dispersion (file name)
1- Run Dispersion              23- ASCII Q(beta) File (file name,lam)
2- Run Velocity Inversion      24- ASCII Q Resolving (file name,lam)
3- Run Q(beta) Inversion
4- Run Simultaneous Veloc-Q Inversion  27- ASCII Veloc Dispersion (file name)
5- Run Depth Inversion        28- ASCII Veloc File (file name, lam)
6- Update Model (need lam)    29- ASCII Vel Resolving(file name,lam)
7- Call Plot Dispersion      30- Change Initial Q(beta) inv
8- Call Plot Model           31- Change dd(i), enter i,dd(i)
10- List Singular Values     32- Enter Damping Factor (lam)
                               33- Reset Ref. Freq Causal Q (1.0=def)
11- Gamma Data Partial Derivatives  34- Reset Qa/Qb (2.25 = default)
12- Gamma Data Dispersion    35- Inversion: (0) Non-Causal (default)
                               (1) Decoupled Causal
13- List Q Model (need lam)   (2) Coupled Causal
14- Q(beta) Resolving Kernel (need lam)  36- Reset Inversion Smoothing:(0) None
                               (1)Differential
16- Velocity Data Partial Derivatives  37- Reset Number of Iterations
17- Velocity Data Dispersion  38- Temporary End
18- List Velocity Model (need lam)  39- Permanent End
19- Velocity Resolving Kernels(need lam)

Enter Command at READY Prompt
ready
34 (Verify qa/qb parameter)
reset Qa/Qb : qaqb =                2.25000
2.25
  2.25000
ready
35 (Verify causality type)
non-causal(0),uncpled cau(1),coup caus(2): invcsl=      0
0

```

0

ready

36 (*Verify inversion type*)

smoothing constraint none(0),diff(1): nft= 0

1

1

ready

1 (*find dispersion and eigenfunctions*)

ready

17 (*list dispersion*)

periods, observed and computed dispersion, standard deviations:

L U	1	8.0000000	3.4000001	3.5034561	1.0000000
L U	1	9.0000000	3.4900000	3.5080583	1.0000000
L U	1	10.0000000	3.3950000	3.5110426	0.2330000
L U	1	12.0000000	3.6600001	3.5164971	0.0710000
R U	1	7.0000000	2.9100001	3.2974966	1.0000000
R U	1	8.0000000	3.0999999	3.2885423	0.1700000
R U	1	9.0000000	3.1400001	3.2682309	0.1700000
R U	1	10.0000000	3.1350000	3.2421734	0.2050000
R U	1	12.0000000	3.1600001	3.1878176	0.2400000

ready

2 (*invert for velocity*)

Weighted RMS(vel) = 0.751308 (*RMS between observed and predicted*)

Model RMS= 0.864821 NOBS= 53.0000 (*NOBS is the number of observations for which there is a corresponding theoretical value. NEGATIVE Model RMS means more model parameters than observations*)

ready

10 (*List singular values*)

8.21969 5.11933 2.49583 0. 0. 0.

(*For convenience of user, singular values are from a scaled matrix, which will have a maximum a maximum singular value of 10. This is done to make the entry of the damping value lam more convenient.*)

ready

32 (*Reset damping value - until convergence, this should be on the order of the largest singular value. If this is too small initially, artificial low or negative velocity layers may be introduced into the model, which may not be removable later due to lack of resolution*)

enter damping factor: lam= 0.

1.00000

ready

18 (*list model for this value of damping. For complicated models, the model listed really depends strongly upon the damping value. A large value of damping causes little change in the model*)

INVERSION FOR S-VEL

Estimated data standard dev.: 0.400034

RMS model perturbation: 8.15731E-02

DEPTH	THICKNESS	S-VEL	SIG	DELVL	RESL	in H DEL (VEL)
1.5500	3.1000	3.2471	0.470E-01	0.996E+01	0.2271	
6.1500	6.1000	3.6665	0.418E-01	0.115E+02	0.1965	
11.2000	4.0000	3.8392	0.343E-01	0.245E+02	0.1692	
14.4500	2.5000	3.3145	0.380E-01	0.439E+02	0.1445	
17.2500	3.1000	3.6000	0.489E-01	0.547E+02	0.1200	
22.4000	7.2000	3.7606	0.590E-01	0.550E+02	0.0906	
28.0000	4.0000	3.8231	0.597E-01	0.518E+02	0.0631	
31.5000	3.0000	3.9045	0.623E-01	0.468E+02	0.0445	
52.9000	39.8000	4.2837	0.706E-01	0.429E+02	0.0337	
102.5000	59.4000	4.4946	0.578E-01	0.594E+02	0.0446	
139.6500	14.9000	4.1833	0.394E-01	0.464E+02	0.0333	
171.9500	49.7000	4.5710	0.228E-01	0.497E+02	0.0210	
221.6500	0.0000	4.7696	0.105E-01	0.447E+02	0.0096	

(*Since the RMS was scaled to 1.0 going into this program, this model will reduce the scaled data RMS*)

to 0.37, which is an improvement. The resolving moment is a second moment of layer depth with the resolving kernel squared, and indicates the ability of the data to resolve information in the layer. If the resolving estimate is less than a layer thickness, the layer thickness is given. The half space value is not useful.)

