EM4Soil

A program for 1-D laterally constrained inversion of EM data

Version-1.05

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DISCLAIMER

The programs (software) included in any version of the **EM4Soil** packed are provided "as are" without any express or implicit warranties including their suitability for a particular purpose. The authors and EMTOMO LDA will not assume any responsibility for any indirect or consequential damages or any loss caused by the use of these programs. Efforts will be made to correct any program bug that appears during the usage of the package.

1. Introduction

EM4Soil is a software package that has been developed in order to enable the inversion of electromagnetic (EM) induction data acquired at low induction numbers (LIN). A review of the LIN theory, as well practical applications of the theory with regard to geology and hydrogeology can be found in Geonics Technical Note 6 (McNeill, 1980).

The input data for **EM4Soil** is the measured apparent soil electrical conductivity (σ_a) as measured by EM instruments. As an example of the type of data that can be inverted by **EM4Soil** is shown in Figure 1.1. It shows DUALEM-421 σ_a data that was collected using the horizontal co-planar (HCP) array at 1 (red), 2 (green) and 4 m (blue) coil spacing. The lower panel shows the equivalent σ_a data that collected using the perpendicular (PRP) array and at 1 (red), 2 (green) and 4 m (blue) coil spacing.

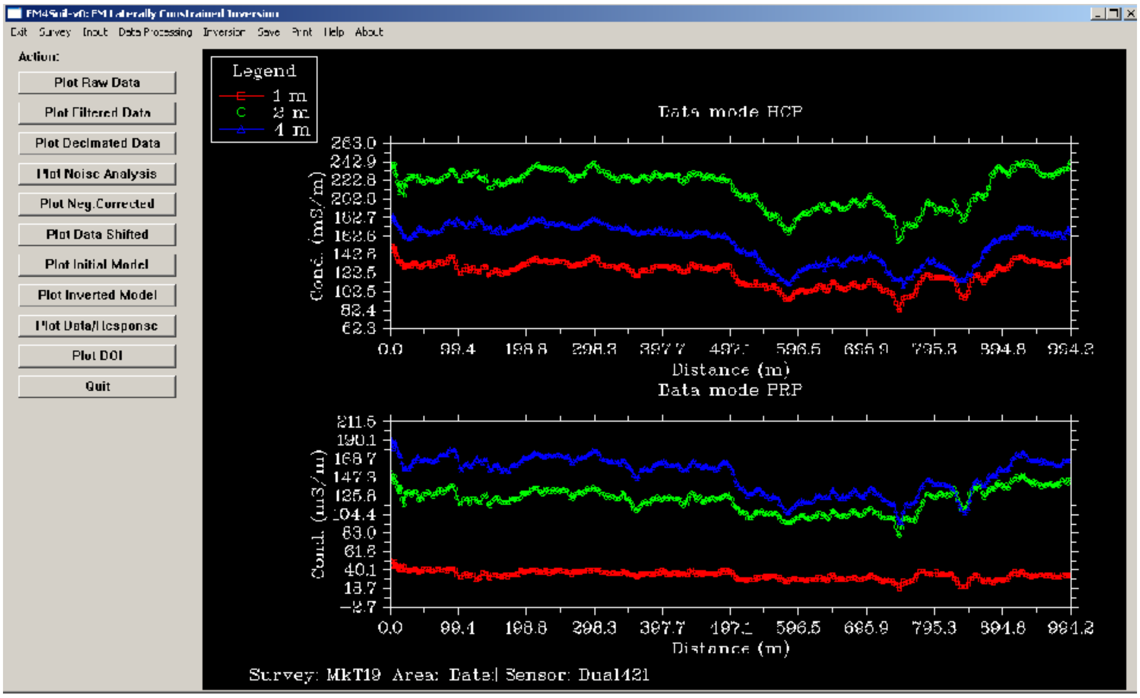


Figure 1.1. Spatial distribution of apparent soil electrical conductivity (σ_a - mS/m) along a transect measured using a DUALEM-421 in horizontal coplanar (HCP) and perpendicular coplanar (PRP) modes of operation and spacing of 1m, 2m and 4m.

EM4Soil is capable of inverting multifrequency EM data along a survey line (i.e. transect). The software is capable of processing and inverting EM data collected by either Geonics (EM38, EM31 and the EM34) as well as DUALEM instruments. In addition, the software is capable of carrying out inversion of data collected with PROFILER and GEM instruments.

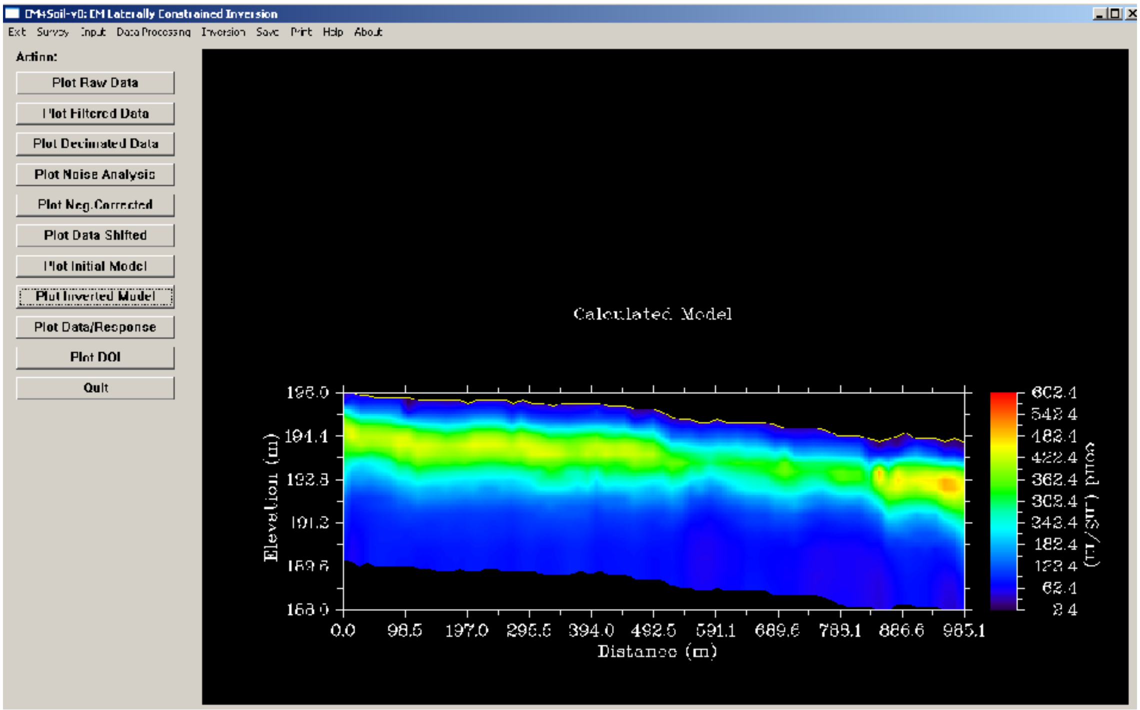


Figure 1.2. Inversion result using the linear approach (Q2D).

The inversion procedure used in **EM4Soil** is a 1-dimensional laterally constrained technique (1-D LCI). It is also known as a Quasi-2D (Q2D) inversion. The forward modelling of the **EM4Soil** software is based upon the cumulative function (McNeil, 1980) or on the full solution of EM fields in a layered earth (Keller and Frischknecht, 1996). The inversion algorithm is based upon the Occam regularization method (e.g. DeGroot and Constable 1990; Sasaki 1989). Figure 1.2 shows the result of inversion using the data shown in Figure 1.1.

The package has a Map Module that allows the user to display the survey and to choose the profiles for inversion.

2. EM4Soil Packed Items

The **EM4Soil** package is a 32-bit application that can run on Windows XP/Vista or even in the 64-bits Windows seven[1]. **EM4Soil** has a graphical user interface based on the DISLIN graphics library (http://www.dislin.de).

The full package contains the files:

EM4Soil-v105.exe
EMSmap.exe
EMSound.exe
EMDepinv.exe (only for GEM and PROFILER)
InvEMQ2D-vSp0.exe
InvFDEMQ2D-v0
Inv1D.exe
InvEM1D-v0.exe
JointEM1D-v0.exe
JointEMQ2D-vSp0.exe
InvEMQ3D-vSp.exe*
InvEMQ3D-2L-vSp0.exe*
JointEMQ3D-vSp.exe*
JointEMQ3D-SMvsP.exe*
INSTEM4Soil.BAT
PathEMSGen.exe
disdll.dll and **disdll_d.dll** (these are the dynamic link libraries for the DISLIN graphics);
this Manual (Instructions to run **EM4Soil** program) and
some example of the input files (*.txt files) required.
Files related to the Q3D (marked with *) are only available if the Q3D module was purchased.

[1] See section **11**.

3. EM4Soil Installation

In order to install the **EM4Soil** software, take the following steps:

1) Open a new folder for the program on your computer (for example: C:\EMTOMO)[2];
2) Copy all package files into the new folder;
3) Run the batch file **INSTEM4S.BAT**
4) Run the **EM4Soil** software by "clicking" twice on the "icon".

The first time a user runs the **EM4Soil** software, the user will be asked to provide an alpha-numeric key (see left hand panel of Figure 3.1). In order to obtain this key the user will need to send an email to **emtomog@gmail.com**. In the email the CODE indicated by the pop-up box generated once **EM4soil** is first run needs to be provided. In the example shown in Figure 3.1 the alphanumeric key is EX8C545. The email reply will include the required input KEY, which once entered will enable **EM4Soil** to run.

Figure 3.1. Screen snapshots which show the **EM4Soil** CODE corresponding to your software package and where to input the key once the CODE has been sent.

NOTE: The key links the program to a particular computer. A new key is necessary to run EM4Soil on another computer.
NOTE: Save the key in a safe place. You may need it in the future.
NOTE: Make a copy of all files in a safe location.
NOTE: All screens displaying the OK button must be closed after clicking on it.

NOTE: To run the EM4Soil in Windows7 could be necessary to redefine Compatibility properties of the program. Please, go to section 11 of this manual.

[2] **Avoid folder names with spaces like C:\EMTOMO EM4S**

4. Running EM4Soil

In order to run the **EM4Soil** software, double click on the **EM4Soil** icon. **EM4Soil** will start up and the screen snapshot shown in Figure 4.1 will appear. This is the welcome page.

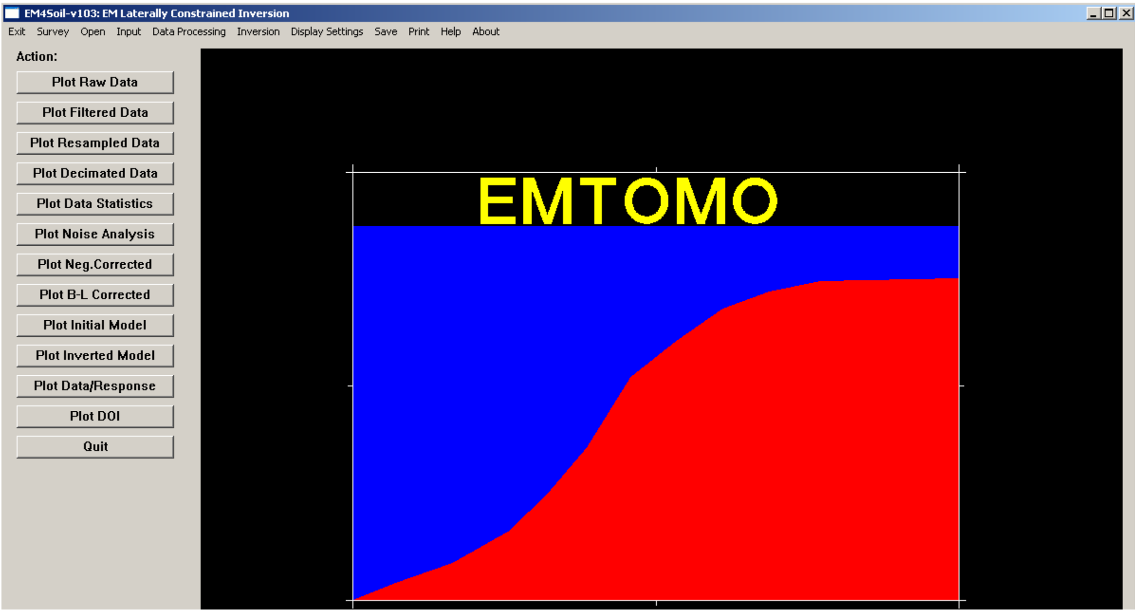


Figure 4.1. Screen shot of the **EM4Soil** main screen.

Figure 4.2 shows the welcome page of **EM4Soil** has 10 operational menu buttons.

Figure 4.2. Screen shot of the **EM4Soil** menu operation buttons.

In addition, Figure 4.3 shows the 11 plotting actions which appear along the left hand side of the welcome page of **EM4Soil**. The rest of the welcome page allows the user, amongst other things, to plot data (e.g. original and filtered) and modelling results (e.g. initial and inverted) to be displayed.

The application's window can be resized using the option Window Size in the **Display Settings** menu bar entrance. Please, see details in 5.7.

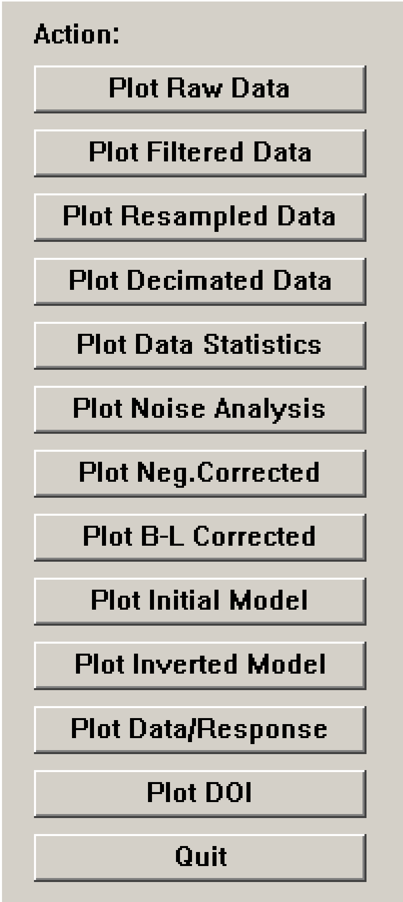


Figure 4.3. Screen shot of the **EM4Soil** plotting action buttons.

5. Menu operations bar

5.1 Exit

Selecting the **Exit** button will cause **EM4Soil** to shut-down. A user's data processing and inversions results will not be saved unless the user has previously saved them.

5.2 Survey

When the **Survey** option is selected, a small drop down box will appear with two options (Figure 5.2.1).

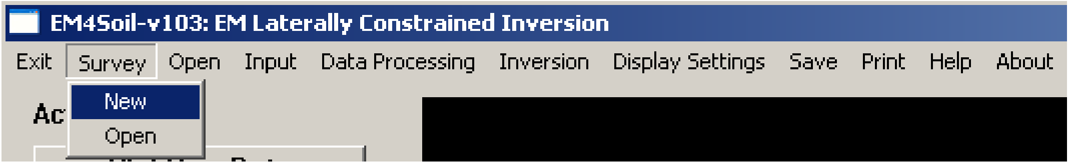


Figure 5.2.1. Screen shot of the **Survey** button options.

5.2.1 Survey: New

Selecting the 'New' option enables meta-data to be entered and pertaining to the σ_a survey data. This meta-data will be displayed in the resulting output files.
NOTE: Entering meta-data is optional.

As shown in Figure 5.2.1, the meta-data that can be entered includes information pertaining to the survey title (i.e. transect number), company the survey was done for or undertaken by, area, country, date of survey or processing, sensor type and operator can be entered.

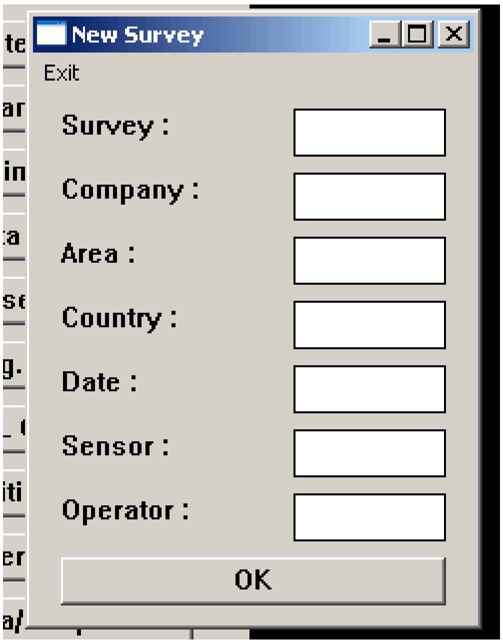


Figure 5.2.1. Screen shot of the input meta-data table to enter information about the survey. This information will be saved upon clicking the OK button.

5.2.2 Survey: Open

Selecting the **Open** option allows **EM4Soil** to read from an ASCII file previously saved. In order to prepare the σ_a data please refer to **Section 9 (Input File Format)**.

5.3. Open

This entrance allows the user to open (input) results obtained in previous inversions, as well as, results obtained in EM4Soil and Map module session.

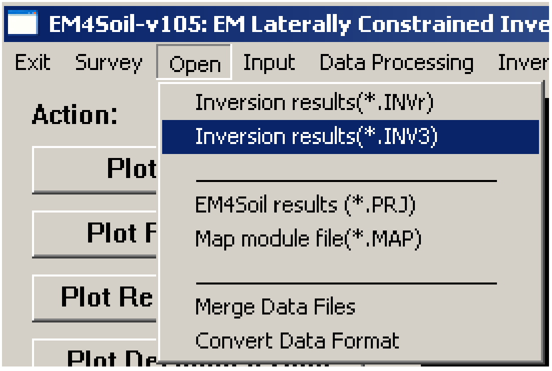


Figure 5.3.1. Inputting previous inversion results generated by **EM4soil**.

5.3.1 Input Inversion Results (*.INVr)

It is also possible to import and see the results of previous Q2D inversions (Figure 5.3.2). Files with Q2D inversion results have the INVr extension (INV3 is reserved for results of Q3D inversions) and are named according to the name of the line survey.

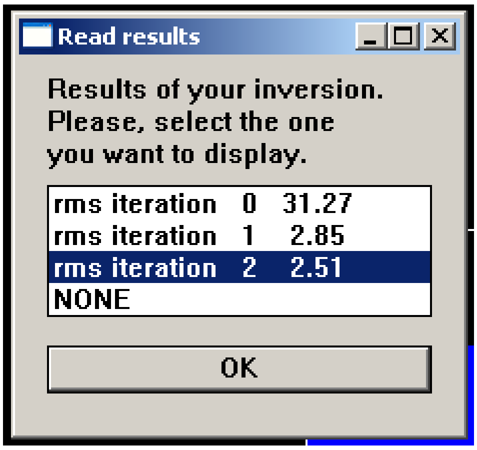


Figure 5.3.2. Inputting previous inversion results generated by **EM4soil**.

5.3.2. Input EM4Soil results files (*.PRJ)

Input files with results obtained during a session in the **EM4Soil** and saved with extension *.PRJ (see item 5.8).

5.3.3. Input Map module files (*.MAP)

Input the files saved in the Map module and containing the processing results (*.MAP) extension.

5.3.4. Merge Data Files

This entrance allows the merge of different data files into one file. The user will be asked to input the files one by one finishing input files clicking in the Cancel button. The user will be asked to save the merged file. Only files from the same survey (i.e., data acquired with the same instrument at same height etc) should be merged.

5.3.5. Convert Data Format

The OTHER sensor, which introduced in this new release of **EM4Soil**, allows processing and inverting any combination of EMI sensors. In this new option a specific format is used to input the data (see section 9 for formats). The entrance Convert Data Format allows the user to convert files written in the standard format into OTHER or vice-versa.

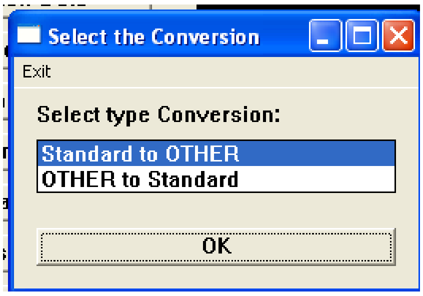


Figure 5.3.2. Converting input files into another format.

5.4. Input

5.4.1 Input Sensors

Selecting the ‘Sensors’ option enables the user to choose the appropriate EM sensor used to collect σ_a data along a transect and to be input into **EM4Soil**. Selecting the appropriate EM sensor allows **EM4Soil** to select the appropriate algorithm to invert the σ_a data.

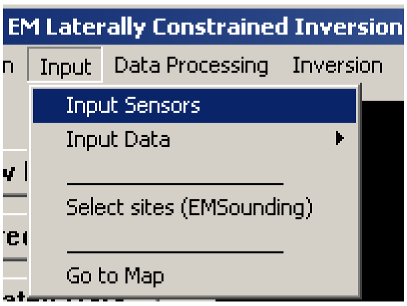


Figure 5.4.1. Screen shot of the **EM4Soil** menu operation buttons with Input Sensors is selected.

As shown in Figure 5.4.2, DUALEM (e.g. DUALEM-1), GEONICS EM (e.g. EM38), GEM or PROFILER sensors can be selected.

A new option[3] of sensor (named OTHER) is made available in this release (not shown in Figure 5.4.2) that allows the user to put together data acquired with different sensors, DUALEM and GEONICS or different GEONICS sensors and jointly invert all data set (see the Manual for this option). However, there are a few functions in the data processing that are not available for OTHER sensors.

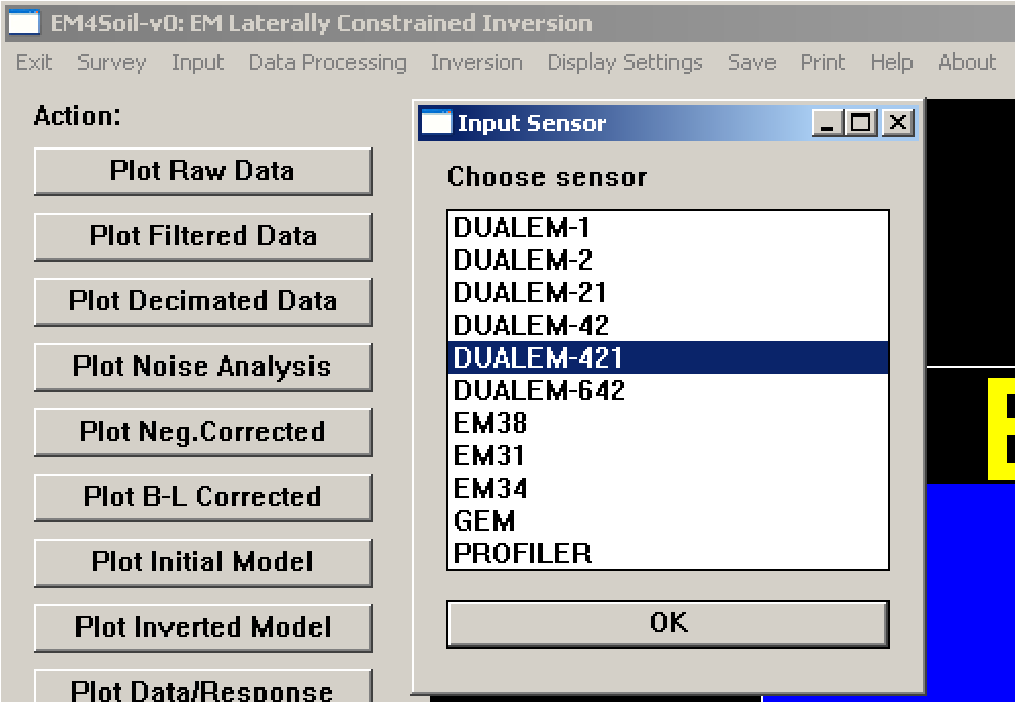


Figure 5.4.2. Screenshot of the drop-down box which allows the appropriate sensor to be chosen.

[3] This option is a module sold separately.

5.4.2 Input Data

Selecting the **Input Data** option enables the user to select the appropriate sensor line (i.e. transect) of σ_a data. A set of profiles (mapping), that is, a series of transects collected as part of a larger survey and carried out across an area can also be imported. This last option will be explained later in this Manual (see **Section 7**).

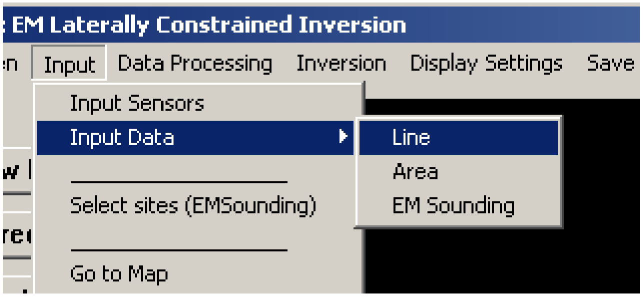


Figure 5.4.3. Screenshot of the drop-down box which allows the appropriate data to be selected.

In order to prepare the EM σ_a data refer to **Section 9 (Input File Format)**.

If a user's data has successfully inputted σ_a data into **EM4Soil**, the following pop-up box will appear on the screen (Figure 5.4.4).

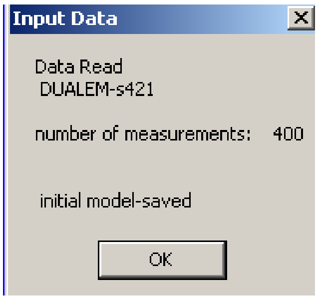


Figure 5.4.4. Pop-up box which indicates that the σ_a data collected along the transect to be inverted was successfully read into **EM4Soil**, type of sensor the σ_a data was collected with, number of σ_a measurement sites that were collected and that the construction of an initial model for inversion has been saved.

An initial multilayer model, based on the EM sensor data selected, is generated from the σ_a values inputted. In this regard a pre-determined number of layers and depths will be constructed by **EM4Soil**. The number and depths of layers is based on the type of EM sensor selected and the theoretical depth of investigation (see **Section 9**).

For PROFILER, the predefined model is based on the frequency range of 1000 to 15000 Hz. For GEM there are two predefined models: one for the frequency range 19950 to 1710 Hz and a second model for a more wide range of frequencies. The users are advised to build their own models taking into account their experience and data characteristics. For further information in this regard refer to **Section 5.5**.

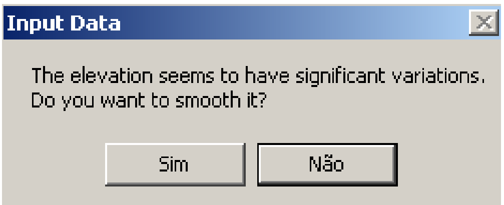


Figure 5.4.5. When the elevation values are too noisy the user can smooth it.

Figure 5.4.5 shows a pop-up box which may appear in the event elevation data, which is scanned by EM4soil, shows a large scattering. This scattering might distort the output inversion models. In this case it is advisable to consider filtering the elevation data.

Selecting this option will allow the user to conduct this type of filtering (see **Section 5.5.5**).

5.4.4 EM Sounding

You can choose a set of EM sensor sites (made at particular sites) to perform individual 1-D inversions (Figure 5.4.6). This will be explained in a next paragraph.

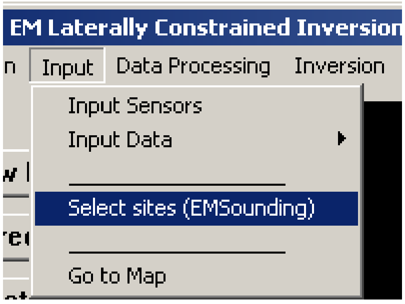


Figure 5.4.6. Choosing a site (a set of measurements) for 1D inversion.

5.5. Data Processing

Once the σ_a data has been successfully entered into **EM4Soil,** the software allows the user to carry out some basic data processing. The raw data are preserved during processing. Therefore, any new processing is done over the raw data.

NOTE: The users must save any processed data if they want to keep it.

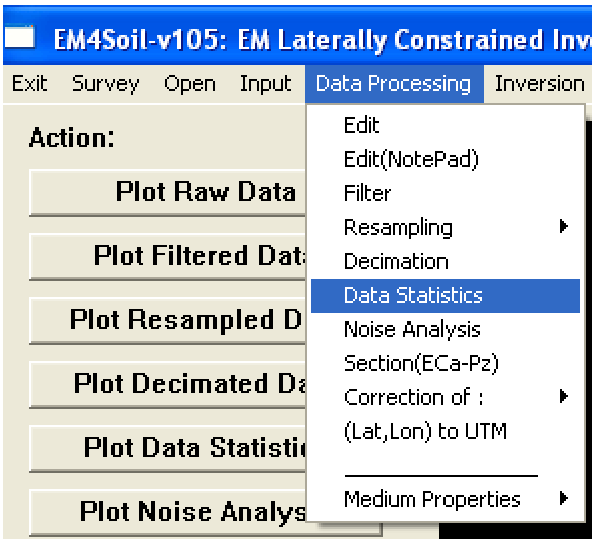


Figure 5.5.1. The **Data Processing** menu and the **Correction option**.

5.5.1 Editing

Selecting **Edit** will open a table with the selected raw EM sensor data (Figure 5.5.2). If changes are made the user will be prompted to save the data in a new file. This will need to be selected in order for this edited data to be inverted.

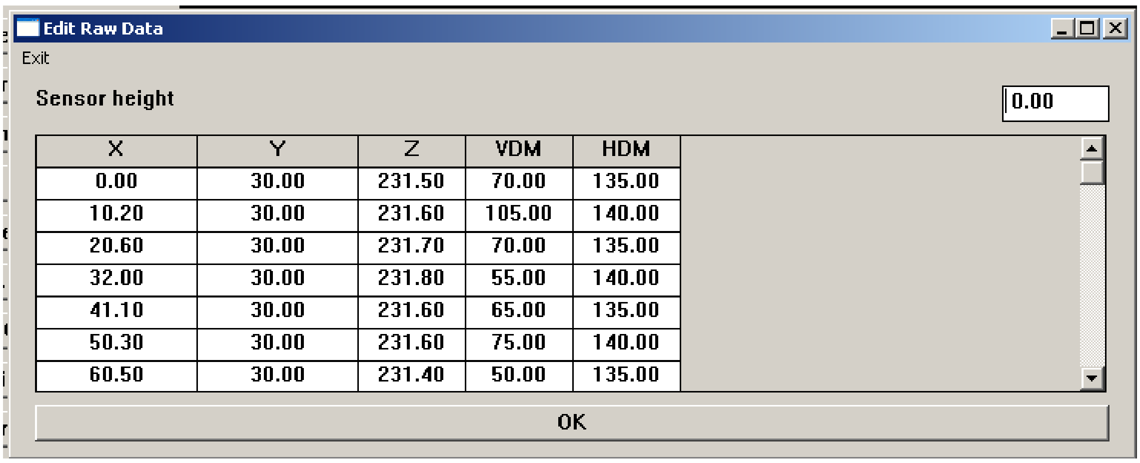


Figure 5.5.2. Pop-up box indicating the layout available to **Edit** raw data.

The **Edit (NotePad)** will start the NotePad program (if available).

5.5.2 Filtering

Prior to inversion **EM4Soil** allows a user to **Filter** the σ_a data. As shown in Figure 5.5.3, the various options include **Running Average**, **Weighted Average** and **Sheppard** filtering. **NOTE: Selections not desirable must be disabled.**

These three filters can be applied to the entire σ_a data set collected (i.e. All) or to selected σ_a data. In Figure 5.5.3, the options available are for the EM34 σ_a data, whereby σ_a data collected in either the vertical dipole (i.e. VDM) or horizontal dipole (i.e. HDM) modes can be individually selected for filtering.

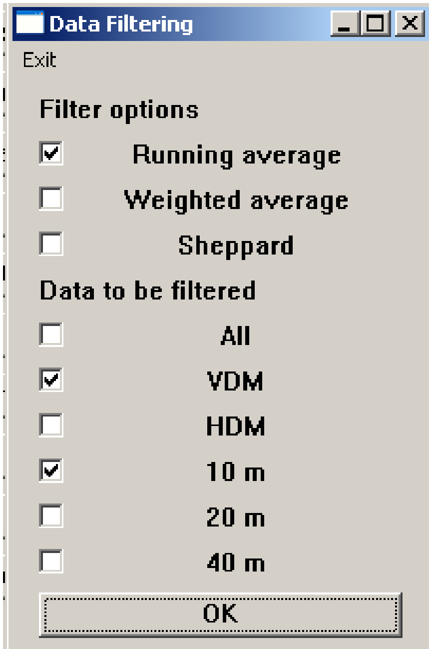


Figure 5.5.3. Pop-up box showing **Filtering options** and **Data to be filtered**.

In order to describe the various filters (i.e. Running Average, Weighted Average and Sheppard filtering) and the effect on σ_a data, Figure 5.5.4 shows an example set of DUALEM-421 σ_a data prior to filtering.

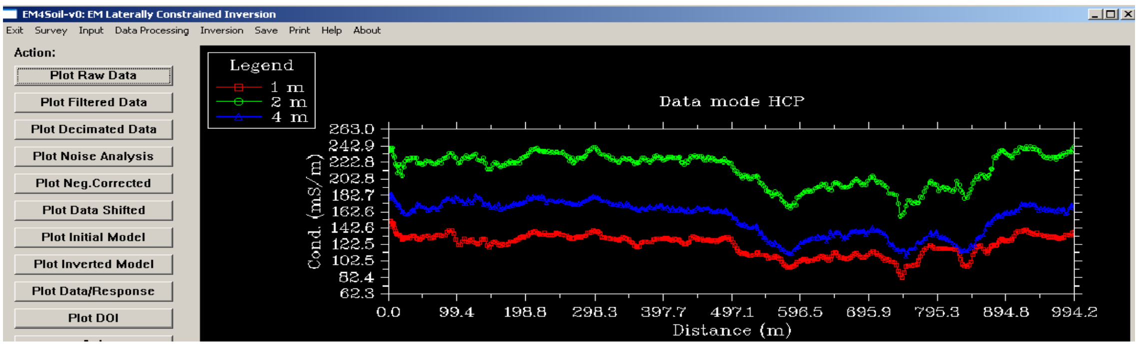


Figure 5.5.4. DUALEM-421 σ_a data prior to filtering

The **Running Average** filter is a three point moving average filter; whereby, a moving average filter averages a number of input σ_a and produces a single output value. Figure 5.5.5 indicates how the DUALEM-421 σ_a data shown in Figure 5.5.4 appears after filtering and using the **Running Average**.

