FDEMINV

1-D interpretation of frequency-domain EM soundings

Version 1.4a (c) 2012 by Markku Pirttijärvi

Introduction:

The FDEMINV program can be used to model and to interpret geophysical frequency-domain electromagnetic (FDEM) soundings over horizontally layered earth. FDEMINV can compute various magnetic field responses derived from the vertical and the horizontal component of the magnetic field due to a vertical and/or a horizontal magnetic dipole. Parameter optimization, which is based on linearized inversion method, can be utilized in 1-D interpretations.

The FDEMINV program is a 32-bit application that can be run on Windows 9x/XP/7 with a graphics display of at least 1024×800 resolution. Memory requirements and processor speed and are not critical factors, since large data arrays are not used and the EM solution is quite fast to compute even on older computers. The FDEMINV program has a simple graphical user interface (GUI) that can be used to change the parameter values, to handle file input and output, and to visualize the EM response and the model. The user interface and the data visualization are based on the DISLIN graphics library (http://www.dislin.de).

Despite its inversion capabilities, FDEMINV is intended primarily for forward modeling and testing. One of the main reasons for me to create this program was to develop a general method to transform FDEM responses into apparent resistivity and phase using the vertical and horizontal magnetic field components and to test the transformation.

Installing the program:

The program requires following files:

FDEMINV.EXE	the 32-bit executable file
DISDLL.DLL	dynamic link library for the DISLIN graphics

The distribution file (FDEMINV.ZIP) contains also a short description file (_README.TXT), this user's manual (FDEMINV_MANU.PDF) and an example data file (EXAMPLE.DAT). To install the program, create a new directory and copy or unzip the distribution files there. To be able to start the program from a shortcut that locates in a different directory move or copy the DISLIN.DLL file into the WINDOWS\SYSTEM folder or someplace else where a system path has been defined.

The EM measurement systems:

Figure 1 illustrates the three measurement systems considered in FDEMINV. The transmitter, *Tx*, is either a vertical (VMD) or a horizontal (HMD) magnetic dipole (that is to say a horizontal or a vertical loop) on or above the ground surface. The receiver, *Rx*, is located at the same height level at some distance, *L*, away from the source. The FDEMINV program computes two magnetic field components. The first component (solid black arrow) is always parallel to the source dipole and the second one (dashed gray arrow) is perpendicular to that. In case of VMD the second component is the horizontal (axial) component directed away from the source. In case of a HMD source, the second component is the vertical one. Please, note that in coaxial HMD configuration no vertical field is generated, which prevents computation of *Hx/Hz*, *Hz/Hx* ratios and apparent resistivity and phase.

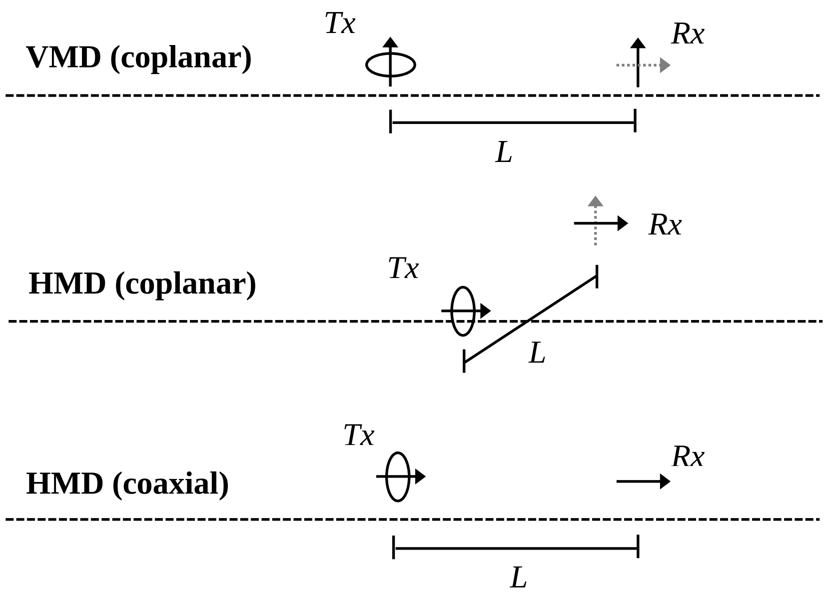

Figure 1. Schematic view of the commonly used VMD and HMD systems.

