2LAYINV

Laterally constrained two-layer inversion of VLF-R measurements

User's guide

Version 1.0a

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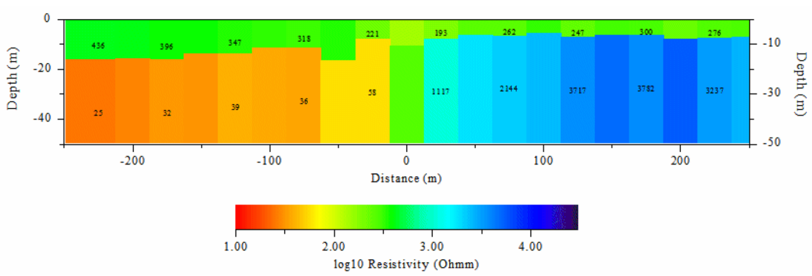

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Introduction

The 2LAYINV program is used to interpret geophysical, electromagnetic VLF-R data (apparent resistivity and phase) measured along a single profile at a single frequency. The inversion is made separately for each data point using a one-dimensional two-layer earth model. As such the program suits well the interpretation of the thickness and resistivity of relatively thin resistive (soil and till) layers and the resistivity variations of the basement rocks. Note that the inversion model is still only one-dimensional and that the interpretation results actually yield a pseudosection of the 2-D resistivity distribution.

Starting from an initial model linearized inversion with adaptive damping is used to optimize the thickness and the resistivity of the overburden layer and the resistivity of the basement so that the model minimizes the error between the measured and the computed VLF-R data. Laterally constrained inversion is obtained by minimizing the roughness of the model that is the variation of the model parameters between neighboring points, together with the data error. As a result a smoothly varying (Occam inversion) model is obtained. The roughness and/or the fix/free status the parameters can be set manually to allow discontinuities and to incorporate a priori data in the model.

The 2LAYINV program requires a PC with 32-bit Windows 9x/NT4/2000/XP operating system and a graphics display of at least 1024×800 resolution. Memory requirements and processor speed and are not critical, since the program uses dynamic memory allocation and the inverse computation is fast to perform even on slow computers. The 2LAYINV program includes simple graphical user interface (GUI) that allows changing some inversion parameters, handling file input and output, and visualization of the VLF-R data and the two-layer model section. The user interface and the data visualization are based on the DISLIN graphics library.

Setting up

The distribution file (2LAYINV.ZIP) can be downloaded free of charge from author's web-site at the University of Oulu, Finland (http://www.gf.oulu.fi/~mpi).

The program requires two files:

2LAYINV.EXE	the executable file
DISDLL.DLL	dynamic link library for the DISLIN graphics

The distribution file contains also a description file (_README.TXT), this user's manual (2LAYINV_MANU.PDF), and an example data file (EXAMPLE.DAT).

To install the program, unzip (Pkzip/Winzip) the distribution file into a new folder. To be able to start the program from a shortcut that locates in a different directory, move or copy the DISDLL.DLL file into the WINDOWS\SYSTEM folder or define the system path (control panel/system/environment).

Starting up

After starting the program it reads graph parameters from the 2LAYINV.DIS file. If the file cannot be found, a new one with default parameter values is created automatically. The program then displays the standard (Windows) Open file dialog so that the user can select the input data file containing the measured VLF-R data. If the file format is incorrect the program halts and error messages may be read from 2LAYINV.ERR file.

The program then creates an initial two-layer model based on the data and computes the synthetic two-layer response. Finally, the program builds up the GUI window and creates the graph of the measured and computed VLF-R response and the two-layer resistivity model as shown in the Appendices. If the user cancels the open file operation the graph area will be disabled.

