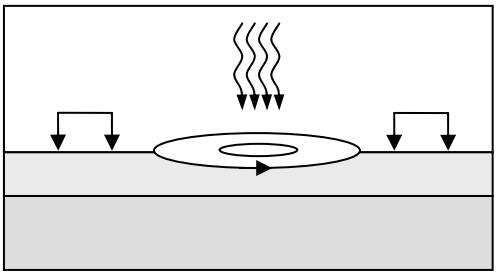
JOINTEM

Joint interpretation of electromagnetic and geoelectrical soundings using 1-D layered earth model

User's guide to version 1.3



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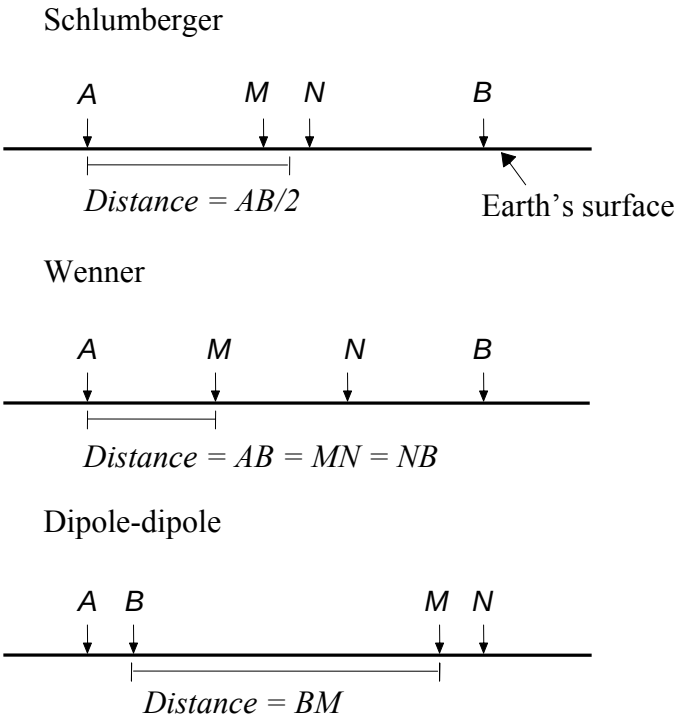
1. Introduction

JOINTEM is geophysical modelling and interpretation software for:

a) geoelectrical direct current (DC) soundings, a.k.a. vertical electric soundings (VES),
b) time-domain electromagnetic (TEM) soundings (single and central loop),
c) audiomagnetotelluric (AMT) soundings based on plane wave impedance, and
d) frequency-domain VLF-R measurements (single frequency).

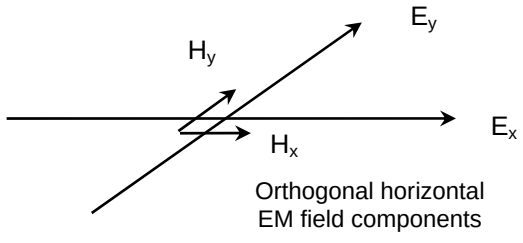
The computation is based on one-dimensional (1-D) horizontally layered earth model. The model parameters are the electrical resistivity and thickness (or depth to the top) of the layers. Cole-Cole model parameters (chargeability, frequency factor, and time constant) can be used in TEM method to account for (induced) polarization and dispersion effects and the chargeability can be utilized in DC soundings. Optimization based on linearized inversion method with adaptive damping is used to minimize the difference between measured field data and synthetic data computed for the model. Both individual and joint inversion of DC, TEM, and AMT data is possible. VLF-R data measured at single frequency can be used as additional constraint. The basic principles of VES, AMT, VLF-R, and TEM methods are illustrated in Figures 1-4. For more information, please, consult any text book of applied geophysics (e.g., Milsom, 2003).

Customary to all geophysical investigation methods, changes in the measured field components, i.e, static or time-harmonic electric field (or potential) and magnetic field (or magnetic induction) or their ratio, are related to changes in the electrical properties of the earth. This relationship and the characteristic behavior of the geophysical system responses can be studied with numerical modeling. The aim of geophysical interpretation is to solve the inverse problem: what kind of a structure could have produced the measurements? To accomplish this, the difference between the measured data and the modeled data is minimized by parameter optimization. The result is a simplified model of the real geoelectrical structure that needs to be interpreted geologically. However, one must remember that the model is only one-dimensional and the geophysical inverse problem is non-unique. Because real geological structures are complex and three-dimensional, the results obtained from JOINTEM interpretation may not represent the geological reality well enough.



$$\rho_a = 2\pi \frac{\Delta V}{I}\left[\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right]^{-1}$$

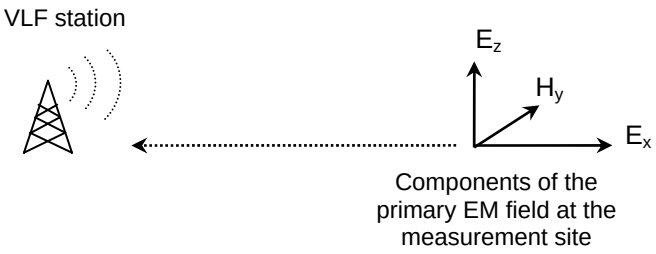
Figure 1. Principle of DC soundings. Current (I) is fed into ground with current electrodes A and B and electric potential (ΔV), which depends on the electrical resistivity structure of the earth, is measured with electrodes M and N. The response is defined as the apparent resistivity (ρ_a) as a function of electrode distance (AB/2, AB/3 or BM). With increasing electrode spacing the geometric sounding gives information from increasing depth. In JOINTEM the three configurations by which the electrodes are positioned are: Schlumberger, Wenner and dipole-dipole.



$$\rho_a = \frac{1}{\omega\mu}\left(\frac{E_x}{H_y}\right)^2 = \frac{1}{\omega\mu}\left(\frac{E_y}{H_x}\right)^2$$

$$\varphi = \arctan\left[\frac{\mathrm{Im}\left(E_x/H_y\right)}{\mathrm{Re}\left(E_x/H_y\right)}\right] = \arctan\left[\frac{\mathrm{Im}\left(E_y/H_x\right)}{\mathrm{Re}\left(E_y/H_x\right)}\right]$$

Figure 2. Principle of AMT method. The four orthogonal components of the natural (plane wave) EM field are measured simultaneously using grounded electrodes (E-field) and induction coils (B-field). After time series analysis, the processed data are represented as complex impedance, Z = |**E**|/|**H**|. Since the earth is considered one-dimensional the diagonal elements are zero and the off-diagonal elements are the same ($Z_{xy} = Z_{yx}$). The AMT response can then be defined as the apparent resistivity and phase. Due to attenuation of the EM fields the measurements made as a function of frequency (typically between 10 Hz and 10 kHz) give information as a depth sounding.



$$\rho_a = \frac{1}{\omega\mu}\left(\frac{E_x}{H_y}\right)^2$$

$$\varphi = \arctan\left[\frac{\mathrm{Im}\left(E_x/H_y\right)}{\mathrm{Re}\left(E_x/H_y\right)}\right]$$

Figure 3. The principle of VLF-R method. Distant VLF antenna (frequency 15-30 kHz) is considered as a vertical electric dipole. The radial electric field (E_x) and azimuthal magnetic field (H_y) components are measured and their ratio gives plane wave impedance. As in the AMT method, the response is defined as the apparent resistivity and phase. Because measurements are made at single frequency, there is minimal amount of depth information. Therefore, VLF-R data is used only as an additional constraining dataset in the interpretation.

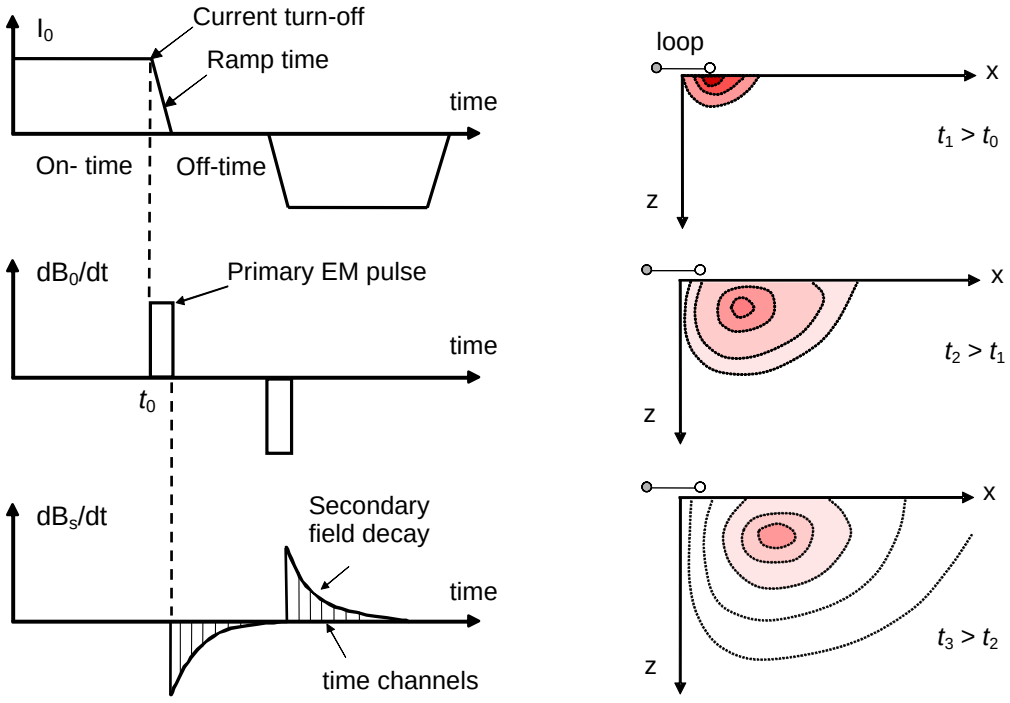


Figure 4. Principle of TEM method. Transmitter loop is laid on the surface of the earth. The (dc) current is turned off (within few microseconds) thus generating an EM pulse, which generates diffusing "smoke-ring" currents in the earth. The decaying secondary field of these currents is measured as the voltage ($V \approx dB/dt$) induced to the receiver loop or coil during the off-time. The decay rate of the secondary field depends on the resistivity of the earth. When considering layered earth, the measurements made as a function of time (typically between 10 μs and 10 ms) give information as a depth sounding.

2. Program setup

The JOINTEM program is a 32-bit application that can be run on Windows XP/Vista with a graphics display with larger than 1024×768 pixel resolution. Memory requirements and processor speed are not critical, since large data sets are not used and the computations, which are based on a convolution algorithms and direct analytical solutions for layered earth models, allows fast computation even on older computers. JOINTEM has simple graphical user interface (GUI) that can be used to change the parameter values, to handle file input and output, and to visualize the data and the model responses and the model. The GUI and graphics are based on the DISLIN graphics library (http://www.dislin.de).

The program requires the following two files:

JOINTEM.EXE	the executable file,
DISDLL.DLL	dynamic link library for the DISLIN graphics.

The distribution file (JOINTEM.ZIP) also contains a short description file (_README.TXT), user's manual (JOINTEM_MANU.PDF), and some example data and model files (*_DC.DAT, *_TEM.DAT & *_.INP). To read the manual you need a PDF reader program like Adobe's Acrobat Reader. To install the JOINTEM program simply unzip (Pkzip/Winzip) the distribution files into a new folder. You can also create a program shortcut on the desktop. However, to be able to start the program from a shortcut that locates in a different directory, please, move or copy the DISDLL.DLL file into the WINDOWS\SYSTEM folder or a folder defined in the PATH environment variable (via Control Panel/System/Advanced/Environment variables).

3. Getting started

On startup JOINTEM reads the model parameters from the JOINTEM.INP file and the graphics parameters from the JOINTEM.DIS file that are located in the program folder. If these files cannot be found when the program starts, new files with default parameter values are created automatically. If the format of these files should have become invalid the program halts and a possible explanation for the error condition can be seen in JOINTEM.ERR file. The program then computes the DC, TEM, and AMT responses based on the initial model and builds up the graphical user interface shown in Figure 5. Initially the TEM response is plotted in the graph area together with a model view (a resistivity-depth curve) and a written description of the model and system parameters.