The FDEMINV program can be used to model both frequency and geometric soundings. In frequency soundings the distance between the source and the receiver is kept fixed and the measurements are made using varying frequencies. The attenuation of EM fields depends on the conductivity (or its reciprocal, the resistivity) and the frequency. Therefore, high frequencies give information about the upper parts of the earth, whereas low frequency data contains information from greater depths. In geometric soundings the frequency is kept fixed and the loop spacing is varied. When the loop spacing is short the data contains information near the surface. When the loop spacing increases more and more information will be obtained from the deeper parts of the earth. For more detailed information about the geophysical EM measurement systems, please, be referred to common geophysical literature (e.g., M.N. Nabighian, 1988 & 1991, SEG).

The FDEMINV program computes the apparent resistivity and phase using the ratio of the vertical and horizontal magnetic field components. Although similar method has been used in the French BRGM Melis frequency sounding system, for example, the method is not widely used and therefore a short description is provided in the following. The 10-base logarithm of the imaginary (quadrature) part of the ratio of vertical and horizontal magnetic field (F= $\mathrm{Log}_{10}(\mathrm{Abs}(\mathrm{Im}(Hz/Hx)))$) is first computed and tabulated using the homogeneous half-space model over a wide range of dimensionless induction parameter $\alpha = k^2r^2$, where r is the loop spacing and $k^2 = \omega\mu_0\sigma_h$ ($\omega = 2\pi f$ is angular frequency, μ_0 is magnetic permeability of the free-space and σ_h is the conductivity of the lower half-space). In practice the computation is made using fixed loop spacing and frequency and varying the host conductivity (or resistivity) values.

Figure 2 illustrates the *F*-ratio for a VMD system on the surface of homogeneous half-space. Since the *F*-ratio is a continuously decreasing function of the induction parameter, the apparent resistivity of the VMD (or HMD) system above layered earth can be obtained using reverse interpolation. Let us assume that at some frequency the computed (or measured) values of vertical and horizontal magnetic field are Hx_i and Hz_I, which gives rise to ratio F_i. Reverse interpolation (from y- to x-axis) of the curve shown in Figure 2 gives an induction parameter value, α_i. In practice the interpolation is made using the $\log_{10}$ values of the induction parameter and linear extrapolation is used beyond the computed range if necessary. By its definition the apparent resistivity is such a value of the resistivity (or conductivity) of the homogeneous half-space that produces the same EM response as the layered earth. Since the loop spacing and frequency are known, the host conductivity, which now represents the apparent resistivity can be solved simply as $\rho_a = 2\pi\mu_0 f \cdot r^2 / \alpha_i$ (Ohmm). The phase response related to the apparent resistivity is computed in the FDEMINV program as $\phi = \tan^{-1}(\mathrm{Im}(Hz/Hx), \mathrm{Re}(Hz/Hx))$ (rad. or deg.).

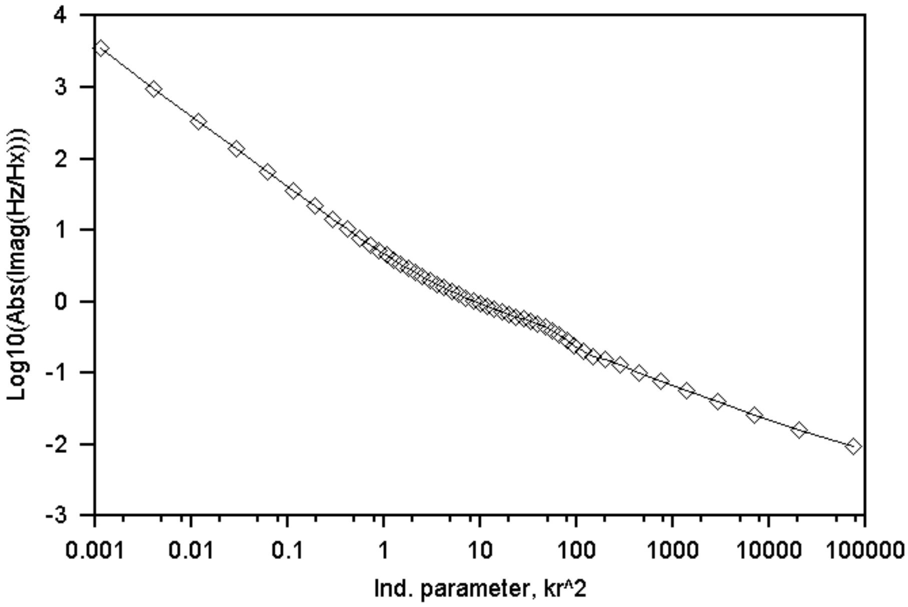

Figure 2. The *F*-ratio used to interpolate the apparent resistivity for a VMD source on the surface of homogeneous halfspace.

