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The DMG Quick Reference Manuals

Hedgehog Non-Linear Inversion

Computer exercises

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Hedgehog Non-Linear Inversion

Required input files

Required input files can be found in **/XDST/Examples/Hedgehog/LF/Base**. Copy them into a directory dedicated to the computations.

Different computations should be performed in different directories. The root name of the run is defined in file pfdg13.par, and should be changed from run to run in order to better distinguish each execution.

Connect to is01 server, using the Terminal application:

```
[im02:/XDST/sg01] sg01% ssh is01
[im02:/XDST/sg01] sg01%
```

To create the working directory and copy the required input files, give the following commands:

```
[is01:/XDST/sg01] sg01% cdt
[is01:/tmpXDST/sg01] sg01% mkdir HedLF
[is01:/tmpXDST/sg01] sg01% cd HedLF
[is01:/tmpXDST/sg01/HedLF] sg01% cp /XDST/Examples/Hedgehog/LF/Base/* .
[is01:/tmpXDST/sg01/HedLF] sg01% ls -l
total 56
-rw-r--r-- 1 sg01 dstguest 11146 Feb 23  2011 E7.25N45.25.inp
-rwxr-xr-x 1 sg01 dstguest   926 Sep 23  2010 GMT_hedgAllMod
-rwxr-xr-x 1 sg01 dstguest 12940 Nov 26  2008 checkInpNew
-rw-r--r-- 1 sg01 dstguest   171 Feb 23  2011 hed.cntl
-rwxr-xr-x 1 sg01 dstguest 17784 Apr 19  2010 hog2mod
[is01:/tmpXDST/sg01/HedLF] sg01%
```