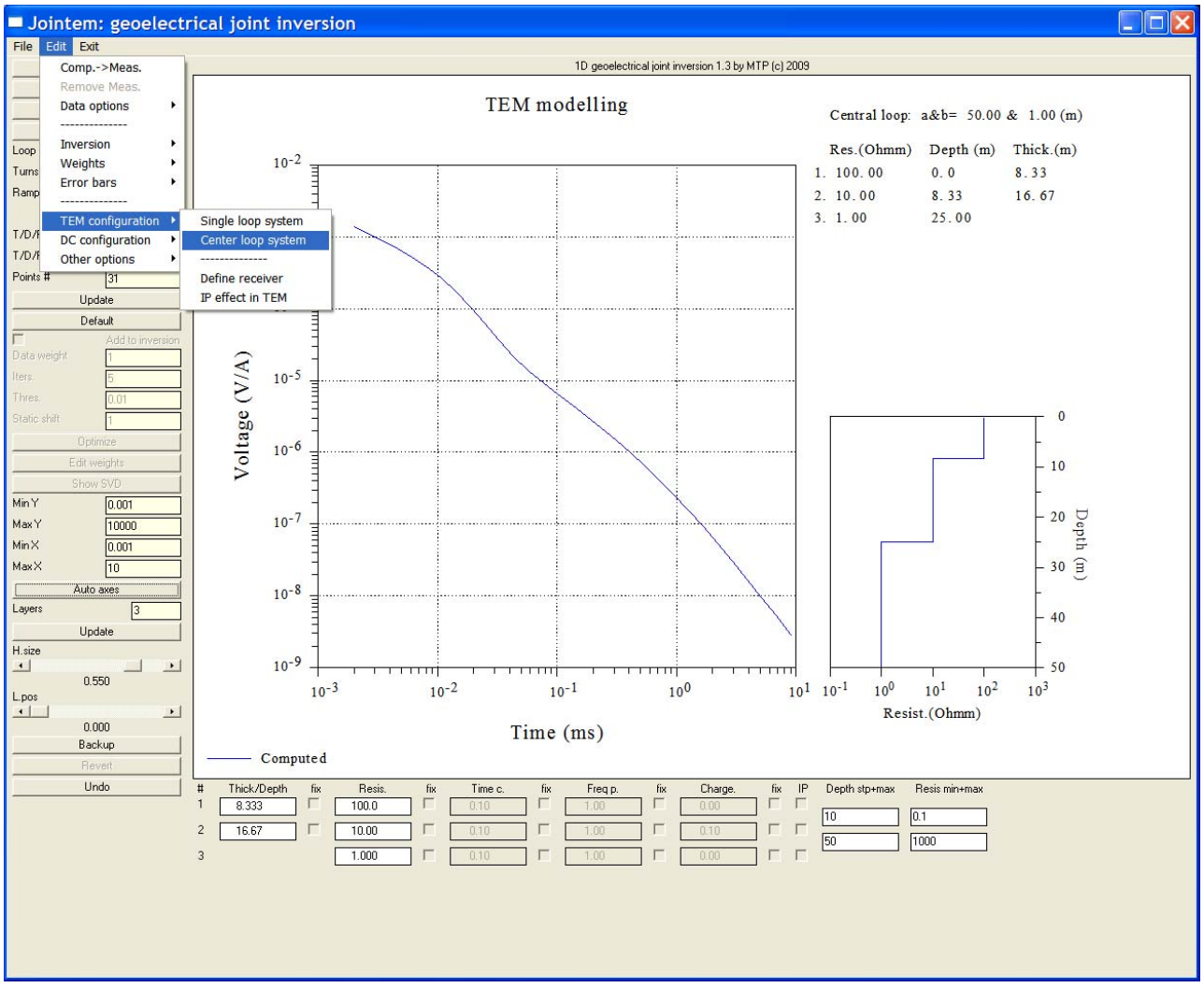


Figure 5. Jointem GUI window showing TEM central loop response of a three layer model.

The parameters controlling the modelling, inversion and graphics can be changed using the menu items and the various controls (widgets) in the main GUI window of the program.

When performing forward modelling the most important functions are:

a) swap between TEM, DC and AMT methods using corresponding push *Plot* buttons,
b) view alternative response components (TEM apparent resistivity, AMT phase, and DC apparent chargeability) using *Swap comp.* button,
c) edit computational parameters such as the minimum and maximum values of TEM time channels, VES electrode distances and AMT frequencies and TEM source parameter by editing the text widgets in the left control panel and use *Update* button to validate changes,
d) set the number of layers and edit model parameters below the graph, or apply *Default* button to generate automatically two and three layer models,
e) change TEM system (single or central loop) using *Edit/TEM configuration* menu, edit source (receiver) parameters using related fields in left control *(Edit/Define receiver* item),
f) change VES configuration (Schlumberger, Wenner or dipole-dipole) using *Edit/DC configuration* item (for dipole-dipole system define also the dipole length),
g) use *Auto axes* button to quickly adjust the axis limit of the current graph (and model view).

In the interpretation of measured field data the most important functions (in addition to those mentioned above) are:

a) import TEM, DC, and/or AMT data using the *Read data* menu items,
b) set the number of layers in *Layers* field (and use *Update* button),
c) create an initial model with *Default* button,
d) edit model parameters and their fix/free status manually to create better initial model,
e) edit data weights and ignore erroneous data using the *Edit weights* button,
f) perform numerical inversion using *Optimize* button.

The optimization is based on linearized inversion scheme where singular values decomposition (SVD) and adaptive damping are used. Based on an initial model ($\mathbf{p}_k$) the inversion iteratively computes parameter change vector $d\mathbf{p}$ from matrix equation $Ad\mathbf{p} = \mathbf{e}$, where $\mathbf{e}=\mathbf{d}-\mathbf{y}$ is the error

vector between measured (**d**) and computed data (**y**), and A is the sensitivity matrix (Jacobian) of dimension $N \times M$, where N is the number of free model parameters (columns) and M is the number of data values (rows). The elements of the Jacobian $a_{ij} = dy_j/dp_i$ are computed numerically as forward differences. The SVD is defined as $A = U\Lambda V^T$, where Λ is a diagonal matrix ($N \times N$) that contains the singular values λ_i, V is a $N \times N$ matrix that contains parameter eigenvectors and U is an $N \times M$ matrix that contains parameter eigenvectors. Since U and V are orthogonal the (pseudo) inverse of the Jacobian is $A^{-1} = V\Lambda^{-1}U^T$, and hence, the inverse solution is $d\mathbf{p} = V\Lambda^{-1}U^T\mathbf{e}$ and the updated parameter vector becomes $\mathbf{p}_{k+1} = \mathbf{p}_k + d\mathbf{p}$.

The visual fit between the measured data and computed response, the RMS error, the mean of the damping factors and the SVD information (singular values and parameter and data eigenvectors) are used to assess the validity and accuracy of the inversion. Optimally, the RMS error should as small as possible and the sum of damping factors should be equal to one. However, data weighting affects the inversion and therefore visual analysis and weight editing play important role also. Note that the resistivity-depth curve of the model view can (optionally) show the estimated error limits. The error bars are equal to the 95% confidence limits, which are computed using the information of the singular value decomposition. Please, refer to Press et al. (1988) for detailed information how the SVD and confidence limits are computed.

JOINTEM is not an "idiot-proof" interpretation program. It requires a good initial model with a predefined number of layers. Depending on the initial model the inversion finds a model, which may be a local minimum of the objective function (data misfit). Therefore, the user should pay attention to the physical meaning of the results. Special care must be used when interpreting conductive layers, since due to the equivalence the optimization tends to yield solutions where the layer conductance (conductivity-thickness product) remains the same but the individual conductivity and thickness values may vary. Moreover, one should try to keep the models as simple as possible and avoid using unnecessary layers unless additional *a priori* information exists. If depth values are known from seismic interpretations, for example, one should fix the depth of those layers that are known and optimize layer depth instead of layer thickness. This effectively reduces the non-uniqueness of the inverse solution.

4. Menu items

The *File* menu contains the following items:

Open Model	open an existing model file (*.INP)
Save Model	save the model into a file (*.INP)
Read TEM data	read in measured TEM data for interpretation (*.DAT)
Read TEM-fast	read AEMR's TEM-Fast 48 data file (*.TEM)
Read DC data	read in measured DC data for interpretation (*.DAT)
Read AMT data	read in measured AMT data for interpretation (*.DAT)
Save TEM data	save the measured and computed TEM data (and weights)
Save DC data	save the measured and computed DC data (and weights)
Save AMT data	save the measured and computed AMT data (and weights)
*Save Result*s	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)
S*ave 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)
Save Graph as GIF	save the graph in GIF file format (*.GIF).

These menu items bring up a typical MS Windows file selection dialog that is used to provide the file name for the open/save operation. Model files (*.INP), data files (*.DAT), result files (*.OUT), and the graph parameter file (*.DIS) are stored in text format. The file formats are discussed later in this document. The graphs are saved in PS, EPS, PDF, WMF and GIF format as they appear on the screen in landscape A4 size. The best quality is obtained using PS or PDF format.

The *Edit* menu contains following items:

Comp.->Meas.	place the computed synthetic response as measured data
Remove Meas.	remove information about (currently shown) measured data
Data options	sub-menu for additional data related settings
Inversion	choose inversion modes and to define VLF-R data
Weights	choose how to use data weights in the inversion
Error bars	choose the type of error bars in model view
TEM configuration	choose the TEM sounding system and enable IP effect
DC configuration	choose the VES configuration and enable IP effect
Options	sub-menu for additional computational and graphical settings.

Comp.->Meas. puts the synthetic data of the current model as if it were measured field data. This option provides a fast method to test the inversion and to compare two different model responses with each other.

Remove Meas. removes information about the measured data (synthetic or real data). If multiple datasets exist (e.g, TEM and DC) the user is asked if the information of all data should be removed. Otherwise only the current data type will be removed. Note that some control widgets and menu items are inactive (grayed out) before data has been read in for the inversion.

Inversion sub-menu is used to quickly change the inversion mode for full joint inversion, AMT phase component and VLF-R data. Except for VLF-R data, one can also use the *Add to inversion* check box in the left control panel to include (and exclude) the currently shown dataset in (from) the inversion. VLF-R data is provided manually by setting the frequency (Hz), apparent resistivity (Ωm), phase (deg.) and weight factor (0,1−10). The VLF-R data is removed from inversion by giving an empty line when the program asks for the VLF-R information. When VLF-R data are active they will be shown in the AMT graph using a different symbol (triangle) shape. Note that joint inversion is possible only after at least two data sets have been read in and that VLF-R data cannot be inverted alone. *Thickness vs. depth* item is used to choose the inversion mode between layer thicknesses and depth to the top of the layers. These two inversion modes are more or less the same if thickness or depth values are not fixed. Otherwise they handle *a priori* data differently. The current inversion mode is identified in the model information (legend) text.

Weights sub-menu is used to include and exclude the user defined data weights in the inversion. Weight values range between 0,01 and 100. The smaller the weight is the less importance the data value has in the inversion. On the contrary, the larger the weight is the more importance the inversion gives to that data value. Data with weights less than 0,01 are excluded from the inversion totally. Unit weights are used by default and if the data file did not contain any weights. Weights can be defined interactively using the *Edit weights* button described later. Normally weights are not shown together with the response curve. Separate weight curve can be added to the graph by selecting *Apply and show* item in *Weights* menu. In this case, however, the tick marks of the weight axis on the right side of the graph are shown without labels and axis title to give room for the model view and information text.

Error bars sub-menu is used to change the appearance of the error bars in model view. The error bars show the 95% confidence limits (minimum and maximum errors) obtained from the singular value decomposition used in the linearized inversion method. Note that the confidence limits depend on the damping factors, which depend on the value of the minimum relative singular value threshold (*Thresh %*). Increasing the threshold value imposes stronger damping that produces narrower confidence limits. Ideally, the confidence limits should be small even if the threshold is small (no damping at all).

TEM configuration sub-menu is used to define the TEM configuration and the receiver for central loop system, and to activate the IP effect and Cole-Cole parameters in TEM computations. The TEM measurement configuration is either: single loop (coincident loop) system, where the source loop is also the receiver, or b) central loop system, where smaller receiver loop or coil is located in the center of the transmitter loop. When central loop system is selected, one needs to define the radius of the receiver loop *b* (metres) and the number of loop turns *Nr* using the *Define receiver* item as illustrated in Figure 6. If the *Nr* is given negative value, *b* is interpreted as the side length of a square loop. If *Nr* is set equal to zero, *Rr* is considered as the effective area of the loop and the radius and number loop turns are computed automatically. Note that after measured data have been read in, the TEM configuration cannot be changed anymore. Also note that in the information text next to the graph, parameters *a* and *b* refer to the side length (and not the radii) of the transmitter and receiver loops when central loop system is used.