Note that the method used to compute apparent resistivity could be used to transform measured data as well. This requires, however, that both the vertical and the horizontal magnetic field have been measured. The transformation method works with coplanar HMD system, which has an *F*-ratio curve very similar to that in Figure 2. Note also that the magnetic field used to compute the *F*-ratio is the sum of free-space and homogeneous half-space magnetic fields and for some dipole-dipole systems the vertical magnetic field is zero. Therefore, the interpolation of the *F*-ratio cannot be used to compute the apparent resistivity for the coaxial HMD system, for example.

Using the program:

On startup the program reads the model parameters from the FDEMINV.INP file and the DISLIN graphics parameters from the FDEMINV.DIS file. If these files can not be found when the program starts, new ones are created automatically using the default parameter values. The program then computes the FDEM response of the initial model and builds up the user interface shown in the Appendix. The FDEM response is plotted in the graph area along with a resistivity-depth curve of the model and a description of the model parameters. The parameters of the layered earth model and the inversion method can be altered using the controls on the left side of the FDEMINV program window.

As shown in Appendix the main window of the FDEMINV application contains two menus. The *File* menu has the following nine options:

Open Model	open an existing model file (*.INP).
Save Model	save the model into a file (*.INP).
Read Data	read in measured data for interpretation (*.DAT).
Save Results	save the results into a file (*.OUT).
Read disp.	read in new graph parameters from a file (*.DIS).
Save Graph as PS	save the graph in Adobe's Postscript format (*.PS).
Save Graph as EPS	save the graph in Adobe's Encapsulated Postscript format (*.EPS).
Save Graph as PDF	save the graph in Adobe's Acrobat PDF format (*.PDF).
Save Graph as WMF	save the graph in Windows metafile format (*.WMF).

Selecting these menu options brings up a typical Windows file selection dialog that can be used to provide the name of the file for open/save operation. Model and result files are saved in standard ASCII text format. The graphs are saved as they appear on the screen in landscape A4 size.

The *Edit* menu contains following items:

Comp.−>Meas.	use the computed response as measured data.
Remove Meas.	remove information about measured data.
Sounding type	choose between frequency and geometric .
Source type	choose between coplanar VMD and HMD and coaxial HMD system
Field component	select real & imaginary (in-phase and quadrature) and modulus & phase response of the first or second (H1 or H2) field components (see note).
Normalized field	select Re,Im and Mod,Pha response of the normalized field (H1/H0) or (H2/H0), where H0 is primary free-space field (see note).
Ratio	select Re,Im and Mod,Pha response of the ratio between first and second field component (H1/H or H2/H1).
Apparent resistivity	select apparent resistivity and phase (between H1 and H2) response.
Free space field	include or exclude the free-space field from the total magnetic field
Response component	show either both components or only the first or second component

Note: In case of the VMD source the first field component is vertical magnetic field and the second is horizontal (axial) magnetic field. In case of HMD the first field component is horizontal (parallel or coaxial) horizontal magnetic field and the second is the vertical magnetic field, which cannot be computed in case of coaxial HMD configuration. Consequently, the normalizing free-space magnetic field H0 is the vertical for VMD source and horizontal for HMD source.

Define freq/dist item can be used to set the minimum and maximum frequency values and number of frequencies in case of frequency soundings or the minimum and maximum loop spacing and the number of loop spacings in case of geometric sounding. The values are provided using an input dialog and the frequencies or loop spacings are automatically computed so that they are evenly spaced on a logarithmic scale.

Phase rad/deg item defines if the phase component is represented as radians or degrees. *Weights in/out* item is used include or exclude the data weights in/from the inversion. *Error bars* item can be used to change the appearance of the error bars of the resistivity and thickness of the layers in the model view. The error bars represent the 95% confidence limits (minimum and maximum errors) obtained from the singular value decomposition used in the linearized inversion method.