Example exercise

1) See the input file **E7.25N45.25.inp** :

```
[is01:/tmpXDST/sg01/HedLF] sg01% cat E7.25N45.25.inp
10.
COMMENT Input for inversion
COMMENT of phase and group velocity
COMMENT of Rayleigh fundamental mode.
COMMENT TransMed geo4 No3 7.25 45.25 e-3 IV. Parameterization by EB. Upper crust
from Tesauro09 & Cassinis06
CLEAR
PROGRAM PROCEDURE
       14         1
   9   2 105 111   3 108 111  12   5 113   8 102   7 102

PARAMETERS
   3.400 0.100 6.000
        11


           2.600   0.100     2.499     4.001
           3.850   0.200     2.499     4.101
           4.400   0.250     3.699     5.201
           4.900   0.400     3.599     5.201
           4.150   0.400     3.849     5.201
```

```
          1.730   1.000     1.710     1.740
          7.000   2.000     1.999    11.001
         26.000  10.000     9.999    46.001
         55.000  25.000    29.999    80.001
         45.000  55.000    44.999   100.001
         55.000  55.000    54.999   110.001
   999
CONLIM
   .002   10.0   .002   10.0   .002   10.0
  500.0    1.0    3.0    1.0    3.0    0.1
0.1    .080   0.10   0.080
99999.099999.099999.099999.099999.099999.0
CROSS SECTION DATA
         1        39        39                              0
6371.00      1.2        2.10      2.10     9999.0
6370.90      1.2        2.10      2.10     9999.0
6370.90      2.65       4.60      2.55     9999.0
6370.50      2.65       4.60      2.55     9999.0
6370.50      3.00       5.20      2.65     9999.0
6369.00      3.00       5.20      2.65     9999.0
6369.00      3.20       5.54      2.70     9999.0
6367.00      3.20       5.54      2.70     9999.0
6367.00      3.30       5.70      2.70     9999.0
6365.00      3.30       5.70      2.70     9999.0
6365.0       0.0        0.0       2.750    9999.0
   0.0       0.0        0.0       2.750    9999.0
   0.0       0.0        0.0       2.950    9999.0
   0.0       0.0        0.0       2.950    9999.0
   0.0       0.0        0.0       3.100    9999.0
   0.0       0.0        0.0       3.100    9999.0
   0.0       0.0        0.0       3.200    9999.0
   0.0       0.0        0.0       3.200    9999.0
   0.0       0.0        0.0       3.300    9999.0
   0.0       0.0        0.0       3.300    9999.0
0000.00      4.75       8.22       3.40    9999.9
6021.00      4.75       8.22       3.40    9999.9
6021.00      4.90       8.48       3.50    9999.9
6004.00      4.90       8.48       3.50    9999.9
6004.00      4.90       8.48       3.55    9999.9
5954.00      4.90       8.48       3.55    9999.9
5954.00      5.00       8.65       3.60    9999.9
5920.00      5.00       8.65       3.60    9999.9
5920.00      5.28       9.13       3.85    9999.9
5885.00      5.28       9.13       3.85    9999.9
5885.00      5.28       9.13       3.95    9999.9
5849.00      5.28       9.13       3.95    9999.9
5849.00      5.28       9.13       4.00    9999.9
5814.00      5.28       9.13       4.00    9999.9
5814.00      5.28       9.13       4.06    9999.9
5778.00      5.28       9.13       4.06    9999.9
5778.00      5.45       9.43       4.12    9999.9
5761.00      5.45       9.43       4.12    9999.9
5761.00      5.45       9.43       4.12    9999.9
    CLAE         1         11         1
    SUBH         1          7         0
    STRE         1         12         1
    STRE         1         13         1
    CLAE         1         13         1
    SUBH         1          8         0
    STRE         1         14         1
    STRE         1         15         1
    CLAE         1         15         1
    SUBH         1          9         0
    STRE         1         16         1
    STRE         1         17         1
    CLAE         1         17         1
```

```
    SUBH        1        10        0
    STRE        1        18        1
    STRE        1        19        1
    CLAE        1        19        1
    SUBH        1        11        0
    STRE        1        20        1
    STRE        1        21        1
    CLAH        1         1        0
    STRE        1        11        2
    STRE        1        12        2
    CLAE        1        11        2
    MLTH        1         6        0
    STRE        1        11        3
    STRE        1        12        3
    CLAH        1         2        0
    STRE        1        13        2
    STRE        1        14        2
    CLAE        1        14        2
    MLTH        1         6        0
    STRE        1        13        3
    STRE        1        14        3
    CLAH        1         3        0
    STRE        1        15        2
    STRE        1        16        2
    CLAE        1        16        2
    MLTH        1         6        0
    STRE        1        15        3
    STRE        1        16        3
    CLAH        1         4        0
    STRE        1        17        2
    STRE        1        18        2
    CLAE        1        18        2
    MLTH        1         6        0
    STRE        1        17        3
    STRE        1        18        3
    CLAH        1         5        0
    STRE        1        19        2
    STRE        1        20        2
    CLAE        1        20        2
    MLTH        1         6        0
    STRE        1        19        3
    STRE        1        20        3
    END
SYSOUT
        14        6 mmmmm
        30        6 AFTER SYSOUT
OUTFLG
        14        1 mmmmmmm
        30        1 AFTER OUTFLG
RAYLEIGH DATA
    0
         1      11     0.0       0.058     0.061
              0.0     150.00     0.0       3.612     0.081    0.10000E-04
              0.0     125.00     0.0       3.697     0.081    0.10000E-04
              4.011   100.00     0.08      3.802     0.081    0.10000E-04
              3.956    80.00     0.06      3.801     0.123    0.10000E-04
              3.864    50.00     0.06      3.627     0.096    0.10000E-04
              3.751    35.00     0.08      3.447     0.096    0.10000E-04
              3.702    30.00     0.09      3.311     0.096    0.10000E-04
              3.65     25.00     0.111     3.067     0.096    0.10000E-04
              3.561    20.00     0.151     2.865     0.096    0.10000E-04
              0.0      15.00     0.0       2.597     0.101    0.10000E-04
              0.0      10.00     0.0       2.267     0.126    0.10000E-04
END OF DATA

10.
```

```
STOP
END
[is01:/tmpXDST/sg01/HedLF] sg01%
```