Menus

The main window of the 2LAYINV application has three menus. The *File* menu has items:

Read VLF-R data	open and read in measured VLF-R data from a *.DAT file.
Save VLF-R data	save the measured and computed VLF-R data into a *.OUT file.
Save 2-Layer model	save the current 2-layer model into a *.LAY file.
Read 2-Layer model	read a previously saved 2-layer model from a *.LAY file.
Read disp.	read new graph parameters from a *.DIS file.
Save Graph as PS	save the graph in Adobe's Postscript format.
Save Graph as EPS	save the graph in Adobe's Encapsulated Postscript format.
Save Graph as PDF	save the graph in Adobe's PDF format.
Save Graph as WMF	save the graph in Windows metafile format.
Save Graph as GIF	save the graph in GIF-compressed format.

Selecting any of these options brings up a typical Open/Save file selection dialog that can be used to provide the name of the file for open/save operation. Data files are stored in text format. The graphs are saved as they appear on the screen in landscape A4 size.

The *2-layer* menu has options:

Weights in/out	enable and disable data weights.
Labels in/out	show or hide the resisitivity labels in pseudosection.
Color scale	contains submenu items to change the current color scale.

Data weights are used to increase or decrease the importance of individual data points in the inversion. The weights are read from the input data file together with the measured VLF-R data. See the chapter on file formats for more information. If weights do not exist the corresponding menu item will be inactive. Total of five color scales can be used in pseudosections. The reverse rainbow scale is the default (red = conductive, blue = resistive).

The *Exit* menu has only one item, which is used to confirm the exit operation. On exit the current results are automatically saved into 2LAYINV.OUT file is that contains the interpreted two-layer model. Errors that are encountered before the GUI starts up are reported in the 2LAYINV.ERR file. Inside GUI mode run-time errors are displayed on the screen.

Controls

The *Freq* text field at the top of the control pane on the left side of the main window is used to define the frequency of the VLF station used in the measurements. The default value is 16000 Hz, which corresponds to GBR. Examples of other (European) VLF stations are DHO38 23400 Hz, JXN/JXZ 16400 Hz and FUO 15100 Hz.

The *R1-mean* text field shows the mean resisitivity of the overburden layer. The resistivity of the overburden is reset to this value when the *2-Layer* push button below it is pressed.

The *2-Layer* button performs direct two-layer inversion using the well known exact inverse solution for the thickness of the overburden and the resisitivity of the basement when the resisitivity of the overburden is fixed (to *R1-mean*). This option does not utilize any lateral constraining and the inverse solution is exact for each point, as long as the response suits two-layer model (e.g., phase ≠ 45 deg.).

The *Update* button is used to validate the changes made to the text fields and to perform a forward computation.

The following six text fields define various inversion parameters:

Lagsca defines the so-called Lagrange multiplier (L), which determines whether the inversion tries to minimize the data error instead of the model roughness. If $L > 1$, then the model will become very smooth and the fit will be poor. If $L<1$, then the fit will be good but the model will become rugged. Typically the values range between 0.1 and 10. Note that both the data and the model parameters are scaled using the maximum data variation and maximum parameter variation (resistivity scale limits and depth limits). Therefore the default value ($L = 1$) provides reasonably good compromise between data fit and model smoothness. However, the Lagrange scaler is the most important parameter in the interpretation, because it greatly affects the final model.

R1-wgh, *Th-wgh* and *R2-wgh* define separate Lagrange scaling for each layer parameter. If any of the values is greater than the other two, then that parameter will become smoother than the others. Vice versa, if some parameter weight is smaller than the others then it will be allowed to vary more. If any of the weights are equal to zero, then the corresponding parameter will be fixed in every point. Because the parameters are scaled as well, the default values (= 1) are quite a good compromise. Often it is useful to increase the weight of the overburden layer if it can be considered to represent similar kind of material.

F-length defines the filter length used to compute the parameter roughness (default $k = 2$). The roughness is defined as the difference of the parameter p_i from the mean of the surrounding points p_i*= [Sum($\delta_{ij} \cdot p_j$), $j=i-k,i+k$]/($2k$), where δ_{ij} is Kronecker delta function. The longer the filter length the smoother the resulting Occam model will be and the less sensitive the model is to data noise.

The *Iter #* field is defines the number of successive iterations to be performed when the *Optimize* button is pressed (default *Iter* = 10).

