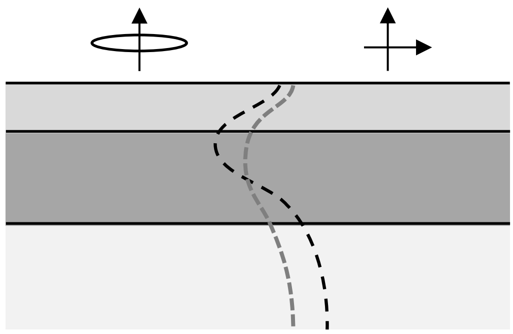
FDEMINV

1-D modelling and inversion of frequency-domain EM soundings

Version 1.5 user's guide



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1. Introduction

FDEMINV is a computer program that can be used to model and to interpret geophysical frequency-domain electromagnetic (FDEM) soundings using a horizontally layered earth model. The 1-D model is defined by the resistivity and thickness of the layers and magnetic susceptibility assigned to one of the layers. The transmitter is either a vertical or a horizontal magnetic dipole. The receiver measures the vertical and horizontal components of the secondary magnetic field. The response can defined in different ways as a function of increasing frequency at fixed loop spacing (frequency sounding) or increasing loop spacing at fixed frequency (geometric sounding). Parameter optimization, which is based on linearized inversion method, can be utilized in 1-D interpretations.

FDEMINV is a 32 bit application that can be run on MS Windows operating system 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. FDEMINV 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 objectives was to develop a general purpose method to transform FDEM responses into apparent resistivity. So far such method has not been found, particularly if the source and receiver are above the surface of the earth.

1.1 Installing the program

The FDEMINV program requires only the 32 bit executable file FDEMINV.EXE. The distribution file (FDEMINV.ZIP) also contains a short description file (_README.TXT), this user's manual (FDEMINV_MANU.PDF) and an example data file (EXAMPLE.DAT). To install the program, simply unzip the distribution files on your hard disk or USB stick and a new folder appears.

2. The EM measurement systems

Fig. 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. FDEMINV 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 primary field is generated, which prevents computation of *Hx/Hz*, *Hz/Hx* ratios and apparent resistivity and phase.

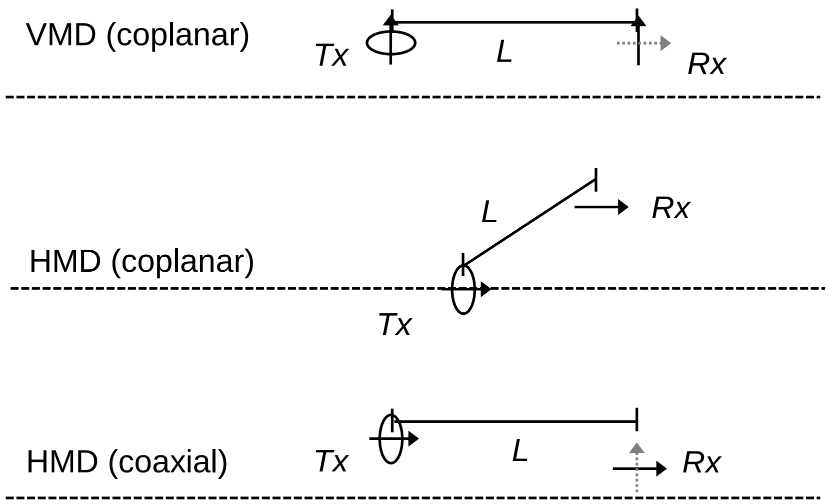

Figure 1. Schematic view of the three VMD and HMD system configurations.

FDEMINV 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., Frischknecht et al., 1991).

FDEMINV 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 components, $F = \mathrm{Log}_{10}(\mathrm{Im}(Hz/Hx))$, is first computed and tabulated using the homogeneous half-space model over a wide range of dimensionless induction parameter $\alpha = k^2 r^2$, 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 a fixed loop spacing and frequency and varying the host conductivity (or resistivity) values.

Fig. 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 Fig. 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 $\rho_a = 2\pi\mu_0 f \cdot r^2 / \alpha_i$ (Ωm). The phase response related to the apparent resistivity is computed as $\phi = \tan^{-1}\left(\mathrm{Im}(Hz/Hx), \mathrm{Re}(Hz/Hx)\right)$ (rad. or deg.).

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 does not work with HMD systems. 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 coplanar HMD system, for example.