ready

32 (lets see the effect of another damping value)

enter damping factor: lam= 1.00000

0.1

1.00000E-01

ready

18

INVERSION FOR S-VEL

Estimated data standard dev.: 0.372798

RMS model perturbation: 1.00090E-01

DEPTH THICKNESS S-VEL SIG DELVL RESL in H DEL (VEL)

1.5500 3.1000 3.3886 0.116E+00 0.141E+02 0.3686

6.1500 6.1000 3.6378 0.616E-01 0.965E+01 0.1678

11.2000 4.0000 3.7905 0.728E-01 0.211E+02 0.1205

14.4500 2.5000 3.3002 0.910E-01 0.357E+02 0.1302

17.2500 3.1000 3.6269 0.985E-01 0.416E+02 0.1469

(lower damping gives better resolution, a reduced data RMS and a greater model perturbation.)

ready

6 (update velocity model with current value of damping)

UPDATING V

ready

1 (rerun dispersion)

ready

2 (invert for velocity)

Weighted RMS(vel) = 0.372238

Model RMS= 0.428478 NOBS= 53.0000

ready

.....

until convergence (Compare observed dispersion data to calculated data)

ready

27 (save the dispersion data in an ASCII file)

disp.out

ready

28 (Save velocity model in ASCII file)

Enter File Name for Velocity Model

vmdl.out

ready

29 (save the velocity resolution in an ASCII file)

Enter File Name for Velocity Resolution

vres.out

ready

38 (Temporary end. Do not remove work files)

The file vmdl.out is the velocity model that existed at the last update. The file is in the same format as the initial model input file. Thus it can be used as starting model in the program.

In addition to the velocity data in ASCII files, the dispersion data plots (Love and Rayleigh), shear wave velocity model plot and resolution kernel plot, are obtained.

Dispersion Data Plots

The plots showing the calculated Love and Rayleigh wave dispersion are produced using the program *srfpvh*, as follows:

```
srfpvh > srfpvh.plt
```

This is an interactive process, where questions are asked and upon answering them all, the dispersion data is piped to the file *srfpvh.plt*. To view the plot, convert the file to postscript using *plotnps* as shown earlier. Since the Love wave and Rayleigh wave dispersion plots are processed separately, the *.plt file should be saved before the next run.

Shear Velocity Model Data Plots

The same procedure as for the dispersion data plots is followed, except that the program *srfpvm* is used instead of *srfpvh*.

Resolution Kernels

The program *vqplt* is a graphic program used to plot shear velocity, compressional velocity, Q beta inverse, resolving kernels, density or Poisson ratio models. In this tutorial it is used to plot the velocity inverse structures together with the resolution kernels (Figure 6). The program uses a control file called *vqplt.d*, which can be edited. An example of the file is found in SEISAN. The program is run by simply typing the command *vqplt*. This produces a plot file whose name format is **plotxxxxx**, and xxxxx can be any number chosen by the program. To view the plot, the program *plotnps* can be used to convert it to postscript. A full explanation of the input parameters is found in the *Computer Programs for Seismology* manual (IV) by Robert B. Herrmann (Saint Louis University, USA).

