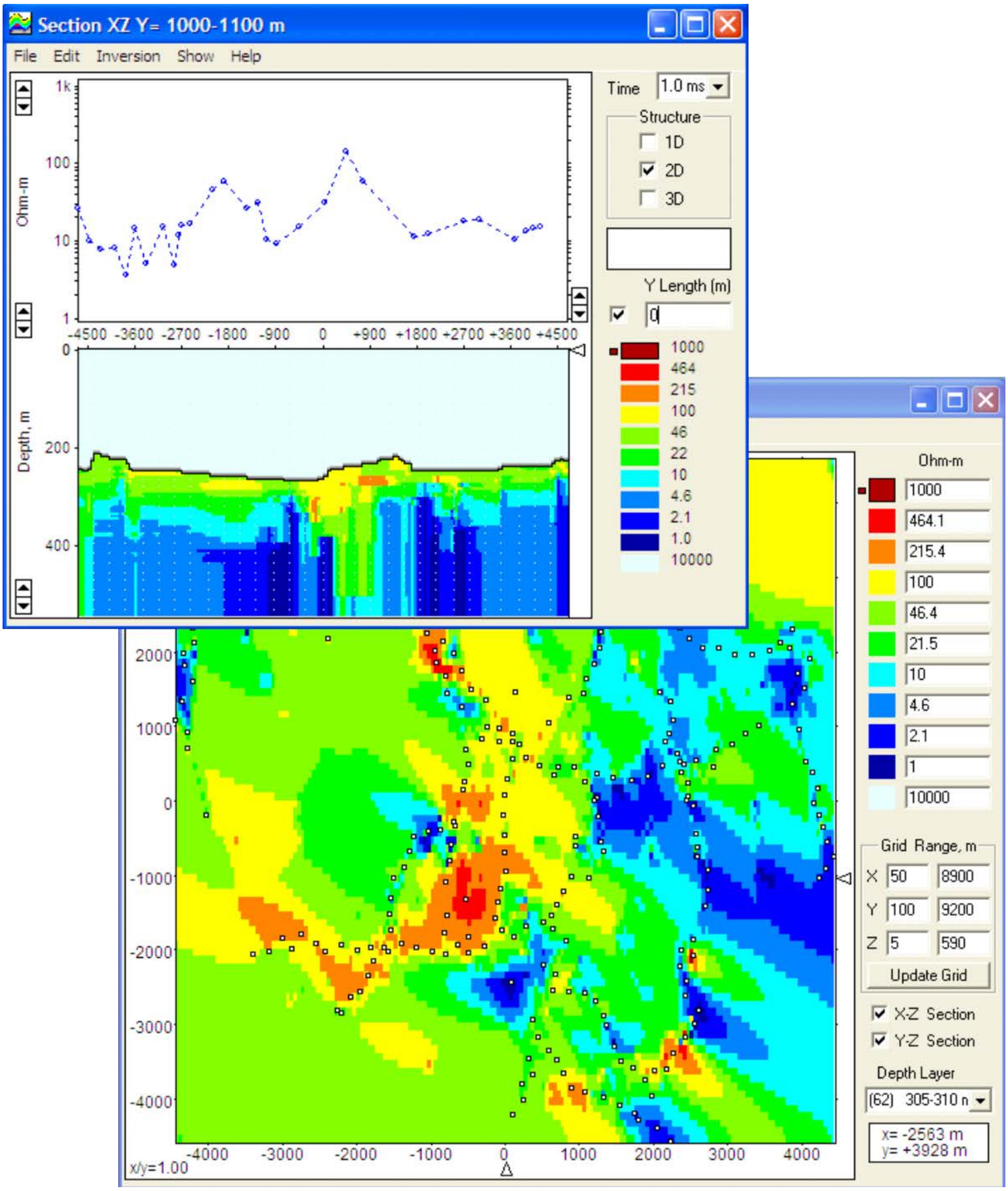
TEM 3D WIZARD
v. 8

User Guide



CONTENTS

Introduction

Method of 3D modelling

The method for the 3D modelling of TEM (Transient Electromagnetic) processes is based on the theory and algorithm developed by Druskin and Knizhnerman [1988].