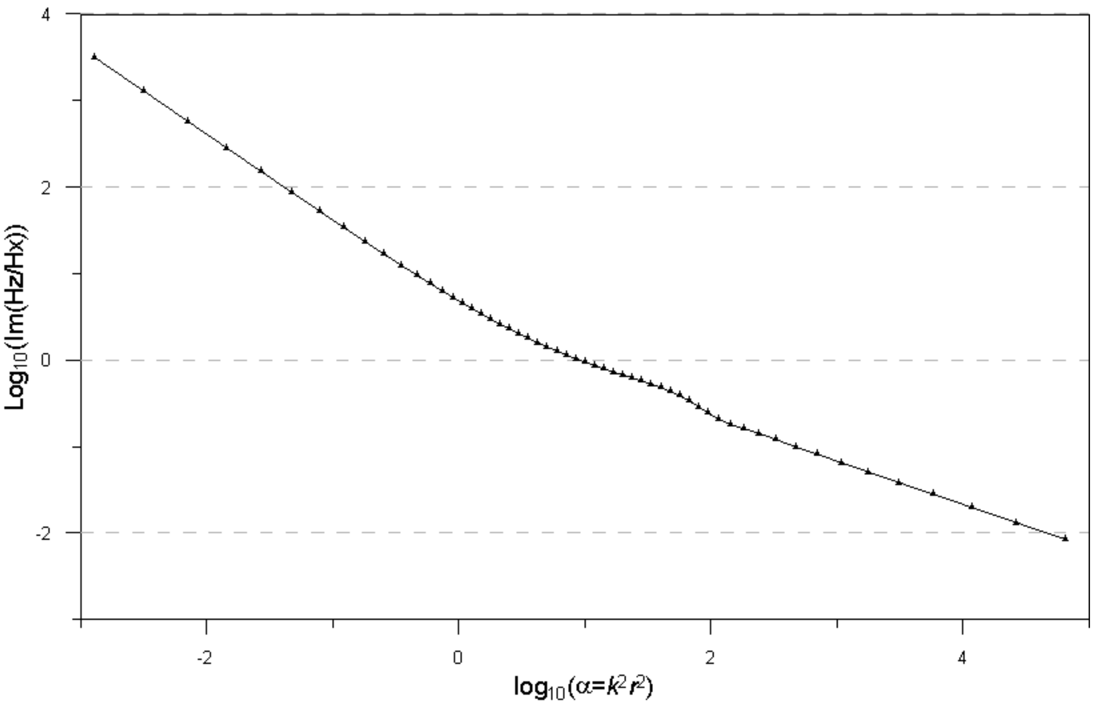

Figure 2. The *F*-ratio used to interpolate the apparent resistivity for a VMD source on the surface of homogeneous half-space.

3. Using the program

On startup FDEMINV reads model parameters from the FDEMINV.INP file and graphics parameters from the FDEMINV.DIS file. If these files can not be found when the program is started, new ones with default parameter values are automatically created. The program then computes the FDEM response of the initial model and builds up the user interface shown in Fig. 3.

The FDEM response is plotted in the graph area along with a resistivity-depth curve of the model and a description of the model and system parameters. If measured data has been read in for interpretation, the data are plotted using symbols (circles and triangles). Red and blue colors are used to display positive and negative response values, respectively.

3.1 Menus

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

Read 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 *.dis	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 PNG	Save the graph in portable network graphics format (*.PNG)
Save Graph as WMF	Save the graph in Windows metafile format (*.WMF)
Save Graph as GIF	Save the graph in Windows metafile format (*.GIF).

Selecting any of these menu options brings up a typical Windows file selection (Open/Save) dialog that can be used to provide the name of the file. 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.