The *Exit* menu has two items - the first one can be used to restart the GUI and swap between traditional 3:4 display mod and widescreen mode (giving an aspect ratio between 0.5-0.9) and the second is used to confirm the exit operation. On exit the latest model is saved in the FDEMINV.INP file replacing the original one, and the results are saved in the FDEMINV.OUT file. Errors that are encountered before the GUI starts up are reported in the FDEMINV.ERR file. When operating in GUI mode, run-time errors arising from illegal parameter values are displayed on the screen during runtime.

After exiting the program one can look at the FDEMOUT.OUT file which contains the results. If data has been used in the interpretation the file contains the model parameters, the RMS error and the mean of the damping factors, the (damped) 95% confidence limits of the parameters, the singular values, the damping factors and the parameter eigenvectors. The result file also contains the measured and computed response components and the differences. If data had not been used the file just contains the model parameters, some system information and the computed FDEM response. Note that result files (as well as model files) can be saved to disk also from within a running FDEMINV application using the *File/Save Results* menu item.

The FDEMINV program is not an idiot-proof interpretation program. It requires an initial model, the parameters of which are optimized during an iterative, linearized process. The inversion method can easily get stuck to a local minimum, and therefore, the user should pay attention to the validity of the resulting model. The RMS error and the mean of the damping factors can be used to assess the validity of the inversion results. Optimally the RMS error should be zero and all damping factors should be equal to one. Note also that after optimization the resistivity-depth section shows the minimum and maximum parameter ranges using dotted lines. These auxiliary curves are derived from the 95% confidence limits.

Program controls:

The leftmost control panel includes some push-button and text-field controls. The *Loop/Freq* text field defines the loop spacing (when modeling frequency sounding) or the frequency (when modeling geometric sounding). The value of the loop spacing or frequency is given multiplied by one thousand (in km or kHz). The other text-fields are used to provide the number of layers and the resistivity and thickness values of each layer. After editing the parameter values one has to apply for the changes using the *Update parameters* push button in the top left corner of the FDEMINV application window. When increasing or decreasing the number of layers the unnecessary text-field controls get hidden. The maximum number of layers is six (6). The *Default* pushbutton resets all layer parameters to their default values (100 Ωm and 100 m).

The text controls in the right control panel are related to the inversion. These controls become active only after some data is read in using the *File/Read Data* item. The *Iters*. text field control defines the number of successive iteration made after the *Optimize* button is pressed. The *Thres*. control defines the minimum singular value threshold used in the optimization. This parameter (actually multiplied by 1000) controls the strength of the damping. Decreasing its value will loosen the damping and make the inversion method work more like a steepest descent algorithm. Increasing its value might be advantageous if the inversion gets unstable. The default values of the iteration number and threshold are 10 and 1.0 (1.e-3), respectively.

The text fields (*Free*) on the right side of each resistivity and thickness value are used to exclude (0) or to include (1) parameters from or to the inversion. By default all parameters are included in the inversion. If you want to fix some parameter during inversion, set the corresponding parameter to zero. The *Sel. all* button can be used to fix or free all parameters for the inversion.

Since the inversion can easily get stuck into a local minimum, the inversion should not be restarted using the previous model as a starting point. When adding new layers to the model, default parameter values (100 Ωm and 100 m) are given to each new layer. A single layer can also be removed by giving it a zero thickness and pressing the *Update* button. Increasing or decreasing layers always affects the layers at the bottom.

File formats:

When using the program for interpretation purposes make sure that your input data files (*.DAT) are formatted properly before running the program. Note also that there is no need to edit model files manually when interpreting field data.

The following example illustrates the format of the input data file.

```
Synthetic data

 1   1  1
 1000.  0.
 12  2  3  0

      4.00   0.14219E+01  0.30574E+02
      8.00   0.12220E+01  0.23876E+02
     16.00   0.15243E+01  0.18217E+02
     32.00   0.22128E+01  0.14607E+02
     64.00   0.32212E+01  0.13006E+02
    128.00   0.63994E+01  0.13824E+02
    256.00   0.17812E+02  0.18135E+02
    512.00   0.47480E+02  0.27415E+02
   1024.00   0.10998E+03  0.42078E+02
   2048.00   0.17153E+03  0.58351E+02
   4096.00   0.10288E+03  0.50792E+02
   8192.00   0.93610E+02  0.45630E+02
```