The 3D problem is solved using quasi-stationary approximation; this approximation is possible when the displacement currents are negligibly smaller than the conduction current. It is valid given the condition

$$\sigma \boldsymbol{E} >> \partial \boldsymbol{D}/\partial t, \tag{1}$$

where $\boldsymbol{D}$ and $\boldsymbol{E}$ are the vectors of the electric induction, and σ is the conductivity of the medium.

In this approximation, Maxwell's equations take the form

$$curl\ \boldsymbol{H} - \sigma \boldsymbol{E} = \boldsymbol{j}_{ext} \tag{2.1}$$

$$curl\ \boldsymbol{E} + \mu \partial \boldsymbol{H}/\partial t = 0. \tag{2.2}$$

Here, $\boldsymbol{E}=(E_x,E_y,E_z)$ and $\boldsymbol{H}=(H_x,H_y,H_z)$ are the vectors of the electric and magnetic fields, $\boldsymbol{j}_{ext}$[A/m^2] is the extraneous current density, μ is the magnetic permeability of the medium, $\mu=\mu_r\mu_0$, $\mu_0=4\pi 10^{-7}$[H/m], μ_r is the relative magnetic permeability, and σ is a scalar function of the coordinates σ(x,y,z).

Equations (2.1) and (2.2) can be transformed into an equation with respect to the electric field vector $\boldsymbol{E}$:

$$curl\ curl\ \boldsymbol{E} + \sigma\mu \frac{\partial \boldsymbol{E}}{\partial t} = -\mu \frac{\partial \boldsymbol{I}}{\partial t} \tag{3}$$

In the TEM-FAST system, the current $\boldsymbol{I}$ is switched off at time t=0, and the function $\boldsymbol{j}_{ext}$ can be presented as

$$\boldsymbol{j}_{cm}=-\phi_0(x,y,z)*h(t), \tag{4}$$

$h(t)=1$ at $t<0$, and

$h(t)=0$ at $t\geq 0$.

Thus, the electric field $\boldsymbol{E}$ for times $t\geq 0$ can be determined from the solution of the Cauchy problem:

$$\boldsymbol{E}|_{t=0}=\phi_0, \qquad \boldsymbol{E}\to 0 \text{ at } |x|, |y|, z\to\infty. \tag{5}$$

Because the electric and magnetic fields in a conductive medium decrease with distance from the source (because of geometrical dissipation and the absorption of the field), far enough from the source it is always possible to restrict the workspace by a prism,

$$0\leq z\leq Z_{\max}\ |x| \leq X_{\max} \text{ and } |y|\leq Y_{\max}, \tag{6}$$

and replace the boundary conditions (5) with (6), which is equivalent to the situation where the work prism is surrounded by a medium with an infinitely large conductivity $\sigma\to\infty$. On the earth's surface, z=0, the normal component of the field E_z is equal to zero because the conductivity of air is extremely small: $\sigma\to 0$.

The entire domain $0 \le z \le Z_{max}$, $|x| \le X_{max}$ and $|y| \le Y_{max}$ is divided into rectangular cells according to the scheme:

$$-X_{max} \le x_1 < x_2 \ldots . x_n \le +X_{max}$$
$$-Y_{max} \le y_1 < y_2 \ldots . y_m \le +Y_{max}$$
$$0 \le z_1 < z_2 \ldots . z_k \le Z_{max}$$

(the working grid size is **n×m×k, where n≤200, m≤200, and k≤200**).

No restrictions are placed on the grid (for instance, $dx_i = x_{i+1} - x_i$) by the provided algorithm, i.e., the grid can be irregular, for example, logarithmic. All the field's derivatives $E=(E_x,E_y,E_z)$ along the spatial coordinates x, y, and z are replaced by their discrete analogues inside each cell.

An application of the well-known finite difference technique can then be used to reduce the system of integro-differential equations to a system of finite difference equations that can be solved by the Galerkin method on the Krylov subspace. The solution is expressed in terms of the eigenpairs of the matrix determined using a simple Lanczos process.