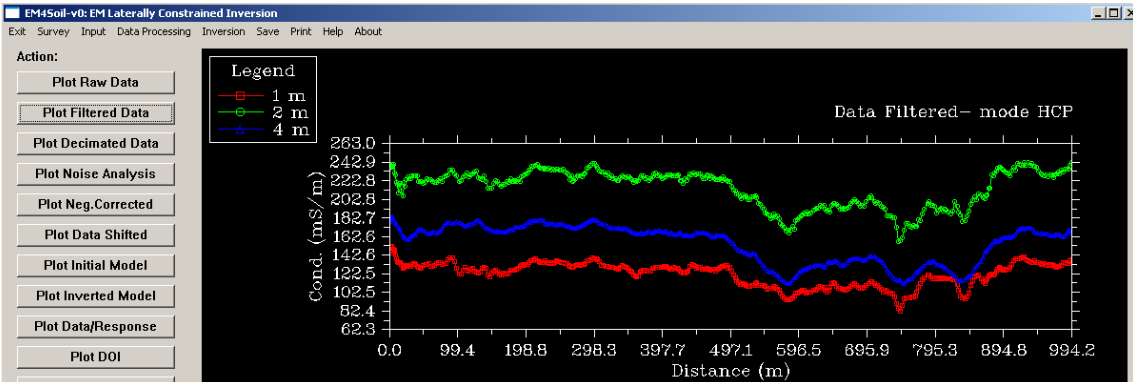


Figure 5.5.5. Filtered DUALEM-421 σ_a generated using the **Running Average**.

The **Weighted Average** filter is a three coefficient filter (0.3, 0.4, 0.3). The weight is calculated taking into account the distance and value of the closest non-negative values. The **Weighted Average** filter should be used carefully and cannot be applied if the number of negative data exceeds 30% of the total values (per channel). Figure 5.5.6 shows an example of DUALEM-421 σ_a post-filtering using the **Weighted Average**. It should be noted, that the correction of a large sector of negative values will produce poor results.

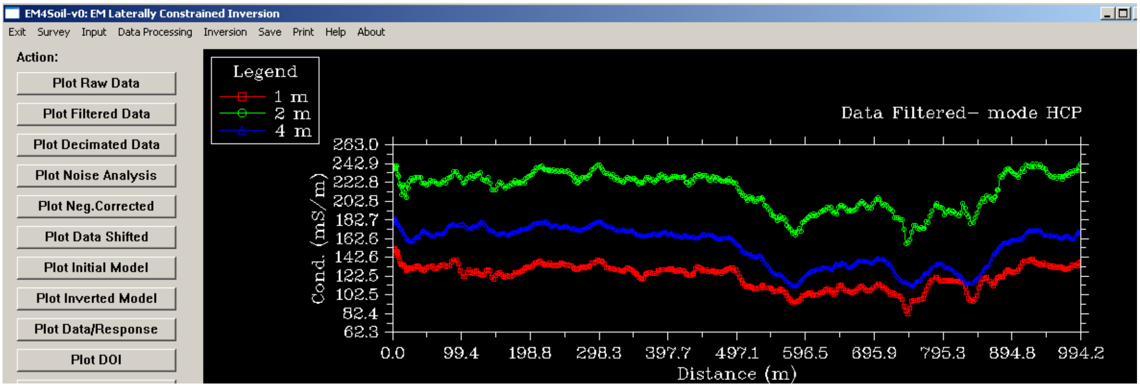


Figure 5.5.6. Filtered DUALEM-421 σ_a generated using the **Weighted Average**.

The **Sheppard** filter is a five coefficient filter (-0.0857, 0.34285, 0.4857, 0.34285, -0.0857). Figure 5.5.7 shows filtering of DUALEM-421 σ_a using **Sheppard** filtering.

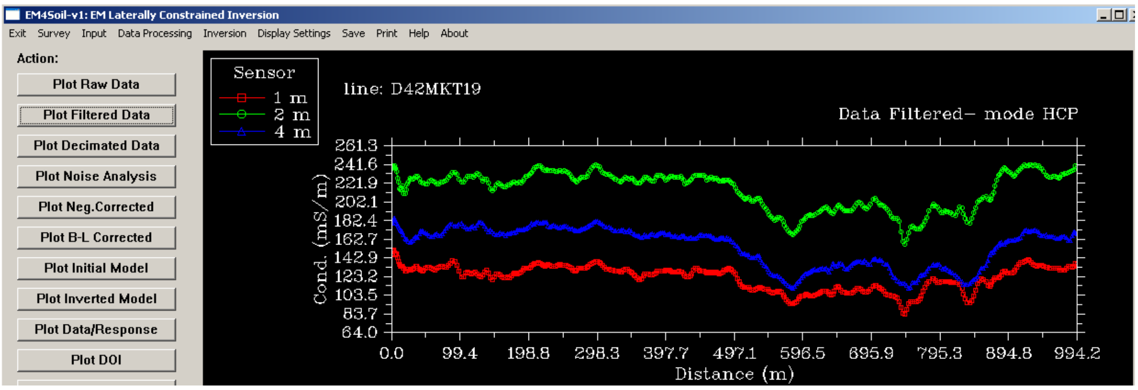
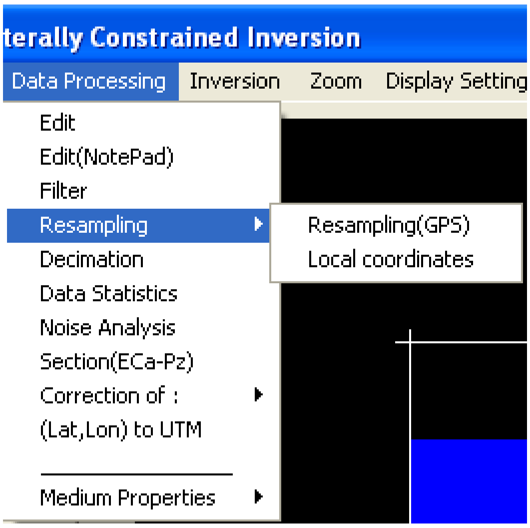
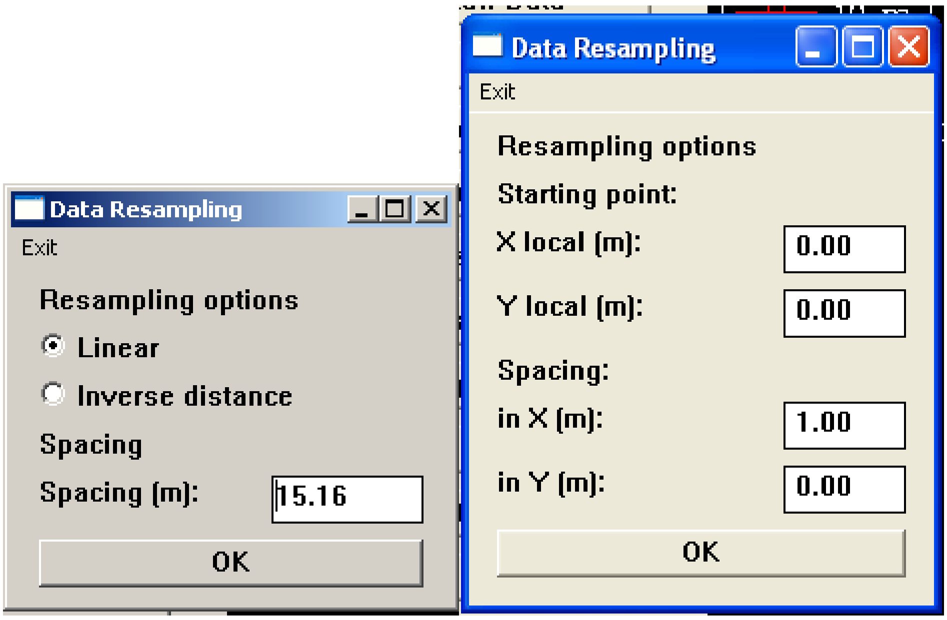


Figure 5.5.7. Filtered DUALEM-421 σ_a generated using the **Sheppard** filter.

5.5.3 Resampling

The data in a line can be resampled at uniform spacing. There are two options for the resampling. In the first (GPS) option, the data, elevation and coordinates are interpolated. The new spacing between measurements should be greater than 1.5*average spacing in the original data. This is the value suggested by the program to the user. This option should be used if data are not uniformly sampled, but the coordinates are good.





In the second option (Local Coordinates) the coordinates in the data file are not considered. New coordinates will be constructed and data and elevation values will be associated to this new system. This option should be used when the coordinates are not credible and the measurements have been done in positions referred in a tape (for example).

5.5.4 Decimation

Decimation allows the **EM4Soil** software to ignore σ_a data measured along a transect. Decimation may be required to allow a user to account for a high sampling rate or redundancy in the σ_a data. The user will be asked about the decimation factor, which represents the number of samples that will be skipped. Figure 5.5.8 shows an example of EM34 σ_a data prior to and post-Decimation and using a Decimation factor of 2. This means that only every third EM34 sensor data is used in inversion modelling.

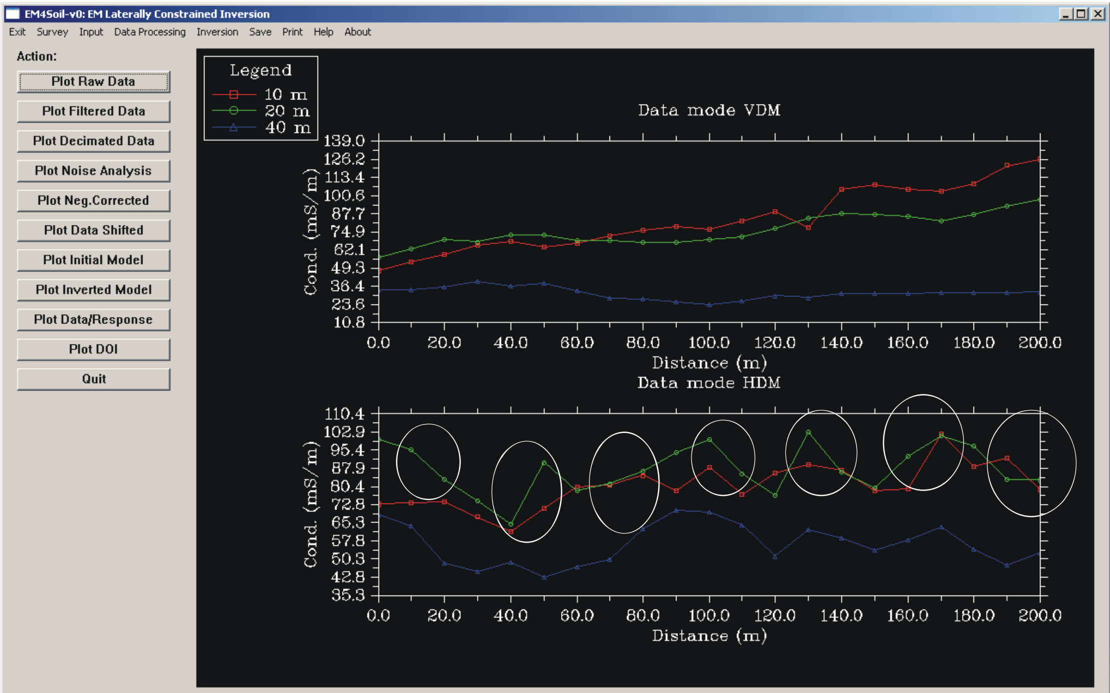


Figure 5.5.8. Screen snapshot of EM34 sensor data that will be ignored if a **Decimation** factor of 2 is selected.

Owing to the large amounts of EM σ_a data that can be collected, using mobile EM sensing platforms, the decimation option also allows a user to experiment with a smaller set of EM σ_a in order to determine a suitable value of λ and the number of iterations to carry out without having to wait for long periods.

In this regard, and once an optimal set has been identified, the entire set of EM sensor data can then be inverted for optimal results. Figure 5.5.9 shows an original set of DUALEM-421 sensor data. Figure 5.5.10 shows the effect of selecting a decimation factor of 2 on this data.

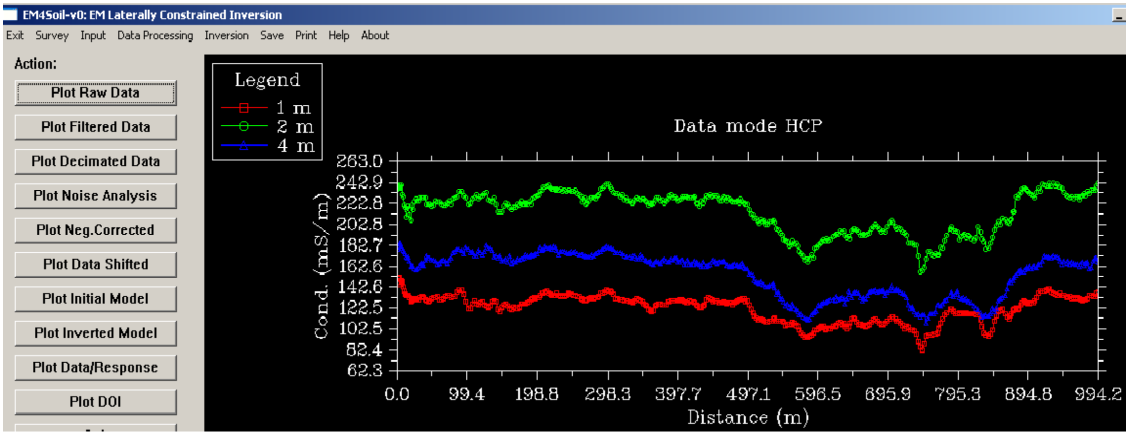


Figure 5.5.9. Schematic representation of DUALEM-421 sensor data collected using a mobile EM sensing platform.

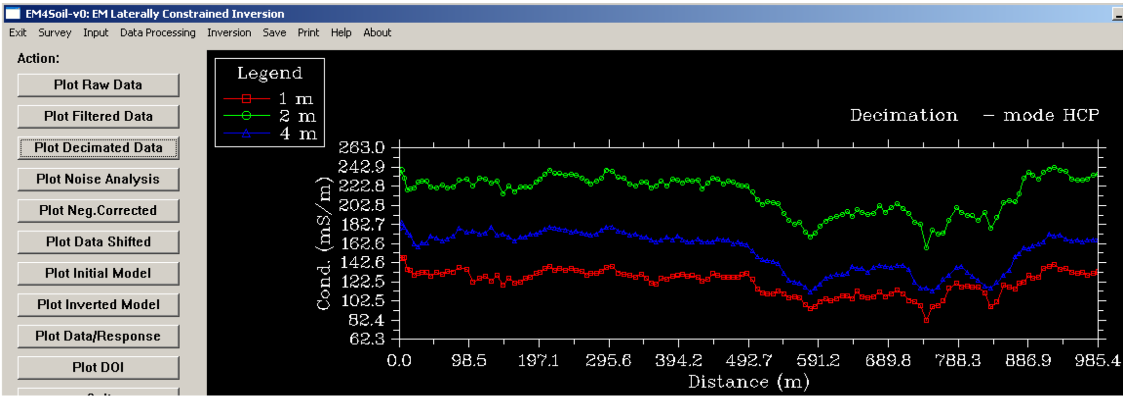


Figure 5.5.10. Schematic representation of DUALEM-421 sensor data decimated using a value of 2.

5.5.5 Data Statistics

A basic statistic of the data is possible using this option. Histogram for each channel will be displayed together with a table showing the mean value and the standard deviation. Also the number of negative values in each channel is shown. The program uses 13 bins to create histograms (Figure 5.5.11).

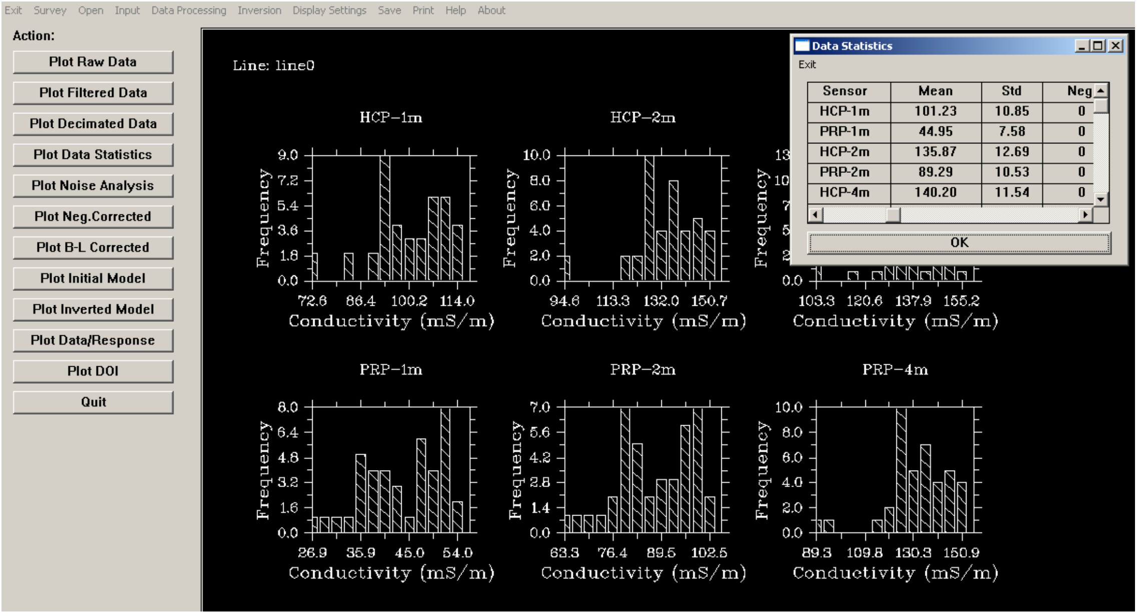


Figure 5.5.11. Presenting results from data statistic.

5.5.6 Noise Analysis

The **Noise Analysis** option is an experimental tool based on Everett and Weiss (2002). When using this option you can generate information about the noise of your σ_a data (see Appendix B).

NOTE: This tool must be used with some caution given its experimental nature.

5.5.7 Pseudo-section (ECa-Pz)

This option allows the display of a pseudo-section calculated from measured apparent conductivity. This is only a different way to present the raw data. The pseudo-section is calculated assuming a pseudo-depth, which is roughly the “depth of investigation” theoretically associated at each sensor.

The user must take into account that this pseudo-section is not a model and can not be used for interpretation.

5.5.8 Data corrections

Individual measurements along a σ_a transect inputted into the **EM4Soil** software can be corrected using the **Correction of values** option (Figure 5.5.12). In the first instance the σ_a data to be corrected should already be plotted and visible on the screen.

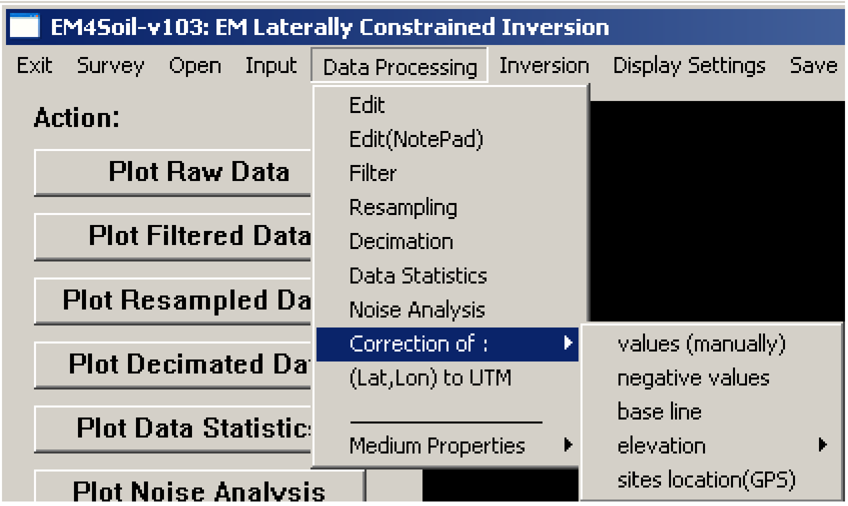
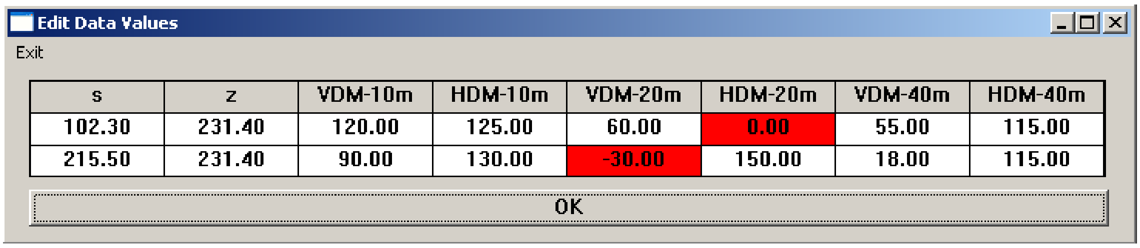


Figure 5.5.12. Drop down box menu for data **Correction of** σ_a data options.

Once the **Correction of values** option is selected, the mouse arrow icon will change to a cross. Go to the sites along the transect and select the σ_a data you want to correct. Click on the left mouse button. A second, third and fourth click will allow the user to select multiple sites. In order to finish the selection of sites, click on the right mouse button. As shown in Figure 5.5.13 a Table appears. Negative and null values will appear with a red background. You can modify these σ_a values. Selecting OK allows any and all subsequent inversions that will be carried out by EM4soil to use these corrected σ_a values (as raw data). However, the original data file will not be modified.


Edit Data Values

Exit

s	z	VDM-10m	HDM-10m	VDM-20m	HDM-20m	VDM-40m	HDM-40m
102.30	231.40	120.00	125.00	60.00	0.00	55.00	115.00
215.50	231.40	90.00	130.00	-30.00	150.00	18.00	115.00

OK

Figure 5.5.13. Drop down box menu for correction option.

Sometimes, negative values are present in the σ_a data[4]. Such values can not be interpreted by **EM4Soil** (and will therefore not be considered during inversion). A user may try to correct these values by interpolation. This can be done within **EM4soil** and using the **Correction of negative values** option.

[4] Negative values can have different origin: electromagnetic noise, weak induction or high conductivity bodies (e.g., metallic objects). Correction of these values can only be useful if the negative values are due to noise.

Figure 5.5.14 shows an example of a transect of DUALEM-421 σ_a which has negative values in the 4mPcon.

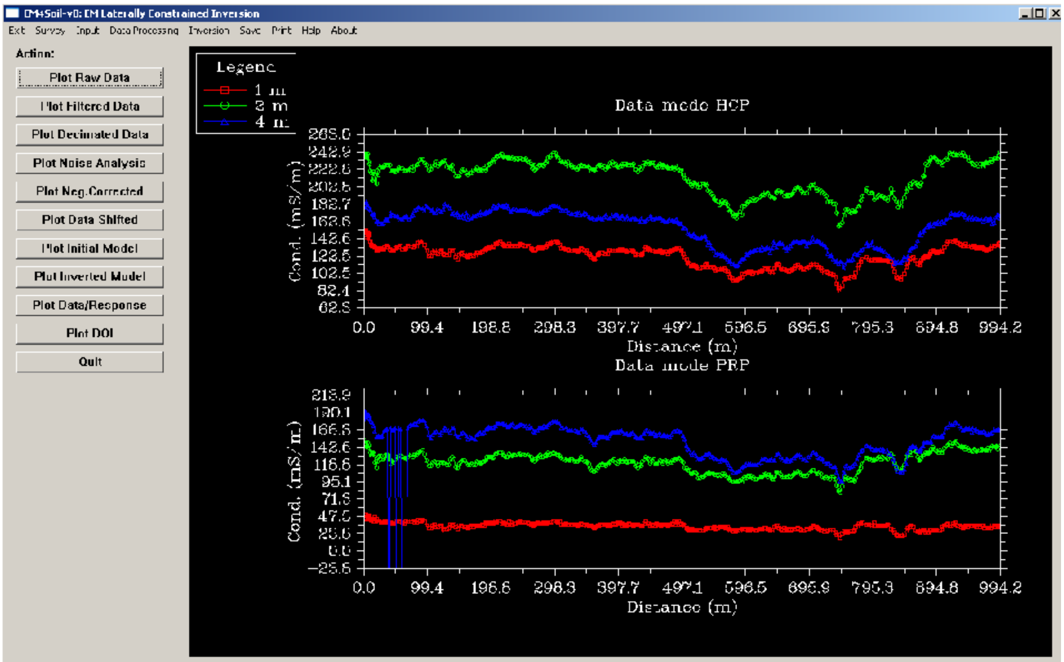


Figure 5.5.14. Transect of DUALEM-421 σ_a which has negative values in the 4mPcon.

Figure 5.5.15 shows how the negative σ_a has been corrected and using the **Correction of negative values** option.

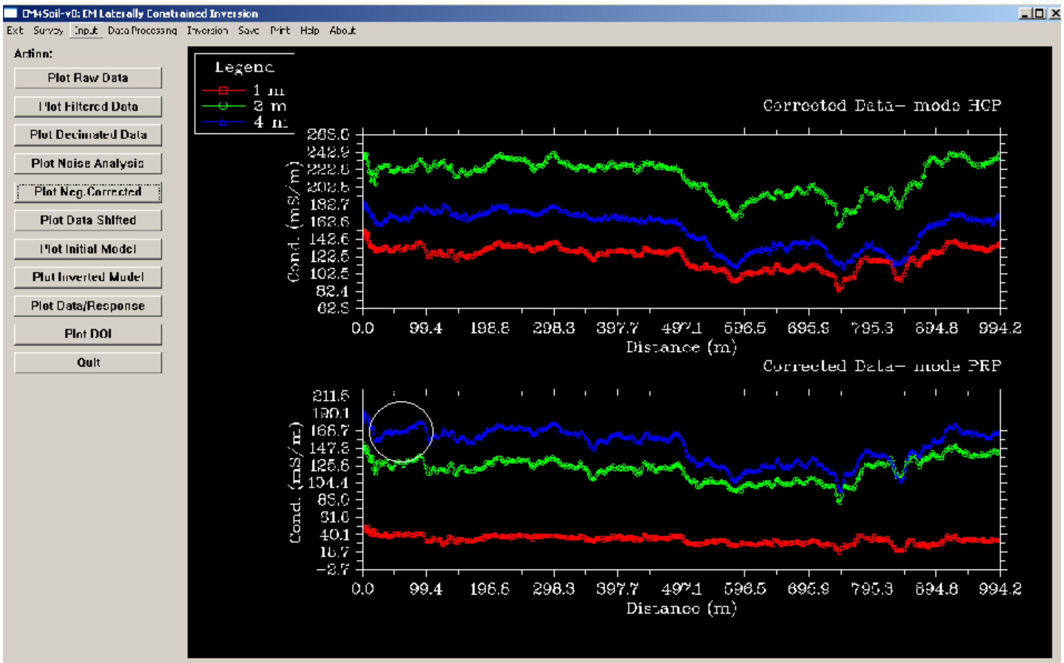


Figure 5.5.15. Correction of DUALEM-421 σ_a which had negative values in the 4mPcon.

If, for some reason, some of the σ_a data has a wrong base line value, Figure 5.5.16 shows where you can apply an **base line correction** to correct any channel.

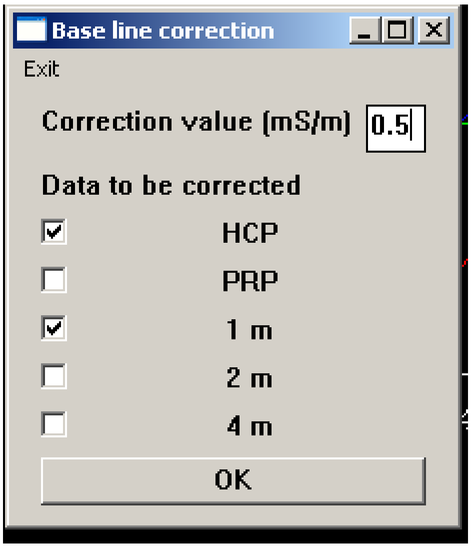


Figure 5.5.16. Drop down box menu for **base line** correction option (Example is for DUALEM-421).

The **Elevation correction** option allows a user to display the elevation along the transect line of interest and active within in **EM4soil** and thereby smooth it (moving average filters of 3, 7 and 11 points are available). It is also possible to disable the elevation. When this option is chosen, subsequent inversion modelling will be assumed data to have been collected across a flat terrain.

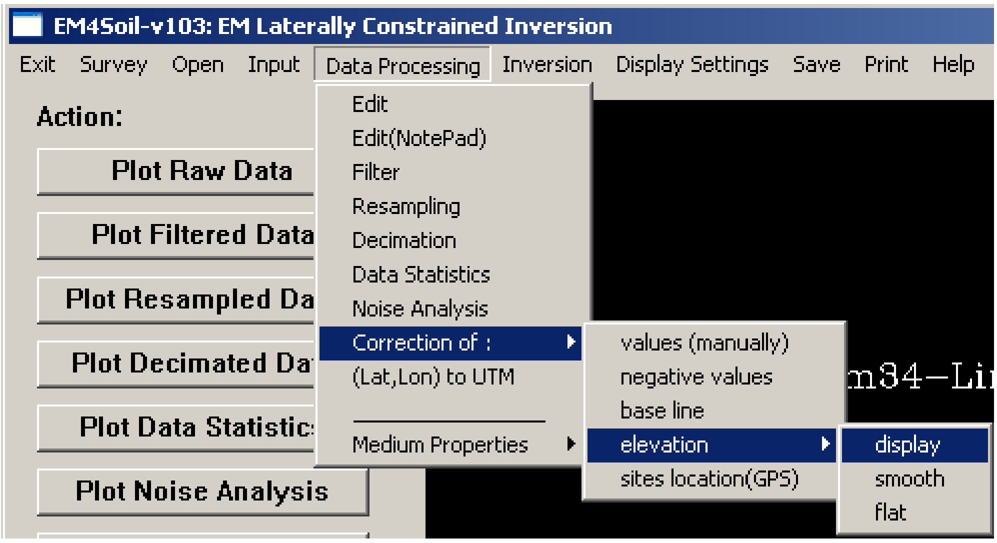


Figure 5.5.17. Drop down box menu for elevation (altitude) corrections.

A GPS receiver is not usually installed near the centre of an EM instrument and during a survey. Therefore, the position of the EM σ_a should be corrected. The **correction of site location** option allows doing this correction as well the correct positioning of the σ_a of the different sensors. This is particularly the case in a multisensor instrument such as the DUALEM-421.

Figure 5.5.18 will appear when the **GPS correction** option is selected. This allows the instrument orientation, the GPS location and the method of GPS correction to the σ_a data collected by each sensor. This last option is valid only for DUALEM instruments. Please, read **APPENDIX C** for further details.

NOTE: Site correction should be applied at profiles. It can be used also in mapping surveys if data was collected in continuous parallel profiles (bidirectional acquisition ↑↓↑). Note that the correction assumes that the transmitter loop is behind receivers during the acquisition.

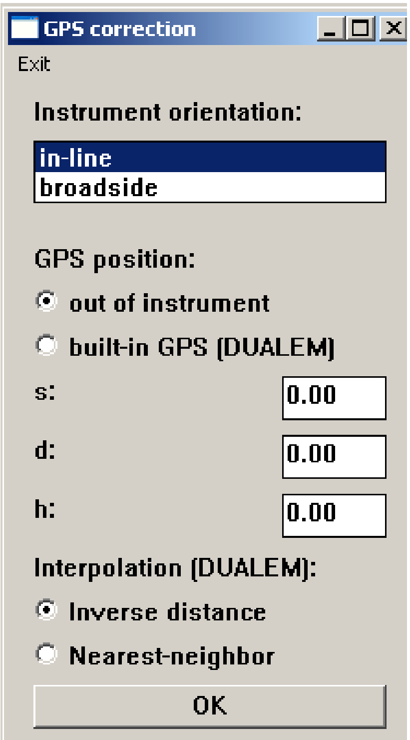


Figure 5.5.18. Drop down box menu for **GPS correction** option.

5.5.9 Converting Latitude and Longitude to UTM

The **Lat/Long to UTM** option tool allows the conversion of GPS data acquired in Latitude and Longitude into UTM coordinates. This conversion is possible for five datum selecting the appropriate central meridian of the zone. The calculations are based on the formulas presented by Steven Dutch (http://www.uwgb.edu/dutchs/usefuldata/utmformulas.htm).

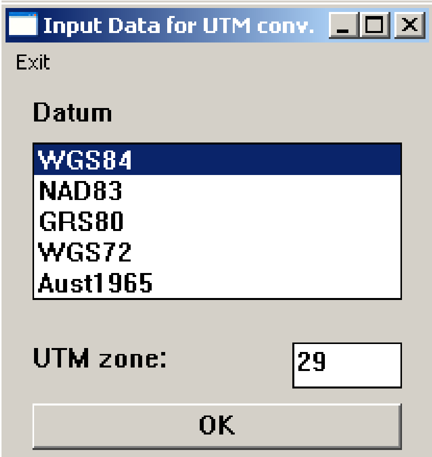


Figure 5.5.19. Drop down box menu for **Lat/Long to UTM** option.

UTM coordinates will be used by EM4soil but the raw data file will be not changed. If you want to use it in the future, you must save it (Save Processed data). To convert coordinates of a survey area proceed as follows: 1) select the sensor 2) go to the conversion and input the data 3) do the conversion and save the result in a file which will be input appropriately after.

5.5.10 Medium properties

The **Medium Properties** menu option allows the user of **EM4soil** to estimate values for some properties of the earth connected to the bulk electrical conductivity (resistivity) like water content and water content variation (Figure 5.5.20). This option works on inversion models calculated previously and saved in the format XYZ.