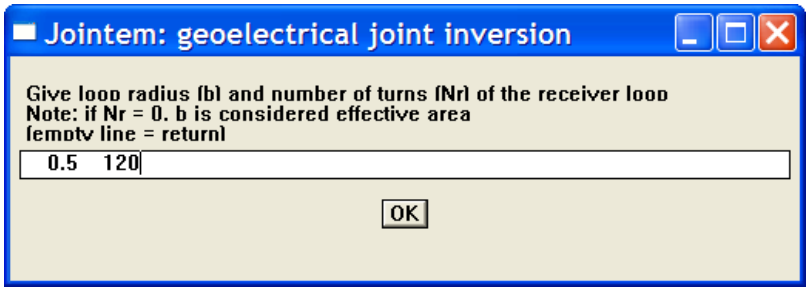


Figure 6. Settings for the receiver in central loop configuration.

DC configuration is used to select between a) Schlumberger, b) Wenner and c) dipole-dipole systems illustrated in Figure 1. Note the different definition of the electrode distance used as the x axis in the response graphs. In Schlumberger system the distance is half the current electrode

separation (AB/2). In Wenner system the distance is the equal to the even electrode separation (AM=MN=NB= AB/3). In dipole-dipole system the distance is the separation between the nearest current and potential electrode (BM). Note that if measured data has been read in, the electrode configuration cannot be changed anymore.

The *Exit* menu has two menu items. The *Widescreen* item is used to restart the program and build up the graphical user interface in a mode that suits either normal 4:3 display or widescreen or laptop displays with greater width. When changing into widescreen mode the user can give additional value for the aspect ratio. The default value 0,83 suits most widescreen displays, but even smaller value should be experimented especially when the screen extends on two displays.

Exit is used to close the program with grace. Emergency exit can be made pressing the close button in the top right corner of the GUI window or pressing Ctrl-C inside the console window. On graceful exit the model, results and graph parameters is saved in JOINTEM.INP, JOINTEM.OUT and JOINTEM.DIS file in the program folder. Copies of the computed (and measured) data are included in the *.OUT results file. Possible error conditions are reported in JOINTEM.ERR file. Inside the GUI mode run-time errors are displayed on the screen. Note that result files (and model files) can be saved at any time using the *Save Result*s (and *Save model*) menu item. See the chapter on file formats for more information.

4.1 IP settings

IP effect in TEM is used to activate and deactivate the effect of induced polarization in TEM computations. By default, IP parameters next to layer resistivities are inactive, which means that the (dc) layer resistivity is the only electrical model parameter. The polarization and dispersion effects are described by the Cole-Cole model (Cole & Cole, 1941), in which the frequency dependent (complex) resistivity or conductivity of the layers is computed using equation (Raiche, 1983)

$$\rho(i\omega) = \rho_0\left(1-\eta\frac{(i\omega\tau)^c}{1+(i\omega\tau)^c}\right) \qquad \text{or} \qquad \sigma(i\omega) = \sigma_0\left(\frac{1+(i\omega\tau)^c}{1+(1-\eta)(i\omega\tau)^c}\right), \tag{1}$$

where ρ_0 and σ_0 are the frequency independent (dc) resistivity and conductivity, $\omega=2\pi/t$ is the angular frequency, η ($0>\eta>1$) is the chargeability, c ($0>c>2$) is the frequency factor, and τ is the time constant. Note that Cole-Cole model parameters also need to be enabled separately for each layer using the IP check marks next to the chargeability values below the graph. Cole-Cole parameters can create drastic changes in TEM responses. Specifically, it can be used to explain negative values in single loop TEM response (see Appendix E). The physical explanation of the Cole-Cole model parameters is still not very well understood, however.

IP effect in DC is used to activate the layer chargeability and the computation of apparent chargeability in VES computations. If IP effect is disabled in TEM, only the layer chargeability fields will be active, because the time constant and frequency factor of the Cole-Cole model are taken into account in TEM computations only. In DC computations the IP affected resistivity or conductivity of the layer is defined using equation (Sumner, 1959)

$$\rho'_i = \frac{\rho_i}{1-\eta_i} \qquad \text{or} \qquad \sigma'_i = (1-\eta_i)\sigma_i \tag{2}$$

Thus, chargeability ($0>\eta>1$) will increase the resistivity (decrease the conductivity) of the layer. Consequently the computed apparent resistivity curve will be different. The difference between the "ordinary" apparent resistivity (ρ_a) and IP affected resistivity (ρ^*_a) is defined as apparent chargeability (Seigel, 1959)

$$M_a = \frac{\rho^*_a - \rho_a}{\rho^*_a} \tag{3}$$

The computed apparent chargeability values are multiplied by 100, so that the unit can be considered to be $[M_a]$= %. Apparent chargeability values plotted as a function of electrode distance on a log-linear scale. To see the apparent chargeability one needs to use the *Swap comp.* button when the DC graph is active. Note that the *Swap comp.* button is inactive if the IP effect is currently disabled.

Important: Apparent chargeability is computed mainly for academic and educational purposes. Different DC and IP instruments measure the induced polarization response differently (e.g.,

integrated voltage, frequency effect FE, and metal factor MF) and currently JOINTEM cannot compute synthetic data for a certain instrument. Therefore, measured chargeability data cannot be used in the inversion (at least not at the moment). To see if measured data could be scaled to percentage data one can try to use the *Edit/Data options/Norm. data* menu item.

4.2 Data options

Data options sub-menu contains following items:

XYZ location	set sounding site number and xyz coordinates
Define title	define secondary title for the current TEM, DC or AMT graph
Reset x-axis	multiply current data axis with a user given value
Norm. data	divide current data with a user given value
Add noise	add random (Gaussian) noise to the data.

The geographic locations of the soundings are not shown anywhere. In practice, measurements are made along a continuous profile and when put together the interpreted models could be used to create two-dimensional vertical cross-section of the electrical resistivity. For this purpose it would be advantageous to be able to use actual geographic coordinates and topographic elevation. At the moment, JOINTEM does not have this kind of functionality, but as illustrated in Figure 7 the information is stored in the model files, nonetheless.

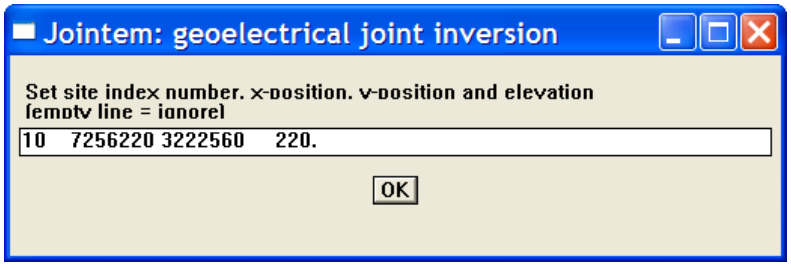


Figure 7. Setting the index number, map coordinates, and elevation of the sounding site.

Reset x-axis is used to multiply current data axis values, e.g, TEM time channels, AMT frequencies or VES electrode distance, with a user defined value. It is important (!) to know that TEM time channels are defined and handled in milliseconds (ms). Thus, a value 1000 would convert microseconds to milliseconds and value 0,001 would convert seconds to milliseconds. Likewise, AMT frequencies can be converted from kHz to Hz and VES distances from feet to metres. Note

that by giving zero value, the data axis is inverted, so in principle time periods that are commonly used in magnetotelluric (MT) studies can be converted into (AMT) frequencies.

Norm. data is used to divide current data with a user defined value. Thus, it can be used to a) normalize TEM voltage data by transmitter current (and surface area), b) scale measured chargeability data with instrument dependent value, or c) change AMT phase angle from radians to degrees ($180/\pi = 57{,}29578$). It is important (!) to know that the TEM response is always computed using unit current (I = 1 A). Therefore, if TEM data have not been normalized with the current before it is read in, one must use the *Norm. data* item before continuing with the inversion. Note that zero value will invert the data, so in principle apparent conductivity can be transformed into apparent resistivity.

Add noise is used to generate and add random (Gaussian) noise in the data. For AMT phase and VES apparent chargeability that are plotted on a linear scale the noise level is defined as a percentage of 45 degrees and 50 %. Thus 100% noise level can give 45 degree change in AMT phase data. For data that are plotted on logarithmic scale (TEM voltage and apparent resistivity) the noise level is defined as a percentage from one decade. Thus, 100% error would give to 10 times smaller or larger values.

4.3 Other options

Other options sub-menu has following items:

Elevation	choose elevation instead of depth
TEM scale	change the scaling of the TEM voltage response
*Depth scal*e	logarithmic vs. linear depth axis in the model view
Auto size	automatic aspect ratio of the response graphs
Skin depth	to enable plotting VLF-R skin depth in model view
Grid lines	show or hide grid lines in response graphs
Colors	use either black or colored (red and blue) lines in response graphs
Line thickness	use either thin or thick lines in response graphs
Symbols size	use either larger or smaller symbols in response graphs

By choosing elevation instead of depth one can change the direction of the z axis. Normally z axis is positive downwards and depth values are computed from the surface or the given z-coordinate of the sounding site. If elevation is used z-axis is positive upwards and the depth values are computed with respect to the given z-coordinate of the sounding site, which in turn is usually the topographic height from the sea level. The use of elevation gives a better possibility to compare models from surrounding sounding sites and to relate them to the actual topography of the groundwater or bedrock.

The TEM voltage response is a rapidly decaying curve ranging over several decades (e.g., 10–10^{-7} V). *Alternative TEM scaling* multiplies the TEM voltage data with $t^{5/2}$, a time dependent factor equal to the (inverse) time dependency of the late time approximation of the single loop TEM voltage response. As such the alternative scaling can be considered as "poor man's" apparent conductivity transform. The alternative scaling is useful when trying to clarify the fit between measured and computed data, but should not be used when plotting final results. The presence of alternative scaling is identified by the additional (x $t^{-5/2}$) at the end of the title of the y-axis.

The remaining items are quite self-explaining. If the depth axis is logarithmic the minimum depth is computed automatically. If the depth axis is linear the minimum depth is always zero (metres). The automatic aspect ratio makes the height of the log-log graphs such that a one decade shows up as a square when the width of the graph is changed using the scroll bar at the bottom of the left control panel. Alternatively, the aspect ratio can change freely but the height of the graphs is fixed based on the value defined in the JOINTEM.DIS graph parameter file.

5. User interface controls

The various controls of the main GUI window of the JOINTEM program are used for easy access to the most frequently used settings and actions needed to run the program. The controls on the left are related to modelling and inversion. The controls below the graph define the model parameters and their fix/free status in the inversion.

5.1 Left control panel

TEM plot, *DC plot* and *AMT plot* buttons are used to change the current response graph between different sounding methods. If VLF-R data were added in the inversion it can be seen in the AMT graphs. Depending on the current response graph the horizontal x-axis is either time (milliseconds), the electrode distance (metres) or frequency (hertz).

Swap comp. button is used a) to change the TEM response graph type between voltage and (late-time) apparent resistivity modes, b) to change AMT response graph between apparent resistivity and phase data, and c) to change DC response graph between apparent resistivity and apparent chargeability mode (if the IP effect is enabled for DC computations). If original data were provided as voltage induced to the receiver loop, it is automatically transformed into apparent resistivity. The TEM apparent resistivity is computed using the solution defined for the late time voltage response of single and central loop system above homogeneous half space. However, if the original TEM data is apparent resistivity it will not be transformed back into voltage data. In this case the *Swap comp*. button will be inactive in TEM mode. Likewise, if the AMT data do not include phase component (so-called scalar AMT measurements) only the apparent resistivity will be used in the inversion. In this case, however, the *Swap comp.* button is still active and the modelled phase data can still be viewed.

Loop, *Turns* and *Ramp* define the size (width of the square loop in metres), the number of windings (integer value), and the length of the ramp time (microseconds) of the TEM transmitter loop. In the actual computations a square loop is approximated by a circular loop with equal surface area ($a^2 = \pi r^2$). Note that simple linear current ramp is currently utilized, although in most modern

instruments the current waveform is a more complicated function of time. If ramp time is set equal to zero the result is a pure (instantaneous) impulse response.

T/D/F min and *T/D/F max* define either the minimum and maximum value of the TEM time channels, VES electrode distances or the AMT frequency range depending on the current graph. The *Points #* field is used to define the number of evenly spaced (log-log axis) computation points between the minimum and maximum values. If dipole-dipole configuration is selected the text field (*Dipole*) used to define the dipole length (in metres) becomes visible also. Note that when measured data has been read in these values cannot be changed, since they are defined in the data.