2) Check that R.M.S. threshold values are correct

```
[is01:/tmpXDST/sg01/HedLF] sg01% checkInpNew E7.25N45.25.inp

The average test for phase velocity from the input file is: 0.0580. The 0.65 of the
average single error is: 0.0587(0.0542-0.0632)
The average test for group velocity from the input file is: 0.0610. The 0.65 of the
average single error is: 0.0634(0.0585-0.0683)
[is01:/tmpXDST/sg01/HedLF] sg01%
```

3) Run hedgehog inversion in background (&), so you will be able to use the terminal while the program is running (run will take up to a few minutes)

```
[is01:/tmpXDST/sg01/HedLF] sg01% hed_lf18.out &
```

Meanwhile you can check the output file and look which periods are “passed” in the inversions, i.e. solutions are found within the single error point range, starting from lowest period:

```
[is01:sg01/HedLF/Sg01Test01] sg01% grep -n 'K =  11 U' outE7.25N45.25.out


1651: K =  11 UREXP =  2.2669999599 UR =  2.3112831655 OR =  0.6283185482 DIFTST =
0.1260000020 DIF =0.0442832056 ....GRVEL ....277
4432: K =  11 UREXP =  2.2669999599 UR =  2.3612556714 OR =  0.6283185482 DIFTST =
0.1260000020 DIF =0.0942557114 ....GRVEL ....277
14524: K =  11 UREXP =  2.2669999599 UR =  2.3612553778 OR =  0.6283185482 DIFTST =
0.1260000020 DIF =0.0942554179 ....GRVEL ....277
18921: K =  11 UREXP =  2.2669999599 UR =  2.3112831259 OR =  0.6283185482 DIFTST =
0.1260000020 DIF =0.0442831659 ....GRVEL ....277

ecc...

[is01:/tmpXDST/sg01/HedLF] sg01%
```

If there are no solutions for the searched period you can check iteratively greater periods till one is passed.

If the lowest period is passed, you can search for accepted solutions (i.e. solutions whose RMS is in the selected threshold level of 60%-70%)

```
[is01:/tmpXDST/sg01/HedLF] sg01% grep -n '..ACC' outE7.25N45.25.out

1655:0 LSTBAS =    1 PNTNBR =    2 ..ACCEPT..100 HHFDEX =  1  1  0  0  0  0  0  0  0  0  1
4436:0 LSTBAS =    1 PNTNBR =    3 ..ACCEPT..100 HHFDEX =  0  0  0 -1  0  0 -1  0  0  1  0
18925:0 LSTBAS =    1 PNTNBR =    4 ..ACCEPT..100 HHFDEX =  1  1  0 -1  0  0  0  0 -1  1  0
29313:0 LSTBAS =    1 PNTNBR =    5 ..ACCEPT..100 HHFDEX =  0 -1  0 -1  0  0 -1 -1  0  1  0
30564:0 LSTBAS =    1 PNTNBR =    6 ..ACCEPT..100 HHFDEX =  0 -1  0  0  0  0 -1 -1  1  0  1
41683:0 LSTBAS =    1 PNTNBR =    7 ..ACCEPT..100 HHFDEX =  1  1  0 -1  0  0  0  0 -1  1  1
53445:0 LSTBAS =    1 PNTNBR =    8 ..ACCEPT..100 HHFDEX =  0 -1  0 -1  0  0 -1 -1  1  1  0
53788:0 LSTBAS =    1 PNTNBR =    9 ..ACCEPT..100 HHFDEX =  0 -1  0 -1  0  0 -1 -1  0  1  1
59827:0 LSTBAS =    1 PNTNBR =   10 ..ACCEPT..100 HHFDEX =  1  1  1 -1  0  0  0  1 -1  1  0
74504:0 LSTBAS =    1 PNTNBR =   11 ..ACCEPT..100 HHFDEX =  0 -1  0 -1  1  0 -1 -1  0  1  1
74806:0 LSTBAS =    1 PNTNBR =   12 ..ACCEPT..100 HHFDEX =  0 -1  0 -1  0  0 -1 -1  1  1  1
79852:0 LSTBAS =    1 PNTNBR =   13 ..ACCEPT..100 HHFDEX =  1  1  1 -1  0  0  0  1 -1  1  1
84318:0 LSTBAS =    1 PNTNBR =   14 ..ACCEPT..100 HHFDEX = -1  0 -1 -1  0  0 -1 -1 -1  1  1
```

```
86273:0 LSTBAS =    1 PNTNBR =   15 ..ACCEPT..100 HHFDEX =  0 -1  0 -1  1  0 -1 -1  1  1  1

[is01:/tmpXDST/sg01/HedLF] sg01%
```