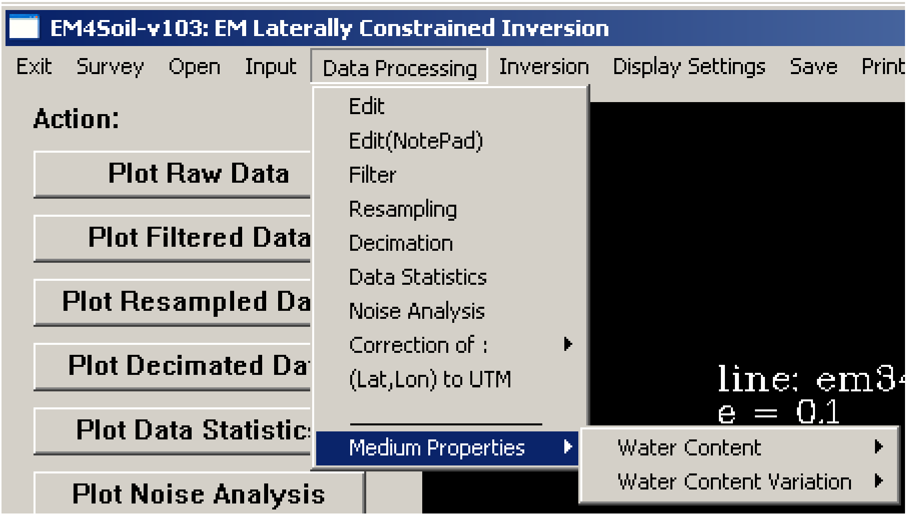


Figure 5.5.20. Drop down box menu for **Medium Properties** option.

As an example, and by selection water content, this property will be estimated. As shown in Figure 5.5.21, there are two approaches, both of which are based on experimental data for fractional (m^3/m^3) water content estimation.

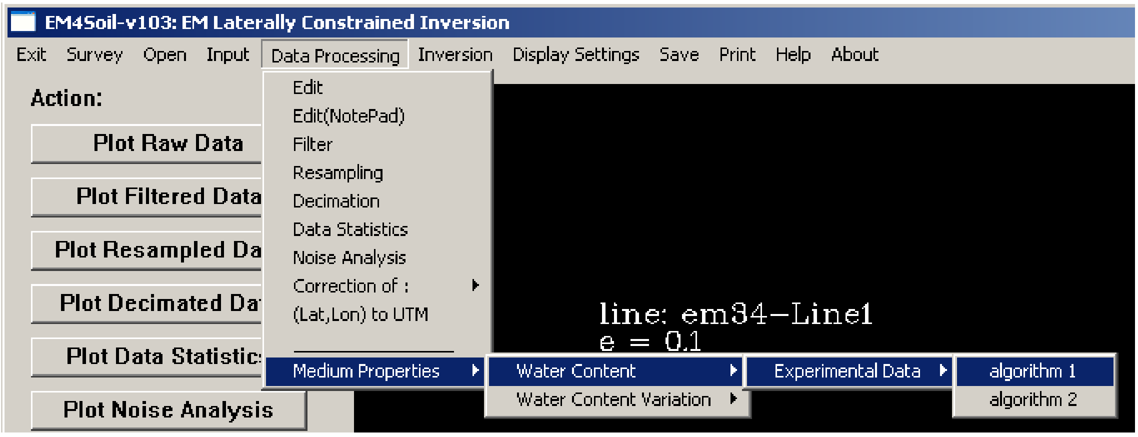


Figure 5.5.21. Drop down box menu for **water content** option.

The first algorithm is based on the equation

$$\rho_b = \rho_o \theta^{-m}$$

The second one is based on

$$\theta = a\rho_b{}^{-m} + b$$

Where θ is the fractional water content, ρ_b is the bulk resistivity, ρ_o is an experimental parameter correlated to the water resistivity, *a*, *b* and *m* are experimental parameters. These parameters can be determined from samples collected at different depths in boreholes located at selected sites, preferentially coincident with EM lines. The water content and bulk resistivity can be measured in laboratory. Alternatively, the resistivity calculated by inversion can be used. The data can then be used to determine the parameters of the equations (Figure 5.5.22).

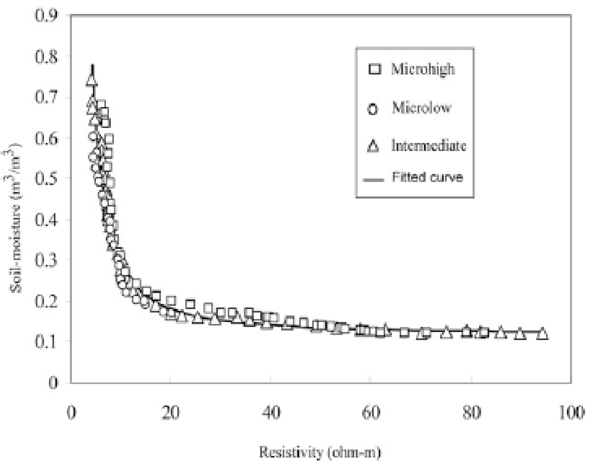


Figure 5.5.22. Example of soil moisture versus resistivity data and fitting curve; a=6.0145, b=0.12 and m=1.536 (from Amidu and Dunbar, 2007).

In addition, water content variation can be estimated from two EM surveys made at different times. This assumes that Archie's law is valid and that the variation in water content is responsible for the variation in σ_a and between the two survey times. The user will be asked to provide the *n* parameter and the files corresponding to the two models. The user must remember that the use of the Archie's law requires a clay-free medium.

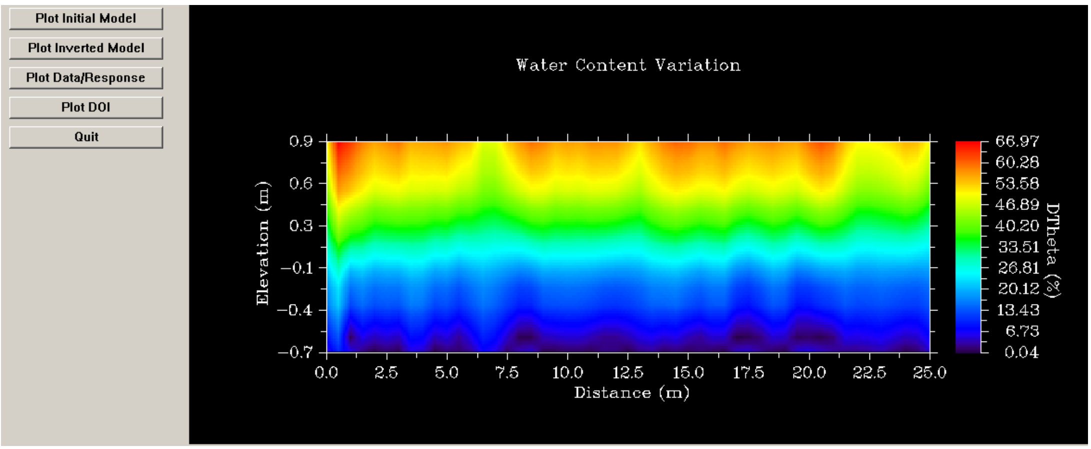


Figure 5.5.23. Example of a pseudo-section of water content variation.

5.6. Inversion

After carrying out various Data Processing options, the σ_a data is ready for inversion. Selecting the **Inversion** option, the program will allow you to perform either 1D or Quasi-2D inversions. These options are indicated in a drop down box shown in Figure 5.6.1.

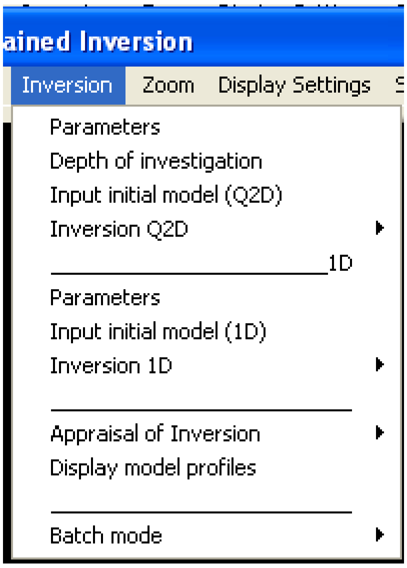


Figure 5.6.1. Drop down box menu for **Inversion** selection.

If the σ_a data does not have any negative value, an initial model is automatically constructed from your data and during the data input stage. However, a user can choose an initial model using the option **Input initial model**.

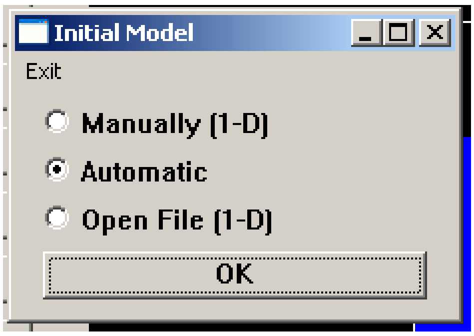


Figure 5.6.2. Menu for input of the initial model.

As shown in Figure 5.65.2, a user has three options to input an **Initial model**:
a) Choosing **Manually** (1-D) the user can input a 1D model, and as shown in Figure 5.6.3 defines the number of layers, the depth of the lowest interface of the layers (in meters) and provide an estimate of the true electrical conductivity (σ) in mS/m;
b) A uniform (constant σ) initial model can be constructed **Automatically**, inputting the initial conductivity (this option should be used if you want to study the resolution of your model through DOI, or your inputted data has negative values);
c) Finally, you can read the initial model from an ASCII file previously saved (see the **Format Section**).

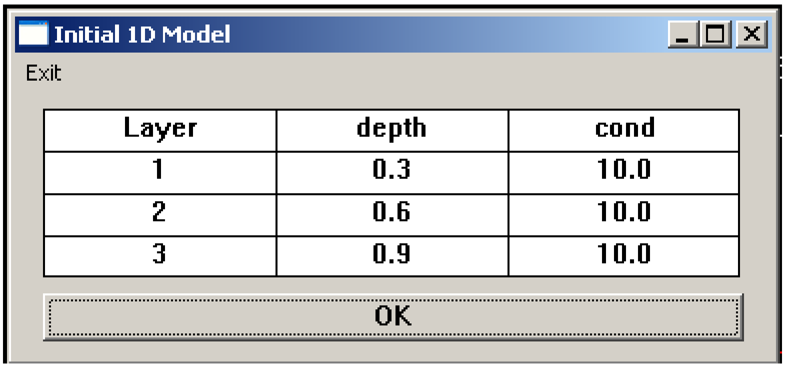


Figure 5.6.3. The Table for input of a 1D model.

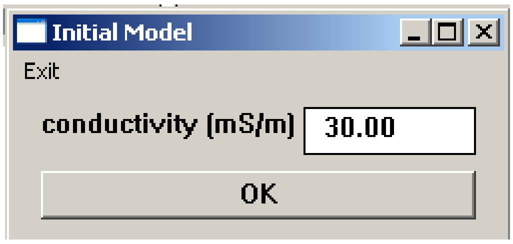


Figure 5.6.4. Inputting the conductivity of the uniform initial model (option **Automatically**).

Selecting the **Inversion Parameters** option, will display the following menu (Figure 5.6.5), which allows the user to define some of the inversion parameters.

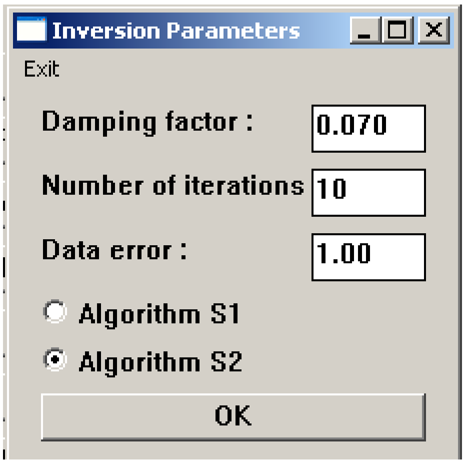


Figure 5.6.5. Input of **inversion parameters**.

The damping factor controls the roughness of the model (see the appendices for details). The larger the damping the smoother the resulting inversion model. A suitable damping factor value should be determined empirically and by performing inversions with different values (e.g. from 0.03 to 30).

NOTE: When written values, follow the format displayed in the menu.

The program allows the use of two different inversion algorithms named here as S1 and S2. They are based on the work published by Sasaki in 1989 and 2001 (see appendices for details). In general, S2 algorithm produces smoother models when compared with those from S1.

EM4Soil allows the user to invert σ_a data using a 1D Laterally Constrained Inversion (Quasi-2D model) algorithm or a 1D inversion without constraints. The user chooses to use the linear or the non-linear approach for the model response (and derivatives) calculations. In any case you must define the σ_a data to invert (Figure 5.6.6).

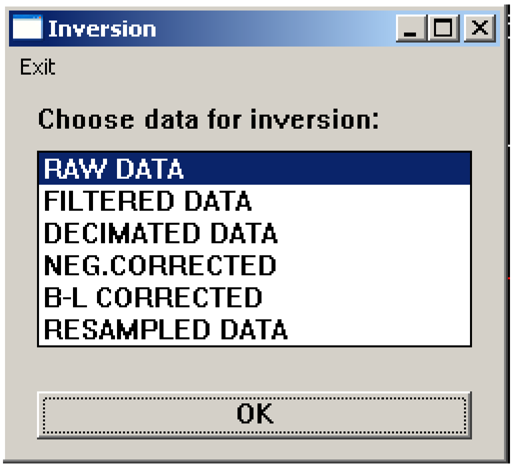


Figure 5.6.6. Choosing data for inversion.

NOTE: Quasi-2D inversion of data collected with EM instruments having only one sensor (like, EM31, EM38, DUALEM-1 or DUALEM-2) only should be done if the data set is complete and, even in such case, the models should be analysed with care. In such cases it is preferable to perform a 1D inversion.

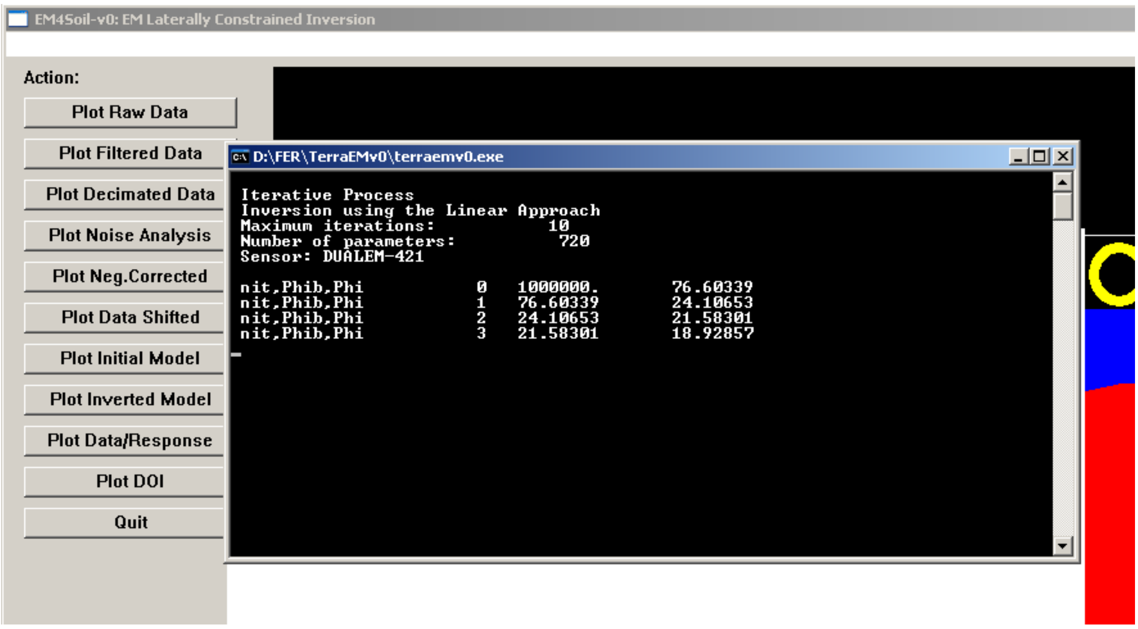


Figure 5.6.7. Following the inversion process.

NOTE: During the inversion (which can take a significant time dependent on the number of sites you have) the program will not process any instruction.

NOTE: you can follow the inversion steps in the DOS windows opened when EM4Soil starts (Figure 5.6.7).

Figures 5.6.8 and 5.6.9 show the models obtained from EM34 data using the Quasi-2D and the 1D unconstrained algorithm, respectively.

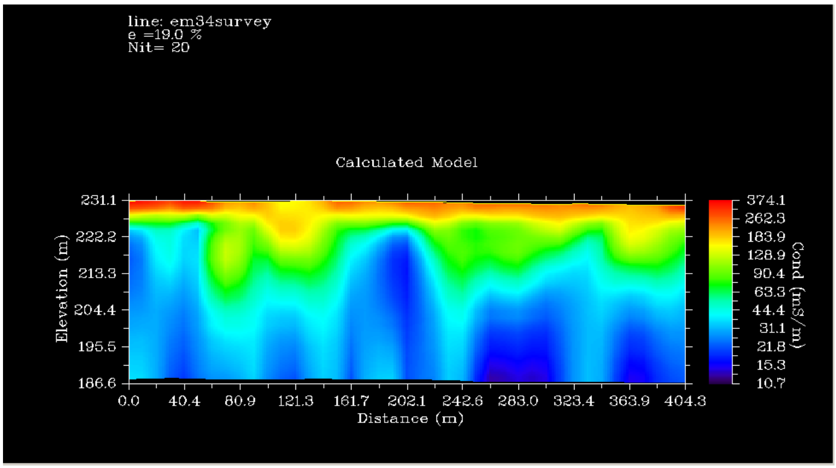


Figure 5.6.8. Q2D model obtained from EM34 data.

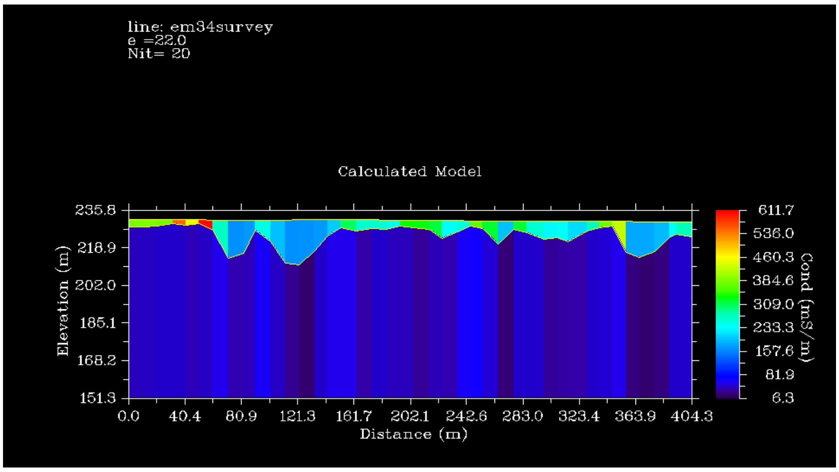
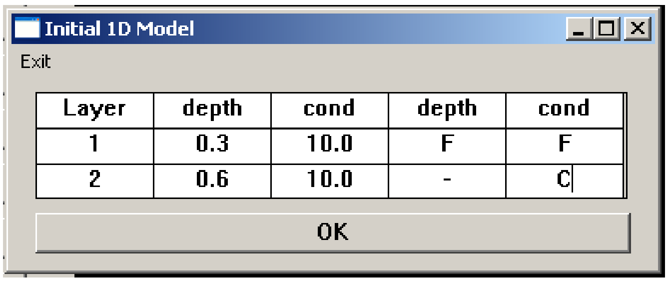


Figure 5.6.9. 1D model obtained from EM34 data, assuming a two layers initial model.

One or more parameters can be fixed during the 1D inversion. To do that, the user must change the F to C in the table used in the definition of the initial model (Figure 5.6.10).


Initial 1D Model
Exit

Layer	depth	cond	depth	cond
1	0.3	10.0	F	F
2	0.6	10.0	-	C

OK

Figure 5.6.10. Defining an initial model for the 1D inversion. F means that the parameter is free to be modified, C means that the corresponding parameters will not be modified during the inversion.

The **Appraisal** option will allow you to evaluate the calculated model. In the present version of the program this evaluation will be done through the **DOI** index (Oldenburg and Li, 1999). Before using the **DOI** option, the user will need to perform two different inversions (using two different uniform initial models, for example of 30 and 300 mS/m) and save the inversion model results (use **Save Inverse Model** in the **Save** menu). When selecting the **DOI** option the program will ask the user to input the files with those models, previously calculated.

The **Fitting** option allows the user to see the correlation between experimental and calculated response (Figure 5.6.12).

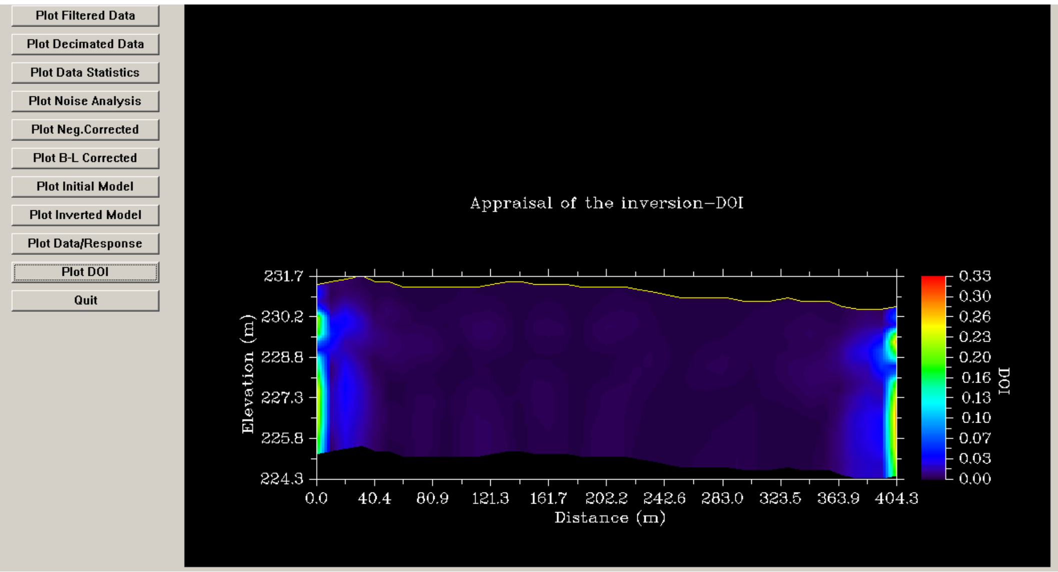


Figure 5.6.11. DOI pseudo-section showing the model is well resolved.

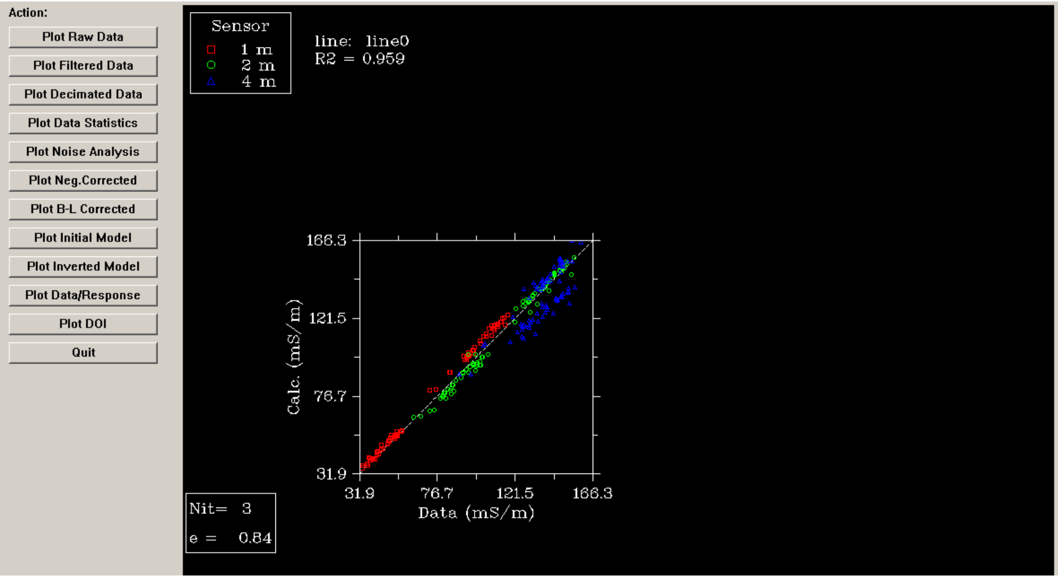
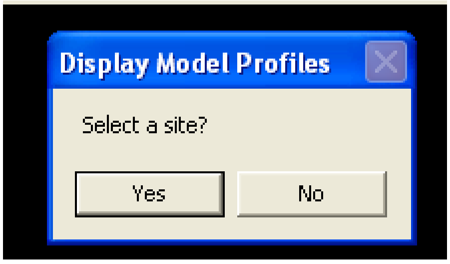


Figure 5.6.12. Correlation between observed and calculated σ_a data.

The **Display Model Profiles** option allows the plot of vertical profiles of electrical conductivity through the model at some specified sites. The proceeding to select sites is the same used for selection of sites for EMsounding inversion (see, **5.4.4**).

Select the sites using the left mouse button and finish clicking on the right button.



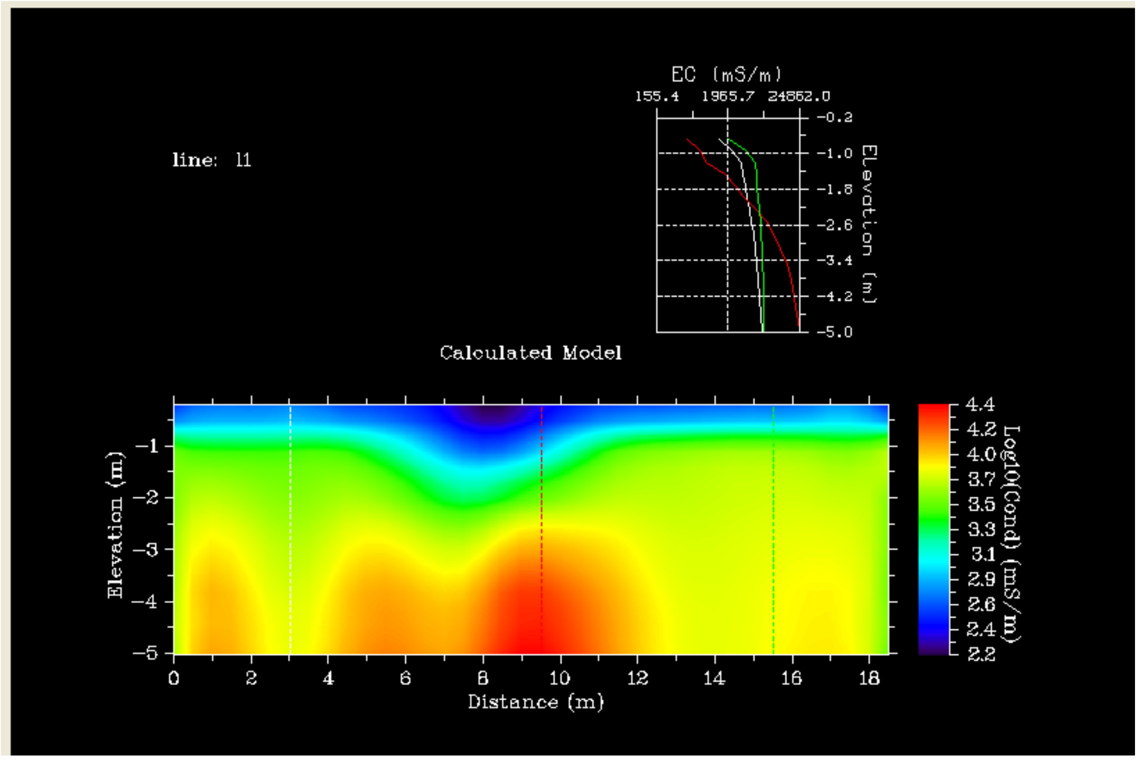
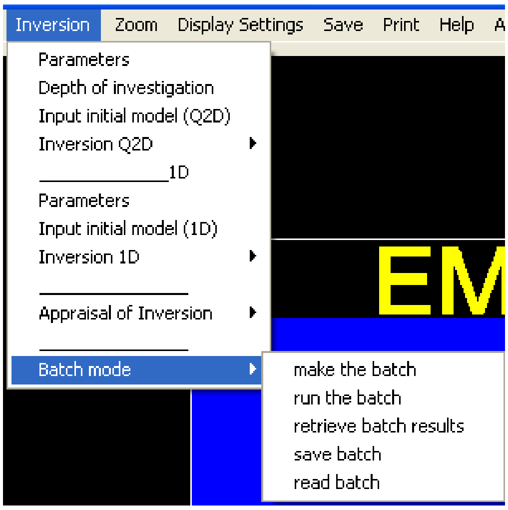


Figure 5.6.13. Vertical conductivity profiles and their location in the Q2D model.

The results can be saved in a file. To do that, go to the menubar/save/save EC profiles.

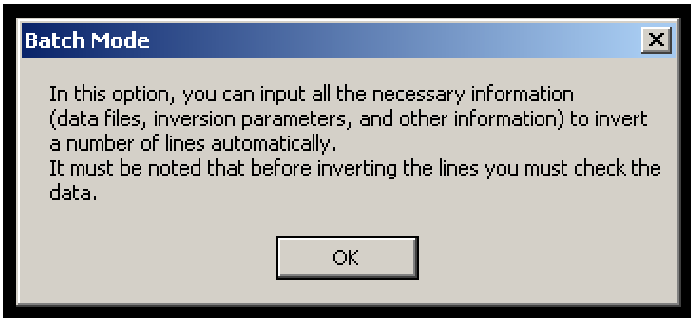
Each time an inversion is calculated a file with extension *.INVr is saved (in the folder …\inverse). These files can be imported using the option **Inversion results** in the **Open** entrance.

The **Batch mode** allows you to define a batch for inversion of several lines automatically. The **Batch mode** is not available for the Q3D inversion module.



There are five options in the batch mode: 1) make a batch, 2) run a batch, 3) retrieve results, 4) save a batch and 5) read a batch.

You can introduce all the necessary information clicking in "make the batch",



All the data files you want to invert should be imported (one by one) after you press OK. Finish clicking in the Cancel button. A table contained the selected files and the default parameters will be displayed (Figure 5.6.14).

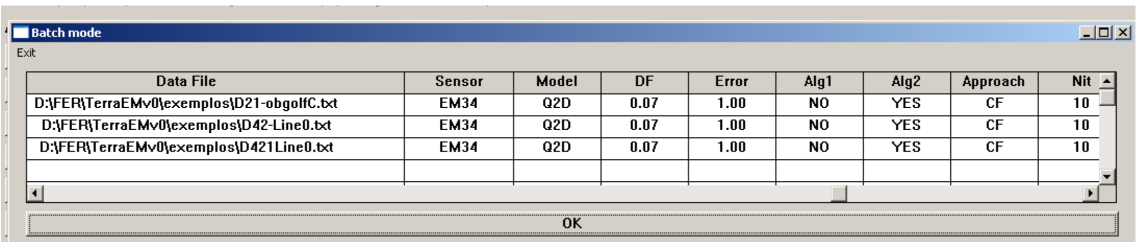


Figure 5.6.14. Making a batch file.

You must modify the wrong or not appropriated information before push the OK. The program will do a basic check of your data and files where problems have been detected will be highlighted (Figure 5.6.15).

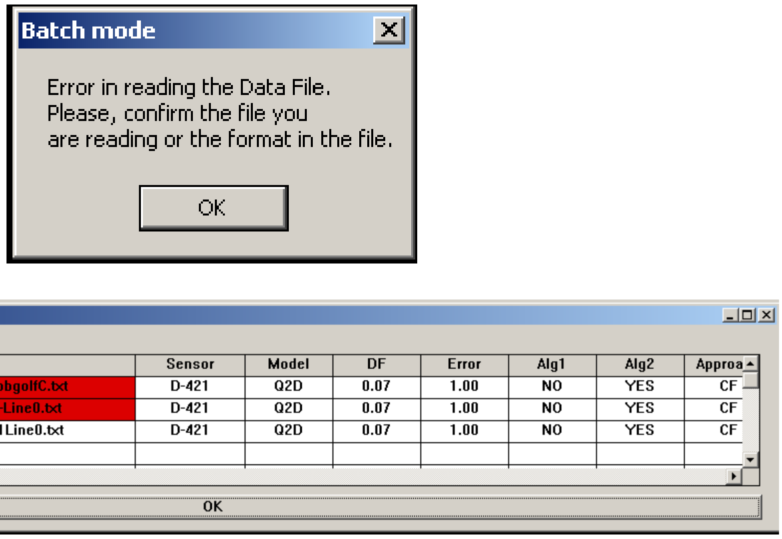


Figure 5.6.15. Checking the batch file.

In this case the sensors assigned to the first two files are wrong. After correct these mistakes the program will check again the information. If every thing is well the batch can be run.

Table-Codes to be used in the batch

Sensor	Model	Approach
D-1	Q2D	CF
D-2	1D	FS
D-21		
D-42		
D-421		
D-642		
EM38		
EM31		
EM34		
GEM		
PROF		

NOTE: The codes for sensors, models and the approach to use in the inversion should be written in capitals. The software is key sensitive to the codes.

NOTE: For PROFILER and GEM the approach must be FS.

NOTE: Do not put in the same batch data files acquired with instruments from different constructers. Do not mix DUALEM data with GEONICS ones.

NOTE: The check made by the program is very basic so the user should verify all the files before start a batching process.

A table with a resume of the inversion results will be presented (Figure 5.6.16) after running the batch. The results of each inversion are saved in the respective *.INVr files which were saved in the folder ..\inverse and can be recovered using the **Open** (**Inversion results**) entrance in the main menu bar.