Lines 2 and 6 are used for comments. The first line defines a header text (max 30 characters). The third line defines the source type (ISYS), response type (IMOD) and sounding type (IOPT). The source is either a VMD (ISYS= 1) or a HMD (ISYS= 2 or 3). The response type is one of the nine possibilities (IMOD= 1,2, …, or 9) defined in the *Using the program* chapter. The sounding type is either frequency sounding (IOPT= 1) or geometric sounding (IOPT= 2). The 4.th line defines first the loop spacing (m) or frequency (Hz) used in the frequency or geometric soundings, respectively. The second parameter on the 4.th line defines the height (in meters) of the dipole-dipole system from the surface of the earth. Note that the source and the receiver are always on the same height level above or on the surface. The 5.th line defines the number of frequencies (NOF) and the column indices (ICO1, ICO2 and ICO3) for the two response components (in this case apparent resistivity and phase, since IMOD= 1) and weights used in the inversion. A data component can be omitted if its column index is set to zero (ICO1= 0 or ICO2= 0). Likewise, weights are not read at all if ICO3= 0 (as in the example above). The next NOF lines define the column-formatted data: frequency (FREQ, Hz), the measured apparent resistivity (Ohmm) and the phase component (deg.).

The maximum amount of frequencies or loop spacings is 80 and the header text is used as a second line in the response graph title. If the header text line is empty the default title in the FDEMINV.DIS file is used instead. The frequencies (or loop spacings) must be either in an ascending or in descending order. Note also that the data file can contain several data columns, from which one or two are read for the interpretation. This means that the same data file can contain, for example, measurements along a profile. Manual editing of the column indices is (currently) required to choose the correct data column for the FDEMINV program. Data values equal to zero are omitted and, thus, used for missing data values.

Although there is no need to edit model files manually, the following example illustrates the format of the model files:

```
FDEMINV model file:

 3
 0.10000E+03  0.10000E+03
 0.10000E+01  0.10000E+03
 0.10000E+05

 1    1    1
 500.00    0.00
 14
 2. 4. 8. 16. 32. 64. 128. 256. 512.
 1024. 2048. 4096. 8192. 16384.
```

Lines 1, 2 and 7 (in this case) are used for comments and can be left empty. The 3.rd line defines the number of layers (NOL), the maximum amount of which is 6. Lines 4 and 5 define the resistivity (RH, Ohmm) and the thickness (TH, m) of the two topmost layers and the 6.th line defines the resistivity of the bottom layer. The 1.st line of the 2.nd paragraph defines the number of frequencies (NOF). The frequency values are then provided at the end of the file. Note that the frequencies can be given on multiple lines.

The results file (FDEMINV.OUT) contains the model parameters and depths, the RMS error, the mean of the damping factors, the (damped) 95% confidence limits of the parameters, the original (W) and normalized (S) singular values, the damping factors (T) and the parameter eigenvectors

(V-matrix). Some general information concerning the measurement system is also given (source and sounding types, loop spacing and height). The results file also contains the measured and computed response components and the difference between the measured and the computed data. It also contains the weights if they were used in the inversion. The FDEMINV.OUT file contains also the computed magnetic field components (H01, H02, Re,Im (H1), Re,Im (H2), Re,Im (H1/H01), Re,Im (H2/H01) and Re,Im ((H1+H01)/ (H2+H02)). Here H01 and H02 are free-space magnetic fields. H01 and H1 are the vertical (or horizontal) magnetic fields of a VMD (or HMD) H02 and H2 are the horizontal (or vertical) magnetic fields of a VMD (or HMD). Note that for historical reasons the #-character is used to comment out lines for the Gnuplot plotting program. At the bottom the FDEMINV.OUT file are given the data values required to create the model curve and the error bars using a third-party plotting program. If data were not read in the output file would just contain the model parameters and the computed FDEM response.

Graph options:

Several graph parameters (see Appendix) can be changed by editing the FDEMINV.DIS file. Note that the format of the *.DIS file must be preserved. If the format of the file becomes corrupted, the program crashes while initializing the GUI. In this case, 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 parameter values are shown below.

```
  40   32   32   26   26
   1    2    1    1
 370  350  0.600 0.850 0.830

FDEM sounding
Test model
Response 1
Response 2
Frequency (Hz)
Loop spacing (m)

1. comp.
2. comp.
1. meas.
2. meas.

System and model description
Resist. (Ohmm)
Thickness (m)
Depth (m)
```