FIGURE 3

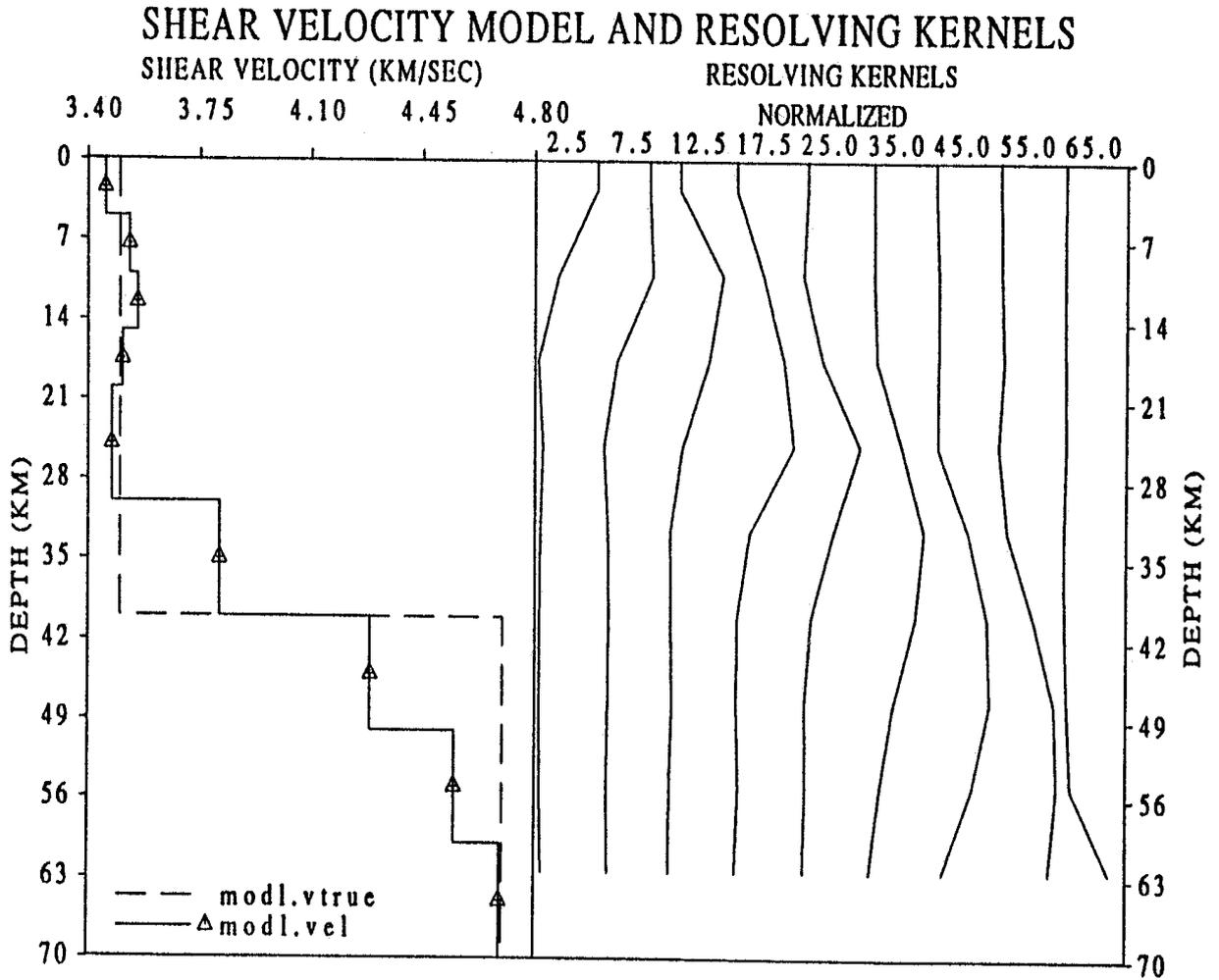


Figure 6: Shear velocity model and resolving kernels

Evaluation of Results

The evaluation of shear wave velocity structure obtained from the inversion of group velocities is complicated and difficult. The inversion of group velocity is very non-unique, meaning that several different velocity structures could match observed group velocities easily.

During the inversion process, one uses the match between the observed and calculated group velocity data for convergence. This can also be used to assess the final results. Resolution kernels are also used to evaluate the reliability of the final model. Sharp peaks in the kernels, where the width of the peaks are smaller than the thickness of the corresponding layer, implies good resolution.

Since several different shear velocity models can produce a good match between observed and calculated group velocities with sharp resolution kernels, it is important to use a priori tectonic and stratigraphic information to decide on the reliability of the

final models.