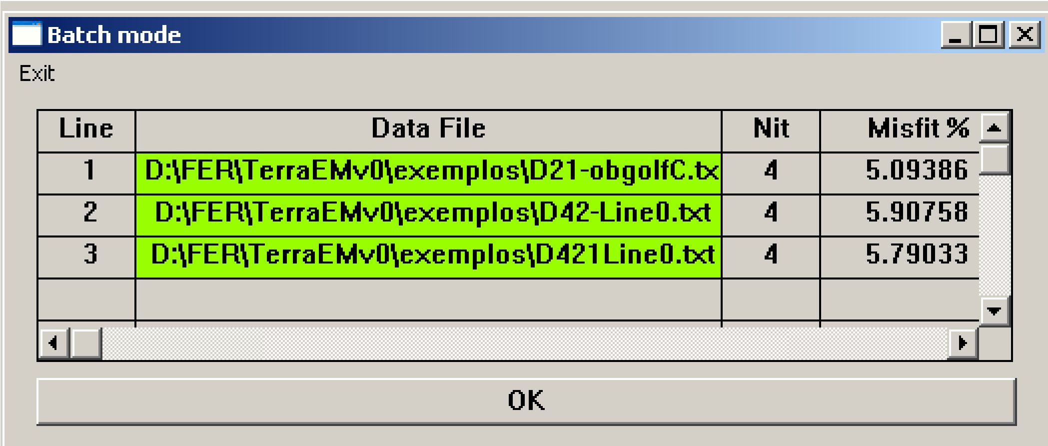


Figure 5.6.16. After running the batch.

The batch file should be saved with the extension BATm to avoid misunderstandings with other type files. These files can be read (with the **read batch** option) and run. See the format section about the batch file format.

NOTE: sometimes the right mask for files does not appear in the windows. The user should look for that.

The **Depth of Investigation** entrance will open a new module that will allow the user to study the depth of investigation of his data. According to Huang (2005) the "depth investigation in EM is a maximum depth at which a given target in a given host can be detected by a given sensor ". The depth of investigation depends on several factors, such as, sensor sensitivity, operating frequencies, target and host properties, noise level, etc. In LIN instruments, like those from GEONICS or DUALEM, the depth of investigation is quite well established. However, the issue is not clear for multifrequency instruments, like GEM and PROFILER. For that reason, this tool is only available for multifrequency sensors.

Clicking in **Depth of investigation** entrance will open the new module (Figure 5.6.17).

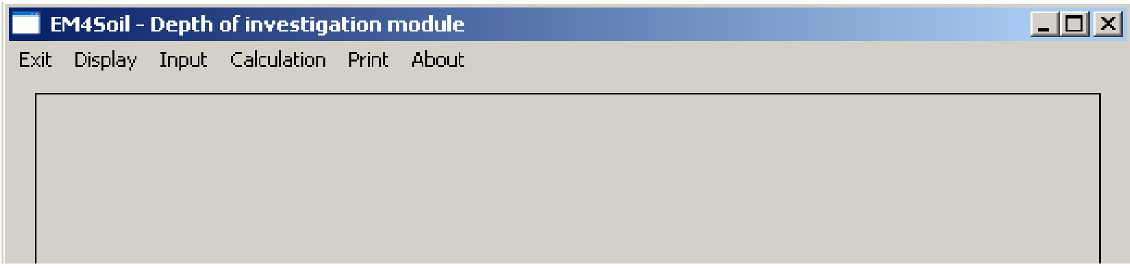


Figure 5.6.17. The **Depth of investigation** module menu bar.

Clicking **Input** will open the menu (Figure 5.6.18) for input of the testing model and relevant parameters (Figures 5.6.19 and 5.6.20).

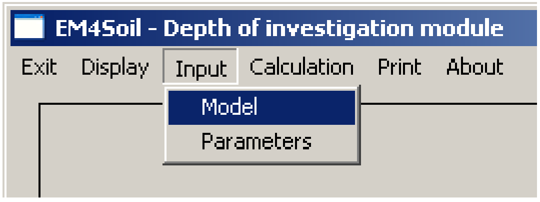


Figure 5.6.18. Choosing the testing model input.

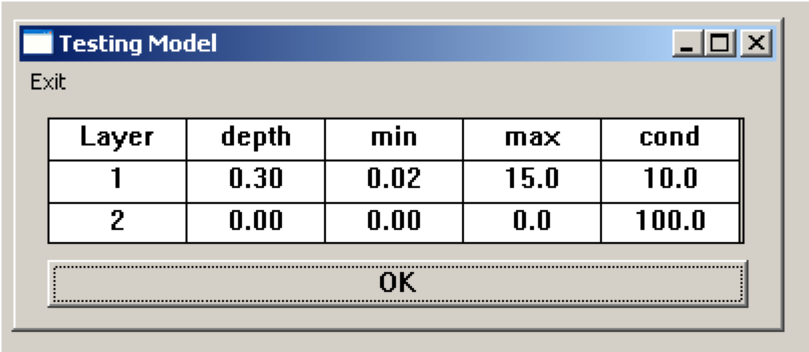


Figure 5.6.18. Defining the testing model. Depths are in meter and conductivity in mS/m.

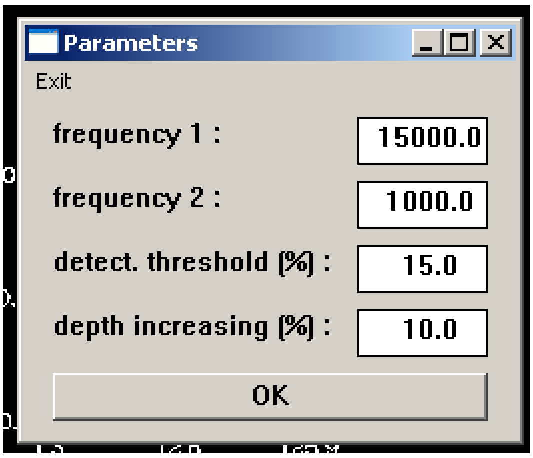


Figure 5.6.20. Choosing the maximum and minimum frequencies, the detecting threshold and the factor for depth increasing.

The depth of investigation is calculated using the ratio A = Sa/So, where Sa is the apparent conductivity of the two-layer model and So the apparent conductivity of a uniform model (host). The depth of investigation is the depth of the second layer (top) at which $A > (1 + T/100)$ or $A < (1 – T/100)$ where T is the detecting threshold.

After model definition and parameters selection the calculation will be performed clicking in the **Calculation** entrance. The output will be displayed as shown in Figure 5.6.21.

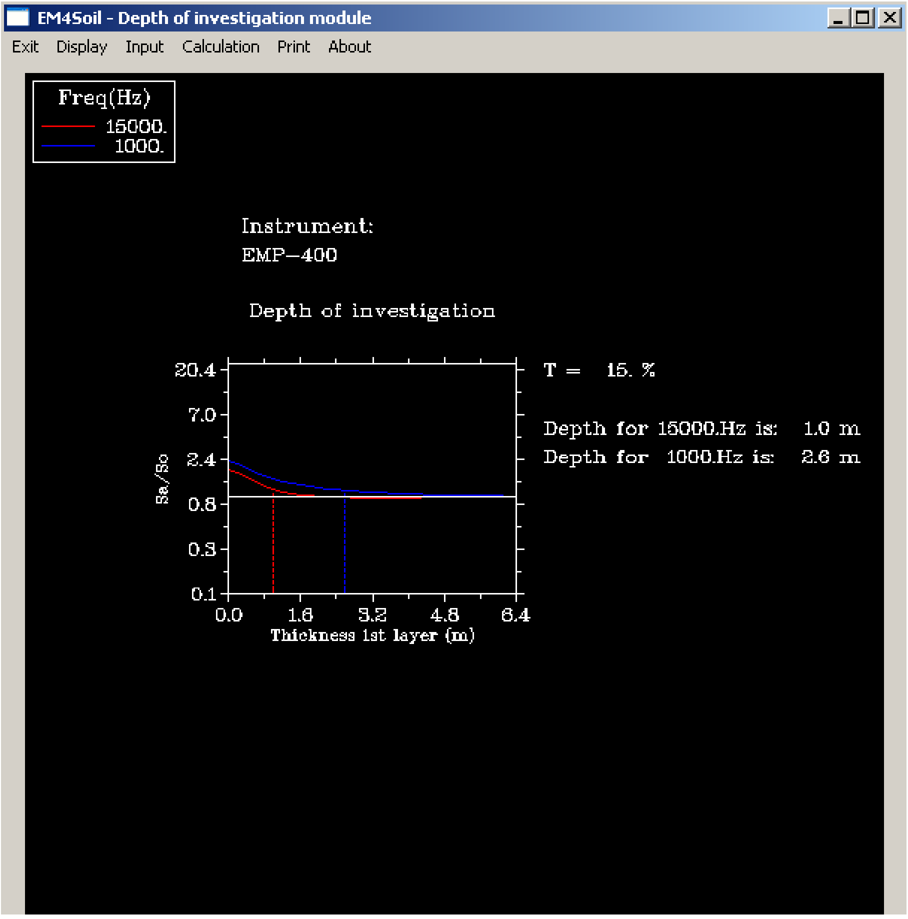


Figure 5.6.21. Showing the depth of investigation for selected testing model and frequencies.

Note: All calculations are considering the VDM mode, which is probably the most used mode in acquisition.

5.7. Display Settings

Figure 5.7.1 shows the **Display Settings** menu options here allow the user to choose how the inversion models are presented.
In the first instance, the user can choose between conductivity (i.e. σ) and resistivity (ρ). The default option is that the results will be presented in σ.
Secondly, these values of σ or ρ can be presented using either a linear or logarithmic contour. The default option is that the results will be presented using a linear scale.
Finally, the user can also choose to display the inversion model alone and also the original σ_a data. The default option is that only the modelled results will be presented.

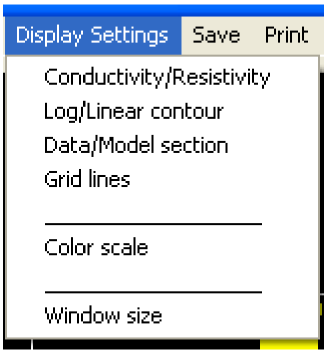


Figure 5.7.1. Choosing display settings.

The option Window size allows the user to adjust the size of the **EM4Soil** application. The defaults size is the normal size (100%). The program should be restarted to validate the option.

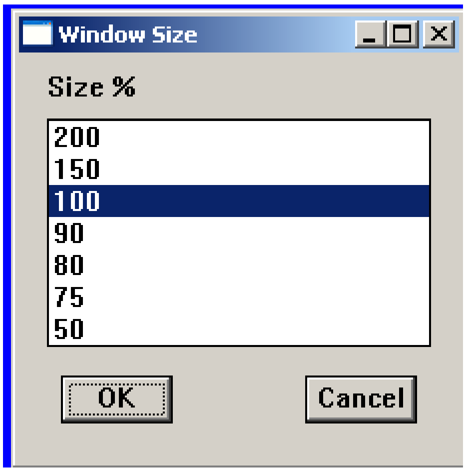


Figure 5.7.2. Window sizes.

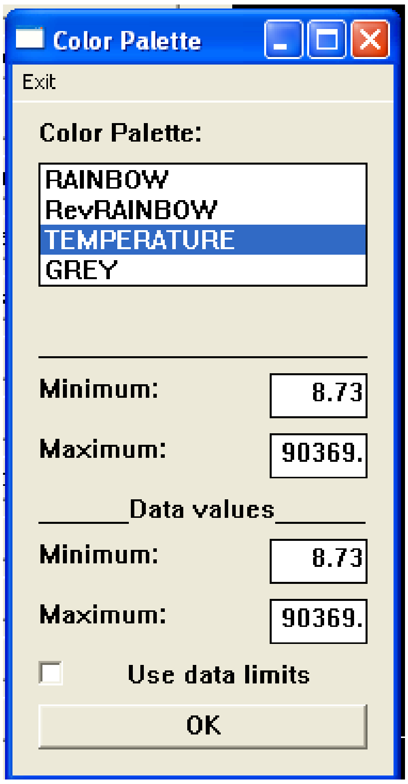


Figure 5.7.3. The color palette menu.

5.8. Save and Print

The **Save** menu allows the user to save files and to print figures of **Inversion** and **Data Processing**.

Figure 5.8.1 shows that the Save menu options include **Save Initial Models** of either **1D** or **Q2D** modelling, **Processed Data** and results from inversion calculations.

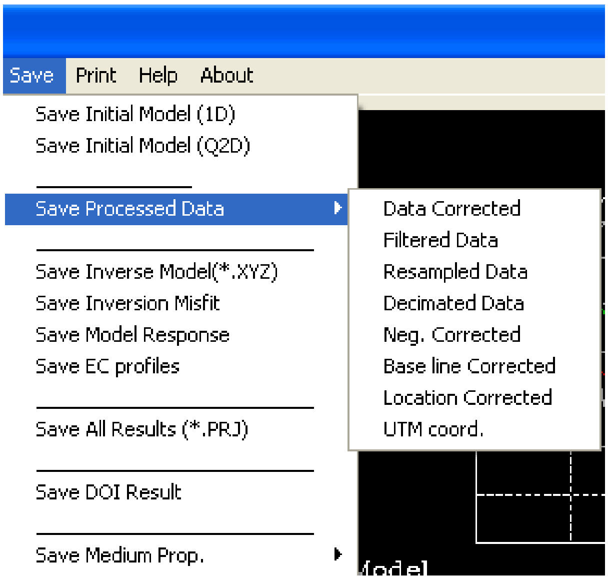


Figure 5.8.1. The **Save** menu.

Inverted models should be save using the option **Save Inverse Model**. These files can be imported in the Map module to construct maps showing the conductivity distributions with depth. All results obtained during a session with the program can be saved in a project file (*.PRJ). The user can also save results obtained from DOI analysis as well as those obtained from Medium properties.

In the **Print** entrance the user can print the results in a file according to a specific format (PS, PDF, PNG, TIFF, WMF) that can be chosen using the **Metafile format** option. PNG is the default format.

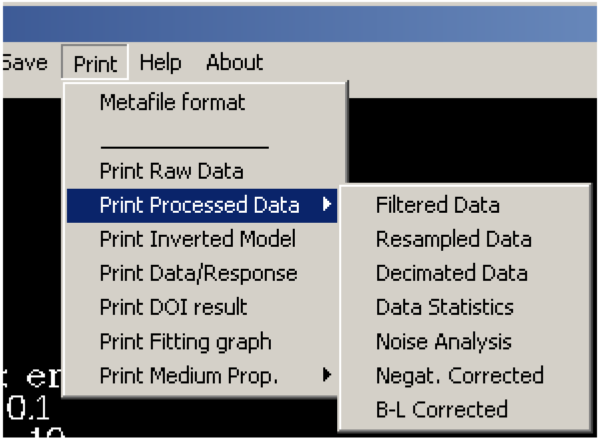


Figure 5.8.2. The **Print** menu.

5.9. Help

You can read a summary of the main function of the program, including a Short Guide on “how to use this program”, using the **Help** menu.

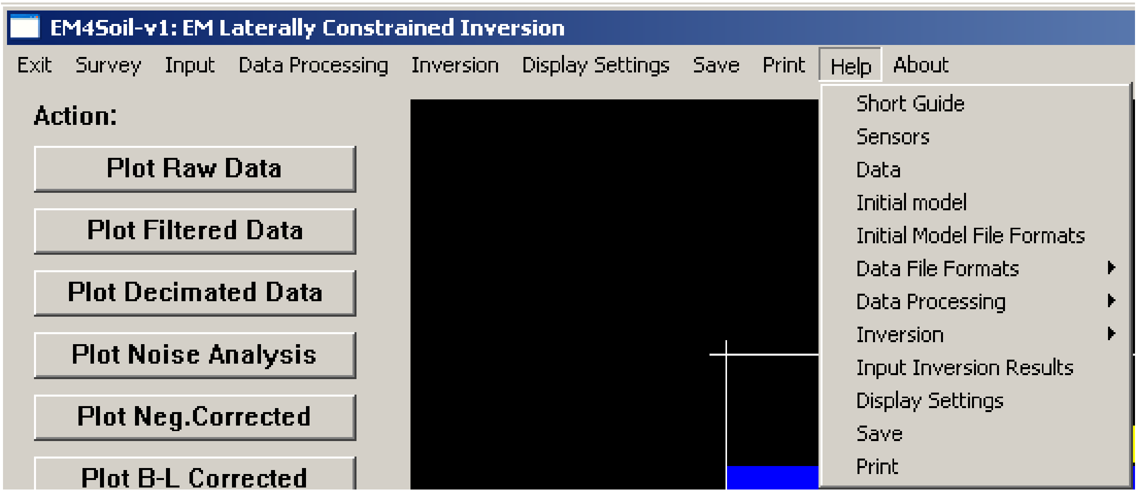


Figure 5.9.1. The **Help** menu.

6. The Action/Display zone

Your data and your results can be displayed on the screen using the buttons available in the **Action zone**. The program will be closed clicking in the **Quit** button. Closing the program using the **Exit** option in the Main top menu bar will delete all temporary files saved during the use of the program. Anyway, these files will be deleted next time you start the program or when you read a new data file.

7. The EM4Soil-Map module program

If your data was acquired in a survey constituted by several profiles covering an area, you can import them using the **Input Data Area** option (Figure 7.1). The format of the data file is the same as that for profiles, but including all measuring sites. Please, see the Data Format Section to read about formats.

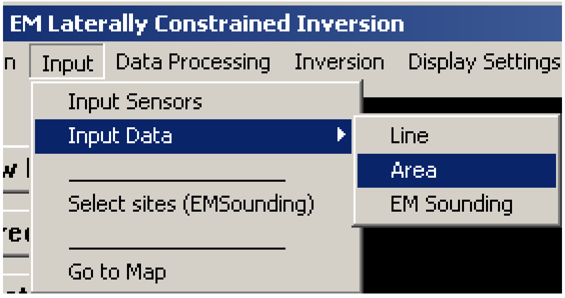


Figure 7.1. Inputting data from a survey.

Inputting data with this option you will run the **EM4Soil-Map module** program which allows you to see your data (as a set) and to select profiles for inversion. Figure 7.2 shows the screen of the program. The main **EM4Soil** program will be inactive during the use of the Map module. Clicking in Quit you return to **EM4Soil**.

NOTE: For the same data set you can go to Map module program using the Go to Map option.

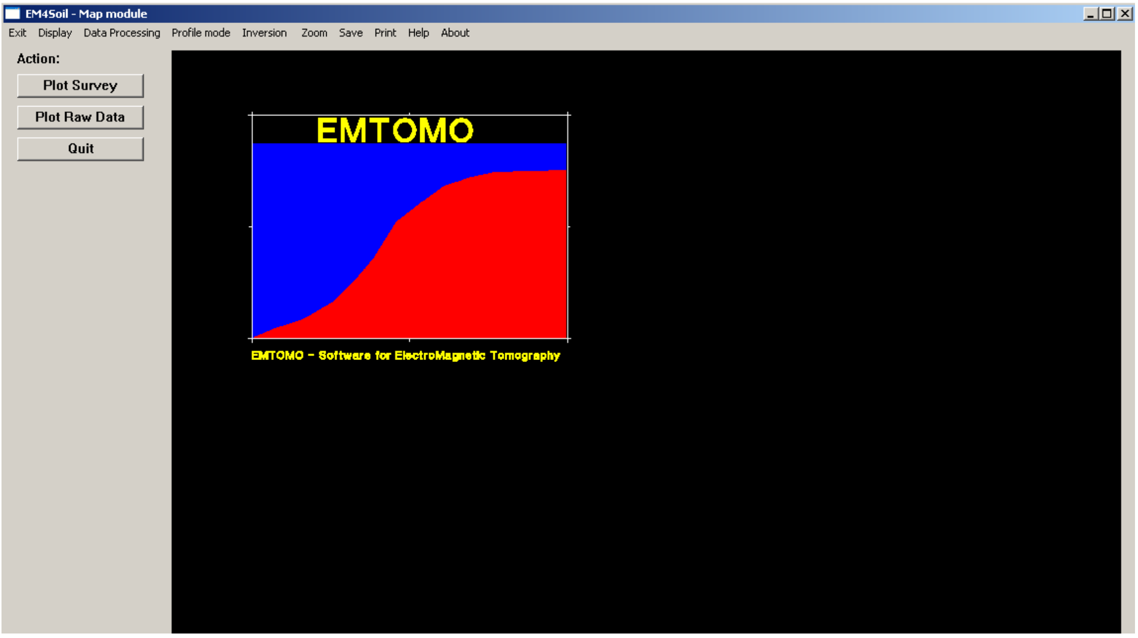


Figure 7.2. The EM4Soil-Map module screen.

Figure 7.3 shows the "default" menu bar of the program.

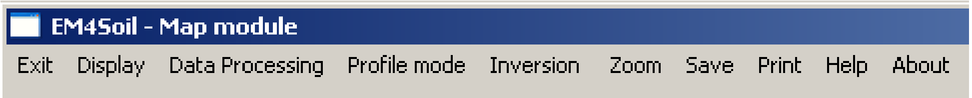


Figure 7.3. The menu bar of **EM4Soil-Map module**.

NOTE: Some options (related to the Q3D inversion) in the MAP module are explained in the Q3D Manual.

7.1 Display

Click in the **Display** entrance to see the location of your sites (**Survey Layout**) and maps of your data (Data Conductivity/Resistivity and elevation). In **Settings** you can make choices about how to display your maps.

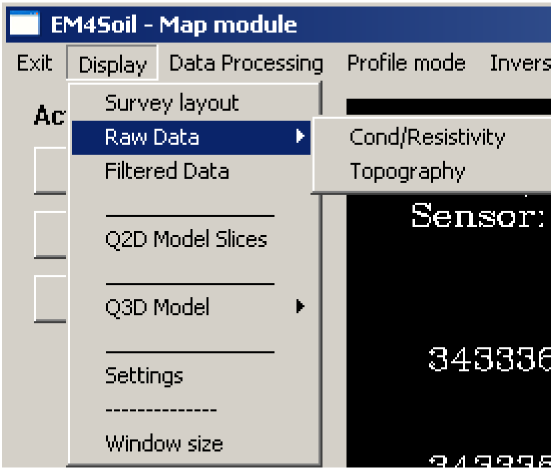


Figure 7.1.1. Displaying data from a survey.

Figure 7.1.2 shows an example of the display of a PROFILER(EMP400)[5] survey with three profiles. The first site is marked in red. Sites with negative values of apparent conductivity are displayed in blue. Figure 7.1.3 shows an example of the display of a map of apparent conductivity that was acquired with a multifrequency equipment (PROFILER). To move through the other maps you must click on the right button of your mouse.

The Window size option is very similar to that explained in the first part of this manual. The Q3D Model option is devoted to display Q3D inversion results and it is explained in the Manual for the Q3D Module.

[5] We thank Mr. Michael Gehrig, P.G., P.E, President of the GEHRIG, Inc. for kindly allowed us to use some of his PROFILER data in this Manual.

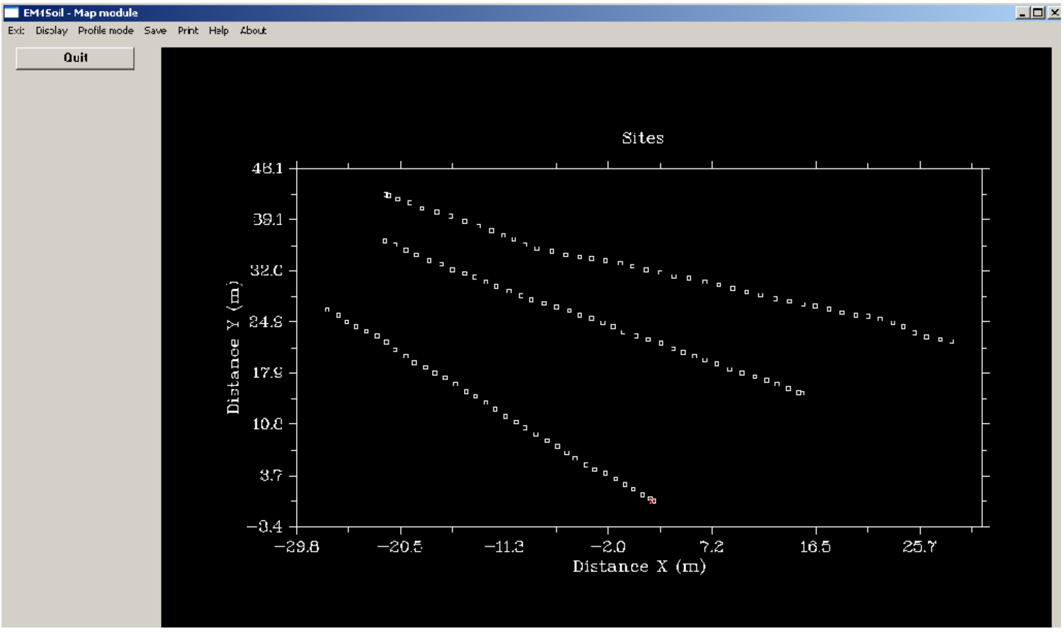


Figure 7.1.2. Displaying your survey.

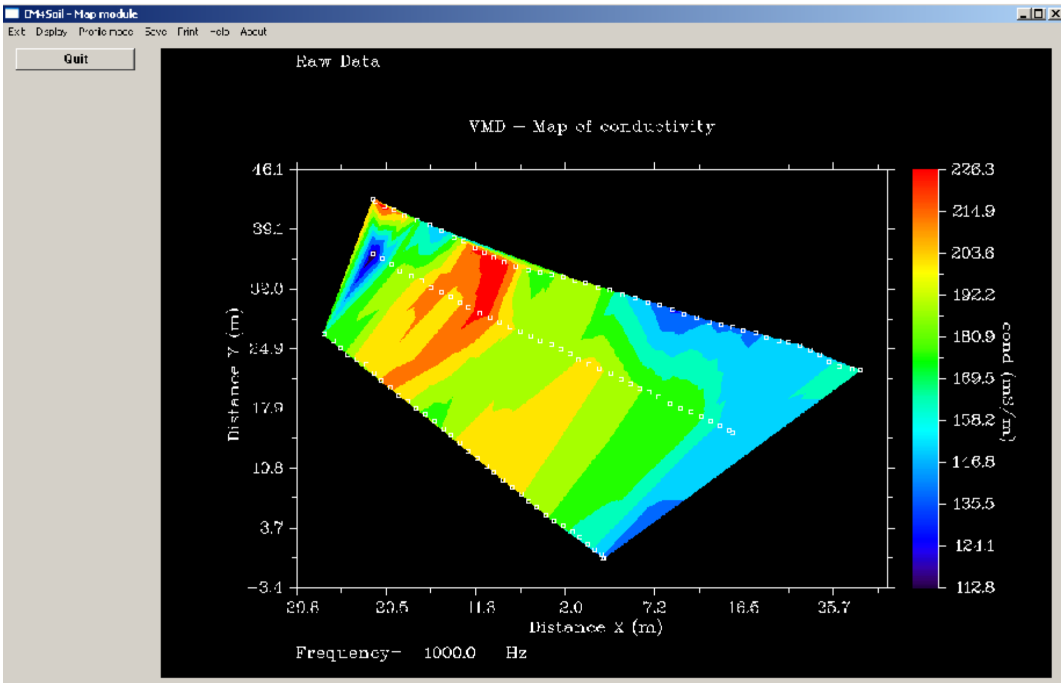


Figure 7.1.3. Displaying a map of apparent conductivity (PROFILER data at a frequency of 1000 Hz).

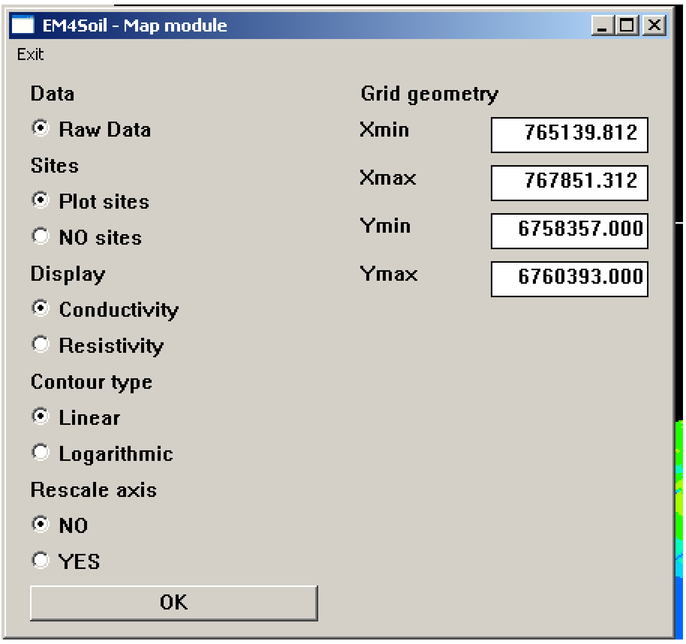


Figure 7.1.4. Settings menu.

You can also import the models calculated from each profile and display horizontal slices at select elevations or depths (Figure 7.1.5 to 7.1.7).

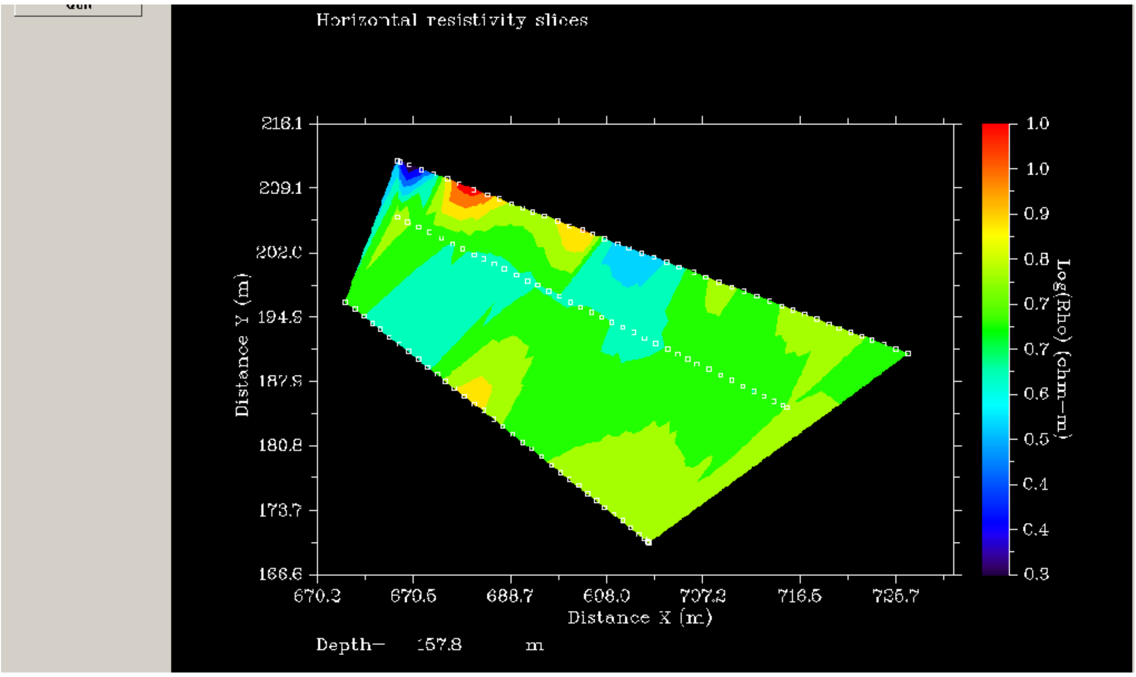


Figure 7.1.5. Displaying a model slice from the inverted models (elev. = 157.8 m).

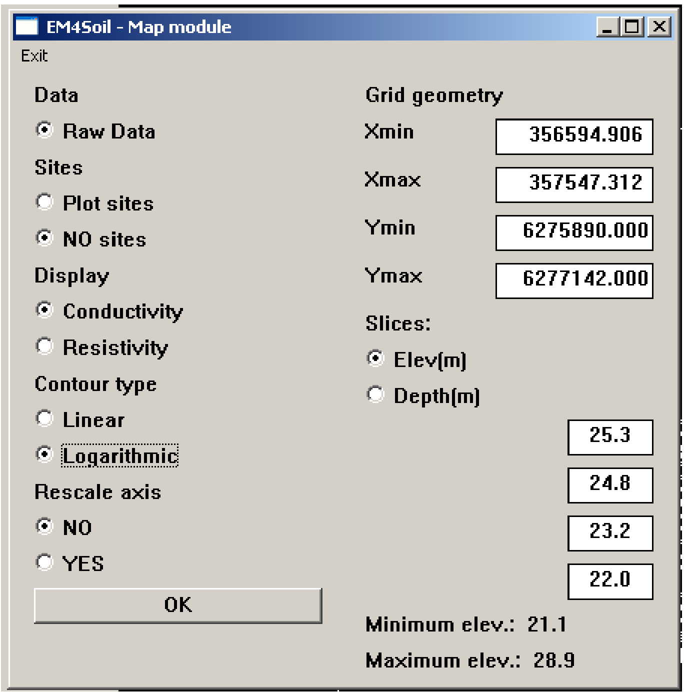


Figure 7.1.6. Defining the model slices elevation (**Settings**) .

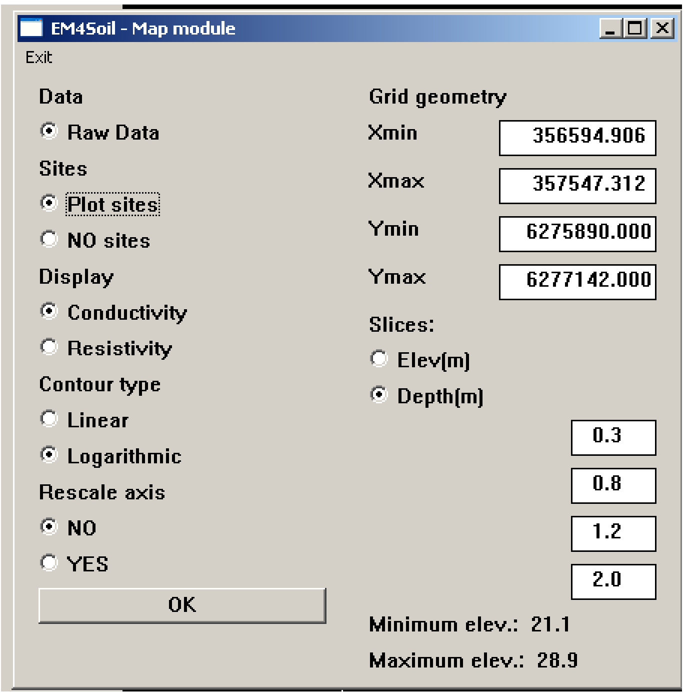


Figure 7.1.6. Defining the model slices depth (**Settings**).