The 3D models of the medium are created on the basis of a model grid that is built as

$$-X_{max} \le \boldsymbol{x_1} < \boldsymbol{x_2} \ldots . \boldsymbol{x_N} \le +X_{max}$$
$$-Y_{max} \le \boldsymbol{y_1} < \boldsymbol{y_2} \ldots . \boldsymbol{y_M} \le +Y_{max}$$
$$0 \le \boldsymbol{z_1} < \boldsymbol{z_2} \ldots . \boldsymbol{z_K} \le Z_{max}.$$

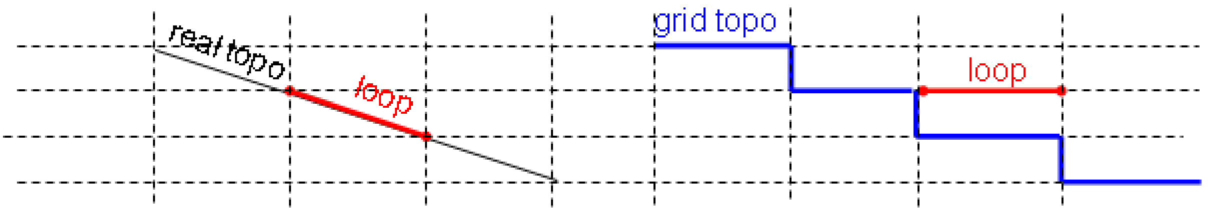
Despite the fact that the algorithm admits the use of an irregular grid, for the convenience of design (drawing), the model grid in the interface is made regular with fixed steps *dx*, *dy* and *dz*. The number of nodes in the grid (**N×M×K**) weakly influences the calculation time because prior to the calculations the mode is automatically simplified; cells with identical resistivities are joined and form an irregular rectangular grid.

Models constructed from experimental data with ten resistivity levels can contain up to 2,000-3,000 cells. However, in complicated geoelectric situations and for large profile lengths, the number of cells can be as large as 100,000-300,000, which somewhat slows the calculations.

The work and model grids do not spatially coincide, which creates a problem when determining the effective conductivity in a work cell. The algorithm uses a special method to calculate the conductivity along the orthogonal *x*, *y* and *z* directions; in fact the conductivity inside each cell is different in the *x*, *y* and *z* directions (macro anisotropic effect): $\sigma=(\sigma_x, \sigma_y, \sigma_z)$.

Because the calculations of 3D models are constructed using experimental sounding data, the problem of an appropriate approximation for the earth surface relief arises. Because the model and work grid are rectangular, it is necessary to essentially decrease the steps (*dx*, *dy* and *dz*) to provide a convenient approximation of the real relief; in addition, we must use high resistivity "air" with a conductivity $\sigma \sim 10^{-4}$ Ohm-m^{-1}. The size of the work grid is thereby sharply increased, ($\boldsymbol{n} \times \boldsymbol{m} \times \boldsymbol{k}$) ~ 100,000-200,000 cells, and the calculation time increases.

The picture shows the position of a transmitter-receiver loop (antenna) located on the surface of a slope (A) and the location of the loop in the grid model (B).



A B

Unfortunately, the algorithm does not permit "A" to be modelled because of accepted limitations on the locations of the receivers and field sources on the insides of grid cells.

Program installation

The program was developed for Windows XP/7/8 x32/64 and is delivered as an executable module (TEM-3D-WIZARD.exe), libraries and drivers. An electronic USB-key is used to protect the user from virus attacks and the unauthorized distribution of the program. The program code is based on OpenMP (Open Multi-Processing) technology and is designed for multi-threaded parallel computing systems with shared memory.

Delivery Set:

1. **TEM_3D_WIZARD.exe** - the main executable file;
2. Three dynamic libraries:

    LIBIFCOREMD.dll
    LIBMMD.dll
    NOVEX32.dll

3. The directory **DRIVERS** with the protection «**GUARDANT**» drivers;
4. The **USB «GUARDANT» key** (dongle); its serial number (s/n) is written in the warrantee and in the About window of the main menu (for example, **2C48-0000**).

5. The standard Windows libraries

    MSVCR80.dll
    MFC80.dll
    KERNEL32.dll
    USER32.dll
    GDI32.dll

must be located in the directory **..\WINDOWS\SYSTEM32**

The installation of the program consists of opening a new directory (for example, 3D- TEM) and coping of all the available components (4 files and Drivers section) to that directory.

After connecting the key and installing the drivers (run DRIVERS\instdrv.exe), the program is ready for operation. When the «**GUARDANT**» driver is correctly installed, the indicator on the USB key glows. The program is ready to start.

ATTENTION!

Each USB key has its own unique number. In case of loss, a replacement cannot be produced. If the key is damaged (mechanically or electrically), the producer can replace the program’s key with another key. The replacement conditions can be found in the guarantee document.