Update button is used to validate, that is to say, to read in, check and change the values of the parameters manually edited in the various text fields of the main program window. Note that to reduce the need for moving the mouse so much the left control panel has two *Update* buttons.

Default button is used to create an initial model automatically. In the modelling mode (when data has not been read in) the model parameters depend on the number of layers (2 or 3) and the resistivity of the top layer. The model is given different resistivity contrasts (10 times larger or 10 times smaller) when the *Default* button is pressed multiple times. In the inversion mode, when data have been read in, the default model is derived from the data. Note that VES data has bigger importance in the creation of an initial model, so the model will be different if only TEM or AMT data is available. The algorithm used to define the initial model is subject to change in the future so it will not be described here in detail.

Add to inversion check box is used to exclude and include current data from the inversion or to the inversion temporarily (without *Remove Meas*. menu item). When looking at AMT phase data it will remove only the phase component. When looking at AMT apparent resistivity it will remove both components, because phase data cannot be used in the inversion without apparent resistivity data.

Data weight is used to give global weight value for individual datasets. By default global data weights are equal to one so that TEM, DC and AMT data have equal weight. If the weight is increased that particular data or measurement system is given greater importance than other datasets. Note that for the AMT data the apparent resistivity and phase components are given

separate data weights, so that phase data, for example, can be given smaller importance than apparent resistivity data. The weight values should preferably range between 0,1 and 10. In principle, weight value equal to zero will remove that data from the inversion totally (the Jacobian will contain zero elements). That, however, is not practical because it is more efficient to remove the data from the inversion using the *Add to inversion* check box.

Note: If both TEM voltage and apparent resistivity data are available, the inversion will utilize that data component which is currently active and visible (*Swap comp*). Because data weights and scaling are based on the data, the results might be a bit different from voltage based and apparent resistivity based TEM inversions.

Iters. defines the number of iterations to be performed at a time when optimization is started and *Thres*. defines the minimum singular value threshold used in the optimization. This parameter (which is actually multiplied by 1000) controls the strength of the damping. Decreasing its value loosens the damping and makes the inversion method work like a steepest descent algorithm. Increasing its value can be advantageous if inversion is unstable. The default values for the number of iterations and the threshold are 5 and 0.01 (1.e-5), respectively.

Static shift is used to account for the well known problem with AMT data, where the measured apparent resistivity values (not the phase data) can be distorted by nearby conductivity variations so that it has static (independent of frequency) level shift in it. Shift values 10 and 0,1 will move the measured apparent resistivity data one decade up or down the y-axis, respectively. The effect of static shift is unknown and can greatly affect the inversion results. Joint interpretation with other geoelectrical data (VES, TEM and VLF-R) is one of the best methods to improve the quality of AMT inversion. Although, it could be possible to include the static shift into the joint inversion as a free parameter, in the current version of JOINTEM it must be adjusted and tested manually. Note that static shift does not affect phase data and VLF-R data is likely to have negligible or at least somewhat different level of static shift. Therefore, the fit of VLF-R and AMT phase data can be used to assess the suitability of the selected value of static shift. If TEM or VES sounding data are available, the joint inversion can reach good solution only if the value of static shift is properly set.

Optimize button is used to perform a predefined number of inverse iterations after data has been read in and initial model has been defined. The algorithm will adjust all free model parameters so that the difference between the measured and the modeled data gets minimized. The forward computation of the VES response of a 1D model is quite fast, so several iterations can be performed in a few seconds on a modern PC. The TEM response, however, is computationally more demanding. Therefore, multiple TEM inverse iterations with multiple layers may take few tens of seconds. After multiple iterations the inversion should converge to a final model and the parameters cease to change (or they start to oscillate around the final model). At this point the inversion should be stopped and the accuracy and the validity of the model should be investigated.

Edit weights button is used to enter the interactive weight editing mode. This push button is active only if data have been read in. Data weights and their editing are discussed later in this document.

Show SVD button, which is only activate after an inverse iteration, will display a graphical view of the singular value decomposition (SVD) of the sensitivity matrix, also known as the Jacobian The SVD plot is illustrated in Appendix F. The first graph shows the parameter eigenvectors, which can reveal the relative importance and sensitivity of each layer parameter and correlation between parameters. The second graph, which appears when *Show SVD* button is pressed again, shows the data eigenvectors that can reveal the relative importance and sensitivity of each data component (TEM, DC, AMT) that give the contribution to the corresponding parameter eigenvectors. For more information about SVD analysis, please, refer to Jupp & Vozoff (1975), for example. When studying the SVD information it might be worth mentioning that the inversion works with the 10-base logarithms of the data and the parameters (resistivity and thickness). The *Show SVD* option is experimental and may have been made inactive in the current distribution version of JOINTEM.

Min Y, Max Y, Min X and *Max X* are used to define the minimum and maximum values of the horizontal x-axis (TEM time channel, DC electrode distance or AMT frequency) and vertical y-axis (voltage, apparent resistivity or apparent chargeability) of the response graph.

Auto axes button is used to compute axis limit values for the current graph automatically. In this case the minimum and maximum values of the axes are set even 10-base logarithms (0.1, 1, 10, 100, etc). If the *Auto axes* button is pressed twice the axis limits of the model view will be updated.

Layers defines the number of the layers in the 1D model. The maximum number of layers is seven. When changing the number of layers one needs to apply the *Update* button to validate the action. When the number of layers is increased new layers are added to the bottom, their text fields become visible and they are given default values (100 Ωm and 10 m) or their previous values become visible (again). Similarly, when layers are removed, they are taken away (hidden) from the bottom of the model. See next chapter how to add and delete layers between other layers.

Update push button is used to validate the changes made to other parameters and to perform single forward computation and to update the response and model graphs. Note that forward computation replaces inversion results so that some information may be lost when working with field data.

The two scroll bars at the bottom of the left control panel are used to set the horizontal width of the response graph (relative value 0,2–0.6 of the page width) and the vertical position of the information (legend) text at the right size of the response graph (relative value 0–0,5 of the page height). The size of the TEM and DC graphs can be different. If automatic graph sizing (*Edit/Other options/Auto size*) is active the height of the graphs is computed automatically so that the one decade on the log-log graph shows as a square. If automatic resizing is inactive the height of the graphs is equal to the value defined in the JOINTEM.DIS file. Note that the size and position of the model view is defined automatically and it cannot be changed and that the position of the origin of the response graph is defined in the JOINTEM.DIS file. The changes made to the graph size are stored in JOINTEM.DIS file and used the next time the program is started.

Backup button is used to take a quick copy of the current model into program memory and *Revert* button is used to replace the current model with the backup. In addition, JOINTEM creates automatic copies of the model a) before updating the model (*Update* button), b) before reading a model file, c) before creating an initial model (*Default* button) and d) before optimization. The *Undo* button will revert the model back to the previous automatically saved model. Note that *Undo* takes a copy of the current model so that pressing the button twice can be used to swap between two different models and to see their difference on computed response.

5.2 Bottom control panel

The parameters of each layer are set using the text widgets below the response graph. The model parameters are: the thickness (or the depth to the top) and the resistivity (ohm-metres) of the layers (metres) and the Cole-Cole model parameters (chargeability, time constant and frequency factor) of the layers. After editing the fields the *Update* push button must be used to activate the changes.

Useful tip: Single layer can be removed if it is given zero thickness or zero resistivity value. A new layer can be added between other layers one if it is given negative resistivity value. Actually in this case, the layer will be split into two layers. The bottom layer cannot be split into two, but increasing the number of layers has the same effect.

When pressed with the left mouse button the check marks (*fix*) on the right side of each parameter field are used to fix and free parameters in the inversion. Fixed parameter will identified by a * character next to its value in the information text. By default all parameters are free.

Important: The inversion works either on layer thickness or layer depth values (*Thickness vs. Depth* menu item). The depth inversion mode allows the depth to the top of a particular layer to be fixed based on a priori information. For example, if the groundwater level is known then the layer related to that should be fixed accordingly. Thickness inversion mode works differently and would require that all layers above the groundwater level are fixed (which is not desirable).

By default the Cole-Cole model parameters are inactive. For TEM computations they are enabled using the *IP effect in TEM* menu item. For DC computations the chargeability is enabled using *IP effect in DC* menu item. Furthermore, for TEM computations the check marks (*IP*) at the right end of each row of layer parameters must be activated to enable the Cole-Cole parameters for each layer. This is not required in DC computations, where the chargeability will be active whenever IP effect is enabled. Note that Cole-Cole model parameters should not be activated for every layer, (because of ambiguity and slowness of inversion). Instead, a single layer (e.g., clays or schists) should be made responsible for the polarization effects. Even then the inversion should not try to optimize all three Cole-Cole model parameters together. Instead, the frequency factor should be

fixed and tested using a trial-and-error method while the time constant and chargeability can be free parameters. Please, note that physical interpretation of IP parameters is quite ambiguous.
Because of the high frequency (10-25 kHz) of the VLF-R method, it has quite limited depth of investigation. The depth of investigation is related to the (plane wave) skin depth defined as:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \approx 503\sqrt{\frac{\rho}{f}} \ [\mathrm{m}] \quad , \tag{4}$$

where ρ is the resistivity of the medium (Ωm) and f is the frequency (Hz). To be able to visually estimate the depth of investigation, the cumulative skin depth at the given VLF-R frequency is shown as a horizontal dashed line in the model view. The cumulative skin depth is computed by adding the electric attenuation in each layer until the amplitude reaches 1/e of its original value. The line can be removed from the graph using corresponding item in *Edit/Other options* sub-menu.

The remaining four text widgets at the right end of the bottom control panel are related to the model view. These values are used to change the minimum and maximum value of the horizontal resistivity axis (in ohm-meters) and the step and maximum value of the vertical depth axis (in metres). The step value is used only when the depth is plotted using linear scaling. Minimum depth value is always zero for linear depth axis and some rounded 10-base logarithm value for logarithmic depth axis. Automatic axis limit values can be set to the model graph by pressing the *Auto axes* button twice.

6. Data weights

Proper use of data weights plays an extremely important role in the interpretation. The weight values can vary between 0,01 and 100. The default value is one, which is given to all data values by default if not defined in the model file or set manually. Weight values larger than one increase the importance of those data points. On the contrary, weights less than one decrease the importance of the corresponding data. Data points with zero weight (less than 0,01) are ignored totally in the inversion. Such discarded data values are plotted with different symbol in the response graph (marked by a plus-sign). Note that the values are relative and if all weights are equal to 10 or 0,01 it has the same meaning as if they were equal to one.

The weights represent the inverse of measured or estimated data errors or variances. When weights are read from the file and the corresponding column number is given a negative value the weights are automatically inverted ($Wg = 1/Wg$) and scale between 0,01 and 100. The method used to define weights from data error is likely to change in the future and will not be discussed here in detail.

6.1 Weight editing

The user should get accustomed with interactive weight editing, because it plays an important role in successful interpretation. After pressing the *Edit weights* button the normal mouse arrow cursor will change to a crosshair cursor and most of the menu items and GUI controls become inactive. Weight editing mode is illustrated in Appendix D. A second, logarithmic y-axis ranging from 0,01 to 100 appears to the right side of the response graph. The model view and the information text disappear from the graph temporarily. To exit the editing mode one needs to press the right mouse button once (or twice).

The weights are plotted on the graph as a curve with dashed line style. By default, all weights are equal to one so the curve is simply a horizontal line in the middle of the graph. If weight value is less than 0,01 the corresponding data value is identified by a plus-sign over it.

Vertical lines are drawn through each data value to guide weight editing. The editing is made by pressing the left mouse button once above or below the corresponding data value. Pressing the right

mouse button finalizes the editing and the weight curve will be updated. This way one can edit the weights one-by-one. To speed up weight editing some special gimmicks are applied:

- If one presses the left mouse button at two different positions (and then presses the right mouse button) the weights between those two points are adjusted based on linear interpolation.

- Likewise, if one presses the left mouse button at different positions from left to right or from right to left (and then presses the right mouse button) spline interpolation is used to adjust all the weight values between the outermost points.

- If one presses the left mouse button above or below or below the actual graph (and then presses the right mouse button) the weight of that particular data point is set value 0.01, which means that it will be excluded from the inversion.