Maps displayed in the MAP module have axis with different scale. The Rescale axis option allows to have axis with the same scale.

7.2 Data Processing

Some basic data processing can be done in the map module. These options are mainly devoted to prepare data for Q3D inversion. However, they can be used in any imported data.

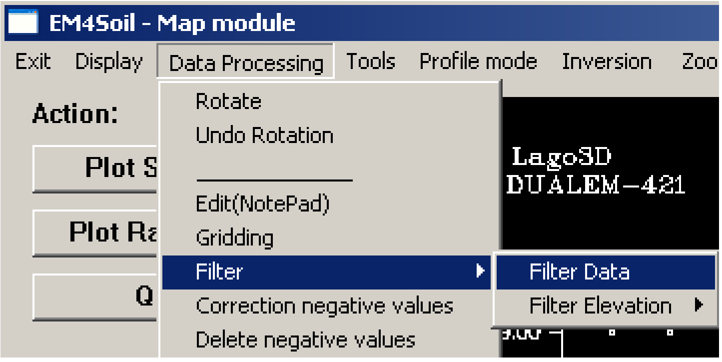


Figure 7.2.1. The **Data Processing** menu.

Grid files are necessary for the Q3-D inversion. Data files contain in general randomly spaced measuring sites, and should be converted into a regular grid before inversion. To create a grid file the user must specify the algorithm and its parameters, as well as, the output file. The output file has the mask EMGr (it is assumed by default).

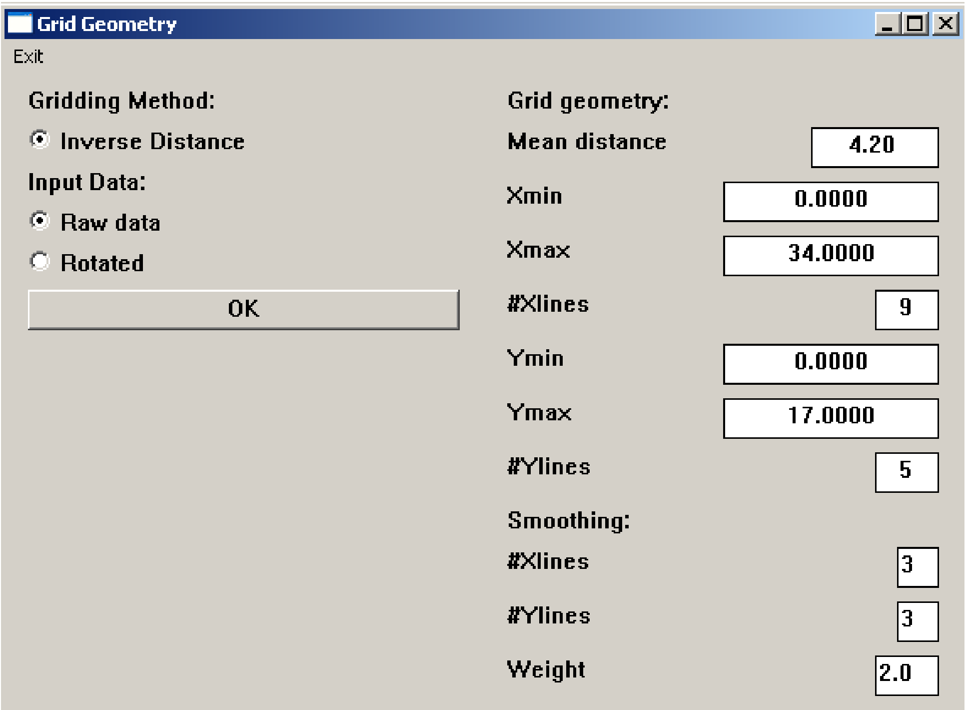


Figure 7.2.1. The **Data Processing** menu.

The inverse distance option used the GETMAT subroutine in DISLIN. The value at the grid point (j,k) is calculated by:

$$z_{i,j} = \frac{\sum_{i=1}^{N} \frac{z_i}{d_i^w}}{\sum_{i=1}^{N} \frac{1}{d_i^w}}$$

Where, (j,k) are the indices from 1 to Nx lines and 1 to Ny lines, respectively, d_i is the distance of the grid point (i,k) from the point P_i, w is a weighting number (default is 2.0) and N is the number of data points lying in the area (controlled by the parameters in the smoothing section) around the grid point (j,k).
The grid file can be filtered. The available filters are linear low-pass filters and should be applied to reduce the high frequency noise. They calculate weighted averages of the neighbouring input grid nodes. In the **Moving Average** (SxT) filter the weight are equal to one.
In the **Inverse Distance** (SxT) filter, the weights fall-off with increased distance. The role of the distance is controlled by the Power. The higher the power the more rapidly the weights fall-off with distance. The filter can be applied to all data set or only to specific channels.

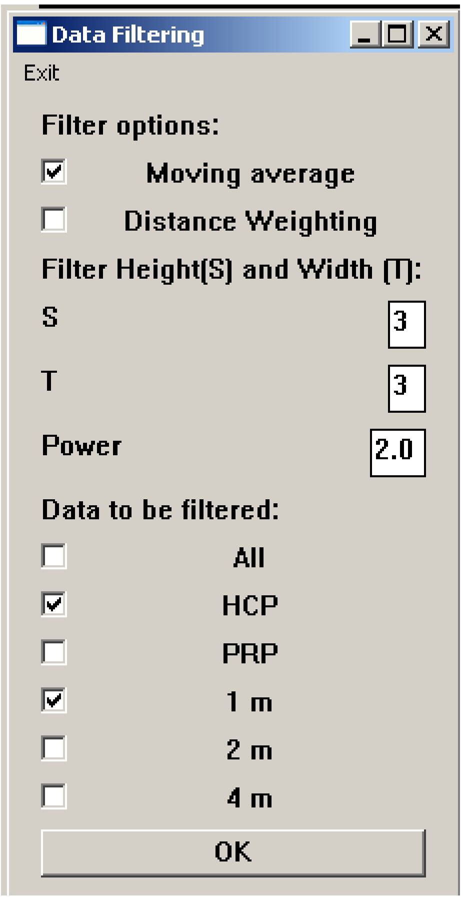


Figure 7.2.2. The **Filter parameters** menu.

If the number of negative values in the data set is less than 30% of all data, the user can try to **correct** or **delete** them.

It must be noted that correcting data can originate false anomalies. The user must pay attention to this relevant issue.

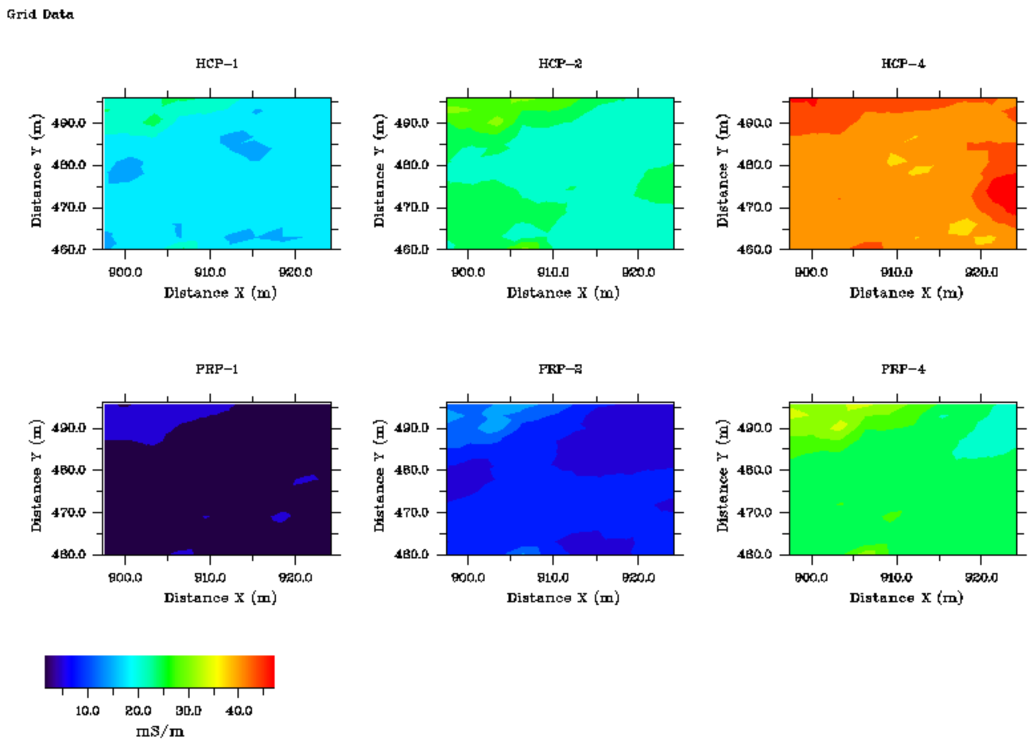


Figure 7.2.3. Example of a gridded data set.

7.3 Profile mode

Clicking in **Add Profile** the arrow of your mouse will change to a cross (+). Click the left mouse button at the beginning of the profile and move till the end of the profile (keeping the button pressed). A menu appears showing the coordinates of the end of the profile (Figure 7.3.2) when you leave the button. In this menu it is possible to identify the profile (name it). The sites included in the profile will be those inside of a region (around the profile) defined through the search radius[6] (wish is defined by the user). The value of this radius should be less than the distance between measuring sites.

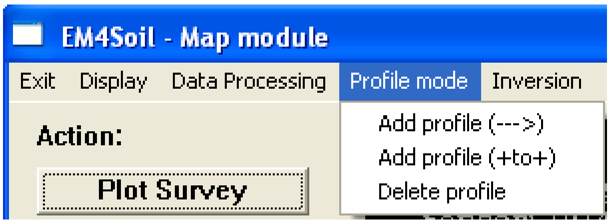


Figure 7.3.1. Adding/Deleting a profile to the survey

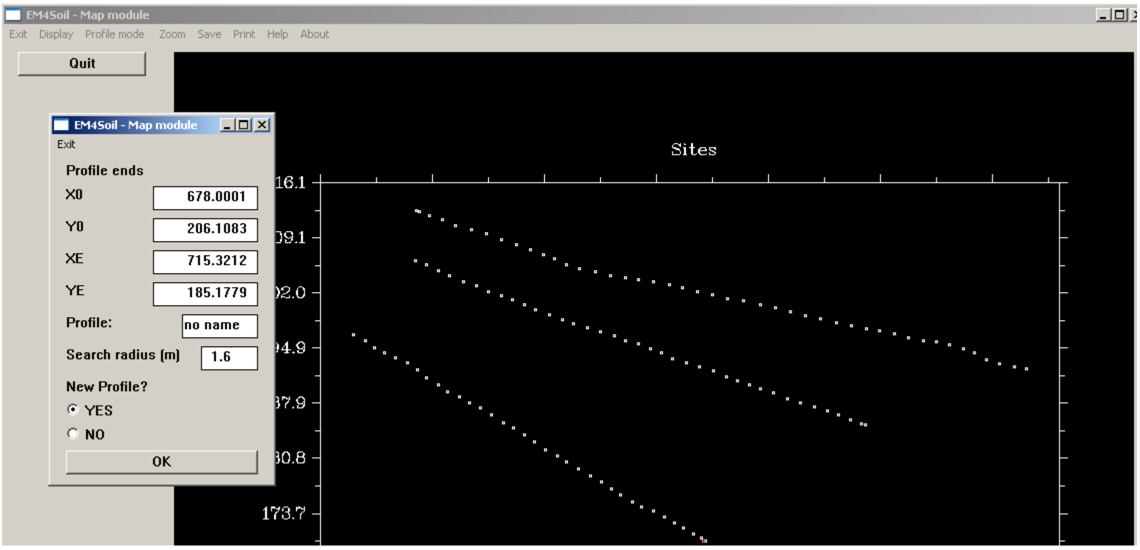


Figure 7.3.2. Adding a profile to the survey.

After close the small menu (clicking OK) the screen will present the sites along the profile (in red) and an arrow indicating the sense of the profile (Figure 7.3.3). It means that a coordinate 0 will be assigned to the site at the begging of the arrow. The other sites will have coordinates according its distance from the first site.
The user must take into account the distance between sites in his survey for correctly choosing the search radius.

6 The search radius that appears in the menu is proposed by the program and roughly corresponds to the half value of the average distance between sites of the survey. However, the user should verify if this value is correct for his application.

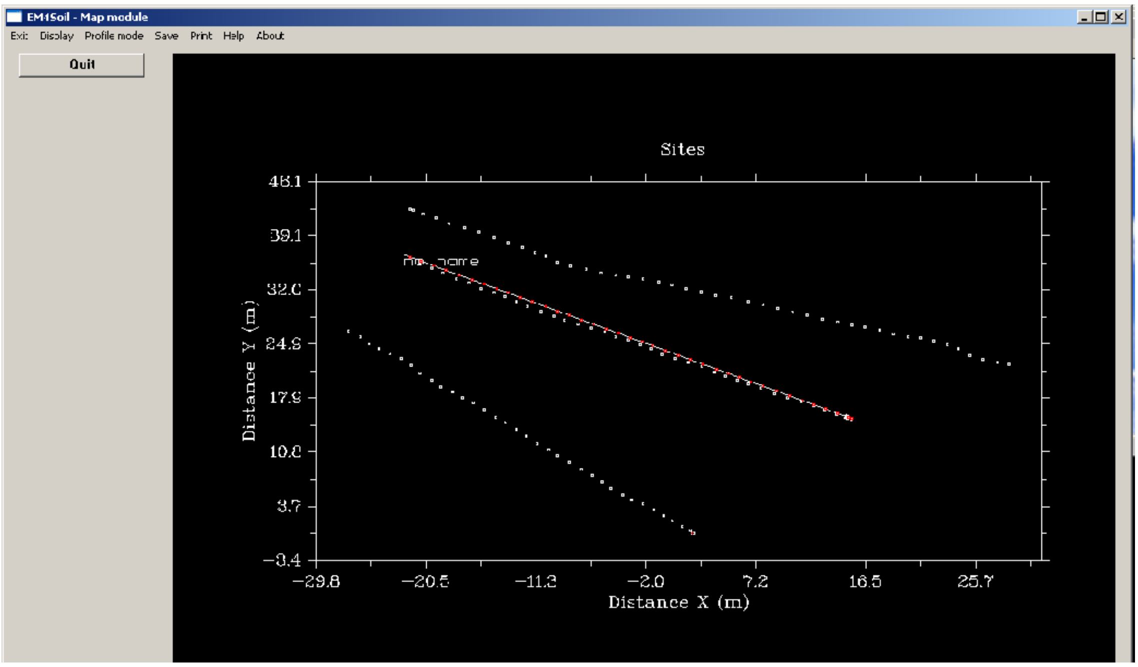


Figure 7.3.3. Screen showing the sites included in the profile which sense is indicated by the arrow.

If this procedure is followed with the second option all sites collected in sequence between the selected sites will be incorporated in the line. This option must be used if the user is confident about the sequence of the measurements, otherwise the program can select wrong data. This option is useful if the survey was acquired in parallel profiles.

NOTE: The most problematic situation occurs when the acquisition paths cross each other. In such case the added profile can show a significant scatter and the data should be filtered (probably) manually.

A similar situation can appear if the survey lines are very close (distance between lines of the same order of the distance between sites). In those cases the sampled profile must be carefully analysed before inversion.

NOTE: The user can sample two or more short lines along the same direction, that will be merged posteriorly into a file.

NOTE: There is a limit for the number of profiles saved in a session: 35 profiles.

7.4 Inversion (Q3D)

Please, see the Manual for Q3D Module.

7.5 Zoom

The user can zoom in the display of the survey and maps. This operation is particularly useful when adding profiles in a survey with closer sites. To apply it, select **Zoom In** in the menu bar and select the area of interest with the left mouse button pressed.
Disable the zoom selecting **Zoom Out**.

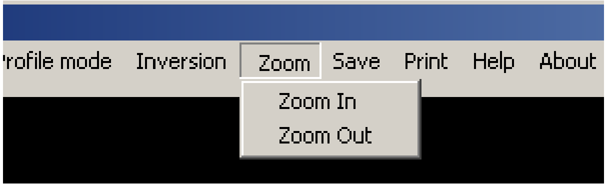


Figure 7.5.1. Printing survey maps.

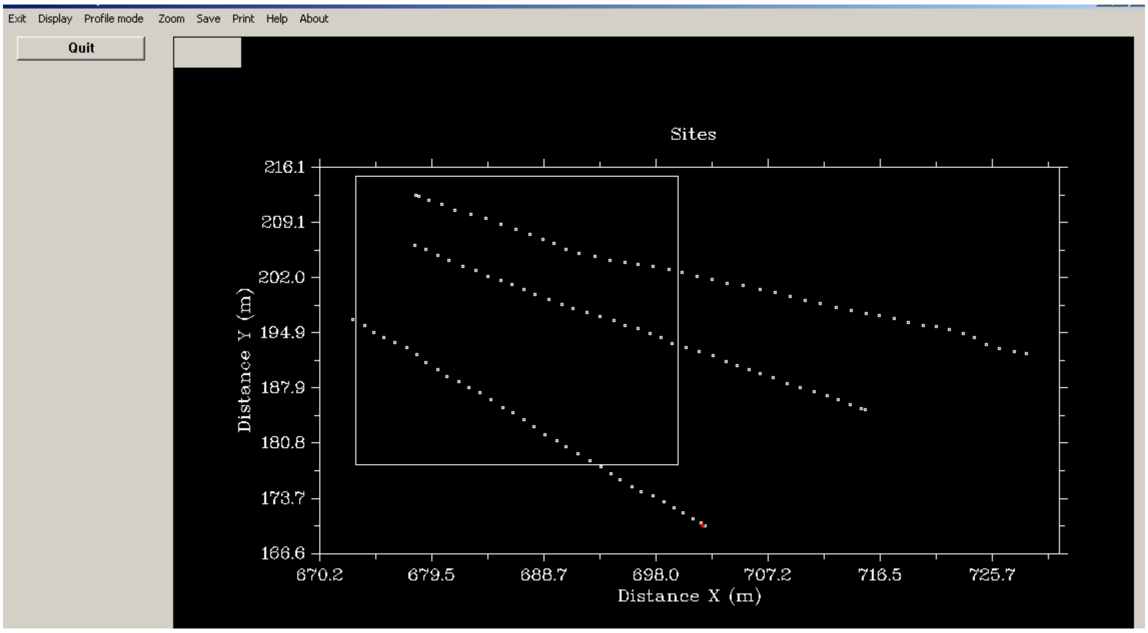


Figure 7.5.2. Zooming in survey maps.

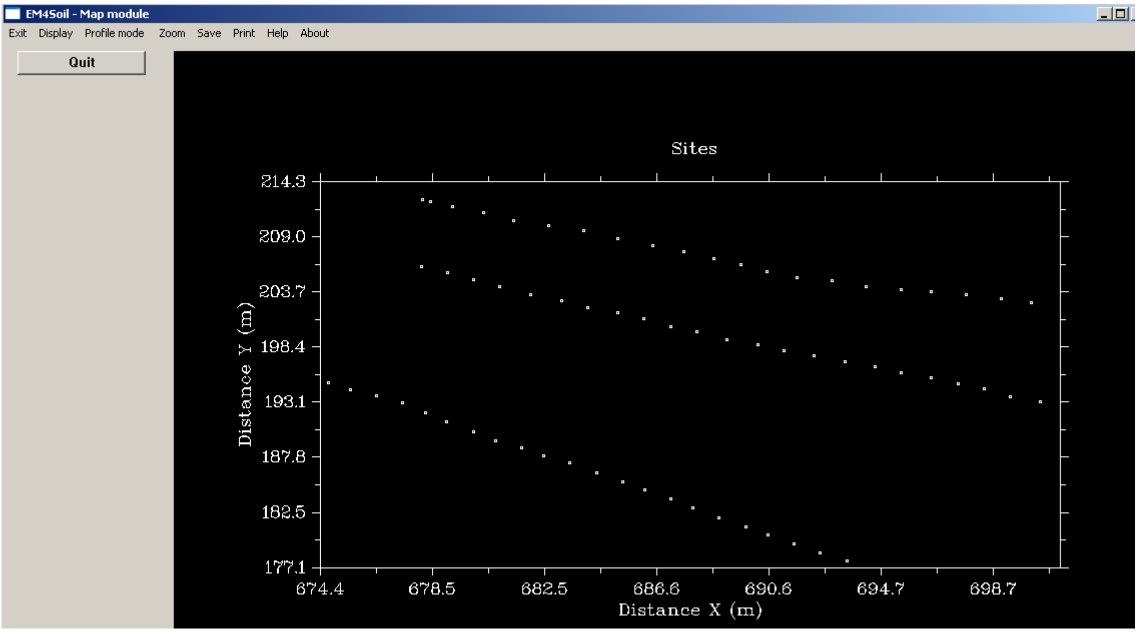


Figure 7.5.3. The **Zoom In** result.

7.6 Save

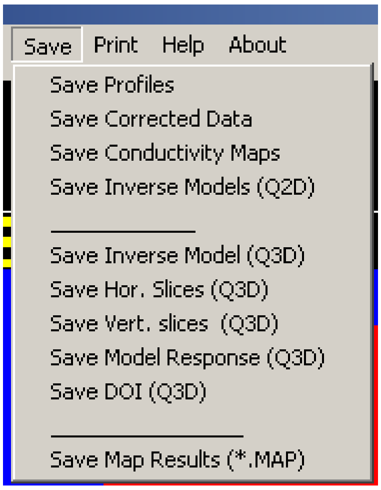


Figure 7.6.1. Options in the **Save** menu.

After select all your profiles they must be saved in separated files. Use the option **Save** in the menu bar to do that. Select the profile you want to save and proceed choosing the folder and file name (Figure 7.6.2). These files can after be input by **EM4Soil** program to be inverted.

NOTE: The file of an added profile will contain the Lat, Lon and Time of the raw data corresponding to sites included in the profile.

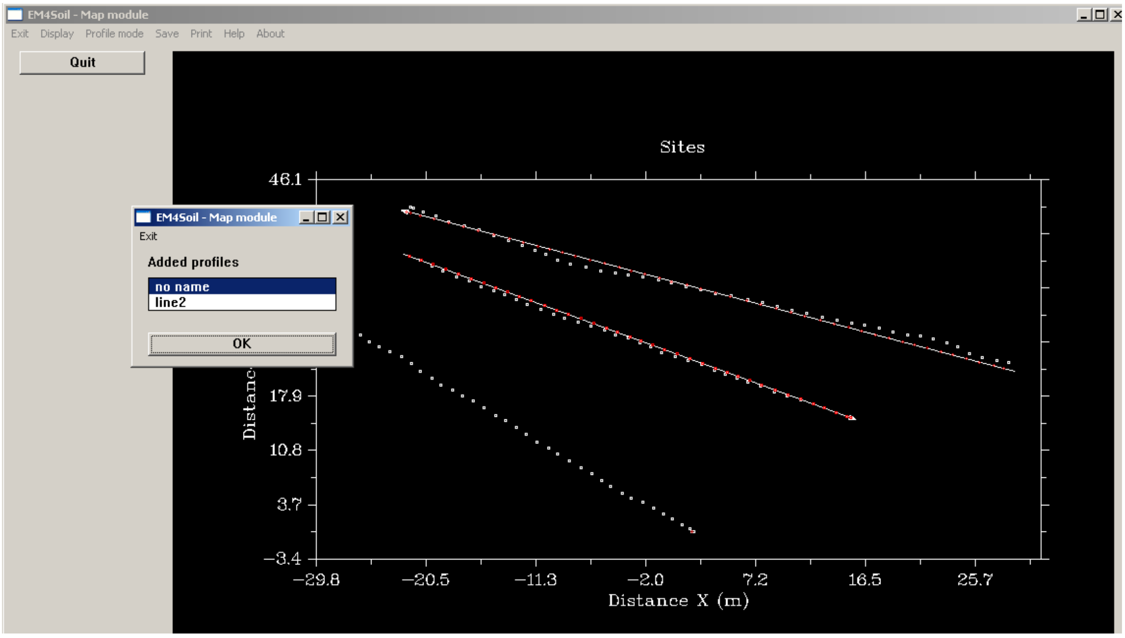


Figure 7.6.2. Saving the data of each added profile.

NOTE: The option Save Inverse Models (Q2D) will save all imported models in one ASCII file. This file can be used in other graphical programs (See Section about the format of output file).

The options referring the Q3D outputs will be explained in the respective Manual.

The option **Save Map Results** is of particular interest because it allows the user to save all the processing done in the Map module in one file (*.MAP). This file can be read by **EM4Soil** program (in the **Open** menu bar entrance).

7.7 Print

The entrance **Print** in the menu bar will allow you to print figures of the survey layout and of the apparent conductivity and elevation maps in the selected metafile format.

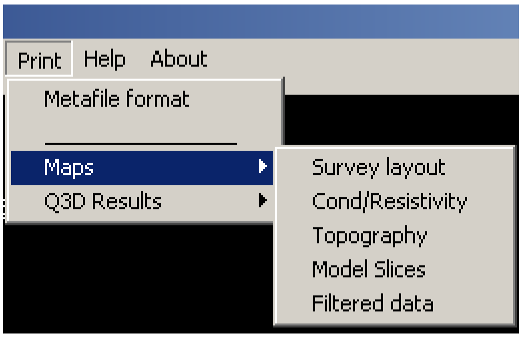


Figure 7.7.1. Printing survey maps.

7.8 Help

An overview of the different tools is given in the **Help** menu.

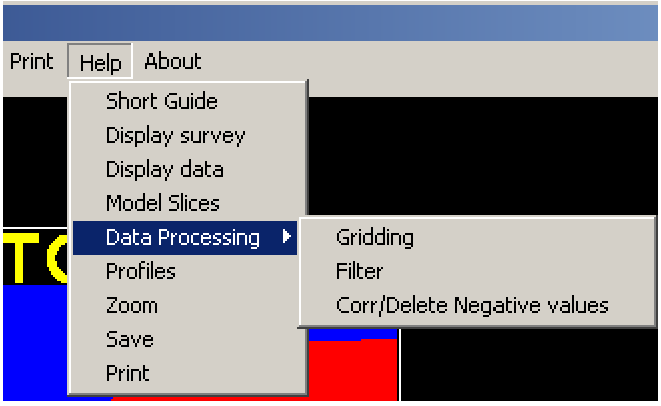


Figure 7.8.1. The **Help** menu.

8. EM Vertical Sounding

Vertical EM soundings stands for measurements made at a range of heights over a given location (see, e.g., http://www.dualem.com/vertsnd.htm). The **EMSound** module was designed to invert such data. However, you can also invert the data collected at a particular site of your survey line. Let's see, this option first. Start displaying the raw data. After that go to **Select Site (EMSounding)** option in the **Input** entrance in the menu bar. This allows you to choose the sites, which data you want to invert. The selection of the sites is made clicking on the left button of the mouse similarly to the process explained in **5.4.5.1. Correction of individual values.** Figures 8.1 and 8.2 shows some spots of the selection process.

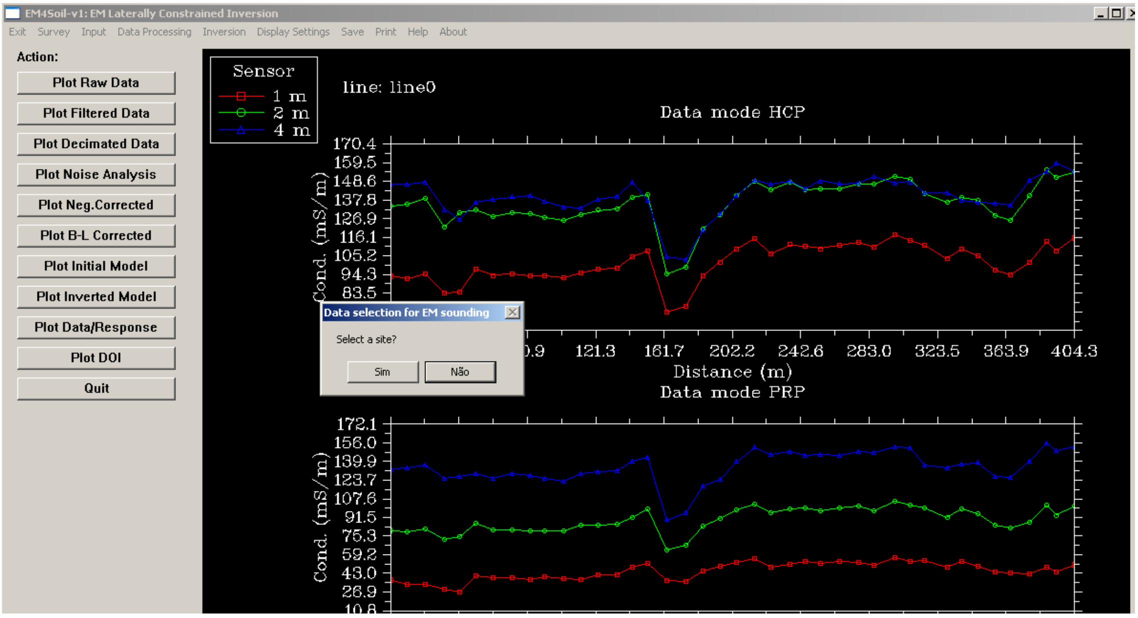


Figure 8.1. Selecting sites for 1-D inversion.

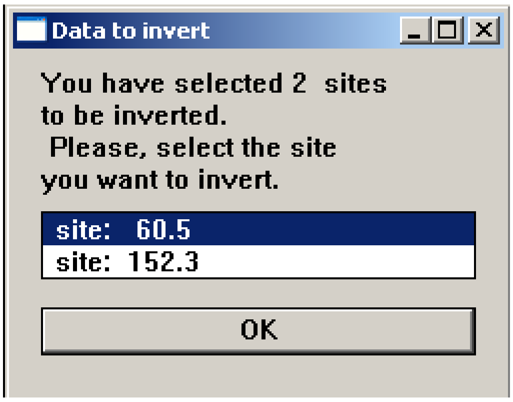


Figure 8.2. Selecting a site from the chosen sites.

After select a site the EMSound module will be activated (Figure 8.3). The screen of this module is divided in two parts: the left part is for data display and the right one for models. The menu bar (Figure 8.4) allows to **Display** data, models and inversion results (Figure 8.5).

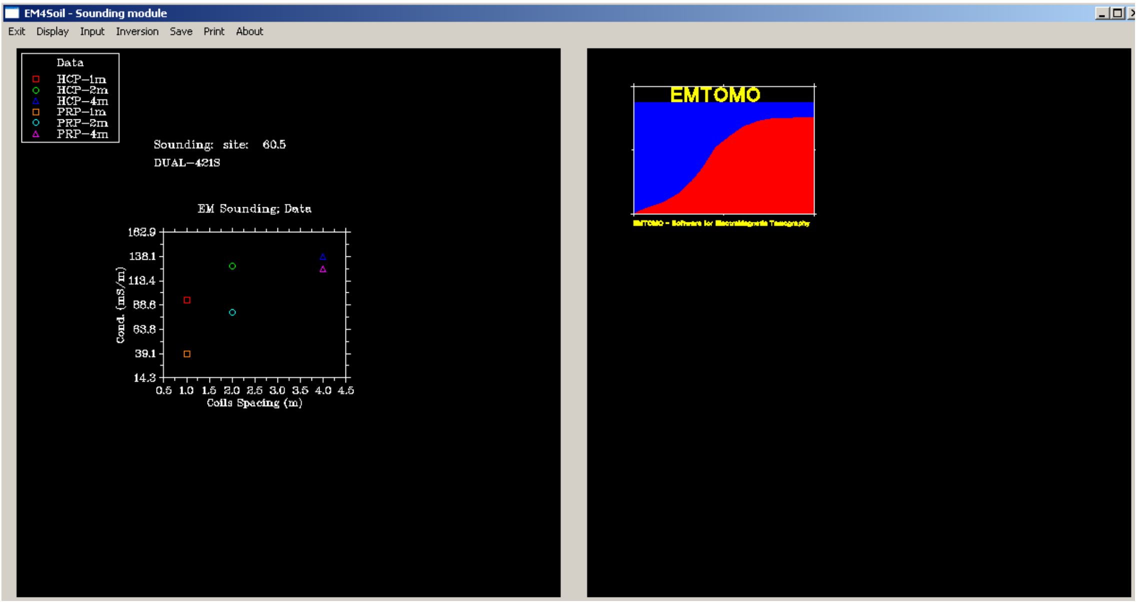


Figure 8.3. The EMSound module screen.

Figure 8.4. The menu bar of the sounding module.

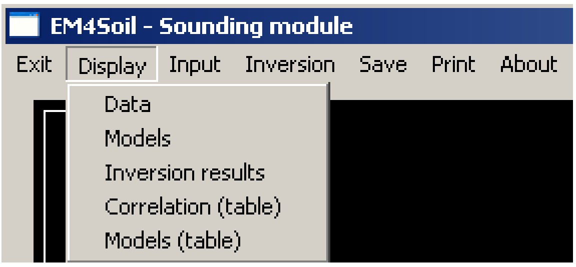


Figure 8.5. Display options.

The entrance **Input** is used to define the layered initial model. This can be done by reading an external file (see the data format section) or filling a table (Manually).

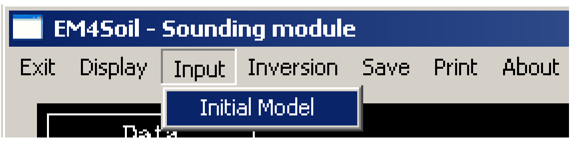


Figure 8.6. Inputting the initial model.

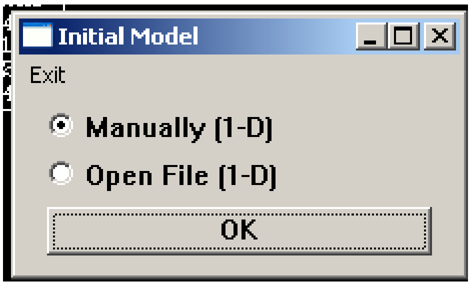


Figure 8.7. Display **Input** options.