4) If the number of solutions is acceptable and parameters step is varying at most ±1, you can print the other output files:

```
[is01:/tmpXDST/sg01/HedLF] sg01% hog2mod outE7.25N45.25.out

YOU CAN USE:
hog2mod hedghog_output_name [[[0|1] 0|1] 0|1]
0 - No, 1 - Yes
1. calculate the models
2. calculate disp.curves
3. terminate the output file

nL = 39  nD = 11  nS = 14
The solution 8 has averige RMS.

[is01:/tmpXDST/sg01/HedLF]
```

Two files, *info* and *0_info* are created. The file *info* contains the codes for all obtained solutions. The file *0_info* contains the following information: codes of all solutions, r.m.s. of phase velocity curve and r.m.s. of group velocity curve, the difference between the r.m.s. at each solution and average r.m.s., as well as the sum of the differences for phase velocity curve and group velocity curve; the parameters section of the input file, the data section of the input file, and the initial model. In this way all changes that are made during the inversion are saved sequentially in the file 0_info.

5) If the results are acceptable, you can calculate the structural models:

```
[is01:/tmpXDST/sg01/HedLF] sg01% hog2mod outE7.25N45.25.out 1
```

A file #model will be created for each accepted solution #. Otherwise repeat points 1) to 4) varying the parameter step (see ***Parameterization guidelines***)

6) Plot the models

```
[is01:/tmpXDST/sg01/HedLF] sg01% GMT_hedgAllMod e-3-IV 350 8

gmtset: WARNING: Both old-style DEGREE_FORMAT and PLOT_DEGREE_FORMAT present
in .gmtdefaults
gmtset: WARNING: PLOT_DEGREE_FORMAT overrides old DEGREE_FORMAT
psxy: Working on file tmp
psxy: Working on file tmp

[is01:/tmpXDST/sg01/HedLF]
```

where e-3-IV is the cell identifier, 350 the maximum depth, and 8 the preferred solution number (e.g. the one with average r.m.s.). The plot with the solutions can be visualized with gs

```
[is01:/tmpXDST/sg01/HedLF] sg01% gs models_e-3-IV_350.ps
```

Variation 1. Modify the parameters step.

Modify the parameters step acting on one parameter at any iteration and look for the differences in the results. Start from the first parameter (red, first inverted layer V_S) remembering that for this parameter Hedgehog search starts from -1, and checking the upper and lower limit variation (green)

```
 2.600    0.100     2.499     4.001
 3.850    0.200     2.499     4.101
 4.400    0.250     3.699     5.201
 4.900    0.400     3.599     5.201
 4.150    0.400     3.849     5.201
 1.730    1.000     1.710     1.740
 7.000    2.000     1.999    11.001
26.000   10.000     9.999    46.001
55.000   25.000    29.999    80.001
45.000   55.000    44.999   100.001
55.000   55.000    54.999   110.001
```

Is the new parameter suitable? If not, try to modify the 7th parameter (first layer thickness).

```
 2.600    0.100     2.499     4.001
 3.850    0.200     2.499     4.101
 4.400    0.250     3.699     5.201
 4.900    0.400     3.599     5.201
 4.150    0.400     3.849     5.201
 1.730    1.000     1.710     1.740
 7.000    2.000     1.999    11.001
26.000   10.000     9.999    46.001
55.000   25.000    29.999    80.001
45.000   55.000    44.999   100.001
55.000   55.000    54.999   110.001
```

You can iteratively act on the others parameters, following the **Parameterization Guidelines**, till a suitable parameterization is obtained.