- If one presses the left mouse button on the left or on the right side of the graph (and then presses the right mouse button) all weights, even the previously excluded ones, are set to that value. This is the easiest way to reset all weights.

The weights are stored both in the data files and in model files. Thus, after editing the weights one should save the data again so that the interpretation can be restarted afterwards using previously defined weights. Note that after measured data has been read in, weights are not read from the model file (just the model parameters).

Also note that VES and TEM data usually have different resolving capabilities at different depths. Unlike DC method that has good resolution for near surface layers, TEM method is more or less blind to near surface resistive layers. Therefore, it may not always be necessary to increase the global weight value. As a matter of fact, it would be advantageous to be able to define relative weight separately for each layer. This would allow the VES soundings, for example, to have bigger importance in resolving the near surface and resistive layers and TEM data could be given more weight to resolve deep layers. Currently, however, this kind of functionality is not provided in JOINTEM.

7. File formats

When using the program for interpretation purposes make sure that your input data files (*.DAT) are formatted properly. Note also that one can determine the file format from the output of modelled data (*File/Save data*). In DC case, however, the measured current and voltage values are replaced by apparent resistivity. Saved data files also include interactively edited weights.

For each data type (VES, TEM, AMT) two file formats are supported: a) generic column formatted data file without header information, and b) column formatted data file with header information.

Important: The first line of the file determines how the file will be handled. If the file starts with #, /, or ! -characters it is considered to be a generic column formatted data file and the user needs to provide all the necessary header information interactively. Otherwise, lines that start with #, /, or ! -characters are considered comment lines and they will be ignored.

7.1 VES data

The following example illustrates the format of the VES data file with header information:

```
DC example
# 07.06.2007
# EDA R-PLUS
# 3422126,7179893 YKJ

 1   0   0
 25  1   2   6   7

  2      0.5     11.8    733.1   92.7    93.318  1
  4      0.5     49.5    216.8   88.1    121.811 1
  8      0.5     200     69.1    100.8   137.103 1
  8      2       47.1    261.6   100.9   122.114 1
 ...
 40      2       1250    8.7     87.2    124.713 1
 40      5       495     22.7    87.1    129.006 1
 60      5       1120    7.69    103.1   83.538  1
 80      5       2002    2.8     89      62.984  1
100      5       3133    1.43    83.2    53.848  1
```

The next relevant line "`1 0 0`" has three integer values that define: a) measurement array (IMOD), b) data type (IDAT), and c) IP related chargeability option (IMOC).

Measurement array is either: Schlumberger (IMOD= 1), Wenner (IMOD= 2), or dipole-dipole (IMOD= 3). Data type is either: apparent resistivity (IDAT= 0) or current and voltage (IDAT= 1). The IP effect is either disabled (IMOC= 0) or disabled (IMOD= 1) in DC computations.

The next line defines the number of data values (NOA), column number of the current electrode AB distances (ICOA), column number of the potential electrode MN distances (ICOM). Depending on the value of data type the line also defines a) if IDAT= 0 the column indices of the apparent resistivity and its weight, or b) if IDAT= 1 the column indices of current, voltage, and weights.

In the example, IDAT= 0 and apparent resistivity will be read from the sixth column. If the first line were "`1 1 0`" (IDAT= 1), the second line could be "`25 1 2 3 4 7`" and current and voltage values would be read from columns 3 and 4. Note that for Wenner data, there is no need to define the column for potential electrodes, so it can be is ignored (e.g. "`25 1 0 6 7`"). Likewise, weights will be ignored if its column number is equal to zero (e.g. "`25 1 2 6 0`"). Moreover, if weight column is given negative value (e.g., "`25 1 2 6 -7`") weights are considered as data error, that means they are inverted and scaled between 1 and 0,01.

If IP effect is enabled in DC computations (IMOC=1), then two additional parameters that define the column numbers of the measured apparent chargeability data and its weight must be given at the end of the second line. In the current version of JOINTEM chargeability data are not used in inversion and therefore the chargeability weights are always ignored (e.g. "`25 1 2 6 7 8 0`").

The remaining lines define (in column format) the electrode distances, the DC sounding data and (optionally) the data weights. For Schlumberger array the first column defines *AB*/2 distances (see Figure 1 for explanation) and the second column the *MN*/2 distances. For Wenner system the first column defines *AM= MN= NB* distances and the second column is not needed, because voltage electrodes are placed evenly between the current electrodes. For dipole-dipole system the first column is the *BM* distance and the second column defines the dipole length (*a=AB=MN*), which is usually constant. Electrode distances are given in metres (m), the apparent resistivity in ohm-meters (Ωm), the current in milliamperes (mA), and the voltage in millivolts (mV). Since the ratio of voltage and current is used to compute the apparent resistivity, the unit of current and voltage data can be amperes and volts as well (but never amperes and millivolts).

If current and voltage values are read from the file they are replaced with apparent resistivity that is computed using the equation for homogeneous half space:

$$\rho_a = 2\pi \frac{\Delta V}{I}\left[\frac{1}{r_{AM}} - \frac{1}{r_{BM}} - \frac{1}{r_{AN}} + \frac{1}{r_{BN}}\right]^{-1}, \quad (5)$$

where ΔV is the measured potential difference between electrodes M and N, I is the current fed into electrodes A and B (positive and negative) and r_{ij} are the distances between the four electrodes.

The maximum amount of VES data (AB/2 values) is 80 data points. The header text is used as a secondary title in the response graphs. If the header text is empty the default title in the JOINTEM.DIS file is used instead (can be left empty). Apparent resistivity (current and voltage) values equal to zero are ignored.

7.2 Duplicate AB/2 values

The electric potential created by a grounded electrode (point source of current) on a homogeneous half space is a proportional to the inverse of the distance (e.g., $1/r_{\mathrm{AM}}$). As the electrode spacing AB/2 increases the potential decreases and it is therefore necessary in Schlumberger configuration to increase the potential electrode distance (MN/2) every now and then. Otherwise the potential difference becomes so small that it cannot be measured accurately anymore.

Unfortunately, the earth is not really homogeneous and the voltage measured using different MN/2 values may produce different value of apparent resistivity. This unknown shift can be corrected if two or three successive AB/2 values are measured using different MN/2 values and the apparent resistivity obtained with the larger MN/2 distance are shifted along the ρ_a axis to fit those obtained with smaller MN/2 distance. The correction, which is illustrated in Fig. 5, is also discussed in the book of Milsom (2003).

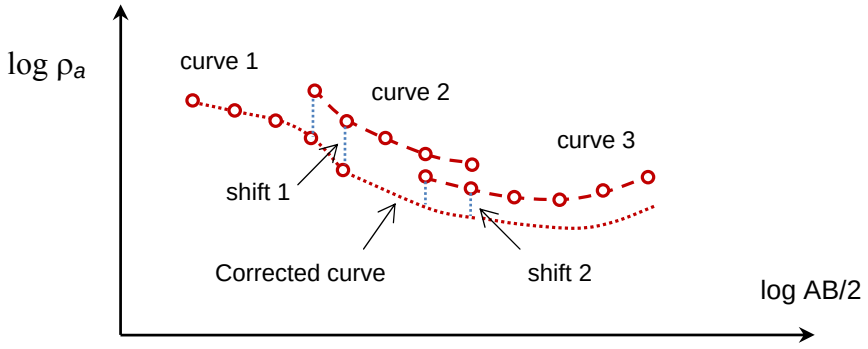


Figure 8. The method used to correct shifted apparent resistivity data measured with overlapping

AB/2 values when potential MN/2 distance is increased in the Schlumberger configuration.

When JOINTEM reads in VES data it automatically searches for data made with same AB/2 and different MN/2 values. Based on the mean of the differences in the apparent resistivity (on a logarithmic scale) the ρ_a values measured with the larger MN/2 spacing are then adjusted accordingly. Note that shift correction may not be successful if any of the duplicate soundings are erroneous. Typically the errors arise from the fact that MN distance has not been increased in time when field measurements were made (small voltage values gives large relative errors). Therefore, one should analyze the response graphs for multiple MN/2 values, preferably with and without the shift correction (may be implemented in future version of JOINTEM).

7.3 TEM data

The following example illustrates the format of the TEM data file with header information:

```
TEM example

# single loop: volts/amps, loop size (m), ramp time (mms), turns
  0   50.00   5.000  1

# number of channels, data column, weight column
 36   1   2   4

# time, measured volts & rhoa, weight
  0.0041   0.4743000E-01   0.1558684E+04   1.0
  0.0051   0.6219999E+00   0.1948152E+03   1.0
  0.0061   0.4837000E+00   0.1709358E+03   1.0
  ...
  1.6561   0.2733000E-05   0.4733648E+02   1.0
  1.9131   0.1899000E-05   0.4744464E+02   1.0
```

The first relevant line defines a) the TEM measurement system and data type (IMOT), b) the side length of the square transmitter loop (metres), c) the duration of the ramp-like current turn-off (microseconds), and d) the number of loop windings of the transmitter loop (integer value).

The measurement system IMOT = 0 or 1 for single loop system and IMOT= 2 or 3 for central loop system. The data type IMOT= 0 or 2 for voltage response (normalized with current) and IMOT= 1 or 3 for apparent resistivity response.

In central loop system two additional parameters that define: 5) side length of the square receiver loop (metres) and number of loop windings of the receiver loop are needed (e.g., "`0 50.0 5.0 1 0.5 100`". If the number of loop windings is negative, then the side length of the transmitter and/or receiver loop is interpreted as the radius of the loop. If the number of loop windings is equal to zero, the side length is interpreted as the area of the loop and the size of the transmitter and/or receiver loop is computed automatically.

The next line defines the number of data values (NOT) and the column numbers of the time channel, the TEM data and weights. Weights are not read if its column number is zero. Moreover, if the weight is given negative column number (e.g., "`36 1 2 -4`") the weights are inverted and handled like data error.

The remaining NOT lines contain the time channels (center of the time windows in ms), the normalized voltage (V/A) or the apparent resistivity values (Ωm), and (optionally) the data weights in column format. Time values should be given in milliseconds but they can be adjusted (e.g., s → ms) using *Edit/Data options/Reset x-axis* menu item. Likewise, TEM data that have not been normalized with transmitter current can be adjusted using *Edit/Data options/Norm. data* item.

If data are provided as voltage induced into the receiver, it will be transformed into apparent resistivity automatically. The apparent resistivity is computed using the late time approximation for a large loop on the surface of homogeneous half space at. The apparent resistivity of single loop and central loop TEM systems are (Spies & Frischknecht, 1991):

$$\rho_a(t) = \left[\frac{\pi \mu_0{}^5 a^8}{400 \cdot t^5 S^2} \right]^{\frac{1}{3}} = \left[\frac{\sqrt{\pi} a^4}{20 \cdot S} \right]^{\frac{2}{3}} \left(\frac{\mu_0}{t} \right)^{5/3} \quad \text{and} \quad \rho_a(t) = \left[\frac{\sqrt{\pi} a^2 n b^2}{20 \cdot S} \right]^{\frac{2}{3}} \left(\frac{\mu_0}{t} \right)^{5/3}, \tag{6}$$

where $\mu_0 = 4\pi 10^{-7}$ Vs/(Am) is the magnetic permeability of the free space, a is the radius of the circular transmitter loop, t is time, $S = v(t)/I$ is the normalized voltage response, b is the radius of circular receiver loop and n is the number of loop turns on the receiver. One should also remember that the voltage response is related to the time derivative of the magnetic field

$$v(t) = -\mu_0 n \pi b^2 \frac{\partial h_z}{\partial t}. \tag{7}$$

Thus, data defined as the time derivative of vertical magnetic field can be rescaled to normalized voltage data (divided with $\pi\mu_0 n b^2 I$) using the *Edit/Data options/Norm. data* item. Please, note that data read in as apparent resistivity will not be transformed back into voltages and therefore *Swap comp.* button will be inactive. Users are recommended to use voltage values for the TEM response, because the other software may compute apparent resistivity differently.

The maximum amount of TEM data (time channels) is 80 data points. The header text is used as a secondary title line in the TEM response graph. If the header line is empty the default title in the JOINTEM.DIS file is used instead (can be left empty). Voltage and apparent resistivity values equal to zero are ignored.

JOINTEM can also read (*File*/*Read TEM-Fast data* item.) text formatted *.TEM data files generated by the TEM-Fast 48 HPC instrument by Advanced Electromagnetic Research (http://www.aemr.net). The file format is specific to the TEM-Fast instrument it will not be described here. Please, note that only the voltage data are read from *.TEM. Also, if the file contains several soundings they are listed together with the xy-coordinates and the user needs to choose one of them interactively (see Figure 9).