The *Optimize* button performs a given number of inverse iterations. The inversion is based on linearized inversion scheme. The sensitivity matrix is constructed numerically using forward differences. The linear system is solved for the parameter steps using singular value decomposition (SVD) together with adaptive and automatic damping.

The *Edit Thic* button is used to give manually varying thickness for the overburden layer using the computer mouse. After pressing the *Edit Thic* button the mouse cursor changes into a crosshair cursor above the graph. The user then starts to pick up depth values by pressing the left mouse button. The editing mode is ended after pressing the right mouse key. The program then interpolates the overburden thickness values between the first and the last depth point and makes a forward computation. The maximum amount of selected points is equal to the original number of data points. Note that the points must be picked in an ascending order, i.e., from the beginning of the profile towards the end.

The *R-min, R-max* and *T-max* text fields in the middle of the control pane define the minimum and maximum value of the resistivity scale and the maximum depth value in the pseudosections. Note that on the actual color scale the 10-base logarithm of the resistivity values is shown.

The three *Edit Fix/Free* buttons *Rho1, Thic, Rho2* are used to manually fix (or free) the parameters from (or for) the inversion. Fixed parameters are indicated by a small cross symbol above the center of the corresponding element in the pseudosection. The editing mode is similar to layer thickness editing: cursor becomes crosshair, left mouse button selects points, and right mouse button stops the editing mode. However, no interpolation is used and therefore each model block must be selected manually. If editing is made without any selections (left mouse clicks), then the particular parameter (Rho1, Thic, Rho2) is set free in every point.

The three *Edit Roughness* buttons *Rho1, Thic, Rho2* are used to manually create discontinuities into the model. The editing mode is similar to fix/free status editing, with the exception that the discontinuities locate between two model blocks instead of above them. Discontinuities are indicated by black vertical (resistivity) or horizontal (thickness) lines between the blocks in the pseudosection. If editing is made without any selections (left mouse clicks), then the discontinuities are removed from the particular parameter (Rho1, Thic, Rho2) in every point.

The three *Reset to mean* buttons *Rho1, Thic, Rho2* are used to reset the resistivity or thickness of the overburden layer or the resistivity of the basement to the mean parameter value. However, if discontinuities have been set up in the model, then the mean value is computed between them (see Appendix C). This option may help the user to create rough categorical interpretation model rapidly.

Interpretation procedure

After the data has been read in it is necessary to check and provide correct value for the measurement frequency (default 16000 Hz). This can be checked from the upper right corner of the graph and changed by editing the corresponding text field and pressing the *Update* button.

The inversion can now be started by pressing the *Optimize* button. The default number of iterations is often enough to get a good fit, but usually the convergence is rather slow and the optimization must be made multiple times before stable solution is found. Sometimes it may be advisable to increase the maximum number of iterations.

Important: To see whether a stable solution has been found, please, pay attention to the values of the data RMS and the model RMS in the upper right corner of the graph as well as to any visible changes in the pseudosections.

The default values will usually create a rather smooth model. To enforce better data fit one should reduce the *L* value (0.1-0.5). This will usually speed up the convergence as well. If the data has been measured densely or if the it has low S/N-ratio, then the *L* value can be increased (2-10).

One should pay attention to the resulting model and see how different initial models affect the final inversion model. The model can be perturbed by pressing the *2-Layer* button, which computes the exact inverse solution and sets the layer resistivity to the current mean value, or by pressing some of the *Reset* buttons, which will place the mean parameter value into every model block.

Without any discontinuities the constrained inversion will create a quite smooth model. After few basic inversions one should have a pretty good idea where there might be lateral conductivity or thickness variations. Using the *Edit roughness* buttons one can create discontinuities manually. After this a few more optimization runs should be made to see how the model changes. Alternatively after editing discontinuities one might first disturb the model using the *Reset* buttons and start the inversion from a new initial model.