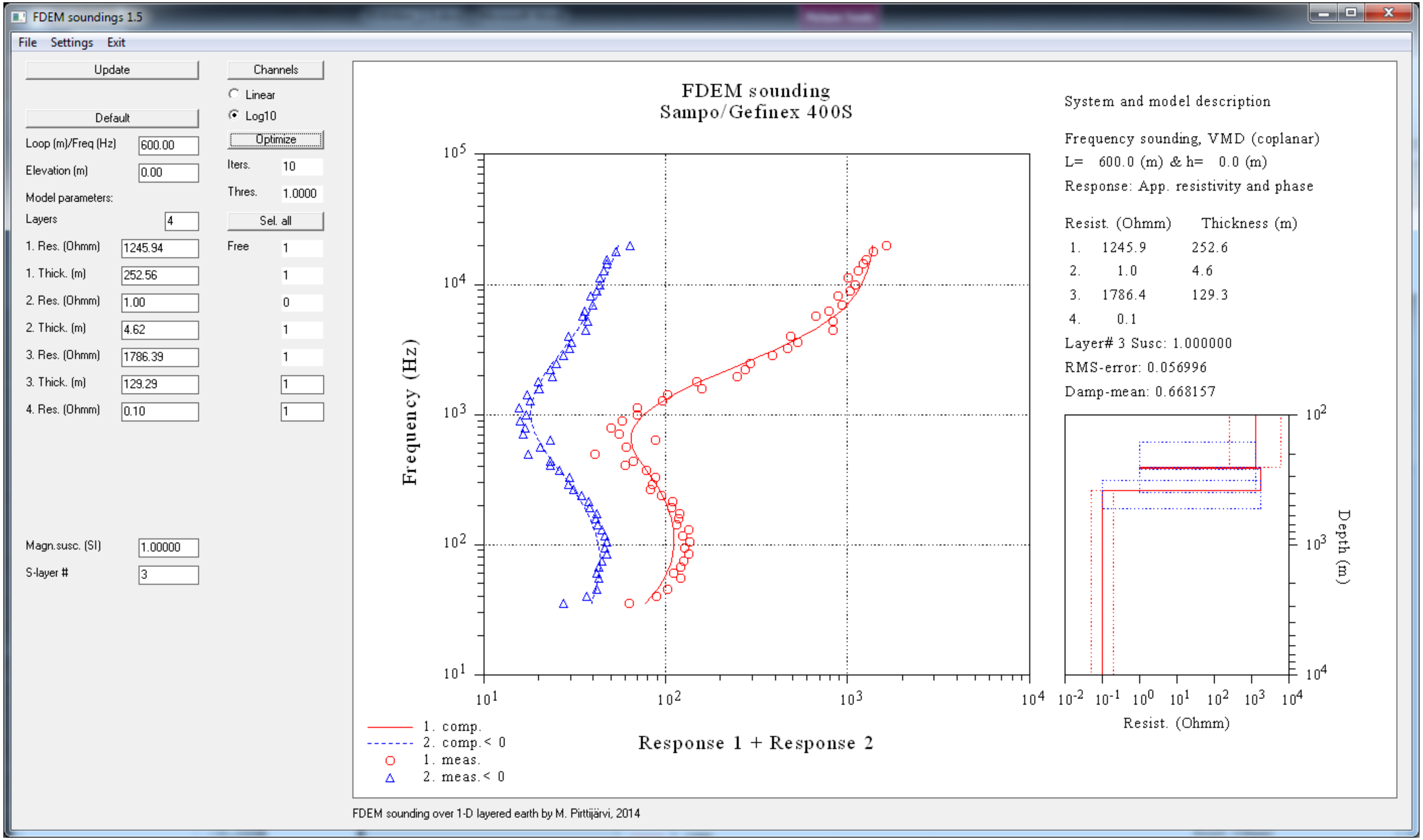

Figure 3. Screenshot of FDEM application where Sampo/Gefinex apparent resistivity and phase data has been interpreted using a 4-layer model. The resistivity of the conductive second layer has been fixed and strong susceptibility (*k*=1 SI) has been assigned for the third layer.

The *Settings* menu contains following items:

Comp.->Meas.	Make the computed response (synthetic) measured data
Remove Meas.	Remove information about measured data
Sounding type	Choose frequency or geometric sounding type
Source type	Choose coplanar VMD, coplanar HMD or coaxial HMD system
Field component	Response is one of the field component (Re,Im or Mod,Pha)
Normalized field	Response is one of the normalized field components
Ratio	Response is the ratio between the two components
Apparent resistivity	Response is the apparent resistivity and phase
Free space field	Include or exclude the free-space field from the total magnetic field
Normalization	Choose response normalization (plain, percent, parts-per-million)
Define freq/dist	Set frequencies or loop spacings for frequency or geometric sounding
Phase rad/deg	Computed phase will be either in degrees or radians
Grid show/hide	Show or grid lines in response graph and model view
Weights in/out	Data weights read from file can be excluded from inversion
Error bars	Choose how the error bars are drawn in the model view.