- The 1.st line defines five character heights. The first one is used for the main title and the graph axis titles, the second height is used for the axis labels, the third height is used for the plot legend text, the fourth height is used for the model description text, and the last height is used for the axis labels in the model view.
- The 2.nd line contains integer valued parameters that define if the info text is shown or not, if model view is drawn or not, if error bars are shown in the model view, in which corner the legend is drawn and if widescreen mode is active or not.
- The 3.rd line defines parameters that define: the x- (horizontal) and y- (vertical) position of the origin of the main graph (in pixels), the length of the x- and y-axis relative to the size of the total width and height of the total plot area (eg. 0.5= 50 % of the width or height), which is equal to 2970×2100 pixels (landscape A4), and the screen aspect ratio for widescreen mode.
- The following lines define various text items of the graph (max. 40 characters).
  - Two main titles of the response graph.
  - Three axis names of the graph. When both data channels are plotted the x-axis title shows both axis names (Response 1 + Response 2).
  - Four legend texts (computed and measured).
  - One title of the model description text
  - Two column headers of the model parameters
  - One additional axis title for vertical axis of the model view

Note that to mimic depth sounding the response lies on the horizontal x-axis and the vertical y-axis is the parametric (frequency or loop spacing) axis. Note also that by default the graph does not contain the actual names and units of all the nine different the response types. Instead, generic names (e.g., Resp. 1 and Resp. 2) are provided and the response type is shown in the description text in the top right corner of the graph page defines. Manual editing of the FDEMINV.DIS file is required, if printed graphs are going to be prepared for presentation purposes.

Note that the DISLIN graphics allows the use of special characters in graph texts. The instructions are placed between "{" and "}" characters. For example, the text "Resistivity ({M2}W{M1}m)" will produce "Resistivity (Ωm)". See the DISLIN documentation for further information.

Additional information

Originally, I made the FDEMINV program at the University of Oulu in December 2001, when I worked as a researcher funded by a grant from Outokumpu Foundation addressed to Prof. Sven-Erik Hjelt. Afterwards I've updated the program every now and then.

The forward computation is based on the well-known solution for magnetic dipole sources above 1-D layered earth (e.g., Keller and Friscknecht, 1967). The convolution algorithm and the filter coefficients used to compute the Hankel transforms are based on the work of N.B. Christensen, (Geoph. Prospecting, 1990, vol 38, pp. 545-568). The inversion method, which is based on the singular value decomposition and adaptive damping method, is described in my PhD thesis (M. Pirttijärvi, 2003. Acta Univ. Oul., A 403).

The FDEMINV program is written in Fortran 90 and compiled with Intel Visual Fortran 11.1. The graphical user interface is based on the DISLIN graphics library (version 10.2) by Helmut Michels. The program distribution includes the DISDLL.DLL that is required for the 32-bit GUI. Since the DISLIN graphics library is independent form the operating system the FDEMINV program could be compiled on other operating systems (Mac OSX, Linux) without any modifications. At the moment, however, the source code is not made available and I do not intend to provide any support for the program. If you find the computed results erroneous or if you have suggestions for improvements, please, inform me.

Note that the FDEMINV program has not been tested thoroughly and that its usability in data interpretation is quite modest. For example, currently the program does not use proper data weighting, although it always works with the 10-base logarithms of both the data and the parameters. Interpretation of frequency domain soundings are going to be implemented in future version of Jointem, software for joint interpretation of TEM, VES, VLF-R and AMT/MT soundings. For more information about the current status of Jointem and other software, please, visit my web page at https://wiki.oulu.fi/display/~mpi@oulu.fi .

Terms of use and disclaimer:

You can use the FDEMINV program free of charge. If you find the program useful, please, send me a postcard.The program is provided as is. The author (MP) and the University of Oulu disclaim all warranties, expressed or implied, with regard to this software. In no event shall the author or the University of Oulu be liable for any indirect or consequential damages or any damages whatsoever resulting from loss of use, data or profits, arising out of or in connection with the use or performance of this software.