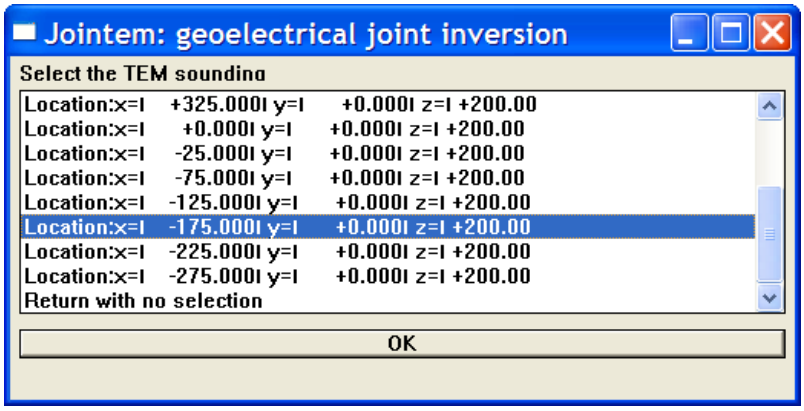


Figure 9. Selecting sounding data from a *.TEM file with multiple soundings.

7.4 AMT data

The following example illustrates the format of the AMT data file with header information:

```
AMT example

# number of frequencies, freq, rhoa, phase & weight columns
 21   1   2   3   4   5
 # freq (Hz), rhoa (Ohmm) & phase (deg.), weights
   30.00  0.9114084E+03  0.4248446E+02  1.00  1.00
   40.00  0.8956744E+03  0.4204181E+02  1.00  1.00
   60.00  0.8773687E+03  0.4152812E+02  1.00  1.00
    ...
20000.00  0.1734963E+03  0.2574255E+02  1.00  1.00
30000.00  0.1449312E+03  0.2679170E+02  1.00  1.00
```

As the example shows, the first relevant line defines the number of data points (NOF) and the column numbers of frequency (Hz), apparent resistivity (Ohmm), phase angle (deg.) and the weights of apparent resistivity and phase. If the column number of frequencies is negative the frequencies are interpreted as time periods, as is common in magnetotellurics, and they will be inverted ($f = 1/t$). If the column index of the phase data is zero, the phase data can be missing as in the so-called scalar AMT measurements. Weights are not ignored if their column numbers set equal to zero (e.g., " `21  1  2  3  0  0`"). If weights are given negative column numbers they are treated like data error that means data with large error is given small weight.

The maximum amount of AMT data (frequencies) is 80 data points. The header text is used as a secondary tile line in the AMT response graph. If the header line is empty the default title in the

JOINTEM.DIS file is used instead (can be left empty). Apparent resistivity and phase values equal to zero are ignored.

7.5 Generic data files

If the first line starts with a comment (#, / or !) character, the file is considered to be in generic column format without any header information.

The example below illustrates the format of the generic data file in case of AMT method:

```
# AMT freq,  rhoa, phase, rhoa wei, phase wei
30.000  0.9114084E+03  0.4248446E+02   1.0   1.0
42.376  0.8956744E+03  0.4204181E+02   1.0   1.0
59.858  0.8773687E+03  0.4152812E+02   1.0   1.0
...
```

Depending on the sounding method (TEM, VES, AMT) the user must provide all the relevant information about measurement system, data type and the column order interactively using the dialogs that will appear on the screen. Most importantly, the user needs to provide correct column numbers for the system variable (time, distance, frequency), data and weights. The header line is shown to the user, and therefore it would be advantageous if it shows the column information as in the example. For example, to read the AMT data above one could provide column information as "`1 2 3 4 5`" or "`1 2 0 4 0`", if phase data is not available or needed (see Figure 10). Note that the number of data values (time channels, distances or frequencies) is not needed and the sign of the weight column is handled as with normal data files with header information. Reading generic TEM data is a special case, since the user is asked to provide transmitter current (A) and a time scale value so that the data can be converted accordingly (V/A and ms). If the data is needed again it should be saved using the *Save data* menu item to avoid the cumbersome interactive reading.

7.6 Model files

The format of model files is not discussed here in detail because they do not need to be edited. The following example shows only the top of the file, where the model is defined.

```
* JOINTEM v. 1.31 model file:

station n:o, xyz-coordinates (m)
   0     -175        0    200.0

layer total number
  4

thi (m), rho(ohmm), charg, tau, freq (fixes between), IP on/off, depth, elev
0.340E+01 1 0.163E+06 1 0.10E+00 1 0.10E+01 1 0.10E+00 1 0 0.000E+00 0.200E+03
0.460E+02 1 0.226E+03 1 0.10E+00 1 0.10E+01 1 0.10E+00 1 0 0.340E+01 0.196E+03
0.112E+03 1 0.259E+02 1 0.10E+00 1 0.10E+01 1 0.10E+00 1 0 0.494E+02 0.150E+03
0.000E+00 0 0.100E+04 0 0.10E+00 1 0.10E+01 1 0.10E+00 1 0 0.162E+03 0.375E+02

TEM, DC, AMT modes & weigths + VLF-R option
  1    1   0    1    1    0    1

Tx side (m), turns, ramp (µs), Rx side (m), turns
...
```

The first line defines the file version number, which is essential information. The x and y coordinates are defined as integers and z coordinate, i.e., the topographic elevation has floating point (real) value. Fixed parameters are labeled with a zero after them and free parameters are labeled with 1. The *IP on/off* parameter (0=no IP, 1= IP used) enables or disables the Cole-Cole parameters for each layer. Depth and elevation are extra information, since they are computed from the values of z coordinate and layer thicknesses.

After line the model parameters defines the different sounding methods. The first three parameters (IMOT, IMOD and IMOA) define TEM, DC and AMT modes. IMOT= 0 for single loop system and voltage response, IMOT= 1 for single loop system and apparent resistivity response, IMOT= 2 for central loop and voltage response and IMOT= 3 for central loop and apparent resistivity response. IMOD= 1 for Schlumberger, IMOD= 2 for Wenner, and IMOD= 3 for dipole-dipole system. Negative value (IMOD < 0) informs that IP chargeability is enabled for DC computations. IMOA= 0 if phase component is used in inversion and IMOA= 1 if the phase information is not going to be used. The next three parameters define whether or not the model file also contains

individual data weights (1 = yes, 0= no) for TEM, VES and AMT data. The seventh parameter defines whether or not VLF-R information is included (1= yes, 0= no) at the end of the model file.

Important: When measured data has been read in for interpretation only the parameters of the layered earth model are read from the model file. In other words, time channels, electrode distances and frequencies are not read from the model file, because they are already defined in the data file. For the same reason, data weights are not read either. To circumvent this possible difficulty one should read the model file before reading the data (without weights).

7.7 Result files

The file created for the results of forward and inverse computations is a general purpose text file that contains information about the model, measurement system, synthetic response, measured data and inversion. The file contains the model parameters, i.e., layer resistivities and thicknesses and (optionally) Cole-Cole model parameters, as well as layer depths and elevations. The file also contains the computed (and measured) data and the data weights. Computed and measured VLF-R data and skin depth are also stored if they have been used in the inversion.

If the result file is stored after inversion it will also contain 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). In addition, the file contains in a suitable format the necessary information required to plot the model curve and the error bars using a third-party plotting program.

7.8 Graph parameters

Several graphical settings can be changed manually by editing the JOINTEM.DIS file. Most importantly, one should be able translate all character strings used in the response graphs into local language if needed. Note that the format of the file is essential and if the file should become corrupted (so that program won't start or the graphs are messed up), one should delete the JOINTEM.DIS file and a new one with default parameter values will be automatically generated the next time the program is started.

The format of the first paragraph of the file is shown below. The remaining paragraphs define various character strings related to different sounding methods, the model and the inversion. They have been omitted because their meaning is quite self-explaining.

```
JOINTEM v. 1.31 GUI & graph parameter file

  40   32   32   26   26
   1   1   1   1   0   0   1   0   1   370   330
 0.500  0.575  0.575  0.575  0.850  0.000  0.830
 0.10000E-02  0.10000E+02  0.10000E+01  0.10000E+07  0.10000E+02  0.10000E+06
 0.10000E+01  0.10000E+03  0.10000E+03  0.10000E+07  0.90000E+02  0.11000E+03
 0.10000E+02  0.10000E+06  0.10000E+04  0.10000E+05  0.40000E+02  0.50000E+02
 0.10000E+02  0.10000E+07  0.10000E+02  0.50000E+02
 ...
```

- The first line is a title or description for the file itself and the second line is left empty.
- The 1.st line of the first paragraph defines five character heights. The first value is used for the main title and the graph axis titles, the second is used for the axis labels, the third is used for the plot legend text, the fourth is used for the model description text, and the last value is used for the axis labels in the model view.
- The 2.nd line defines some integer valued parameters that modify the graph appearance:
  #1 is used to set (1/0) the model information text to/from the top-right corner of the page.
  #2 is used to set (1/0) the model view to/from the bottom-right corner of the page.
  # 3 is used to define the corner where the legend text is positioned. Values 1-4 put the legend in SW, SE, NE or NW corner of the page (outside the graph). Values 5-8 put the legend in the SW, SE, NE, or NW corner inside the graph. Default is the SW corner outside the graph.
  #4 is used to define screen aspect ratio, 0= 3:4 display and 1= wide screen/laptop displays.
  #5 is used to set (1/0) logarithmic depth scale for the model view.
  #6 is used to set on (1/0) automatic aspect ratio for the log-log response graphs. Normally log-log plots should be plotted using 1:1 aspect ratio. Thus, automatic sizing adjusts the graph height according to its width and axis limit values
  #7 is used to define either black or colored lines (0/1) for the curves in the response graphs.
  #8 is used to define either thin or thick line (0/1) in the graphs.
  #9 is used ti define either small or large symbols (0/1) in the response graphs.

The last two numbers define the x- (horizontal) and y- (vertical) offset distance (in graph pixels) of the origin from the bottom-left corner of the page. Note that these values are related to the size of the (landscape A4 sized) page area, which is equal to 2970×2100 graph pixels.

- The 3.rd line defines some real valued (floating point) parameters. The first defines the relative length of the x axes of the TEM (voltage 0.5 & app. resistivity 0.575), DC (0.575) and AMT (0.575) graphs and the maximum height (0.85) of the y axis (in all graphs). These values are relative to the size of the width and height of the plot area (eg. 0.5= 50 % of the width or height) without the offsets of the origin. The sixth parameter defines the relative vertical position (from the top of the graph) of the model information text next to the graph. The last parameter defines the value used to change the aspect ratio of widescreen displays. Note that workstations with two display screens make DISLIN to compute the horizontal width of the.
- The 4.th line defines x and y axis ranges for the TEM graphs. The six parameters are the limiting values of the logarithmic time axis (in milliseconds), the limiting values of the logarithmic voltage axis (micro-volts) and the limiting values of the logarithmic apparent resistivity axis (ohm-meter).
- The 5.th line defines x and y axis ranges for the DC graphs. The six parameters are the limiting values of the logarithmic distance axis (in metres), the limiting values of the logarithmic apparent resistivity axis (ohm-meter), and the limiting values of the linear apparent chargeability axis (%).
- The 6.th line defines x and y axis ranges for the AMT graphs. The six parameters are the minimum and maximum value of the logarithmic distance axis (in metres), the minimum and maximum value of the logarithmic apparent resistivity axis (ohm-meter).
- The 7.th line defines x and y axis values for the model view graph. The four parameters are the limiting values of the logarithmic resistivity axis (ohm-meter), the step and the maximum value of the linear or logarithmic depth axis (ohm-meter). The minimum depth is always zero if the depth axis is linear and automatically computed if the depth axis is logarithmic.

Note that DISLIN graphics uses ISO Latin-1 character codes and control characters that allow displaying Greek alphabets as well as sub- and superscripts. For example, character string "({M2}W{M1}m) " will create text "(Ωm)" in the graphs. See DISLIN documentation for further information.

8. Additional information

The JOINTEM program was made to replace the DCINV program for VES soundings and the original (unpublished) TDEMINV program for TEM (single loop) soundings. Experiences obtained from TEM interpretations, however, suggested the need for joint inversion with VES data to constrain the model and to better resolve the topmost layers of the earth. Thus, instead of updating existing programs a totally new joint interpretation program was written. VLF-R option was added because VLF-R measurements can be made faster than DC soundings and yet they provide additional and alternative information of the near-surface electrical structure. AMT and TEM central loop configuration were implemented in JOINTEM version 1.3 for additional functionality. The computation of DC apparent chargeability was implemented to satisfy personal curiosity.