In case of the VMD source the first field component (H1) is vertical magnetic field and the second (H2) is horizontal (axial) magnetic field. In case of HMD the first field component (H1) is horizontal (parallel or coaxial) horizontal magnetic field and the second (H2) is the vertical magnetic field, which cannot be computed in case of coplanar HMD configuration. Consequently, the normalizing free-space magnetic field H0 is the vertical for VMD source and horizontal for HMD source.

The computed response is one of the thirteen possibilities (Re= real (in-phase) component, Im= imaginary (quadrature or out-of-phase) component, Mod= modulus & Pha= phase of the response).

Apparent resisitivity and phase between vertical and horizontal field (IMOD= 1),
Normalized field: 2= Re,Im(H1/H0), 3= Re,Im(H2/H0), 4= Mod,Pha(H1/H0), 5= Mod,Pha(H2/H0)
Ratio: 6= Re,Im(H1/H2), 7= Re,Im(H2/H1), 8= Mod,Pha (H1/H2), 9= Mod,Pha (H2/H1),
Field component: 10= Re,Im(H1), 11= Re,Im(H2), 12= Mod,Pha(H1), 13= Mod,Pha(H2)

Except for apparent resistivity the response depends on the choice of *Free space field* menu item, because normally the free space field (H0) is added to the total magnetic field (eg. H1=H0+Hs1). Excluding the free space field, thus, allows inspecting the secondary magnetic field alone.

Normalization (percents or parts-per-million) is possible for the following four response types: Re,Im(H1/H0), Re,Im(H2/H0), Re,Im(H1/H2), Re,Im(H2/H1) (IMOD= 2,3,6 or 7).

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.

The *Error bars* menu is used to hide or show the 95% confidence limits in the model view. Error bars can be shown as a) cumulative minimum and maximum curves, b) vertical and horizontal sticks, c) rectangular boxes (as in Fig. 3).

The *Exit* menu has two items. The first one can be used to restart the GUI and swap between traditional 3:4 display mode and a widescreen mode (giving an aspect ratio between 0.5-0.9). The second item is used to confirm the exit operation. On exit the latest model is saved in the FDEMINV.INP file 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 take a 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 was not used the file contains just the model parameters, some system information and the computed FDEM response. Note that normally the result files (as well as model files) are saved using the *File/Save results* menu item.

3.2 GUI widgets

Update button needs to be pressed to validate the changes made to any of the text fields defining the system, model and inversion parameters.

Default button resets all layer parameters to their default values (100 Ωm or 10 Ωm and 150 m).

Loop/Freq text field defines the loop spacing (m, for frequency sounding) or the frequency (Hz, for geometric sounding).

Layers text field is used to define the number of layers in the model. To update the number of layers one needs to press the *Update* button. When increasing or decreasing the number of layers the unnecessary text widgets get hidden. The maximum number of layers is six (6). Single layer can also be removed by giving it a zero thickness and pressing the *Update* button. Increasing or decreasing the number of layers always affects the layers at the bottom. There is no possibility to add a new layer in between existing layers.

The remaining text fields define the resistivity (Ωm) and thickness (m) of each layer and the resistivity of the basement layer. The two text fields (*Magn. susc* and *S-layer #*) at the bottom of the left control panel are used to assign magnetic susceptibility to one of the layers. If the model has more than one layer the susceptibility cannot be assigned to the top layer. The susceptibility is given in SI units. If S-layer # is equal to zero the magnetic susceptibility is not assigned to any of the layers.

Channels button at the top of the right control panel is used to show either both response components or just one of the response components. To select desired component the button needs to be pressed multiple times. The scaling of the graph changes according to the selected component. If data has been read in for interpretation, only the currently visible data component(s) is (are) used in the inversion. The radio buttons below the *Channels* button are used to set the scaling of the horizontal axis of the response graph linear or logarithmic ($\log_{10}$).

The remaining widgets become active only after some data has been read in using the *File/Read data* item. *Optimize* button is used to start the inversion. *Iters*. text field defines the number of successive iterations. *Thres*. text field 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 for the number of iterations and the threshold are 10 and 1.0 (actually 1.e-3), respectively.

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

3.3 About the inversion

FDEMINV is not an idiot-proof interpretation program. It requires a proper initial model. The *Default* button provides just one way to define the initial model. It is essential that the number of layers is set appropriately before inversion. The iterative, linearized inversion method can get stuck to a local minimum, and therefore, the user should pay attention to the validity of the resulting model. Due to the well-known equivalence condition of conductive layers, the conductivity and thickness cannot be interpreted separately. To reduce the error estimates of other parameters, the resistivity or the thickness of conductive layer should be fixed to some reasonable value before continuing on with the inversion (see Fig. 3). The RMS error, the mean of the damping factors and the width of the error bars 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. If all parameters are well resolved the error bars, which are based on the 95% confidence limits, will be very small.