Variation 2. Modify the upper fixed structure.

Upper fixed structure is very important in the inversion process and is usually fixed according to reliable independent data. Different upper structure can lead to different results even in the deep inverted parameters.

For example modify the input file **E7.25N45.25.inp**, reducing the thickness of the sediments in this way:

```
CROSS SECTION DATA
         1        39         39                           0
6371.00      1.2        2.10      2.10     9999.0
6370.90      1.2        2.10      2.10     9999.0
6370.90      2.65       4.60      2.55     9999.0
6370.80      2.65       4.60      2.55     9999.0
6370.80      3.00       5.20      2.65     9999.0
6369.00      3.00       5.20      2.65     9999.0
6369.00      3.20       5.54      2.70     9999.0
6367.00      3.20       5.54      2.70     9999.0
6367.00      3.30       5.70      2.70     9999.0
6365.00      3.30       5.70      2.70     9999.0
6365.0       0.0        0.0       2.750    9999.0
```

Which are the differences? Are all the parameter steps still suitable for this upper structure? If not, modify the parameters one by one, following the ***Parameterization Guidelines.***

Parameterization Guidelines.

2.1. It is suitable to explore the layers between 5km (or 10km) to 350km, because the surface waves in these period ranges are mainly sensitive to the S-wave velocity of the layers at these depths.

If from the literature it is known that the crust is thin (10km - 15km), the fixed part should be thinner and vice versa for thick crust.

2.2. At these period ranges of surface wave dispersion curves, it is suitable to parameterize the structural model with 5 layers that can be explored comprehensively. One parameter for the S-wave velocity and one parameter for the thickness of each layer can be used.

2.3. When the thickness of the crust is normal (about 30 km) it is convenient to parameterize the first inverted layer as upper crust and the second layer as lower crust, fixing a priori the sedimentary cover.

The following should be taken into account:

2.3.1. The S-wave velocity in the crust could not exceed 4.0 km/s (there are some cases where the velocity can exceed 4.0 km/s, but they are exceptions and should be in agreement with other results in literature – the relevant references must be mentioned in the paper describing the inversion results).

2.3.2. When the starting values for the thickness of this 2 layers in the crust are chosen, it should be kept in mind that the sum of the fixed upper part and the thickness of the first 2 layers have to be approximately equal to the thickness of the crust in this region, usually known from literature. The thickness step for these 2 layers should be suitable to allow for some variation in the thickness of the crust.

2.3.3. Sometimes during the inversion the second layer can convert into a mantle layer. In this case the thickness variability range for the first layer should be increased in order to reach the crustal thickness and the velocity and thickness variability ranges of the second layer should be increased also with values suitable for the mantle layers (be sure that also P-wave velocity and density is changed).

2.3.4. When the region under study has a thin crust, it is obvious that only the first layer should be parameterized as a crust layer.

2.4. **Velocity parameterization** of the mantle layers. The following recommendations should be taken into account:

2.4.1. The mantle below 50km couldn't have S-wave velocity less than 4.0km/s taking into account some a priori information from the literature. This rule is valid also for the layers just below the Moho.

But for regions with active volcanoes the S-wave velocity in the upper mantle can be very low because of the high temperature and the melting of the materials.

2.4.2. The highest S-wave velocity in the mantle could not exceed 4.8km/s taking in to account some a priori information from the literature. This value can be increased to 4.9km/s, but only if independent data from literature indicate reliable values larger than 4.9km/s.