If the user has a priori information, for example about the thickness of the overburden at some point, then one can use the *Edit thic* button to set the thickness and the *Edit fix/free* button to fix that element. The inversion will then keep that parameter fixed during the inversion and the constraining will (try to) adjust the neighboring elements to fit the fixed value to minimize the model roughness. Alternatively one can save the current model into a *.LAY file and manually edit the parameter and fix/free values. After reading in the edited model file it will allow to use fixed resistivity values as well (that is currently not possible interactively).

The user should always test different models and different values of the various inversion parameters (particularly the global Lagrange multiplier and the separate parameter weights). As often in geophysical interpretations there is no unique inverse model. The practice, however, will create masters.

File formats

Before starting up the program make sure that your input data files (*.DAT) are formatted properly. The format of the input VLF-R data file is shown below.

```
Synthetic VLF-R data

30 4 5 0

  20.000   2.349  -14.636  2222.633  37.753
  40.000   3.731  -16.339  2159.510  38.755  0
  60.000   5.763  -18.146  2079.178  39.902  0
  80.000   8.158  -20.152  1981.082  41.240  0
  ...
 580.000   1.003   10.426  2370.703  35.563  0
 600.000   1.490    9.340  2394.223  34.925  0
```

Lines 2 and 4 are used for comments and can be left empty. The first line defines a header text (max. 40 characters), which is used as a second title in the graph. If the beginning of the header line is empty the default title in the 2LAYINV.DIS file is used instead. Usually the header line should define the name of the measurement site and possibly the name of the VLF station.
The 3.rd line defines the number data points on the profile (NOP) and the column indices (ICO1 and ICO2) for the components of the VLF-R data (apparent resistivity and phase) and the column index (ICO3) of the data weights. Data weights are used to increase (wgh > 1) or decrease (wgh < 1) the importance of individual data points. If the data file does not include data weights, which is normally the case, the corresponding column index should be set to zero (ICO3=0). The remaining NOP lines define the profile coordinate (X, meter) and the measured data values.

There is no (theoretical) limit for the number of data points, because dynamic memory allocation is used. However, since only a single profile can be used the simultaneous processing of large datasets should be avoided. The profile coordinates must be in continuously ascending or descending order. If they are in descending order, the whole profile is reversed automatically.

Furthermore, if the distance between the first two profile points X_2-X_1 < 0.5, the profile coordinates are converted from kilometers to meters (multiplied by 1000). Note also that the data file can contain several data columns, two of which are read for processing. This means that the same data file can contain other data components (as in the example above). Manual editing of the column indices is (currently) required to choose the correct columns for the interpretation.

The parameters of the two-layer model are saved into a column formatted text file (default suffix *.LAY). The header of the file defines the parameters used in the inversion and the normalized root-mean-square (RMS) values of the data and model error. For historical reasons the #-character is used in the results file to make comment lines for the Gnuplot plotting program. Along with the model parameters (Rho1, Thic and Rho2) the file includes the fix/free status (0=fixed, 1= free), the roughness parameters (0= smooth, 1= left, 2= right and 3= totally discontinuous) as well as the 95% confidence limits of the parameters (min, max values). Note that in this example the remaining columns (minR1, maxTh, minTh, maxR2, minR2) are omitted for clarity.

```
# Results from 2LAYINV: the interpreted 2-layer model

# Data file:

# Data RMS error: 0.251280E-02
# Mod. RMS error: 0.137378E-03
# Weights are not used
# Computational parameters:
# Lagrange scale      0.10
# Rho 1 scale         1.00
# Thickness scale     1.00
# Rho 2 scale         1.00
# Filter length          3
# Roughness              1

# Number of data points: N=   21
# Dist, Rho 1, Thic, Rho 2, Fx1, Fx2, Fx3, Rg1, Rg2, Rg3, minR1, maxR1 ...
   -250.00    591.629     18.280     27.820  1  1  1  0  0  0    586.964 ...
   -225.00    579.886     18.340     27.689  1  1  1  0  0  0    575.548 ...
 ...
```