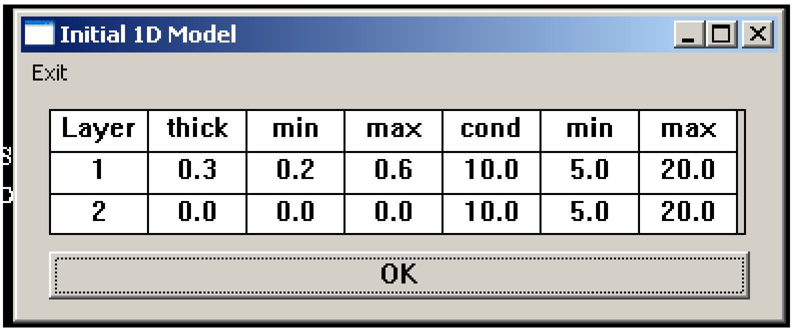


Figure 8.8. Defining the initial model manually.

This version of **EMSound** module only has implemented the SA (Simulated Annealing) algorithm (Figure 8.9). Please, read **APPENDIX D** about Simulated Annealing method.

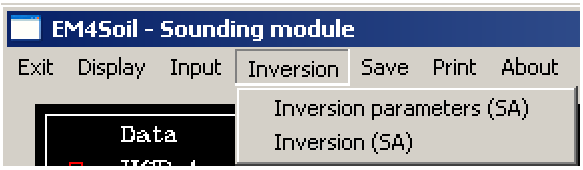


Figure 8.9. The **Inversion** options.

The user needs to define the parameters to use in SA inversion (Figure 8.10):

- the number of iterations in the external loop (the *temperature* decrease with the number of iterations);
- the number of iteration of the internal loop (the iterations of the internal loop are done with a constant *temperature*);
- the initial *temperature*;
- the number of models (these models will be used to build the correlation of the parameters and an average model). This information can be displayed as tables in the **Display** entrance of the menu bar;
- the target misfit;
- and the approach to be used for forward calculations.

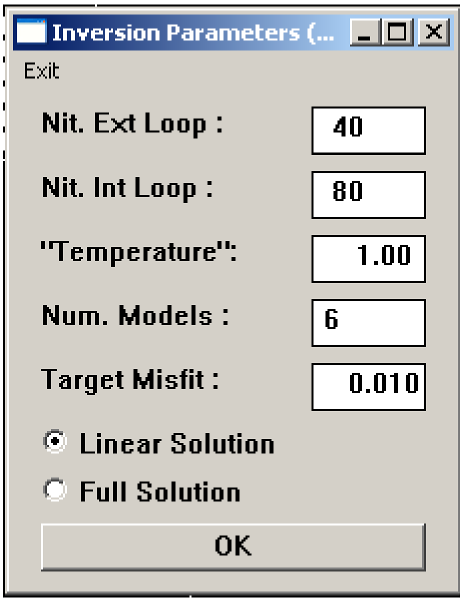


Figure 8.10. Defining SA parameters.

Save and **Print** entrances in the menu bar can be used to save the results.

Note: Use the Exit entrance in the menu bar to back to the EM4Soil program.

9. Input File Format

9.1. Input Data Files (Standard EM4soil format)

All the input files required by **EM4soil** and output files generated by **EM4soil** are **ASCII** files. Files with data acquired with LIN instruments along a transect should have the following format.

For **DUALEM-s1**:

Name of line
N, h
X, Y, Z, HCP1m, PRP1m, Lat, Lon, Time
Sequence of values row by row
....

For **DUALEM-s2**:

Name of line
N, h
X, Y, Z, HCP2m, PRP2m, Lat, Lon, Time
Sequence of values row by row
....

For **DUALEM-s21**:

Name of line
N, h
X, Y, Z, HCP1m, PRP1m, HCP2m, PRP2m, Lat, Lon, Time
Sequence of values row by row

....

For **DUALEM-s42**:

Name of line
N, h
X, Y, Z, HCP2m, PRP2m, HCP4m, PRP4m, Lat, Lon, Time
Sequence of values row by row
....

For **DUALEM-s421**:

Name of line
N, h
X, Y, Z, HCP1m, PRP1m, HCP2m, PRP2m, HCP4m, PRP4m, Lat, Lon, Time
Sequence of values row by row
....

For **DUALEM-s642**:

Name of line
N, h
X, Y, Z, HCP2m, PRP2m, HCP4m, PRP4m, HCP6m, PRP6m, Lat, Lon, Time
Sequence of values row by row
....

For **EM31 / EM38**:

Name of line
N, h
X, Y, Z, VDM, HDM, Lat, Lon, Time
Sequence of values row by row
....

For **EM34**:

Name of line
N, h
X, Y, Z, VDM10m, HDM10m, VDM20m, HDM20m, VDM40m, HDM40m, Lat, Lon, Time
Sequence of values row by row
....

Where:
N is the number of EM sensor sites (e.g. 20, 40, etc);
h is the height of the sensor in m (e.g. 0.1, 0.2, etc),
X, Y and Z are the coordinates in Easting and Northing and the elevation (m) of each EM sensor sites, respectively.
In addition:
HCP and PRP (or VDM and HDM) are the measured σ_a at each EM sensor site.
Lat and Lon are the Latitude and the Longitude in decimal degrees and Time is the time in any format not exceeding 14 characters.

NOTE: The data can be separated by comma or by space.

NOTE: If N is negative the program will input all sites in the file assuming them as belonging to the survey.

NOTE: If there is no data for a particular channel (mode of acquisition) then a value of -9 should be entered. This is because the program assumes that you have used both modes for each coil spacing during acquisition.

NOTE: If only Lat and Lon coordinates are available, fill with the X and Y fields with values of 0.0. After input EM4soil will use the conversion (Lat,Lon) to UTM option to calculate X and Y.

NOTE: If Lat and Lon coordinates are not available, fill the respective fields with 0.0.

Example of an EM34 data file (complete data set) corresponding at a line of 11 sites measured in a flat zone with coordinates in a local referential. Lat and Lon fields are filled with 0.0 values because these coordinates are not available.

Line EM34
11 0

X	Y	Z	VDM10m	HDM10m	VDM20m	HDM20m	VDM40m	HDM40m	Lat	Long	time
0	0	0	47.5	73.2	56.8	99.8	34.1	68.8	0.0	0.0	0.0
10	0	0	53.5	73.5	63	95.5	33.8	64.1	0.0	0.0	0.0
20	0	0	58.9	73.9	69.2	83.3	35.9	48.4	0.0	0.0	0.0
30	0	0	65.5	67.6	67.8	74.5	39.8	45.2	0.0	0.0	0.0
40	0	0	68.4	61.5	72.7	64.6	36.5	49.1	0.0	0.0	0.0
50	0	0	63.9	71.4	72.4	90.4	38.6	42.8	0.0	0.0	0.0
60	0	0	66.6	80.1	69.1	78.6	33.5	46.9	0.0	0.0	0.0
70	0	0	71.8	80.9	68.9	81.5	28.1	50.2	0.0	0.0	0.0
80	0	0	76.3	85	67.2	86.7	27.2	62.7	0.0	0.0	0.0
90	0	0	78.8	78.7	67.4	94.2	25.3	70.7	0.0	0.0	0.0
100	0	0	76.5	88.1	69.4	99.6	23.6	69.9	0.0	0.0	0.0

Example of an EM34 data file, corresponding at a line of 11 sites measured in a flat zone, but not containing the VDM20m data:

Line EM34
11 0

X	Y	Z	VDM10m	HDM10m	VDM20m	HDM20m	VDM40m	HDM40m	Lat	Long	time
0	0	0	47.5	73.2	-9.00	99.8	34.1	68.8	0.0	0.0	0.0
10	0	0	53.5	73.5	-9.00	95.5	33.8	64.1	0.0	0.0	0.0
20	0	0	58.9	73.9	-9.00	83.3	35.9	48.4	0.0	0.0	0.0
30	0	0	65.5	67.6	-9.00	74.5	39.8	45.2	0.0	0.0	0.0
40	0	0	68.4	61.5	-9.00	64.6	36.5	49.1	0.0	0.0	0.0
50	0	0	63.9	71.4	-9.00	90.4	38.6	42.8	0.0	0.0	0.0
60	0	0	66.6	80.1	-9.00	78.6	33.5	46.9	0.0	0.0	0.0
70	0	0	71.8	80.9	-9.00	81.5	28.1	50.2	0.0	0.0	0.0
80	0	0	76.3	85	-9.00	86.7	27.2	62.7	0.0	0.0	0.0
90	0	0	78.8	78.7	-9.00	94.2	25.3	70.7	0.0	0.0	0.0
100	0	0	76.5	88.1	-9.00	99.6	23.6	69.9	0.0	0.0	0.0

For **GEM/PROFILER**:

LinePROF
N, h, Nop
Nf, f1, f2,...fNf
X, Y, Z, condf1, condf2,......condfNf, InPf1,…InPfNf, Qf1...QfNf, Susf1....SusfNf, Lat, Lon, Time
Sequence of values row by row
....

Where N is the number of measuring sites, h is the height of the sensor (m), Nop is =1 if the data was acquired in VDM mode or =2 if acquired in HDM mode. Nf is the number of frequencies, and f1,…fNf are the frequencies of the survey (in Hz). X, Y and Z are the easting and northing linear coordinates and the elevation (m) of each measuring site, respectively. condfi, InPi, Qfi and Susfi are the measured apparent conductivity (mS/m), InPhase (ppm), Quadrature (ppm) and Susceptibility for the i-th frequency.

NOTE: Unlike the LIN instruments, if you have all data corresponding to one frequency with negative values, it is advisable do not use this frequency.

Example of a data file (only the first rows of the file are shown) corresponding to a line of 20 sites measured with a PROFILER instrument at 0.2 m above the surface. The data was collected at three frequencies (1000, 9000 and 15000 Hz) in VDM mode.

```
line1m
20   0.2000000          1
3    1000.000      9000.000      15000.00
X Y Z Caf1 Caf2 Caf3 Inpf1 Inpf2 Inpf3 Qudf1 Qudf2 Qudf3 susf1 susf2 susf3 Lat Long time
0.0078        0.5000     0.00     2616.530      1460.490      1160.610      2761.000     22007.000     33481.000      7662.000
38492.000     50980.000       0.010       0.060       0.090         0.000000        0.000000 0.
0.0086        1.0000     0.00     2601.390      1467.510      1166.490      2526.000     21795.000     33378.000      7618.000
38677.000     51238.000       0.010       0.060       0.090         0.000000        0.000000 0.
0.0093        1.5000     0.00     2640.600      1497.530      1192.360      2671.000     22137.000     33846.000      7733.000
39468.000     52375.000       0.010       0.060       0.090         0.000000        0.000000 0.
………….
```

Data for EM sounding

For GEONICS instruments (EM31, EM38) the data format for EM soundings is as follow:

soundingName
N, ho
H1, VDM1, HDM1
H2, VDM2, HDM2
....
HN, VDMN, HDMN

For DUALEM instruments (-S1, -S2, -S21...) the format is (this is an example for DUAL EM-S21):

soundingName
N, ho
H1, HCP1-1m, PRP1-1m, HCP1-2m, PRP1-2m
H2, HCP2-1m, PRP2-1m, HCP2-2m, PRP2-2m
....
HN, HCPN-1m, PRPN-1m, HCPN-2m, PRPN-2m

Where N is the number of measurements Hi is the height of the sensor (m) and ho must be 0.0. HCPi- and PRPi- (or VDM and HDM) are the measured apparent conductivity at each sensor. Lat and Lon are the Latitude and the Longitude in decimal degrees and Time is the time in any format not exceeding 14 characters

For GEM or PROFILER the format should be as follow:

soundingName
N, ho
Nf, Nop
f1, f2,…..,fNF

H1, cond1f1, cond1f2,......cond1fNF
H2, cond2f1, cond2f2,......cond2fNF
....
HN, condNf1, condNf2,......condNfNF

Where N is the number of measurements, Hi is the height of the sensor (m), Nop is =1 if the data was acquired in VDM mode or =2 if acquired in HDM mode. Nf is the number of frequencies, and f1,…fNf are the frequencies of the survey (in Hz). condif1…. are the measured apparent conductivity at high *i* for each frequency (mS/m).

The format for OTHER sensors

This format is to be used when the sensor is OTHER. The format allows the user to input in EM4Soil program data acquired from different instruments. In this format the data of each sensor is defined individually. The format is:

Nameofthesurvey [character]
Number of sensors [integer]
Code of the sensor [character]
Number of readings, height [integer, real]
Coils spacing, frequency, mode acquisition, type of data, units [real, real, integer, integer, integer]
X Y Z Ca Lat Long time [labels corresponding to the data in the following rows]
The following rows contains the measured data and the format depends on the type of data.
For data type 1:
Xeasting, Ynorthing, Z, Ca, lat, long, time [all real]
For data type 2:
Xeasting, Ynorthing, Z, Ca, In-phase, lat, long, time [all real]
For data type 3:
Xeasting, Ynorthing, Z, In-phase, Quad, lat, long, time [all real]
For data type 4:
Xeasting, Ynorthing, Z, Ca, In-phase, Quad, lat, long, time [all real]
For data type 3:
Xeasting, Ynorthing, Z, Ca, In-phase, Quad, Susc, lat, long, time [all real]

The information in blue must be repeated (for each sensor).

The codes for the sensors and the data type are summarized below. $X_{easting}$ and $Y_{northing}$ are UTM coordinates (or other linear system od coordinates), Z is the elevation (m), Ca is the apparent conductivity (mS/m), In-phase and Quadrature and magnetic susceptibility components can be in ppt (unit = 1) or ppm (unit = 2), the frequency is in Hz and the mode the acquisition can be VDM (mode =1), HDM (mode = 2), HCP (mode = 3) or PPR (mode = 4). Latitute and Longitude must be in decimal degrees. Time can be expressed in any format (for example 2:12:32).

Example of a data file (3 sensors PROFILER (PROF), 40 measurements for each sensor (only displayed 3), mode the acquisition is VDM, the data type is 5, and the units of In-phase and quadrature are ppm.

```
GSSIsurvey
          3
 PROF
          40  0.2000000
  1.220000       1000.000              1          5           1
 X  Y  Z  Ca  Inp  Quad  Sus  Lat  Long  Time
 -1.320000000000000E-002  0.500000000000000       0.0000000E+00   45.02300   2632.000   132.0000  7.0000002E-03   0.00   0.00   0.
 -1.250000000000000E-002   1.00000000000000       0.0000000E+00   518.5630   1378.000   1519.000  4.0000002E-03   0.00   0.00   0.
 -1.180000000000000E-002   1.50000000000000       0.0000000E+00   1007.727   663.0000   2951.000  2.0000001E-03   0.00   0.00   0.
.........
 PROF
          40  0.2000000
  1.220000       9000.000              1          5           1
 X  Y  Z  Ca  Inp  Quad  Sus  Lat  Long  Time
 -1.320000000000000E-002  0.500000000000000       0.0000000E+00   588.3160   2823.000   15505.00  7.0000002E-03   0.00   0.00   0.
 -1.250000000000000E-002   1.00000000000000       0.0000000E+00   581.6630   2831.000   15330.00  7.0000002E-03   0.00   0.00   0.
 -1.180000000000000E-002   1.50000000000000       0.0000000E+00   588.4750   2894.000   15509.00  8.0000004E-03   0.00   0.00   0.
...............
PROF
          40  0.2000000
  1.220000       15000.00              1          5           1
 X  Y  Z  Ca  Inp  Quad  Sus  Lat  Long  Time
 -1.320000000000000E-002  0.500000000000000       0.0000000E+00   552.0920   3719.000   24251.00  9.9999998E-03   0.00   0.00   0.
 -1.250000000000000E-002   1.00000000000000       0.0000000E+00   548.5830   3698.000   24097.00  9.9999998E-03   0.00   0.00   0.
 -1.180000000000000E-002   1.50000000000000       0.0000000E+00   556.9490   3800.000   24464.00  9.9999998E-03   0.00   0.00   0.
```

The codes for the sensors are:

Sensor	**Code**	**Coil spacing**	**Frequency**
DUALEM-1s	D1	1.10	9000
DUALEM-2s	D2	2.10	9000
DUALEM-4s	D4	4.10	9000
DUALEM-6s	D6	6.10	9000
EM31-MK2	E31	3.66	9800
EM31-SH	E31	2.00	9800
EM34	E34	10.0	6400
EM34	E34	20.0	1600
EM34	E34	40.0	400
EM38	E38	0.50	14500
EM38	E38	1.00	14500
PROFILER	PROF	1.22	variable
GEM	GEM	1.66	Variable

The codes for the mode of acquisition are:

Mode	**Code**
VDM	1
HDM	2
HCM	3
PRP	4

9.2. Initial model

9.2.1. Initial model for quasi-2D inversion.

The format for the file containing a 1D initial model is as follows:

NL
D_1, D_2, ….$D_{(NL-1)}$
C_1, C_2, …..$C_{(NL)}$

Where NL is the number of layers, D_i and C_i are the depth of the bottom interface (m) and the conductivity (mS/m) of the ith- layer.

Example of a 1D model of 3 layers, with conductivities of 20, 100 and 20 mS/m:

3
10 30
20 100 20

9.2.2. Initial model for 1D inversion of profiles

The format for the file containing a 1D initial model is as follows:

NL
D_1, D_2, ….$D_{(NL-1)}$
C_1, C_2, …..$C_{(NL)}$
F_1, F_2, ….$F_{(NL-1)}$ -
F_1, F_2, ……....$F_{(NL)}$

Where NL is the number of layers, D_i and C_i are the depth of the bottom interface (m) and the conductivity (mS/m) of the ith- layer. F_i or C_i are used to say that ith is Free or Constrained.

NOTE: when the data are input through the OTHER sensor the initial models should contain the value of the magnetic susceptibility (mSI) after the conductivities (see the section about the use of OTHER format at the end of this manual). For example,

NL
D_1, D_2, ….$D_{(NL-1)}$
C_1, C_2, …..$C_{(NL)}$
Ms1, Ms2………$Ms_{NL)}$

9.2.3. Initial model for EM sounding inversion.

The format of the file containing a 1D initial model for inversion of EM soundings is as follow:

N
Cond1, Cond1Min, Cond1Max
Th1, Th1Min, Th1Max
Cond2, Cond2Min, Cond3Max
Th2, Th2Min, Th2Max
….
CondN, CondNMin, CondNMax

Where N is the number of layers, Condi, CondiMin and CondiMax are the average, minimum and maximum values of the conductivity (in mS/m) of *i*-layer. Thi, ThiMin and ThiMax are the average, minimum and maximum values of the thickness (in m) of the *i*-layer. If Min and Max values of a parameter are equal and equals to the average values, the parameter will not change during the inversion.

9.2.4. (Default) Initial models for Q2D inversion

In normal conditions, a initial model (default) is built when a profile is input in **EM4Soil**. The number of layers and depth of the different initial models are as follows (the conductivities are defined according the data):

For **DUALEM-21s**
7; 0.3, 0.6, 1.0, 1.5, 2.3, 3.3

For **DUALEM-421s**
9; 0.3, 0.6, 1.0, 1.5, 2.3, 3.3, 4.5, 5.7

For **DUALEM-642s**
8; 0.6, 1.5, 2.7, 3.8, 4.2, 5.7, 8.0

For **EM34**
10; 3, 6, 9, 12, 18, 24, 30, 40, 50

NOTE: it must be noted that these models are very general and might not be the best approach for some particular data set. The user should define his models according the information available for the area in investigation.

10. Output File Format

10.1. Data/Model response

The file containing the data/model response has a format as follow (DUALEM/GEONICS):

Dist, rh1o, rh1c, rp1o, rp1c, rh2o, rh2c, rp2o, rp2c, rh4o, rh4c, rp4o, rp4c
S_1, h_1o, h_1c, p_1o, p_1c, h_2o, h_2c, p_2o, p_2c, h_4o, h_4c, p_4o, p_4c
S_2, h_1o, h_1c, p_1o, p_1c, h_2o, h_2c, p_2o, p_2c, h_4o, h_4c, p_4o, p_4c
......
S_N, h_1o, h_1c, p_1o, p_1c, h_2o, h_2c, p_2o, p_2c, h_4o, h_4c, p_4o, p_4c

Where, S_i is the distance along the line. Subscript o indicates an observed value (measured) and the subscript c indicates a calculated apparent conductivity value, h and p represent the HCP and PRP modes in DUALEM sensors (for GEONICS they correspond to VDM and HCM, respectively).

Example of a file from EM34,

dist	vdmo	vdmc	hdmo	hdmc	vdmo	vdmc	hdmo	hdmc	vdmo	vdmc	hdmo	hdmc
00.00	47.50	69.89	73.20	81.49	56.80	53.77	99.80	71.42	34.10	36.62	68.80	57.76
10.00	53.50	72.51	73.50	80.71	63.00	56.50	95.50	72.55	33.80	36.22	64.10	58.87
20.00	58.90	70.56	73.90	73.52	69.20	57.47	83.30	68.93	35.90	36.95	48.40	57.57
30.00	65.50	69.09	67.60	66.76	67.80	59.33	74.50	65.87	39.80	39.02	45.20	57.13
40.00	68.40	68.01	61.50	62.47	72.70	59.84	64.60	63.72	36.50	39.28	49.10	56.28
50.00	63.90	72.69	71.40	71.83	72.40	60.50	90.40	69.55	38.60	38.23	42.80	58.95

Example of a file from DUALEM42. The value -9 means that there is no data for the 1m sensors.

dist	rh1o	rh1c	rp1o	rp1c	rh2o	rh2c	rp2o	rp2c	rh4o	rh4c	rp4o	rp4c
0	-9	-9	-9	-9	15.27	17.52	17.91	16.82	20.16	18.5	16.32	16.61
2	-9	-9	-9	-9	22.92	23.68	27.9	27.88	22.16	21.93	25.09	24.59
4	-9	-9	-9	-9	24.09	24.89	28.7	28.8	23.08	22.72	26.46	25.88
6	-9	-9	-9	-9	25.06	26.08	29.39	29.22	23.92	23.71	27.63	27.05
8	-9	-9	-9	-9	31.54	31.87	32.76	33.51	29.48	29.44	33.66	32.48
9	-9	-9	-9	-9	29.95	31.52	31.59	31.72	30.12	29.77	33.04	31.73
11.24	-9	-9	-9	-9	30.37	32.13	31.5	31.57	31.46	30.77	33.29	32.08
13.24	-9	-9	-9	-9	30.68	32.63	31.73	31.88	31.98	31.33	34.04	32.53

Example of a file from PROFILER.

dist	Cf1o	Cf1c	Cf2o	Cf2c	Cf3o	Cf3c
0.00	134.06	127.44	113.76	118.96	124.74	115.34
0.19	140.18	143.05	124.02	133.20	133.75	128.98
1.24	149.33	150.39	133.92	139.98	142.25	135.51
1.80	155.70	157.15	141.39	146.21	148.59	141.51
3.09	164.35	163.76	146.30	152.25	154.00	147.28
4.46	165.78	168.39	151.41	156.44	158.04	151.28

10.2. Processed data (Filtered…)

This format is common to all processed data and is the same of the input data file to allow to be read as input file (for DUALEM-421, for example is as follow):

Name of line
N, h
X, Y, Z, HCP1m, PRP1m, HCP2m, PRP2m, HCP4m, PRP4m, Lat, Lon, Time
....

10.3. Initial Model

The file of the initial model (generated automatically) used in 1D laterally inversion has the format as follow:

N, NL
S_1 , D_1 , C_1
S_2 , D_2 , C_2
……..
S_{NL} , D_{NL} , C_{NL}

Where N is the number of sites along the line, NL is the number of layers, D_i and C_i are the depth (m) and the conductivity (mS/m) of the ith- layer. S_j is the distance along the line of the ith- site, having the first measurement as an origin.

NOTE: this file cannot be used as input file.

10.4. Final Model

The file contains an interpolation of the final model. The format of the file is as follow:

Xcoord, Ycoord, Distance, Elevation, mS/m, ohm-m
X_1 , Y_1, S_1, Z_1 , C_1, r_1
X_2 , Y_2, S_2, Z_2 , C_2, r_2
………….
X_{NL} , Y_{NL}, S_{NL}, Z_{NL} , C_{NL}, r_{NL}

Where X_i , Y_i represent the easting and northing coordinates and Z_j the elevation (or thedepth in a flat earth). S_i is the distance between measuring sites along the line, having the first measurement as the origin. C_j and r_i are the conductivity and resistivity at (X,Y,Z) or (S,Z), in mS/m and ohm-m, respectively.

10.5. Inverse Models (Q2D)

The file contains all the models imported in the Map module. The format is as follow:

Xcoord, Ycoord, Altitude, Distance, Elevation, Cond(mS/m)
X_1 , Y_1, ZT_1, S_1, Z_1 , C_1
X_2 , Y_2, ZT_2, S_2, Z_2 , C_2
………….
X_{NL} , Y_{NL}, ZT_{NL}, S_{NL}, Z_{NL} , C_{NL}

Where X_i , Y_i represent the easting and northing coordinates, ZT_i the altitude (topography) and Z_j the elevation (or the depth in a flat earth). S_i is the distance between measuring sites along the line, having the first measurement as the origin. C_j is the conductivity and resistivity at (X,Y,Z) or (S,Z), in mS/m.

10.6. DOI

The file contains the calculated values for the DOI and the format is:

x, y, s, z, doi
X_1 , Y_1, S_1, Z_1 , doi_1
X_2 , Y_2, S_2, Z_2 , doi_2
…………
X_N , Y_N, S_N, Z_N , doi_N

Symbols have the usual meaning.

10.7. Example files

The package contains examples of input files (and others) that can be used to clarify the formats and to help the user to explore the different tools of the program. Some of the files are generated synthetically.

Example of data files corresponding to data acquired in a line:

EM31.txt - data from EM31
EM38.txt – data from EM38
EM34line0.txt - data from EM34
D21-data.txt - data from DUALEM-21s
D421-data.txt - data from DUALEM-421s
D421Line0.txt - data from DUALEM-421s
Line4Profiler.txt -

ProfilerSurvey.txt - is a data set of three PROFILER lines.

11. Common Errors that must be avoided (troubleshooting)

- Select the correct sensor (there is no default).
- The format of the input files must be followed strictly. The most part of the troubles are related with mistakes in the data file.
- You can not input data only for one mode of a sensor. If you only have data for one mode, fill the other modes with -9.0 .

Take care with the number of measuring sites you have and with the right sequence of the measured values. The program can verify that you have made a mistake with the number of points but it can not verify the correctness of the instrument height or if the values have been acquired in a VDM mode or with a PRP sensor.

- When filling the boxes in the screen, follow the displayed format.
- Use only data of good quality in the inversion. The final model greatly depends on the quality of your data. With low quality data one cannot expect a high quality final model.
- If your GPS does not have enough resolution, you should use a local reference system.

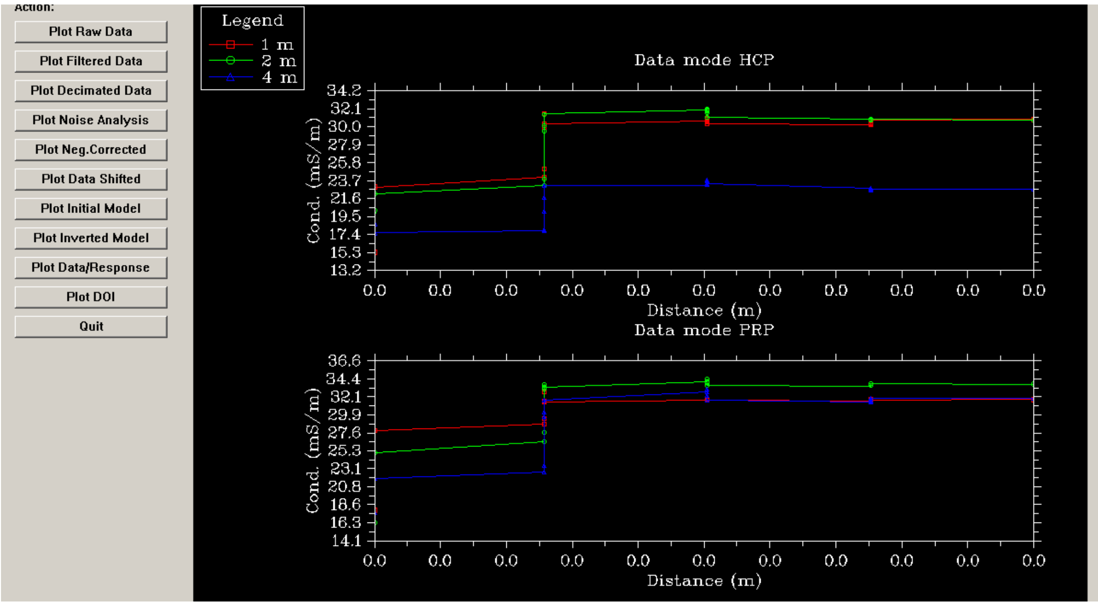


Figure 11.1. Using coordinates without enough resolution produces strange graphics.

- If your operating system is the W7 then verify the following: i) is the Pack Service 1 installed?, ii) is the option “run programs made for previous versions of Windows” active? iii) are the permission for read, write and modify files in the folder active?
- If the program is not working properly do the following before contact EMTOMO: i) open a MSDOS command prompt window (go to the start button; all programs; accessories), ii) move to the folder using the cd command (for example cd users\emtomo), iii) run the program just typing the name and pressing the return., iv) after the problem occurs make a print screen of the MSDOS windows. Send this together your comments to EMTOMO.

12. Examples

DUALEM-642 survey

Figure 12.1 shows a site location map of a survey carried out with DUALEM-642[7]. The survey has more than 7000 sites, which correspond to a more than 42000 measured values.

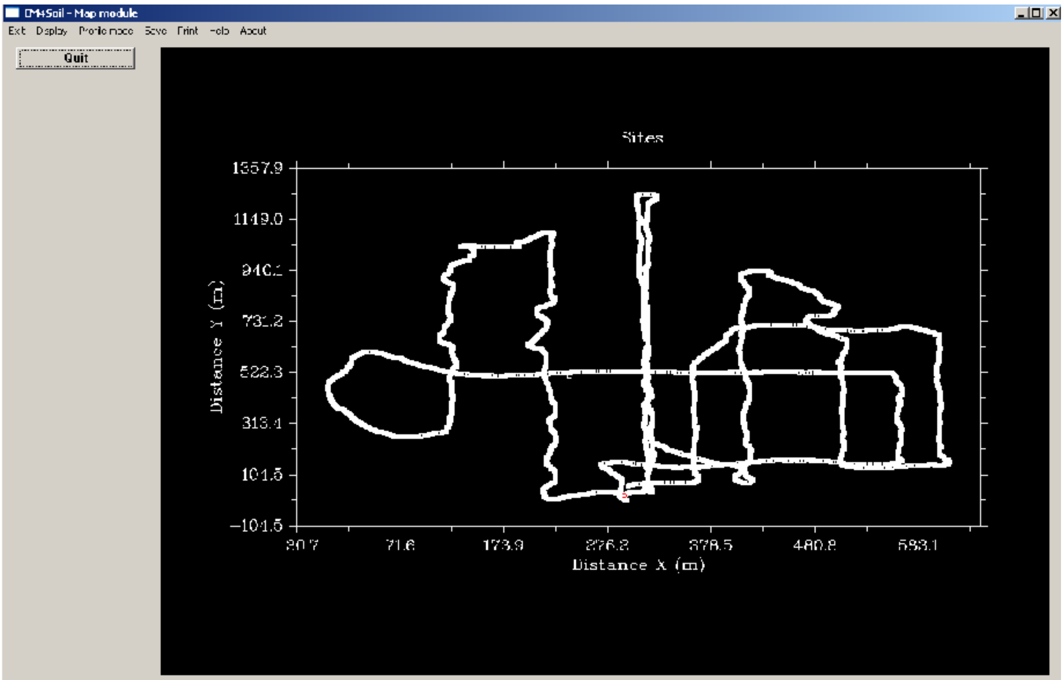


Figure 12.1. Site location of a DUALEM-642 survey.

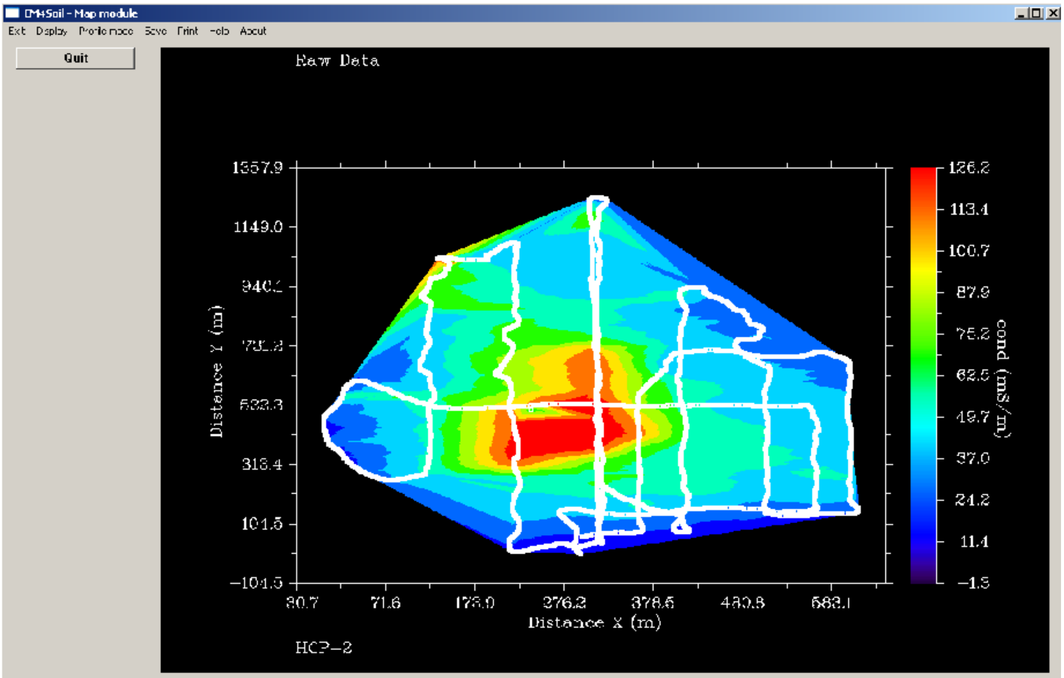


Figure 12.2. Apparent conductivity map for sensor HCP-2 m.