2.4.3. Usually for the deepest parameterized layers (but if necessary for all the layers) of the model, the step of the velocity can be quite large and the whole parameter space (between 4.0km/s and 4.8km/s for the mantle layers) can be explored only if a proper choice of the initial value is made.

For the mantle layers, there are two cases. The first one is when the initial velocity in the layer is close to the lower a priori boundary (4.0km/s). In this case the initial value should be changed according to the step so the minimum value of the velocity obtained as a solution is 4.0km/s and the maximum value of the variability range can be, if necessary, extended to velocities higher than 4.8 km/s, so that the entire range (4.0km/s - 4.8km/s) is explored. The second case is when the initial velocity in the layer is close to the maximum acceptable value (4.8 km/s). The initial value of the velocity should be adapted according to the step so that the maximum possible velocity of the solutions is 4.8 km/s. In analogy with case one, to explore the whole velocity range between 4.0 km/s and 4.8 km/s the minimum of the velocity range should be extended to lower velocities than 4.0km/s.

2.4.4. The first fixed layer just below the last parameterized layer (5th) has fixed velocity (in the models that are used in the Mediterranean, the velocity is 4.75 km/s) and varying thickness (depending upon the thickness parameterization and the obtained solutions). The initial value of the velocity should be adapted according to the step so that the maximum possible velocity of the solutions is 4.75 km/s, keeping in mind the criteria described at 2.4.3.

2.5. **Thickness parameterization** for mantle layers. The thickness of the mantle layers are restricted by the maximum explored depth, because of this there is some limitation in the thickness parameterization. The steps should be in agreement with the results given by the partial derivatives computed for the model defined by the initial values of the parameters. During the inversion, these initial values and their steps may have to be changed, but not so significantly that the indication given by partial derivatives looses meaning. The thickness ranges can be varying, but taking into account the following:

2.5.1. When the variability range of the thickness of a layer is changed the sum of the fixed upper crust and the maximum possible value that the thickness can reach should be less then 350km (or the maximum depth that is explored).

2.5.2. It should be kept in mind that the period and the wavelength of the surface waves increases with increasing depth therefore at mantle depths the inverted layers cannot be very thin or their steps very small, as indicated by partial derivatives. So the thickness of the parameterized layers should increase with increasing depth or at least should not decrease. There may be some exceptions for regions with some special features.

2.5.3. When, for some layer, the maximum thickness is reached during inversion, the variability range of the thickness should be extended (keeping in mind 2.5.1), but the maximum limit should not be more than 4 times the step. There are some exceptions for the crustal layers - see 2.3.2.

2.5.4. If the maximum thickness isn't reached by the obtained solutions, it is necessary to decrease this limit and in this way some of the thickness variability ranges of the deeper layers must be increased.

2.5.5. If the minimum limit of the thickness is reached it can be decreased, but it couldn't be less than the step, and greater than 2 times step.

2.5.6. Usually for the deepest parameterized layers of the model the thickness can vary only between the extreme values defining the thickness range. In the case, it should be kept in mind that: the minimum thickness couldn't be equal or less than the step and greater than 2 times the step.

2.5.7. If in all obtained solutions the maximum limit of the thickness ranges is reached for all layers, if the velocity in the last parameterized layer is close to 4.0km, and if the maximum explored depth is reached, the limiting depth can be increased, but only if there isn't any other possibility to extend the thickness range of the last layer.

2.6. The first layer in the fixed part of the lower structure has fixed velocity (4.75 km/s in the example) and varying upper boundary that depends of the sum of the obtained thickness of the parameterized layers. This layer behaves as a buffer zone between the explored layers and layers with the fixed parameters. It reaches the depth of 350km (or the deepest explored depth, in general not much larger than 350 km) and couldn't be very thin, especially in the cases when the velocity in the layer immediately above it is around 4.0 km/s. When the parameterized layers from the obtained solutions reach the depths of 350km the lower limit of 350 should be increased (see 2.5.7).

Appendix 1

Example of the inversion of group velocity data in the period range 10-150s and phase velocity data in the period range 25-150s