The measured and the computed VLF-R data and the data weights can be saved into a column formatted text file (default suffix *.OUT). The data can be used, for example, to prepare response graphs using other plotting programs. An example of the file format is given below.

```
# Results from 2LAYINV: VLF-R data

# Number of data points: N=   21
# Dist (m), Rhoa c (Ohmm), Phase c (deg), Rhoa m, Phase m, Weight
   -250.00     110.00      67.00     110.57      66.40       1.00
   -225.00     110.00      67.00     111.13      66.11       1.00
  ...
```

Graph options

Several graph parameters (see Appendix) can be changed editing the 2LAYINV.DIS file. Thus, the graphs can be translated into another language, for example. Note that the format of the 2LAYINV.DIS file must be preserved. If the format of the file becomes invalid, one should delete the file and a new one with default parameter values will be generated automatically the next time the program is started. The file format and default values are shown below.

```
  32   32   32   18    0
 300  300 0.82 0.72
  10.000   50000.  10.0  90.0  20.0  50.0  20.0

VLF-R measurement
Test data
2-Layer model
Distance (m)
Apparent resistivity (Ohmm)
Phase (deg.)
Rhoap m
Phase m
Rhoap c
Phase c
Resistivity (Ohmm)
Depth (m)
```

- The 1.st line defines four character heights. The first one is used for the main title and the graph axis title, the second is used for the axis labels, the third is used for the plot legend, and the fourth is used for the resistivity labels of the pseudosection. The fifth parameter (0) is reserved for future use.
- The 2.nd line defines first the x- (horizontal) and y- (vertical) position of the origin of the main graph (in pixels). The third and the fourth parameter define the length of the x- and y-axis relative to the size of the total width and height of the plot area (eg. 0.5 = 50 % of the width or height), which is equal to 2970×2100 pixels (landscape A4). Note that in vertical direction the length defines the relative height of both the response plot and the pseudosection.
- The 3.rd line defines the minimum and maximum value of the logarithmic resistivity axes, the minimum and maximum values and the tick-mark step of the phase axis, and the maximum value and the tick-mark step of the depth axis.
- The fourth line should be left empty.
- The following lines define various text items of the graph (max. 40 characters).

- Main titles of the VLF-R data graph.
- The second title line of all graphs (used if the data file does not include a title).
- Main title of the two-layer interpretation graph.
- Title of the x-axis (defined in the data file - usually the distance along profile).
- Two y-axis names of the VLF-R data graph.
- Four legend names of the VLF-R data graph (measured and computed VLR-R data).
- The label of the color scale defining resistivity values (log10 -prefix added automatically).
- The vertical axis name of the resistivity pseudosection.

Additional information

The forward computation of the VLF-R response of two-layered earth is based on the same (traditional) algorithm as in the MT and AMT modelling and inversion programs (MTINV and AMTINV). The original reference is Kunetz (1972). However, in 2LAYINV the algorithm has been optimized for two-layer earth model. The optimization is based on a linearized inversion method, where singular value decomposition and adaptive damping method is used. The method has been described in my PhD thesis. The constrained Occam inversion algorithm is based on the unpublished results of a 3-D block model inversion code of gravity data. The direct two-layer inversion is based on an old traditional code edited by several persons at the University of Oulu (J. Mursu, K. Komminaho). The original reference is Orellana (1974). More information about the theory and applications of the VLF-R method can be found from McNeill and Labson (1992).

The 2LAYINV program is written in Fortran-90 style using Compaq Visual Fortran 6.6. The graphical user interface is based on the DISLIN graphics library (version 9.0) by Helmut Michels. The program distribution includes the required DISDLL.DLL file. The official WWW homepage of DISLIN is at "http://www.dislin.de". Since the DISLIN graphics library is available for other operating systems (Solaris, Linux) the 2LAYINV program could be compiled and run there without any major modifications.

I do not intend to provide any support for the program. However, if you find the computed results erroneous or if you have suggestions for improvements, please, inform me.

References

Kunetz G., 1972. Processing and interpretation of magnetotelluric soundings. Geophysics, 37, 1005-1021.