[7] This data set is used with the kind permission of Drs. Rick Taylor (DUALEM) and Scott Holladay (GEOSENSORS Inc.).

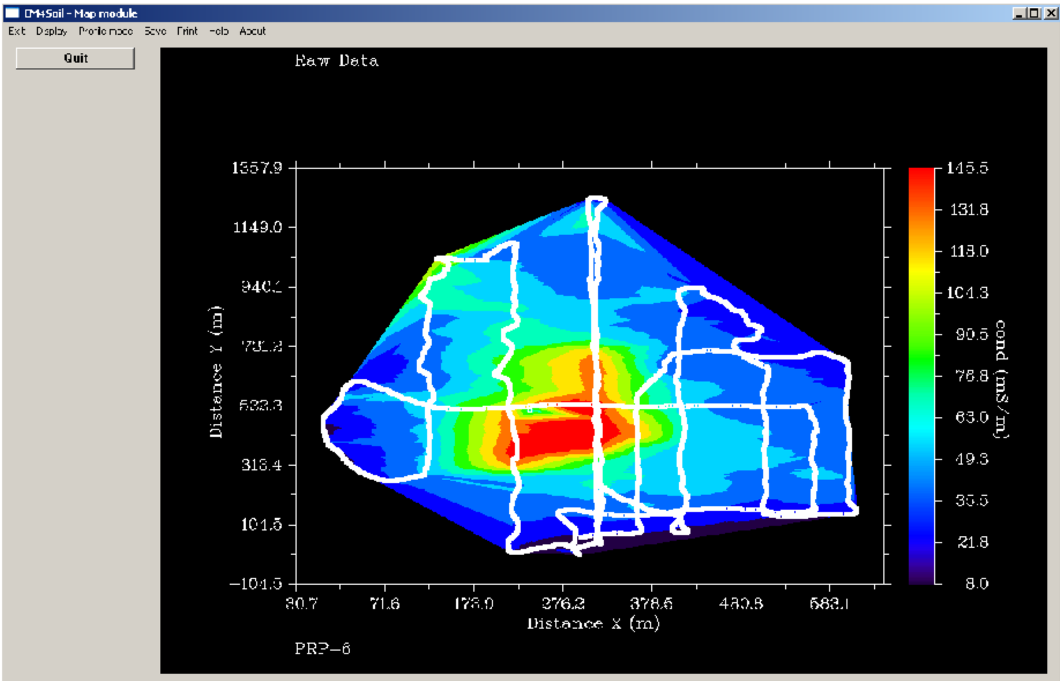


Figure 12.3. Apparent conductivity map for sensor PRP-6 m.

Figures 12.2 and 12.3 show the apparent conductivity maps for two sensors. The apparent conductivity values corresponding to the profile shown in Figure 12.4 are shown in Figure 12.5.

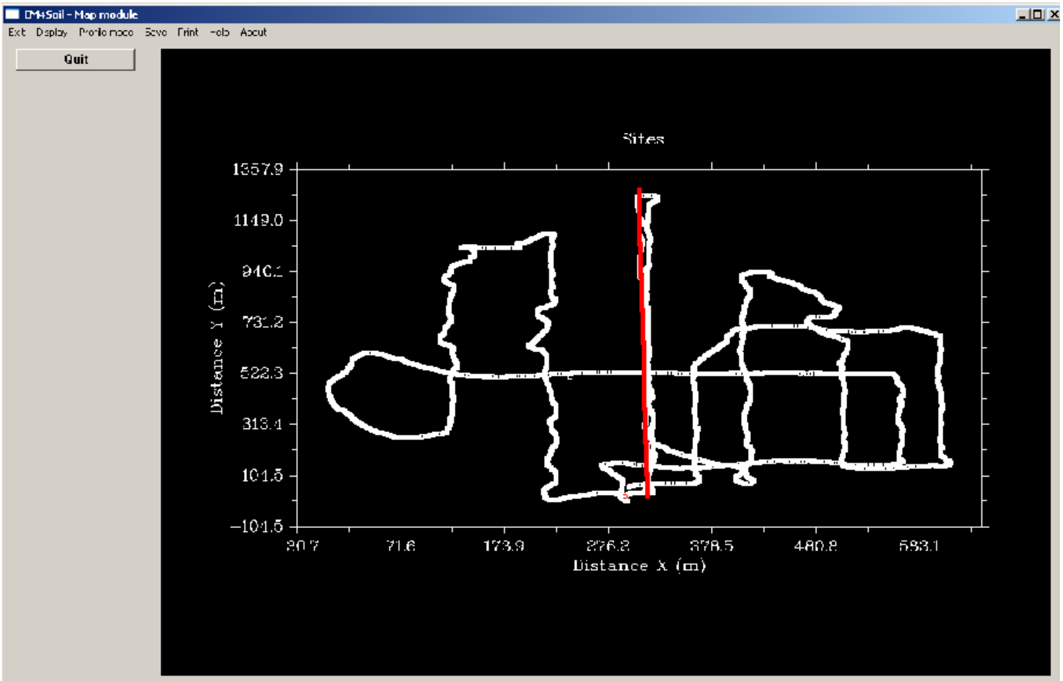


Figure 12.4. Apparent conductivity map for sensor HCP-2 m.

The north-south profile has 1279 sites. For a first interpretation there is no need of such density of sites. Figure 12.6 shows the decimated (n = 10) curves together with the response of the model shown in Figure 12.7. This model was calculated using the linear approach algorithm, 20 iterations and lambda of 0.3.

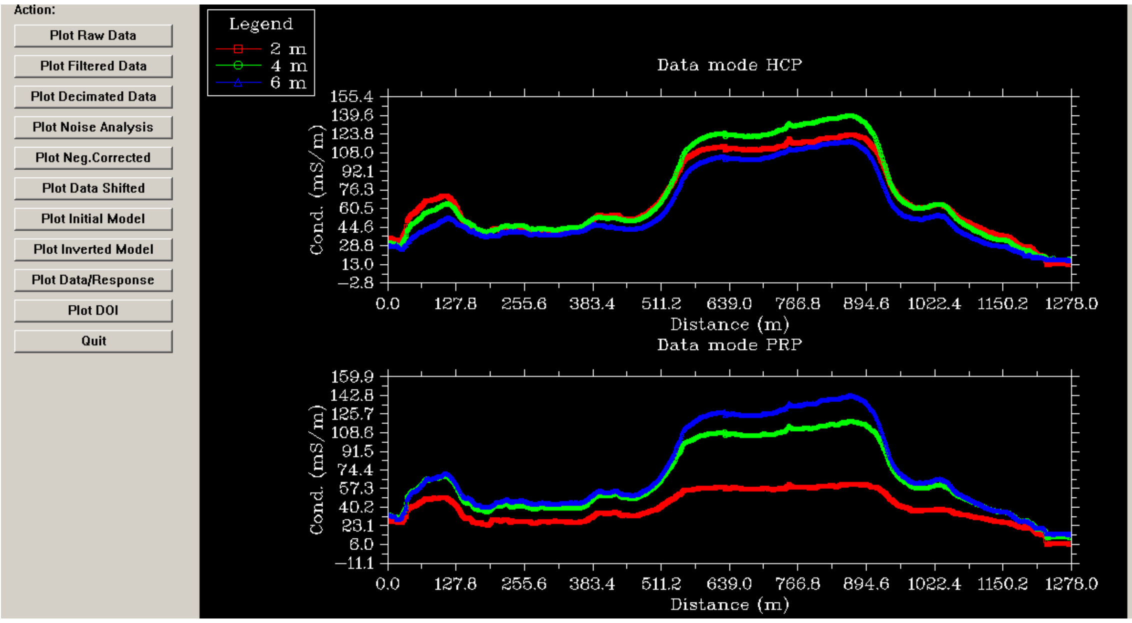


Figure 12.5. Apparent conductivity curves.

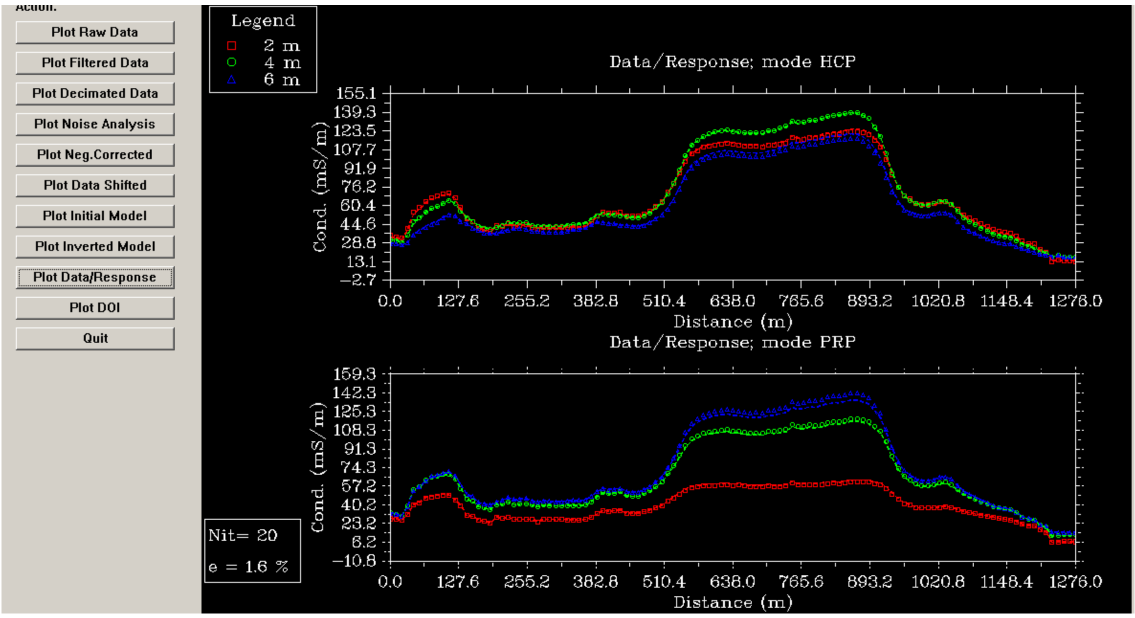


Figure 12.6. Decimated apparent conductivity curves and model responses.

Figure 12.8 shows the model calculated using the full solution. The model response is shown in Figure 12.9.

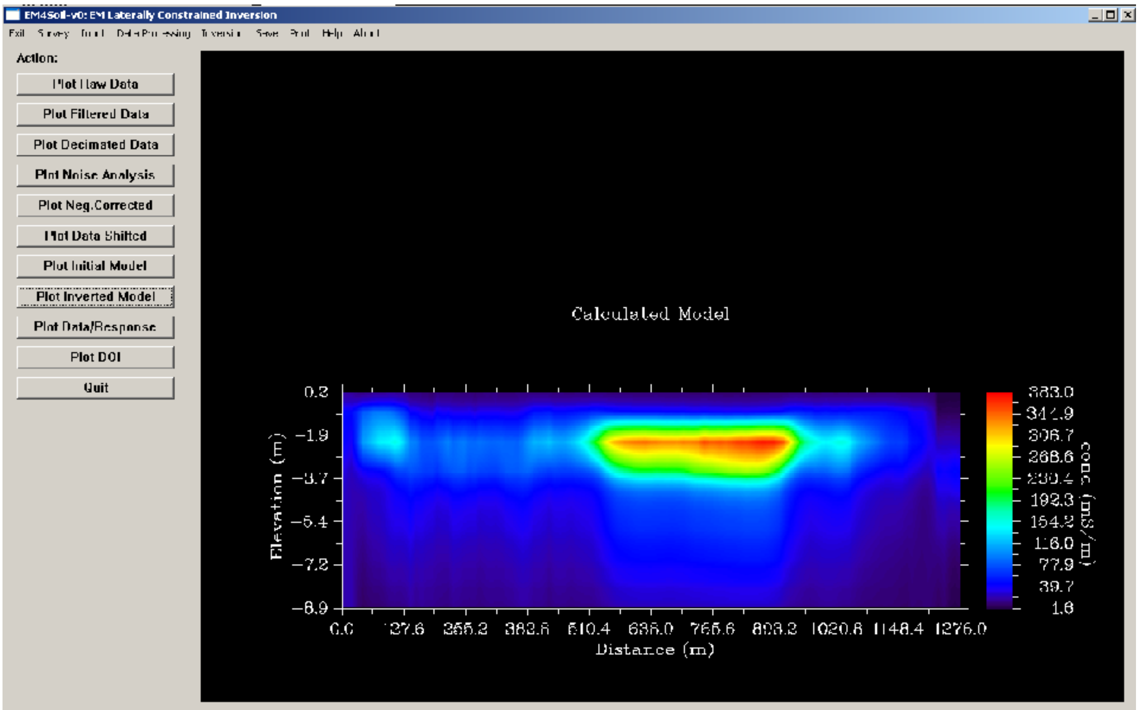


Figure 12.7. Conductivity model calculated with the linear approximation.

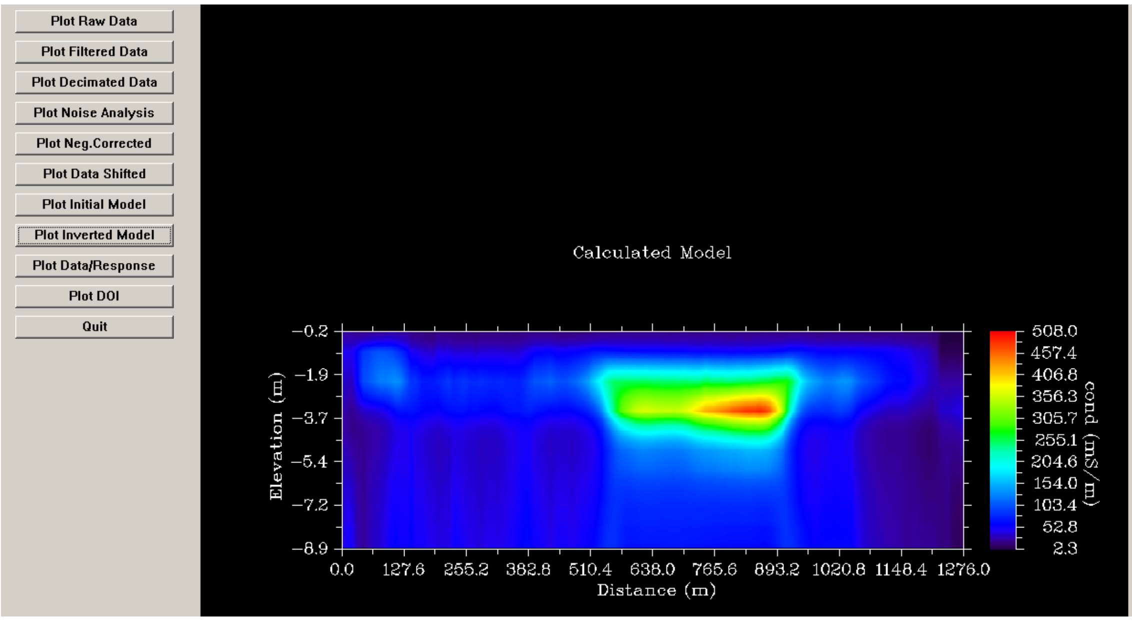


Figure 12.8. Conductivity model calculated using the full solution.

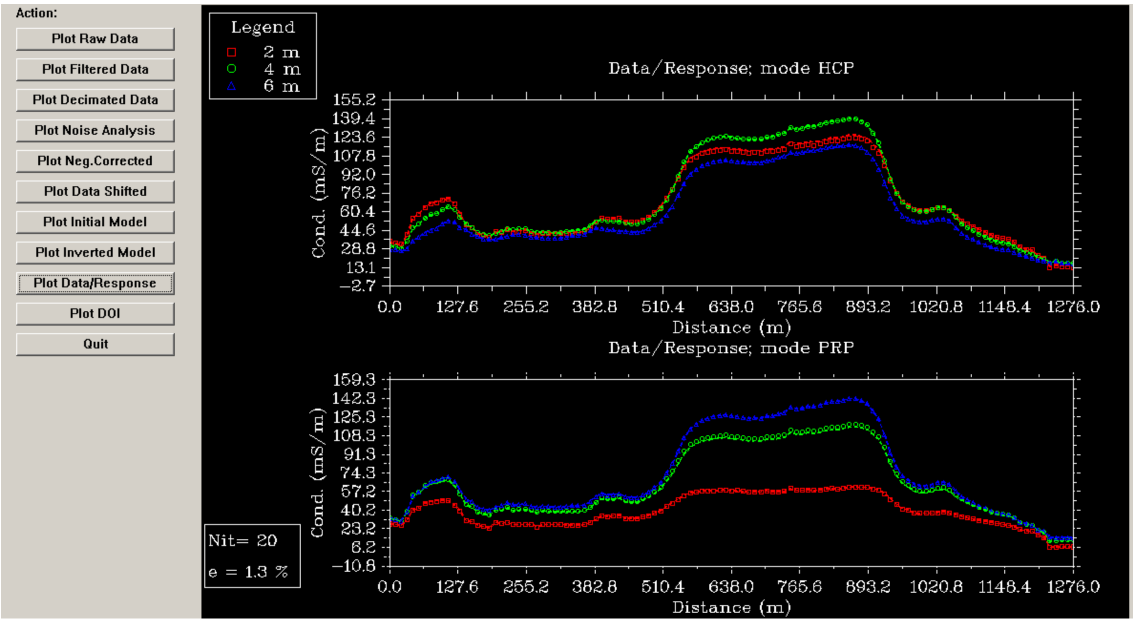


Figure 12.9. Data and model responses from the full solution model.

PROFILER SURVEY

Figures 12.10 and 12.11 show the model and its apparent conductivity responses obtained by inverting the data collected along the north profile of the survey shown in Figure 7.1.2.

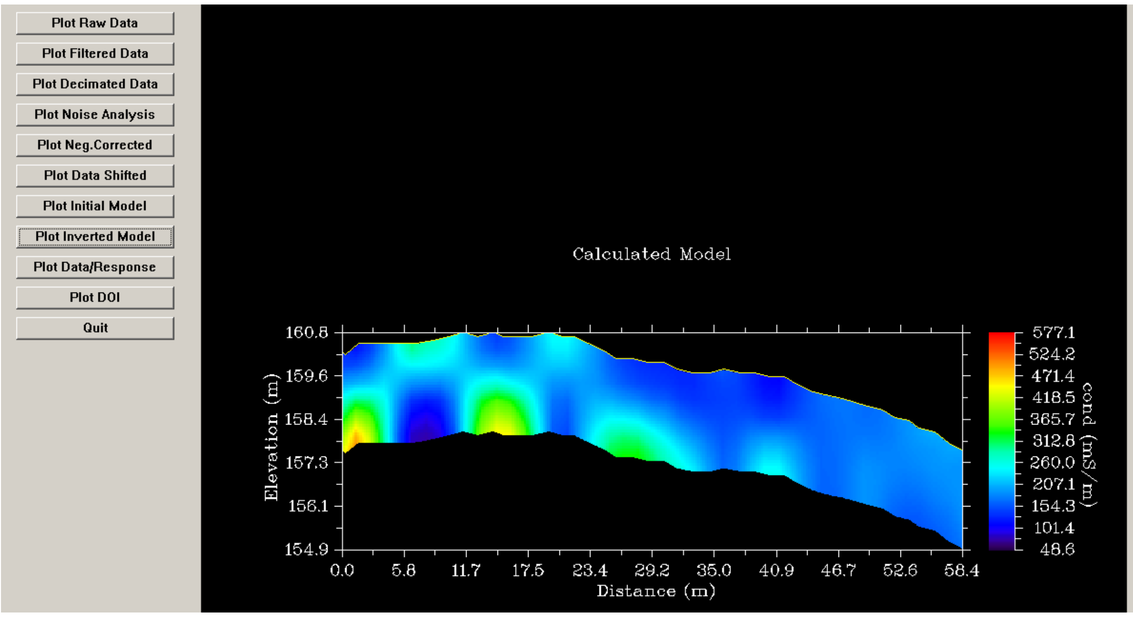


Figure 12.10. Conductivity model obtained by inversion of a PROFILER data line.

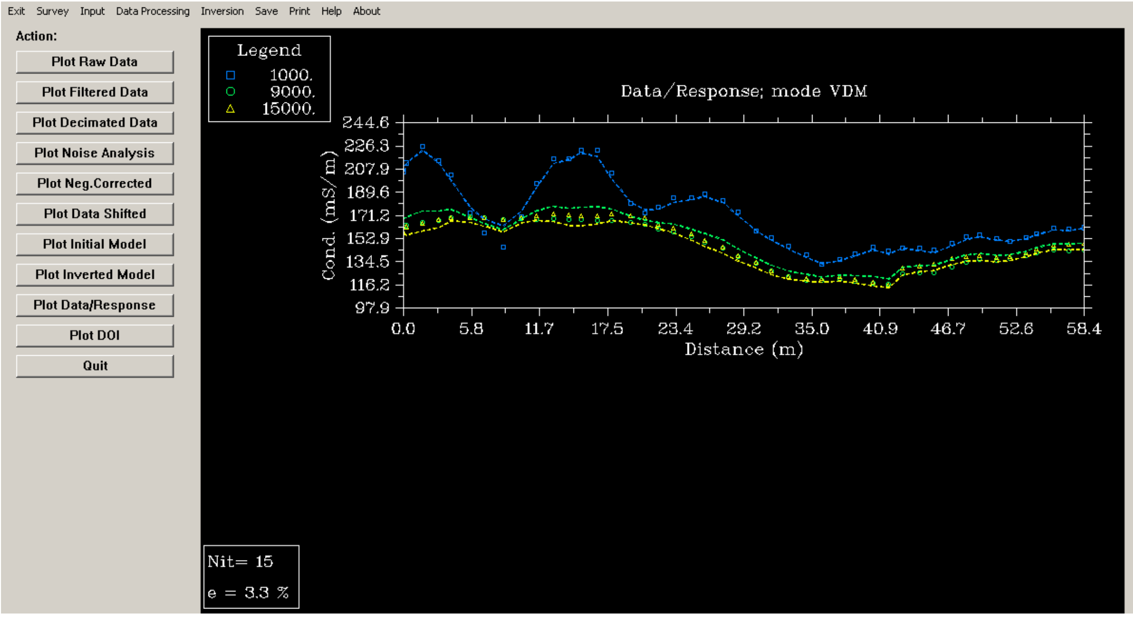


Figure 12.11. PROFILER data and model responses corresponding to the model shown in Figure 56.

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APPENDIX A. Inversion of EM data

Inversion of geophysical data is a mathematical procedure that seeks to obtain the distribution of one (or more) physical property in the survey area (or volume). In the EM case electrical conductivity (or resistivity) is the property of interest. Therefore, from a finite number of data (apparent conductivity values) one want to know the true conductivity distribution that justify such data set. Having a discrete sampling of the apparent conductivity it is only possible to calculate discrete conductivity distributions, that is, conductivity values representative of some limited zones of the survey earth's zone. It means that an earth model should be adopted. There are three candidates: a layered earth (1D); an earth model allowing the variation of conductivity in two directions (2D) or a more realistic model allowing that the conductivity vary in the three directions (3D). The parameterization of each model is obviously different and the number of unknown parameters increases from 1D to 3D models. The model to be adopted depends on several factors but the most important are the geology and the geophysical array used in the data acquisition. In any case the information about the conductivity distribution will be limited by the number of data and model correctness. One cannot expect to have more information than that contained in the data set. Because this information is partial, several models can fit the data. The decreasing of this ambiguity can only be done using additional information from boreholes or other geophysical indirect methods.

Let's look closely to an example. Consider the synthetic data shown in Figure A1 acquired with EM38. The data consists of VDM and HDM apparent conductivity values measured over a two-layer earth (10 and 85 mS/m and 1 m thick). With these two data values at each site what kind of information do we expect to obtain? In the best situation a rough two layer model can be reached. The parameters will be the thickness of the top layer and the conductivity of both layers. The ambiguity of this model will be also a function of the geoelectrical profile. The model resolution of a low/high-conductivity layer sequence will be different of a high/low-conductivity sequence.

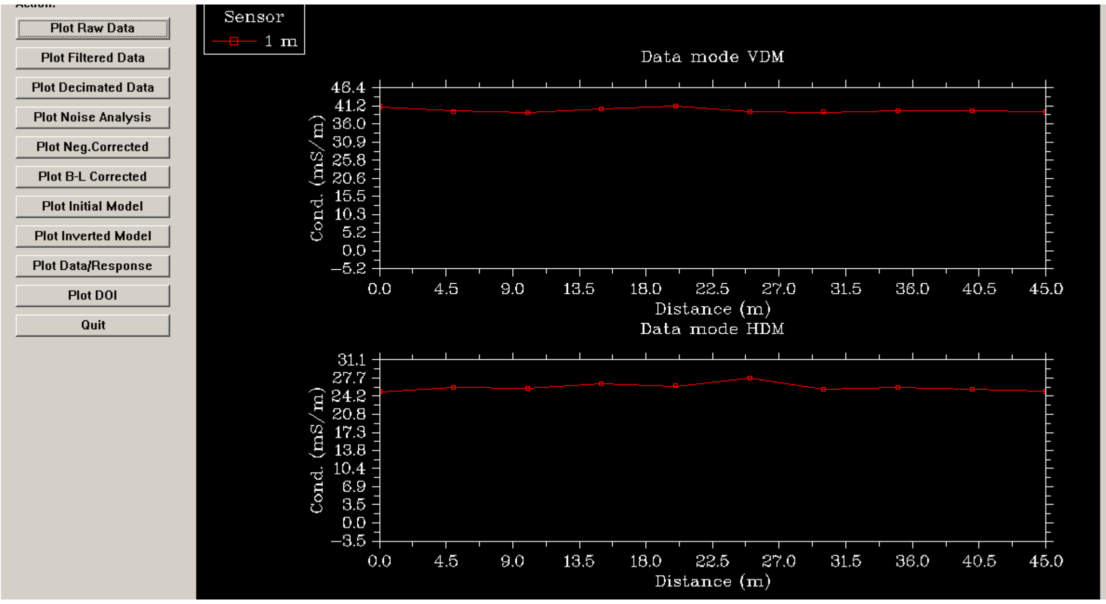

Figure A1. Apparent conductivity over a two-layer model (conductivity of 10 and 85 mS/m and thickness of 1 m).

Inverting the data using a 1D model program, the solution depends on the initial model (Table 1). These results show that the ambiguity of the inversion of these data can be important.

Table 1. Results if the 1D inversion for two different initial models.

Parameter	Initial model	solution	Initial model	solution
C1 (mS/m)	20	7.8	20	9.2
C2	40	72	40	77
T1 (m)	0.7	0.74	1	0.84

Figures A2 and A3 shows the result obtained by **EM4Soil** using the same data set. The results of the 1D LCI inversions are quite good. Due to the lateral constraints the solution at the ends of the profile is worst. Both solutions show a conductivity contrast at a depth of 1-1.1 m. However, the conductivities are not well resolved.

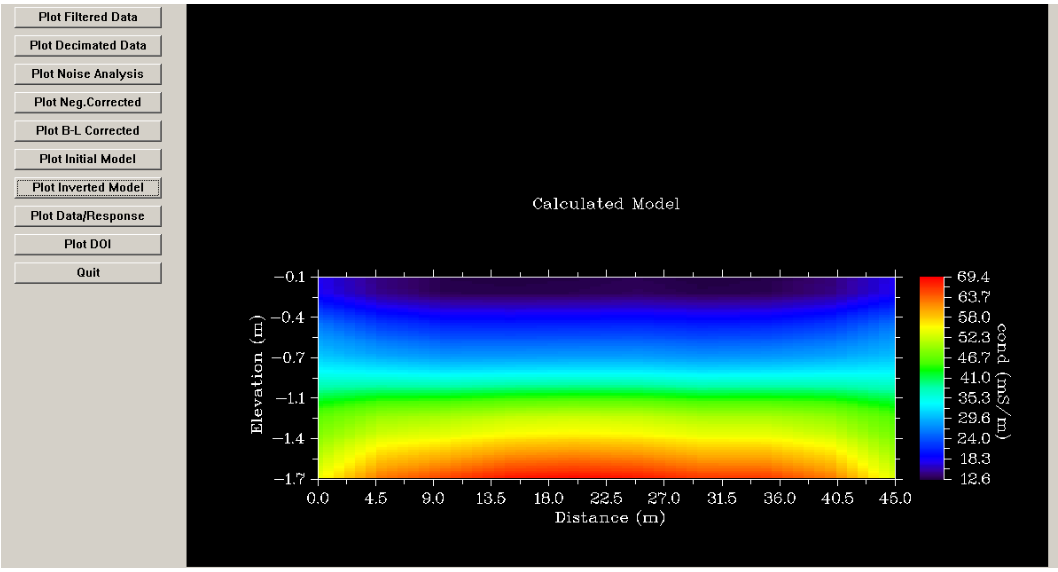

Figure A2. Model obtained by EM4Soil using the linear approach (misfit of 4.3% after 10 iterations).

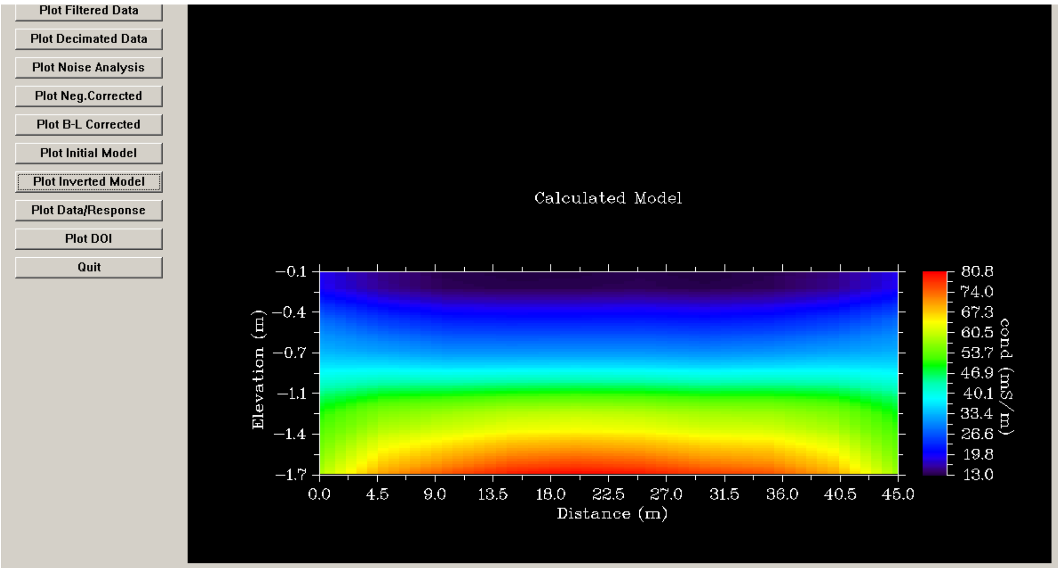

Figure A2. Model obtained by EM4Soil using the non-linear approach (misfit of 4.8% after 3 iterations).

Inversion algorithm

The discrete inverse problem can be formulated as follows: calculate M parameters of the model (values of conductivity and thickness of the layers in 1D models) knowing N values of apparent conductivity measured on surface.

The nonlinear, smoothness-constrained inversion algorithm described by Monteiro Santos (2004) was adopted in **EM4Soil**. The earth model used in the inversion process consists in a set of 1D models distributed according to the locations of the measurement sites. All the models have number of layers whose thickness is kept constant. Two forward modeling subroutines, one based on the cumulative response (McNeill, 1980; Wait, 1962) and another based on the full solution of the Maxwell equations (Kaufman and Keller, 1983), are used optionally to calculate the σ_a responses of the model. Two inversion algorithms are available: in the S1 algorithm the optimization equations are represented as follows (Sasaki, 1989):

$$\left[\left(\mathbf{J}^{\mathrm{T}}\mathbf{J}+\lambda\mathbf{C}^{\mathrm{T}}\mathbf{C}\right)\right]\delta\mathbf{p}=\mathbf{J}^{\mathrm{T}}\mathbf{b} \qquad [1]$$

In the second algorithm S2 the equations are (Sasaki, 2001):

$$[(\mathbf{J}^{\mathrm{T}}\,\mathbf{J}+\lambda\mathbf{C}^{\mathrm{T}}\,\mathbf{C})]\,\delta\mathbf{p}=\mathbf{J}^{\mathrm{T}}\,\mathbf{b}+\lambda\mathbf{C}^{\mathrm{T}}\,\mathbf{C}\,(\mathbf{p}-\mathbf{p}_{\mathrm{o}}) \qquad [2]$$

where $\delta\mathbf{p}$ is the vector containing the corrections applicable to the parameters (logarithm of block conductivities, p_j) of an initial model, $\mathbf{p}_{\mathrm{o}}$ is a reference model, **b** is the vector of the differences between the logarithm of the observed and calculated σ_a [$b_i = \ln(\sigma_a^{o}) - \ln(\sigma_a^{c})$], **J** is the Jacobian matrix whose elements are given by $(\sigma_j/\sigma_{ai}^{c})(\partial\sigma_{ai}^{c}/\partial\sigma_j)$, the superscript T denotes the transpose operation, and λ is a Lagrange multiplier that controls the amplitude of the parameter corrections and whose best value is determined empirically. The value can be determined empirically by comparing the models calculated using different values with the available information. The elements of the matrix **C** are the coefficients of the values of the roughness in each parameter, which is defined in terms of the four neighbors parameters. The elements of **C** are -4, 1, or 0. An iterative process allows the final model to be obtained, with its response fitting the data set in a least square sense.