4. File formats

When using the program for interpretation purposes make sure that your input data files (*.DAT) are formatted properly before reading in the data. 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
```

The first line defines a header text (max 30 characters) to be shown in the response graph. 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 13) 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 either the loop spacing (LOOP, m) or frequency (FREQ, Hz) used in the frequency or geometric soundings, respectively. The second parameter on the 4.th line defines the height (HEI, m) of the dipole-dipole system from the surface of the earth. 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 the data 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 remaining 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 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 1.4 model file:

   2
 0.10000E+03  0.10000E+03
 0.10000E+01

   1    1    1
    500.00       1.00
  0.000000   0
  23
   2.000000       3.000000       4.500000       6.750000       10.12500
   15.18750       22.78125       34.17188       51.25781       76.88672
   115.3301       172.9951       259.4927       389.2390       583.8585
   875.7878       1313.682       1970.522       2955.784       4433.676
   6650.514       9975.771       14963.66
```

The first line is used as a title defining the contents of the file. The 3.rd line defines the number of layers (NOL), the maximum amount of which is 6. Lines 4 and 5 (in this case) define the resistivity (RH, Ωm) and the thickness (TH, m) of the two topmost layers. The 6.th line defines the resistivity of the bottom layer. The 7.th line defines the source type (ISYS), response type (IMOD) and sounding type (IOPT) as they were defined for model files. The 8.th line defines the loop spacing or frequency (LOOP, FREQ) and the height of the source-receiver system from the ground level. The 9.th line defines the magnetic susceptibility and the layer number to which the susceptibility will be assigned. The 10.th line defines the number of frequencies (NOF) or loop spacings in case of geometric sounding. The frequency or loop spacing values are then provided at the end of the file. Note that the values 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.

5. Graph options

Several graph parameters can be adjusted by editing the FDEMINV.DIS file. Note that the format of the *.DIS file must be preserved. If the file format 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    0    0   0
 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)
Susc. (SI)
```

- 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: 1) is the info text is shown, 2) is the model view is drawn, 3) in which corner the legend is drawn, 4) are the grid lines visible, 5) is widescreen mode is active, 6) normalization (plain, percent, ppm) for some response modes, 7) how phase data is shown (radians or degrees) and 8) how error bars are drawn.
- 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 remaining lines define various text items of the graph (max. 40 characters).

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 thirteen 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 graphs are going to be prepared for presentation purposes.

The DISLIN graphics allows using 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)". Superscripts and subscripts can be initiated using control characters "^" (hat) and "_" (underscore). Text will be reset to baseline after control character "$" (dollar). See the DISLIN documentation for further information.

6. 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 Frischknecht, 1967). The convolution algorithm and the filter coefficients used to compute the Hankel transforms are based on Christensen's (1990) optimized filter coefficients. The inversion method, which is based on the singular value decomposition and adaptive damping method, is described in my PhD thesis (Pirttijärvi, 2003).

The FDEMINV program is written in Fortran90 and compiled with Intel Visual Fortran 15. The graphical user interface is based on the DISLIN graphics library (version 10.4) by Helmut Michels (http://www.dislin.de). Because DISLIN is available for other operating systems, FDEMINV could be compiled on Mac OS and Linux without major modifications. At the moment, however, the source code is not made available and I do not intend to provide active support for the program. If you find the computed results erroneous or if you have suggestions for improvements, please, inform me.

Please, note that FDEMINV has not been tested thoroughly and that its usability in data interpretation is quite modest. For example, data weights cannot be edited manually. Interpretation of frequency domain soundings is going to be implemented in future versions of Jointem, software for combined a.k.a. 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 home page of free geophysical software at https://wiki.oulu.fi/x/EoU7AQ.

7. References

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Keller, G.V., Frischknecht, F.C., 1966: Electrical methods in geophysical prospecting. Pergamon Press.

Pirttijärvi M., 2003. Numerical modeling and inversion of geophysical electromagnetic measurements using a thin plate model. PhD thesis, Acta Univ. Oul. A403, Univ. of Oulu.

8. Terms of use and disclaimer

You can use the FDEMINV program free of charge. The program can be downloaded from a website at the University of Oulu; https://wiki.oulu.fi/x/MoU7AQ.

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.