McNeill J.D. and Labson V.F. 1992. Geological mapping using VLF-radio fields. In M.N. Nabighian (Ed.): Electromagnetic methods in applied geophysics, Volume 2, Application. SEG.

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Terms of use and disclaimer

You may use the 2LAYINV program free of charge. If you find the program useful, please, send me a postcard. If you use the 2LAYINV program and wish to publish the results, please, provide a notice "2Layinv © University of Oulu" (without the quotes).

Since I have not had time to prepare a proper paper on this subject, please, use this manual as a reference, e.g. Pirttijärvi, M., 2006. 2LAYINV - Laterally constrained two-layer inversion of VLF-R measurements, User's guide. University of Oulu, Division of Geophysics.

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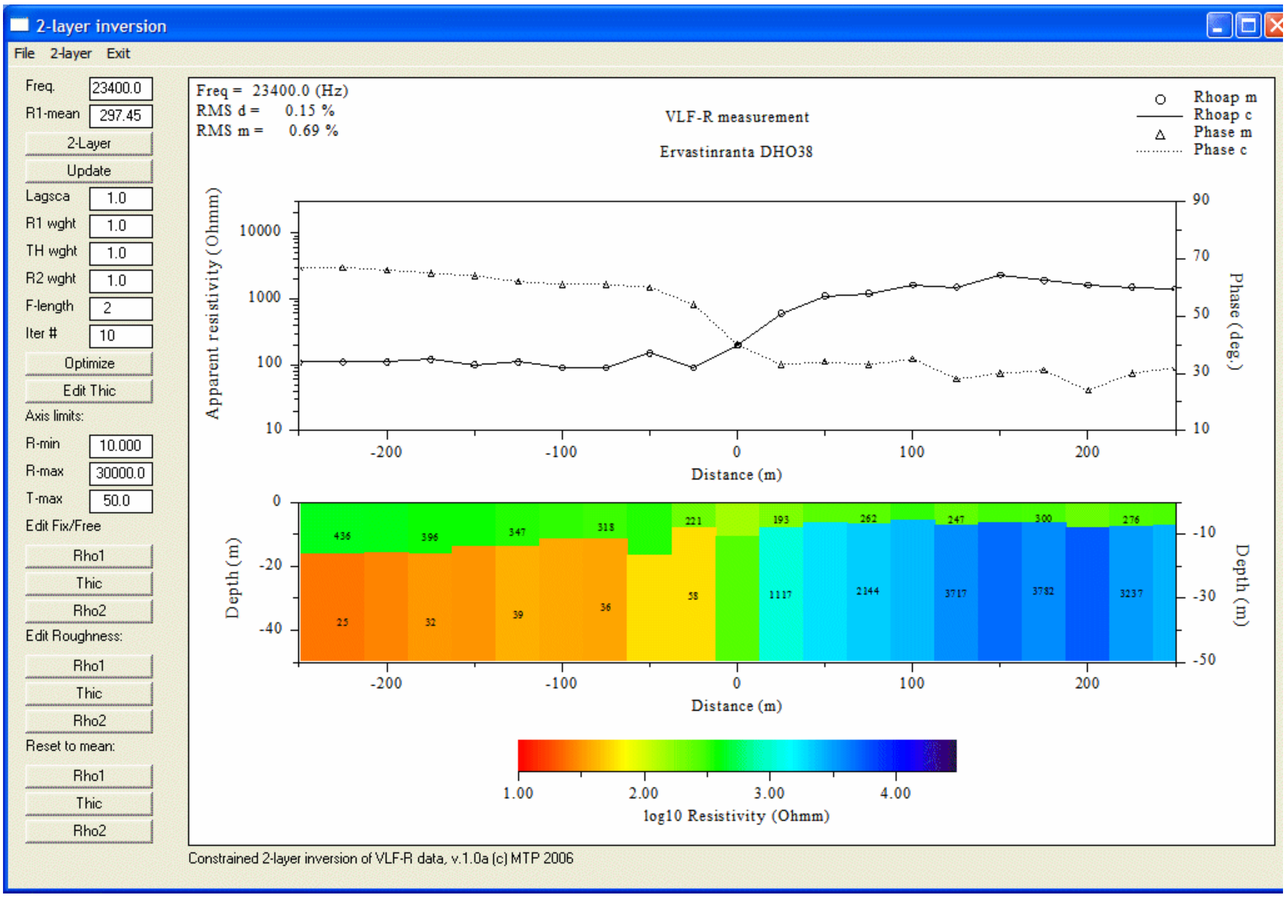
Appendices