The misfit between data and model response is measured through the rms defined by:

$$rms=\sqrt{\frac{1}{N}\sum(\sigma_{ai}^{o}-\sigma_{ai}^{c})^{2}} \qquad [3]$$

Cumulative Response of a Multilayered Earth

At low induction numbers, the magnetic coupling between ground current loops induced by the primary field is negligible and, for this reason, the secondary magnetic field measured at the receiver is the sum of the independent magnetic fields from each individual induced current loop (McNeill, 1980). In this case, and properly normalizing the measured fields, the depth of investigation depends only on the transmitter–receiver separation and not on the frequency or σ (Kaufman and Keller, 1983). It is then possible to construct a mathematical function of depth that describes the relative contribution to the secondary magnetic field, measured at the receiver, due to the homogeneous material within a thin horizontal layer at a depth *d* (McNeill, 1980; Kaufman and Keller, 1983; Gómez-Treviño et al., 2002; Callegary et al., 2007). It is worth mentioning that this approach is only valid for fairly resistive environments. For highly conductive structures, the instrument response is not linear and the use of the cumulative function will produce biased models (the conductivity of deeper layers will be underestimated if covered by highly conductive layers). In the presence of a layered-earth model, the relative contribution to the secondary magnetic field from all material up to a depth *d* below the sensor can be expressed by the cumulative function *R* (for HCP or PRP configurations used in the DUALEM instruments) as defined the McNeill (1980) and Wait (1962):

$$R_{\mathrm{HCP}} = 1 - \frac{1}{\sqrt{4z^2+1}} \qquad [4]$$

$$R_{\mathrm{PRP}} = \frac{2z}{\sqrt{4z^2+1}} \qquad [5]$$

where z (= d/s) represents the depth normalized by the coil spacing s. Taking into account these definitions, the response of an M-layer earth is calculated by adding the contribution from each layer independently, weighted according to its conductivity and depth as

$$\sigma_a^c = \sigma_1 R(z_1) + \sum_{i=2}^{M-1} \sigma_i \left[R(z_i) - R(z_{i-1}) \right] + \sigma_M \left[1 - R(z_{M-1}) \right] \qquad [6]$$

The derivatives of the apparent conductivity σ_a^c with respect to the layer conductivities are

$$\frac{\partial \sigma_a^c}{\partial \sigma_1} = R(z_1) \qquad [7]$$

$$\frac{\partial \sigma_a^c}{\partial \sigma_i} = \left[R(z_i) - R(z_{i-1}) \right] \quad i = 2, \ldots, M-1 \qquad [8]$$

$$\frac{\partial \sigma_a^c}{\partial \sigma_M} = \left[1 - R(z_{M-1}) \right] \qquad [9]$$

Similar equations can be written for GEONICS instruments, EM31, EM38 and EM34(McNeill, 1980):

$$R_{VDM} = \frac{1}{\sqrt{4z^2+1}} \qquad [10i]$$

$$R_{HDM} = \sqrt{4z^2+1} - 2z \qquad [11i]$$

and,

$$\sigma_a^c = \sigma_1 [1 - R(z_1)] + \sum_{i=2}^{M-1} \sigma_i [R(z_{i-1}) - R(z_i)] + \sigma_M R(z_{M-1}) \qquad [12i]$$

for the apparent conductivity calculations.

Usually the initial thickness of the layers is kept constant in the inversion process. The use of the cumulative response to calculate the model response at each measuring site means that we are not considering the EM interaction between constituent blocks of the model; however, the smooth inversion algorithm constrains each block σ to be somewhat dependent on its neighbors. That is, the method represents a one-dimensional, laterally constrained approach and the final model is a rough representation of a two-dimensional model (Quasi-2D).

Full Solution of the Maxwell Equations

Forward calculations based on the work of Keller and Frischknecht (1966), Wait (1982) and Anderson (1979) are used to calculate sensor responses at each measuring site, assuming a 1-D model. For a vertical dipole as primary source the secondary components of the magnetic field measured at a site with coordinates (*x*,*y*,*h*) over a N-layer model are given by Keller and Frischknecht (1966)

$$H_{zs} = -\frac{m}{4\pi\delta^3} T_o(A,B)$$

$$H_{xs} = -\frac{m}{4\pi\delta^3} \frac{x}{r} T_1(A,B) \qquad [13]$$

where m is the magnetic moment of the source and r is the transmitter-receiver distance. A, B and δ are given by

$$A = h/\delta$$
$$B = r/\delta$$
$$\delta = \sqrt{2/\sigma_1 \mu_0 \omega} \qquad [14]$$

and

$$T_o = -\int_0^\infty R_0(g)\, g^2 e^{-gA} J_0(gB)\, dg$$

$$T_1 = -\int_0^\infty R_0(g)\, g\, e^{-gA} J_1(gB)\, dg \qquad [15]$$

Here, $J_0(\ )$ and $J_1(\ )$ are Bessel functions of the first kind of order 0 and 1, respectively. $R_0(g\ )$ is calculated recursively taking into account the conductivity and thickness of each layer.
Integrals in equations [9] are evaluated using a subroutine developed by Anderson (1979).

The predicted values of the Quadrature component for HCP and PRP configurations at height h above the ground are given by

$$Q_{HCP} = \mathrm{Im}(H_{zs} / H_{zp})$$

$$Q_{PRP} = \mathrm{Im}(H_{ys} / H_{zp}) \qquad [16]$$

APPENDIX B. Noise analysis

Everett and Weiss (2002) have shown that the Power Spectral Density (PSD) of apparent conductivity measured with LIN instruments follows a power-law of the form $|A(w)|^2 \approx w^b$, where w is the spatial wavenumber and *b* is the slope of a best-fit straight line in a log-log graphic. Those authors shown that a) values of |b|>1.0 indicates a non-Gaussian fractal signal, b) |b|<1.0 indicates a non-fractal signal similar to Gaussian noise and c) |b|=0 indicates a pure white-noise signal. Therefore, the slope can be an indication of the noise level of the data. However, as *b* is a measure of heterogeneity in a fractal signal it can be used to have general information about the geoelectrical structure of the survey area. The reading of Everett and Weiss paper is recommended to the interested users.

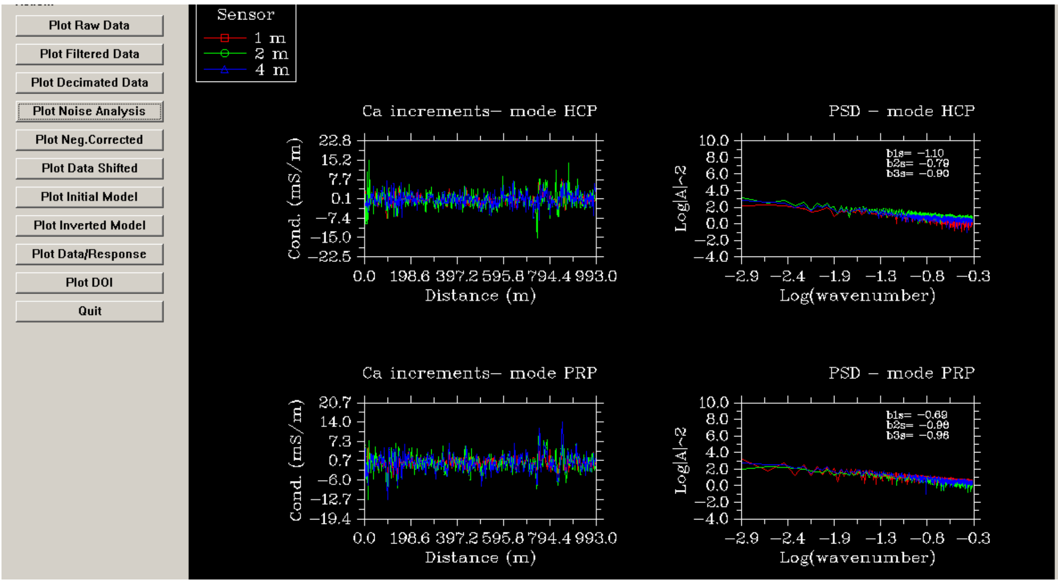

Figure B1. Left- increments of apparent conductivity for each sensor. Right- PSD of the apparent conductivity with values of *b* for each sensor.

APPENDIX C. Correction of the sites location

Positioning survey sites with the use of an external GPS is a common procedure. In general the GPS does not stand in the center of the instrument at where the measured values correspond. For this reason a correction of the sites coordinates is necessary. The correction can be done knowing the GPS position relatively to the center of the instrument as well as the instrument position relatively to the line survey (Figure C1). DUALEM instruments included (optionally) a built-in GPS which location in a local referential is shown in Table 1.

Table 1. Built-in GPS location in the local reference system (s=0). These values are averaged from the distances corresponding to HCD and PRP sensors

Model	d (m)
DUALEM-1S	+0.325
DUALEM-2S	-0.175
DUALEM-21S	-0.175
DUALEM-42S	-1.175
DUALEM-421S	-1.175
DUALEM-642S	-2.175

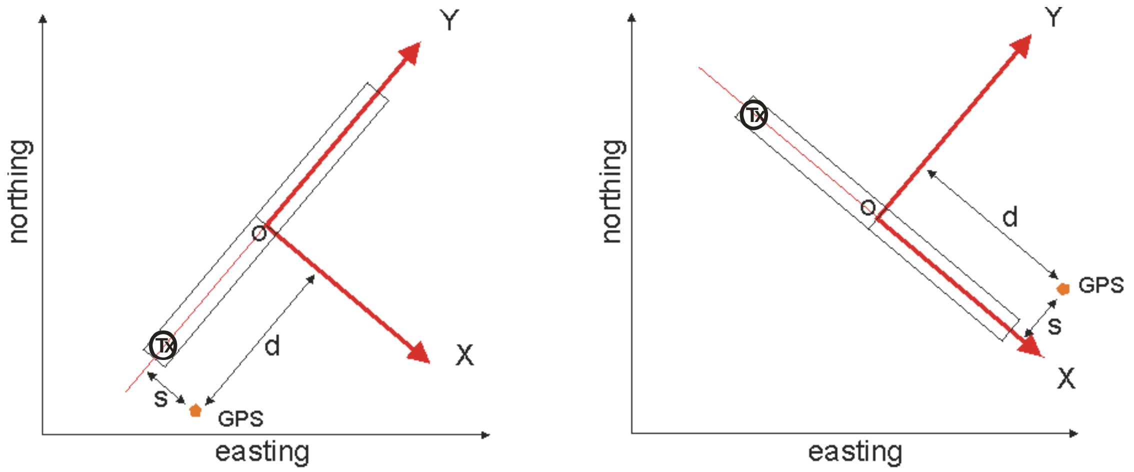

Figure C1. Local reference system (X,Y) to localize the external GPS assuming that the survey is carried out in the Y direction. The figures show the instrument in the in-line position (left) and in the board-side position (right). O represents the center of the instrument and Tx the transmitter position (DUALEM instruments).

When using multisensors, like DUALEM-421S the values measured by the different sensors are not referenced to the same coordinate. The program allows you to refer all measurements to the same coordinate (the center of the instrument) using two different algorithms: by inverse distance to a power interpolation or by nearest-neighbor. The second algorithm is probably more adequate for continuous measurements with short distance between sites.

APPENDIX D. THE SIMULATED ANNEALING METHOD

The name SA comes from the analogy with the process of physical annealing in thermodynamics once the undetermined parameters of the geophysical model are analogue to the particles of the physical system and the objective function of the inverse problem is analogue to the energy of the physical system. Similar to the annealing process, which is controlled by an initial temperature and a cooling schedule, the estimation of the solution in the inverse problem is also controlled by a positive parameter T, which limits the perturbation of the parameters values to acceptable values. The acceptability of a perturbation is based on the algorithm presented by Metropolis et al. (1953). According to this algorithm, perturbations of the parameters leading to a decrease in the objective function are systematically accepted. When an increase in the objective function is verified the changes in the parameters are not systematically rejected. Instead, the acceptance of the new parameters depends on the value of the function

$$\psi = \exp(-\Delta E / T) \qquad [1]$$

where ΔE represents the objective function variation, that is compared with a randomly generated number χ, between 0 and 1. The changes in the model are accepted if $\psi > \chi$ and rejected otherwise. For high values of T (corresponding to high temperatures of a 'melted' physical system) almost all changes are accepted. The Metropolis algorithm iterates over a sequence of models at a constant T value (*Internal loop*). This renders the solution independent of the initial model and allows the algorithm to escape from local minima. Looping over the Metropolis algorithm, while T decreases, there is also a decrease in the acceptance probability (eq. 1) and only perturbations decreasing the objective function are accepted. Therefore, it is expected that the accepted models will concentrate in the vicinity of the global minimum of the objective function. A slowly decreasing T parameter (*External loop*) is important in the efficiency of the SA algorithm, allowing a representative sampling of the parameters space.

The simulate annealing (SA) algorithm was adopted to perform the 1-D inversion of EM soundings. The objective function, *E* based on l_1-norm and involving M conductivity data is defined as:

$$E_{EM} = \frac{2\sum_{i=1}^{N} | d_i - y_i |}{\sum_{i=1}^{N} | d_i - y_i | + \sum_{i=1}^{N} | d_i + y_i |} \qquad [2]$$

where N is the number of measuring points. The value of the parameter T was taken as 10 times the initial value of the objective function. The number of iteration (external and internal loops) is usually of 100 allowing each parameter to change more than 20,000 times.

APPENDIX E. THE 1D INVERSION

EM4Soil allows the inversion of the data collected along a line assuming a layered model. In this case the model may have a few layers (2 or 3) and the inversion is performed at each measuring site without any constraint. This option is useful when dealing with data collected with one sensor only (in both modes of acquisition). The inversion algorithm is based on a least square method using singular value decomposition (SVD) to solve the equation system. The solutions is stabilized using the Levemberg-Marquardt algorithm (Johansen, 1977).

A description of the algorithm can be found at Johansen (1977). In this method, we try to find a set of earth parameters p_1, $p_2, \dots, p_M$ that minimize an error function. This problem is nonlinear and its solution requires a linearization procedure near the correct solution in order to obtain an improved solution. The nonlinear problem is linearized using the Taylor-series expansion:

$$\vec{d} = \vec{y} + J\,\delta\vec{p} \qquad [1]$$

where $\vec{d}$ is an N-dimensional vector containing the data, $\vec{y}$ is an N-dimensional vector containing the theoretical responses of a model with parameters specified in the M-dimensional vector $\vec{p}$, and $\delta\vec{p}$ is a M-dimensional vector containing the unknown correction of the parameter. J is an N x M Jacobian matrix defined $J_{ij} = \dfrac{\partial y_i}{\partial p_j}$. The parameter corrections are calculated by solving equation (1) using the Singular Value Decomposition (SVD) technique (Golub and Reinsch 1970).

ACKNOWLEDGMENTS

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USING OTHER sensors

Manual

This Software is produced by EM-TOMO

Email: emtomog@gmail.com

EMTOMO

February 2013

1. Introduction

The OTHER sensor is the option that allows putting together data collected with different EMI instruments and jointly inverting the data set. The OTHER sensor is also used to input data to be analysed with the DMO Tool (Detecting Metal Objects Tool).

The majority of the processing and graphical tools available for standard formats are also applied to data input as OTHER. There are particularities that are explained in the following sections.

2. Input Data

Input the data using the entrance in the menu bar and one of the options (line or area). After that the program will display the main characteristics of the data in a table (Figure ??.

Data Summary

Exit

Sensor	Space	Freq	Mode	Height	NPoint	Ca	In-P	Quad	Ka	Neg
PROF	1.22	3000	VDM	0.2	4549	YES	YES	YES	YES	57.7
PROF	1.22	6000	VDM	0.2	4549	YES	YES	YES	YES	6.4
PROF	1.22	15000	VDM	0.2	4549	YES	YES	YES	YES	0.9

OK

Figure 2.1. Displaying the main data characteristics. The red highlighted cells means that there are more than 30% of negative apparent conductivity values in the first sensor.

Finishing the input the program will display the data according its type: data from a line or data from a survey area.

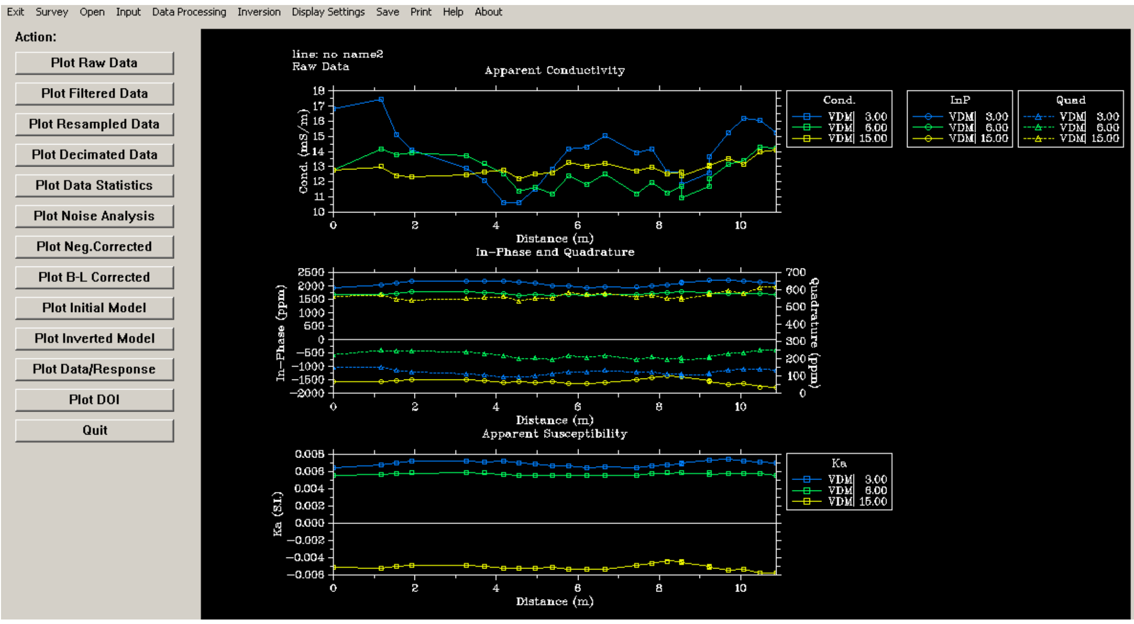


Figure 2.2. Data from a line.

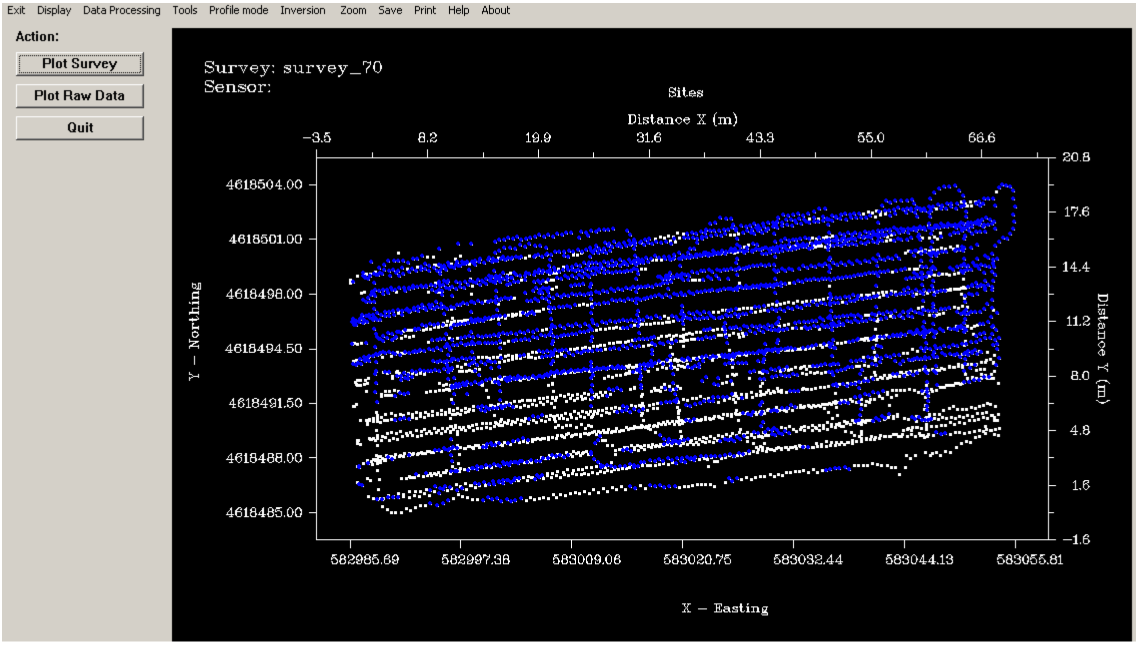
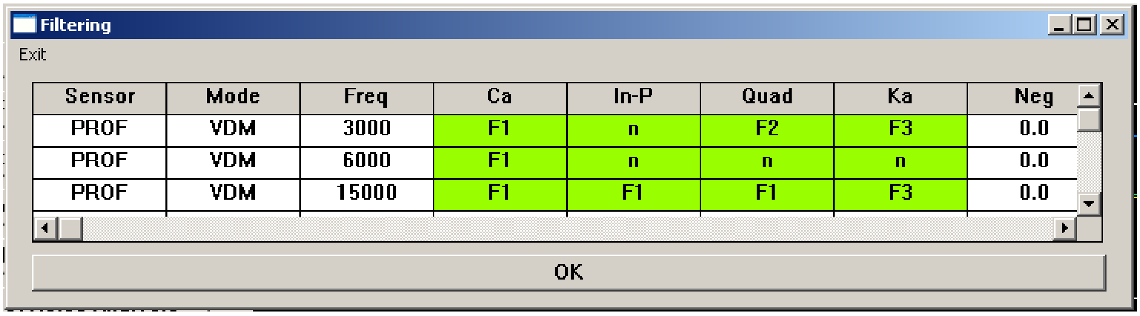


Figure 2.3. Data from a survey area.

3. Data Processing
3.1. Filtering

The sensors and components to be filtered can be selected in a table (Figure 3.1). NON, N or n can be used to say that a channel is not to be filtered. F1, F2 and F3 are used to define the filter to be applied: **Running Average**, **Weighted Average** and **Sheppard**, respectively



Sensor	Mode	Freq	Ca	In-P	Quad	Ka	Neg
PROF	VDM	3000	F1	n	F2	F3	0.0
PROF	VDM	6000	F1	n	n	n	0.0
PROF	VDM	15000	F1	F1	F1	F3	0.0

Figure 3.1.1. Selecting the filter and the sensor to be filtered.

3.2. Resampling

This option allows the resampling of the measured line at a different spacing from that used in data acquisition (Figure 3.2.1 and 3.2.2). Lines acquired at different time and at slightly different positions can be put together in the OTHER format. However, the joint inversion of this data set only can be done if a common reference exists for all lines. This can be done resampling the data with spacing 0.0.

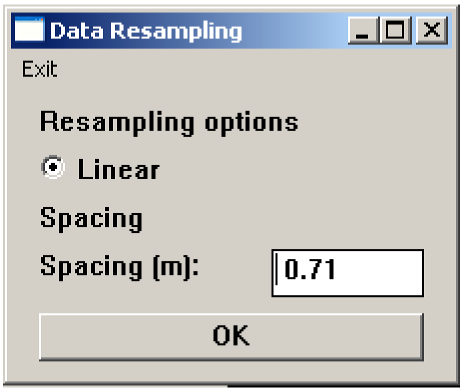


Figure 3.2.1. Resampling data.

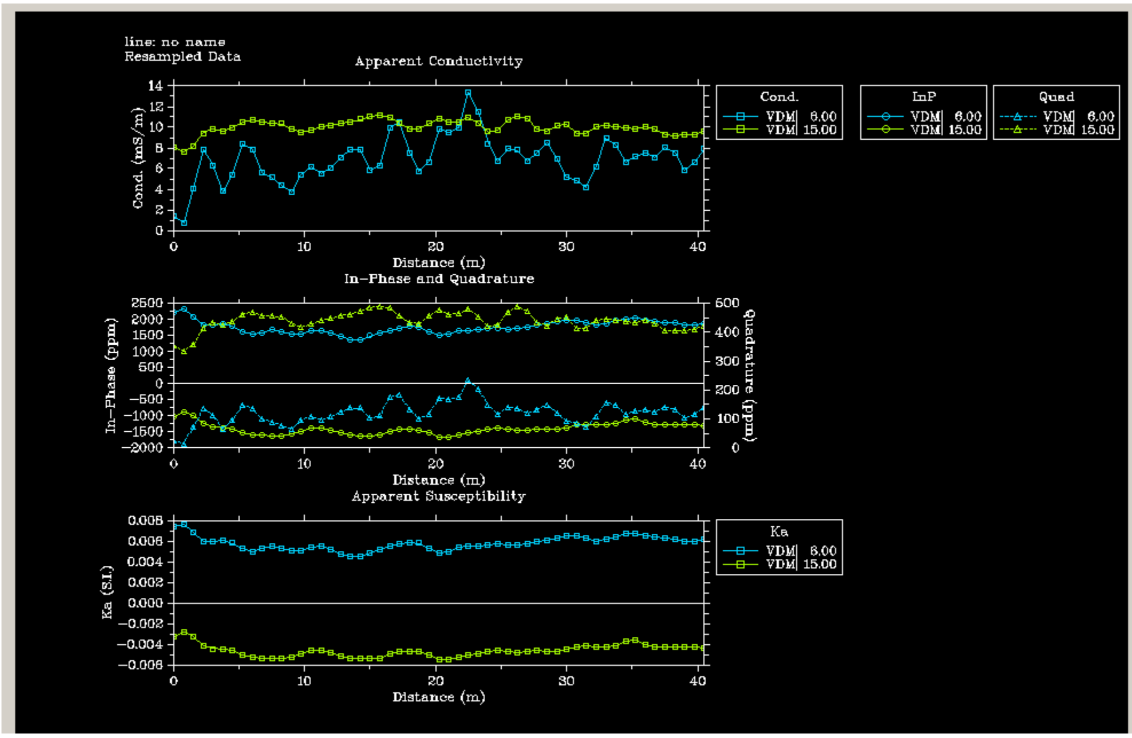


Figure 3.2.2a. Original data.

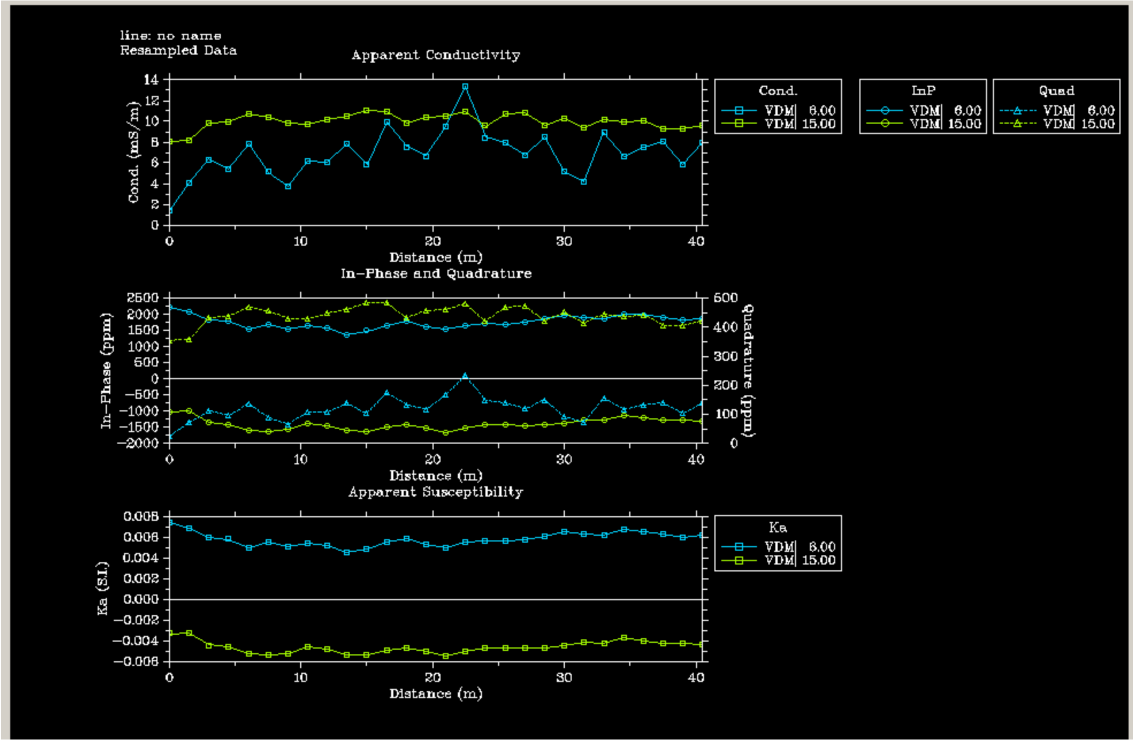


Figure 3.2.2b. Data resampled (spacing = 1.5 m).

3.3. Inversion

To invert OTHER data use the option Inversion (OTHER) (Figure 3.3.1).To invert the data it is necessary to input an initial model using the appropriated entrance in the menu (Figure 3.3.1). Note that in this case the Automatic option is not available due to the variability of sensors that can be used.

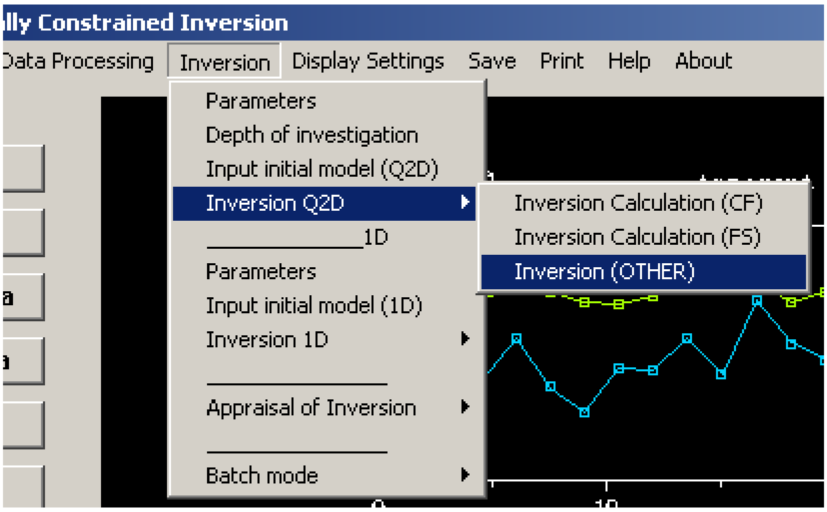


Figure 3.3.1. Inversion of OTHER data with Q2D approach.

To construct the initial model the information gave by the Depth of investigation tool can be useful. The initial values of the magnetic susceptibility can be calculated taking into account that the susceptibility (in ppt) is gave by,

$\chi_a = 0.002\,(In - phase\, in\ ppm)$.

The program will ask to choose the data,

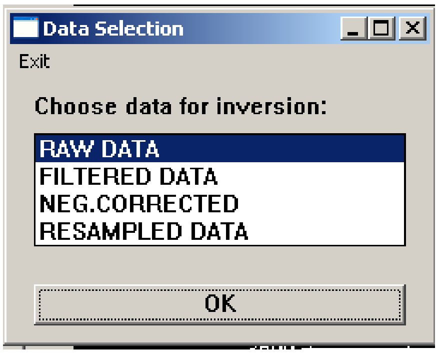


Figure 3.3.2. Data to invert.

And,

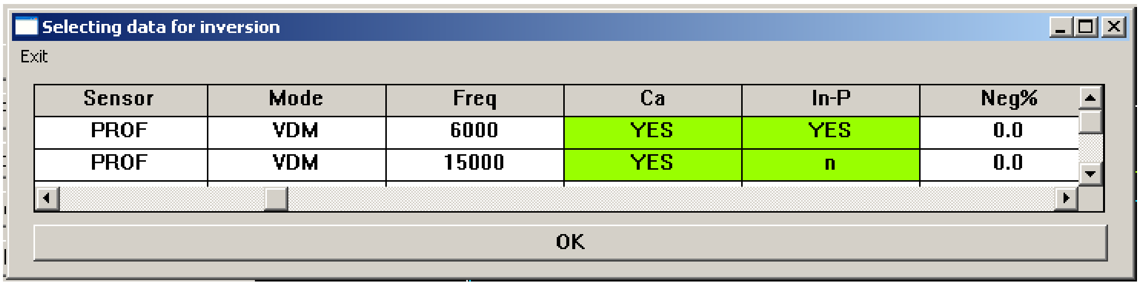


Figure 3.3.3. Data to invert (continuation). YES to be inverted; with N, n or NO the data will not be inverted. The available data will be highlighted in green (in red if there is no data).

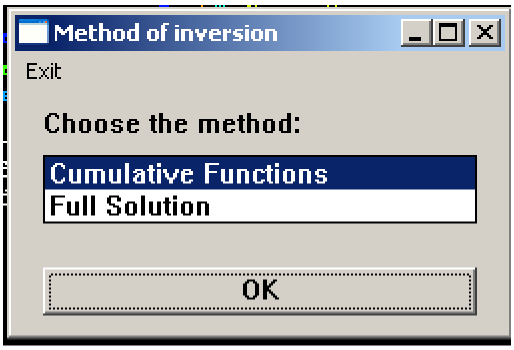


Figure 3.3.4. Choosing the approach (linear or full solution).

4. Formats

4.1. Format of Input data file

The format of the input data file is explained in **Section 9** of this Manual.

4.2. Format of Initial Model

The format for the file containing a 1D initial model (which will be used in the Q2D inversion) is as follows:

NL
D_1, D_2, ….$D_{(NL-1)}$
C_1, C_2, …..$C_{(NL)}$
mS_1, mS_2…$mS_{(NL)}$

Where NL is the number of layers, D_i, C_i amd mS_i are **the depth of the bottom interface** (m), the conductivity (mS/m) and the magnetic susceptibility (mSI or ppt) of the ith- layer.

Example of a 1D model of 5 layers:

5
0.4 0.8 1.3 2.0
3.0 3.0 3.0 3.0 3.0
6.0 6.0 6.0 6.0 6.0

The format for 1D initial models for 1D inversion is similar but should contain the reference to the constraints of each parameter using the symbol F (free parameter) or C (constrained).