VES computations are based on the algorithms of Rijo (1970), Sandberg (1990), and Anderson (Bankey & Anderson, 1995). TEM computations are based on the algorithms of Knight & Raiche (1982), Raiche & Spies (1981), Raiche (1984), and Sandberg (1990). The Hankel transforms are computed using a convolution method and the filter coefficients defined by Anderson (1984), Anderson & Bankey (1995), and Christensen (1990). AMT and VLF-R computations are based on the theoretical solution defined by Kunetz (1972). The linearized inversion method has been described by Jupp & Vozoff (1975) and Hohmann & Raiche (1988). The adaptive damping method and usage of SVD information have been discussed in my PhD thesis (Pirttijärvi, 2003).

JOINTEM is written in Fortran 90 and compiled with Intel Visual Fortran 11.1. The user interface and graphics are based on DISLIN graphics library (version 9.5) by Helmut Michels. The program distribution includes the necessary DLL file. For more information, please, visit DISLIN homepage at `http://www.dislin.de`. In principle JOINTEM could be compiled and run on Mac OS X and Linux without major modifications. At the moment, however, the source code is not available and I do not provide active support for the program. If you find the computed results erroneous or if you have suggestions for improvements, please, inform me.

8.1 Terms of use and disclaimer

You can use the JOINTEM program free of charge. If you find the program useful, please, send me a postcard and tell me about it.

The program is provided as is. The author (MP) and the University of Oulu disclaim all warranties, either 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.

8.2 Contact information

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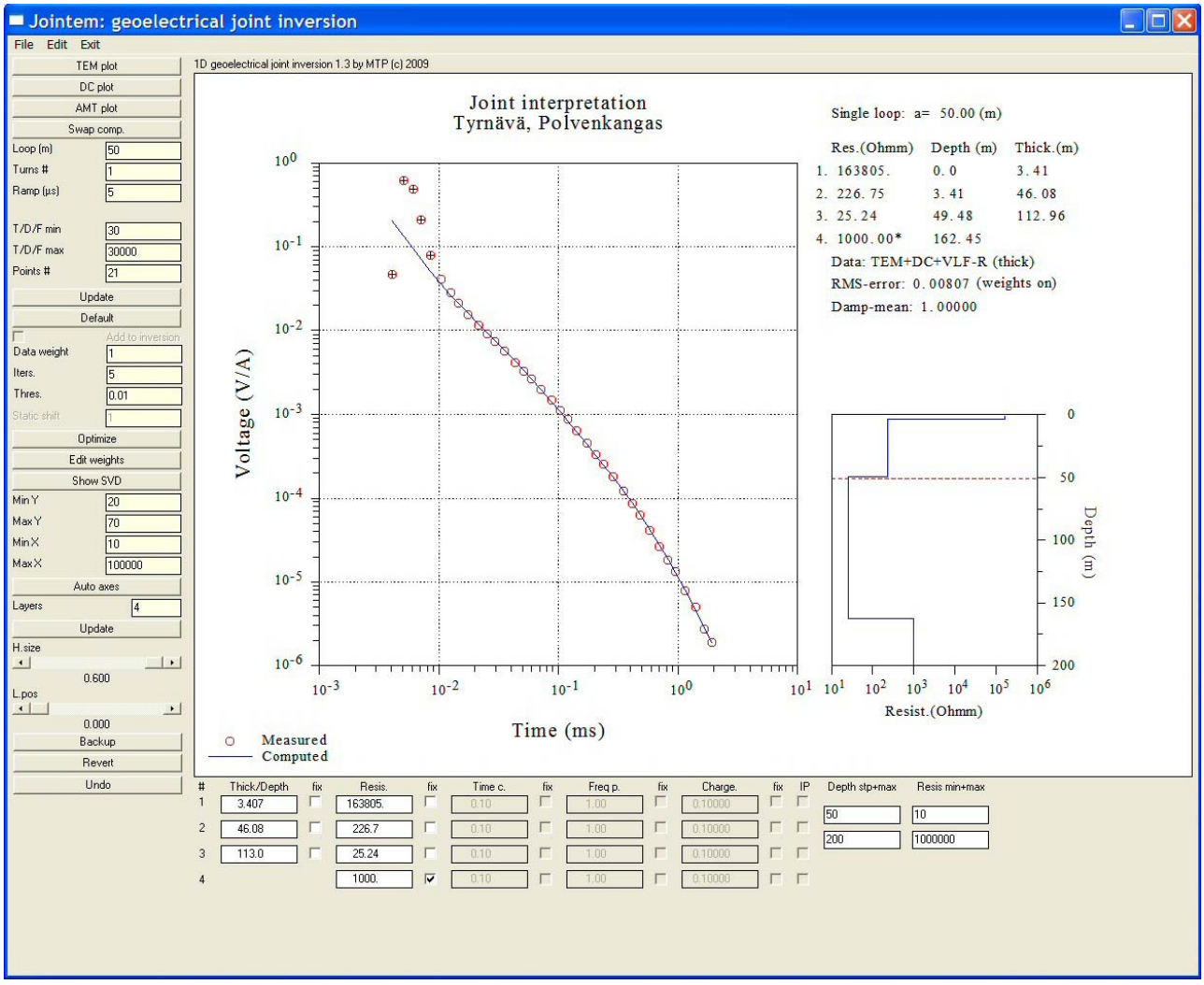
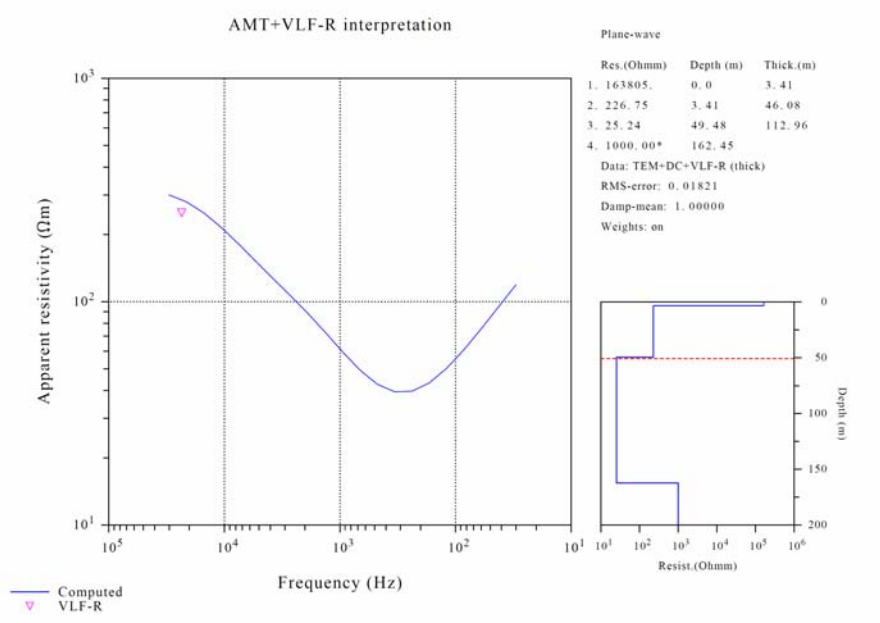
Appendix A: TEM graph

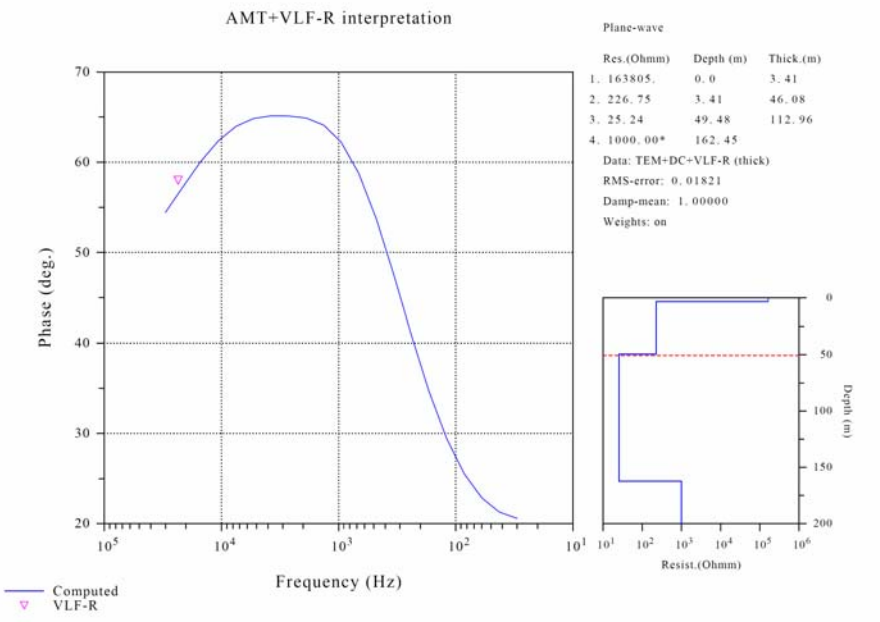
Joint interpretation of TEM, DC and VLF-R data. The five earliest time channels have been ignored, because the modelling cannot take into account the very early stage transient behavior in the transmitter=receiver loop. VLF-R data was active and the horizontal dashed line in the model view shows the cumulative (plane wave) skin depth at the VLF-R frequency. The model can be interpreted as highly resistive top layer (dry sand), with groundwater table at the depth of 3,4 metres. The total thickness of the overburden (sand and loam) is 50 metres. The bedrock is conductive mudstone (ρ=25 Ωm) and an indication of resistive basement (1000 Ωm, fixed) is made at the depth of 160 metres.



Appendix B: AMT/VLF-R graph

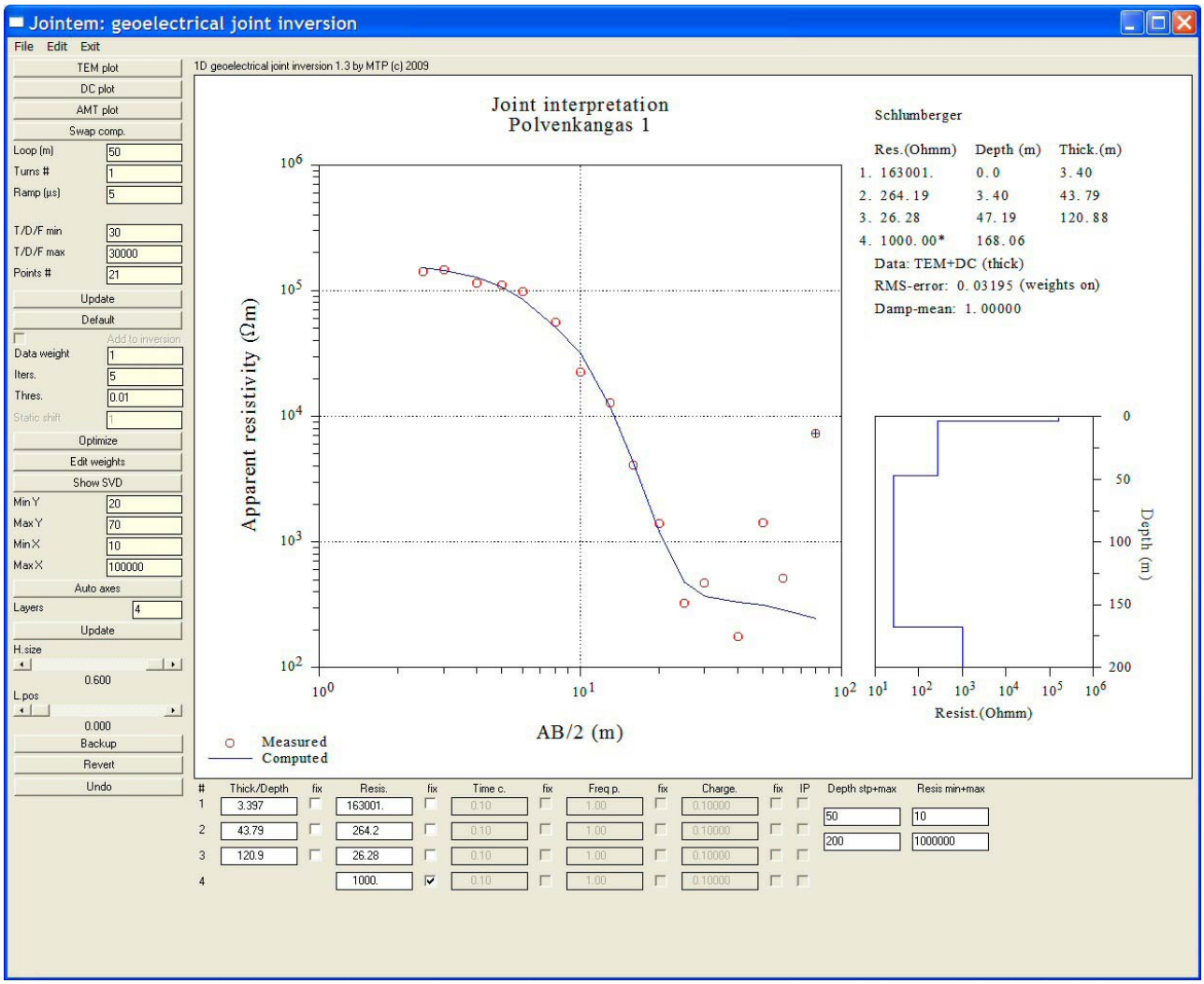
The AMT/VLF-R (apparent resistivity and phase) response is related to the joint interpretation of TEM, DC and VLF-R data in Appendix A. Measured AMT data was not used the example, yet the modelled AMT curve shows the fit with the VLF-R data a (ρ_a= 250 Ωm, ϕ= 58°) depicted by a triangle at single frequency (f= 23.4 kHz) and the behavior of the AMT response at lower frequencies (down to 30 Hz) corresponding to deeper layers of the model. Note that the RMS-error is related to the AMT/VLR-R data and is therefore different from that in Appendix A.