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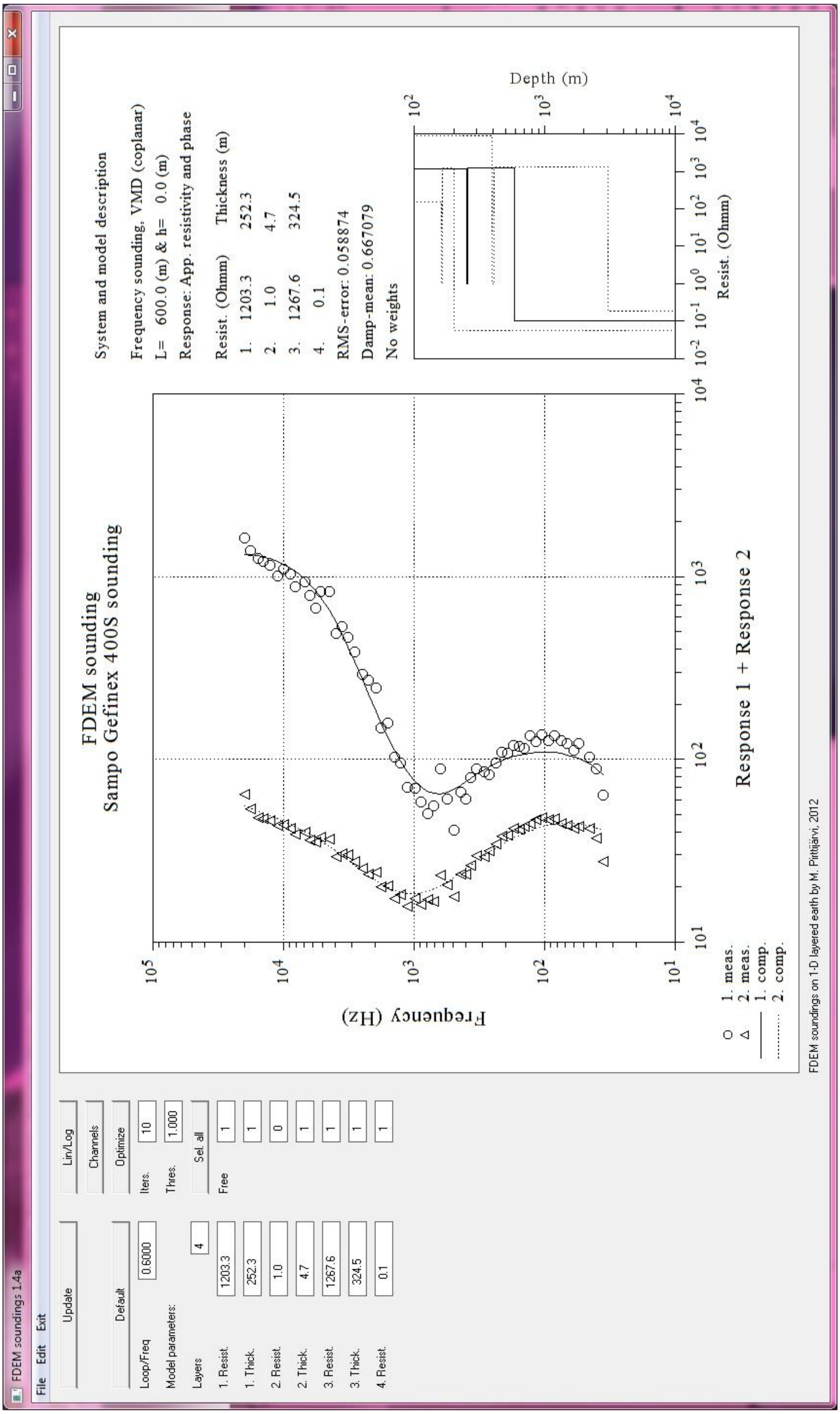
Appendix:



FDEM soundings 1.4a
File Edit Exit
Update
Default
Loop/Freq 0.6000
Model parameters:
Layers 4
1. Resist. 1203.3
1. Thick. 252.3
2. Resist. 1.0
2. Thick. 4.7
3. Resist. 1267.6
3. Thick. 324.5
4. Resist. 0.1
Lin/Log
Channels
Optimize
Iters. 10
Thres. 1.000
Sel. all
Free
FDEM sounding
Sampo Gefinex 400S sounding
Frequency (Hz)
Response 1 + Response 2
1. meas.
2. meas.
1. comp.
2. comp.
System and model description
Frequency sounding, VMD (coplanar)
L= 600.0 (m) & h= 0.0 (m)
Response: App. resistivity and phase
Resist. (Ohmm) Thickness (m)
1. 1203.3 252.3
2. 1.0 4.7
3. 1267.6 324.5
4. 0.1
RMS-error: 0.058874
Damp-mean: 0.667079
No weights
Depth (m)
Resist. (Ohmm)
FDEM soundings on 1-D layered earth by M. Pirttijärvi, 2012