Appendix A shows a screen dump of the 2Layinv program. The interpretation was made using default inversion parameters (no fixed points no discontinuities).

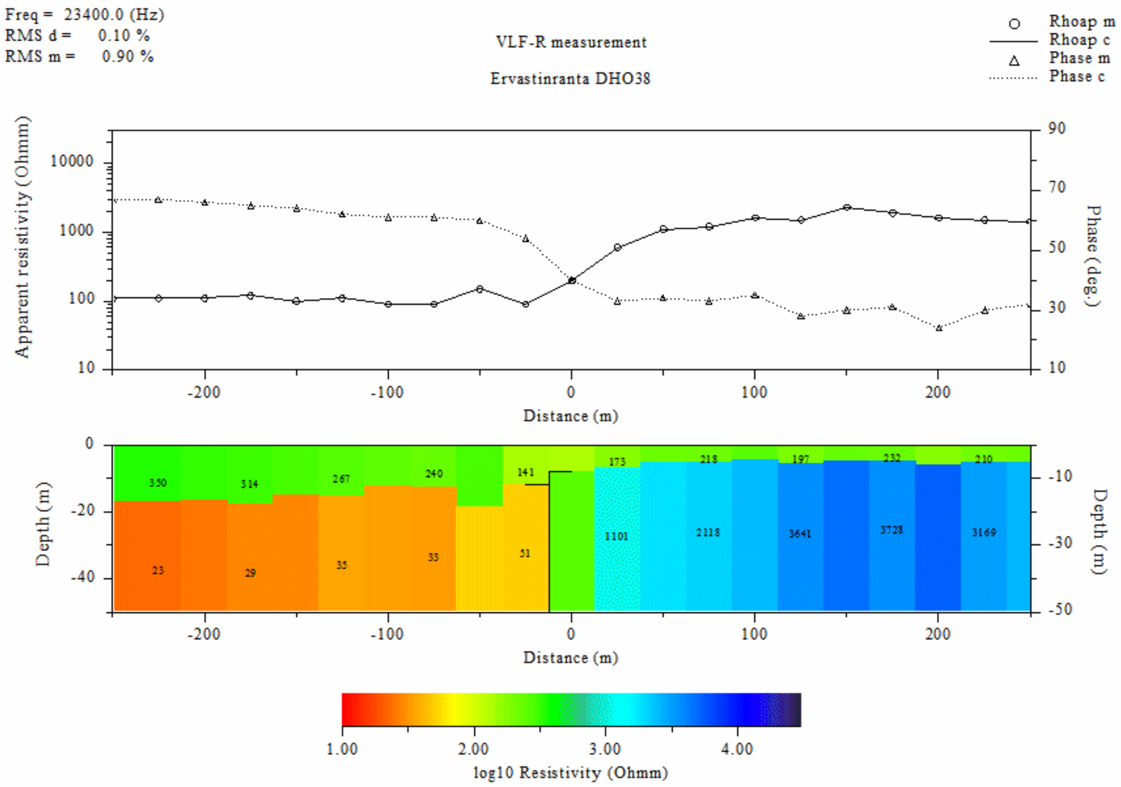
Appendix B demonstrates the use of manually edited roughness lines to create a discontinuous model (resistivity contact and overburden thickness variation).

Appendix C shows the same model after the resisitivity and thickness of each layer was reset. Note that the mean values are restricted between discontinuities.

Appendix A



Appendix B



Appendix C