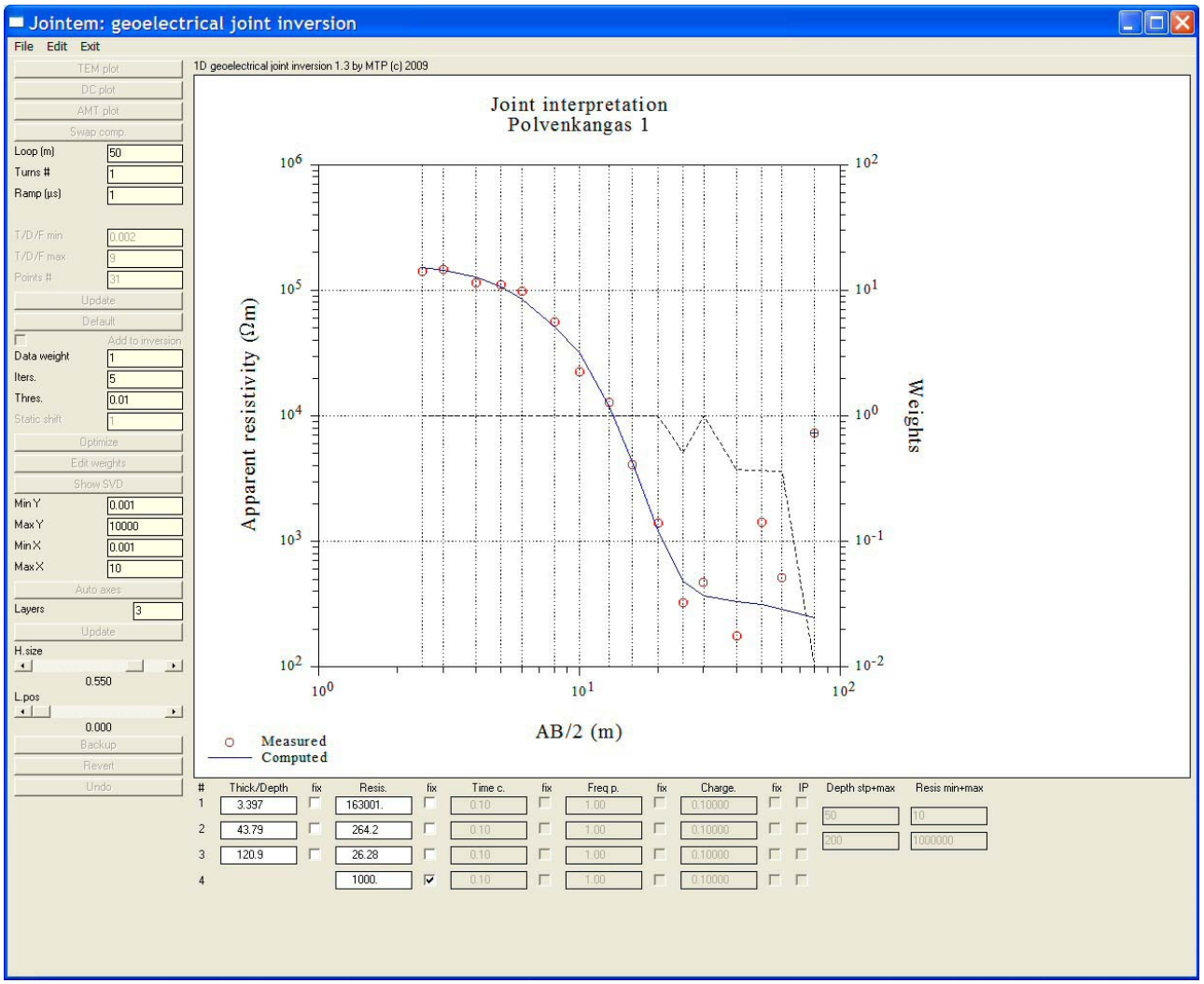
Appendix C: DC/VES graph

Joint interpretation of TEM and DC data. The VES graph is similar to that in Appedix A, but the inversion was made without the VLF-R data and, hence, there are slight differences in the resistivity of the second layer and the fit of VLF-R data (not shown here). Because of resistive top layer and problems with current injection, the data are noisy at large electrode distances (AB/2 > 30 m) and their weights have been edited as shown in Appendix D. Note that the RMS-error is related to the VES data only and therefore it is different from those in Appendices A and B.



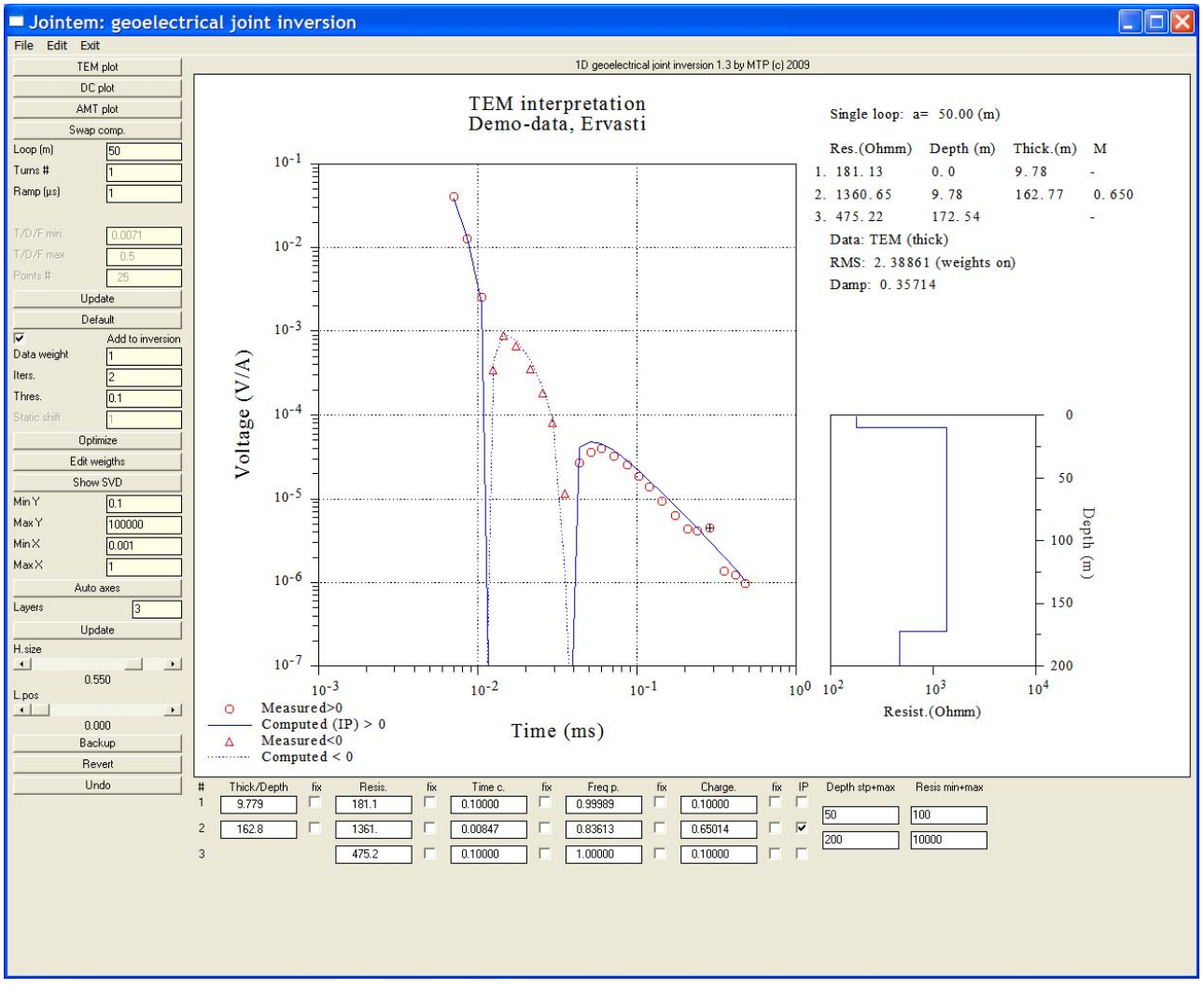
Appendix D: Weight editing

When weight editing mode is active most of the other GUI controls are disabled and the graph is drawn differently. Additional vertical y axis ranging from 0,01 to 100 appears to the right side of the graph, vertical dotted guiding lines are drawn through each data point and the weights are depicted using a dashed line. By default all weight values are equal to one. Weight should be increased to emphasize the contribution of important data points. Weight of noisy data values should be decreased and erroneous values should be ignored by giving them weight value less than 0,01. Ignored data values are shown with an additional plus-symbol inside them. Weight editing is accomplished by pressing the left and the right mouse buttons above the data points. Weight editing mode is disabled by pressing the right without any left button selections.



Appendix E: IP effect in TEM inversion

Interpretation of negative TEM responses encountered in single loop configuration can be made possible using complex resistivity defined by Cole-Cole model parameters (time constant, frequency factor and chargeability), which describe the induced polarization (IP) effects. Note the different line type and symbol shape of negative response values. In this case, however, the response shape allowed optimization of the frequency factor that usually should not be done because of ambiguity. In this example the polarization ($\eta \approx 0.65$) is attached to the second layer (mica schists). The third layer accounts for nearby sandstones (2D effect) and should not be considered as a deep conductor.



Appendix F: SVD graphs

The SVD graphs are column diagrams that reveal information about the properties of the inverse problem. The graphs below arise from a synthetic inversion example with a three layer model. The rows display (normalized) columns of V and U matrices which are put in the order of descending singular values from top to bottom. Both graphs also show the largest singular value (W_1), the remaining normalized singular values (S_2-S_5), and the value of the largest eigenvector (V_{max}, U_{max}) used to normalize the eigenvectors.

The first SVD graph displays parameter eigenvectors as a function of model parameters (T1= thickness of first layer, R1= resistivity of first layer, etc.). The graph reveals the sensitivity and relative importance of the model parameters or (correlated) parameter combinations. The parameters that show up on the eigenvector that corresponds to the largest singular value (top row) are the most sensitive and usually best resolved. The parameters that appear in the bottom row are the least sensitive and difficult to resolve. If two or more parameters show up on the eigenvector they are said to be correlated (T_1 and R_1). Uncorrelated parameters (R_2) show up on one eigenvector only. The second SVD graph shows (normalized) data eigenvectors. Different sounding methods (TEM, VES, AMT) are separated by vertical lines. The graph reveals the (relative) importance of individual data components that give the contribution to the corresponding parameter eigenvectors. The graph reveals, for example, that the resistivity of the second layer (R_2) arises evenly from TEM data, long AB/2 distance VES data, low frequency AMT apparent resistivity and mid-frequency AMT phase data. Note that individual and global data weights affect the amplitude of the data eigenvectors. Also note that the AMT data are not reversed (frequency increases towards right).