Part 1. The interface for constructing a medium's model

Main window menu

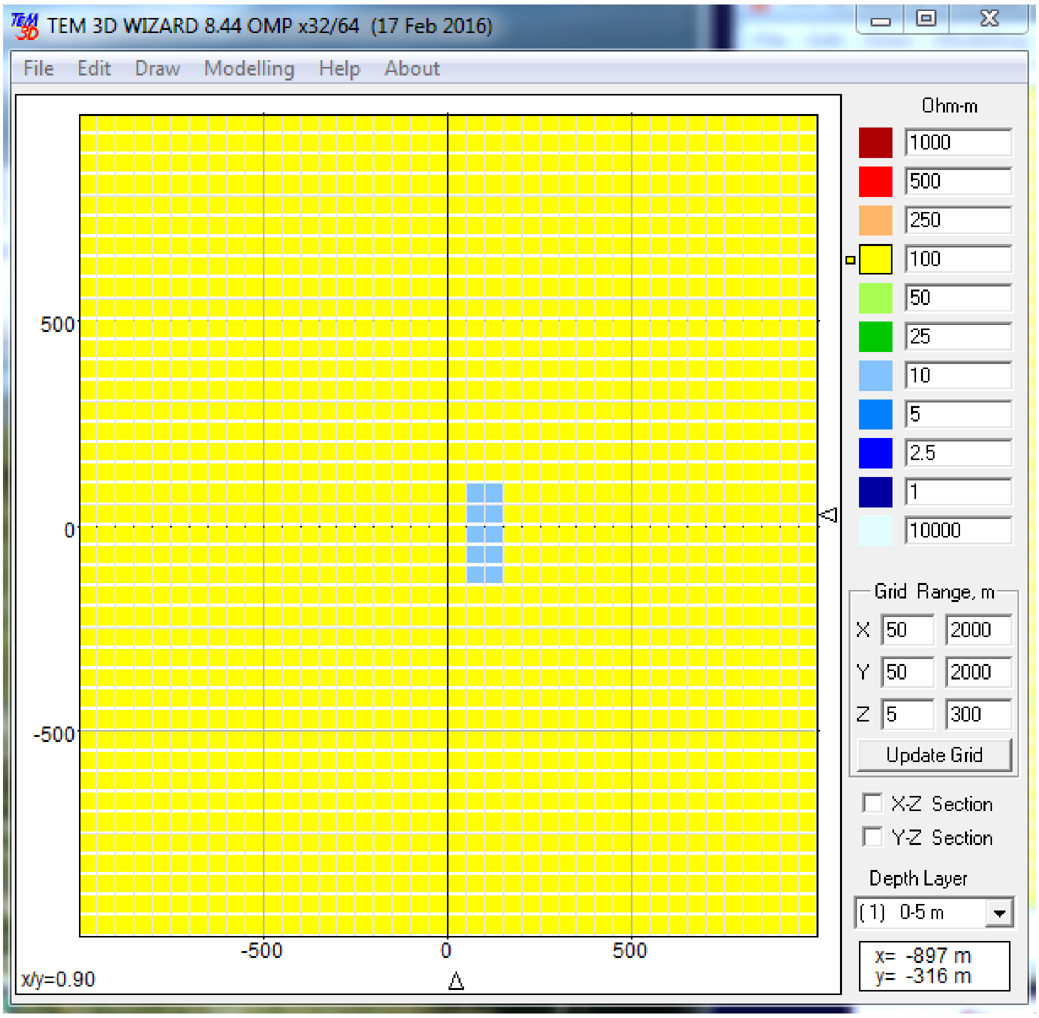


Fig. 1.1. The TEM 3D WIZARD main window. The work map is the XY plane

The Grid Range, m, is the table for setting the grid's parameters to create the medium's model.

Here, the left column (Dx, Dy, Dz) of the table is the size of the steps along the X, Y, and Z grid directions, and (Xmax, Ymax, Zmax) on the right side of the table is the size of the map (the size is in meters). The limitations of the parameters are

Nx=X_max/Dx - even number, Nx≤300,
Ny=Y_max/Dy - even number, Ny≤100, and
Nz=Z_max/Dz - integer number, Nz≤300.

If the specified Nx, Ny or Nz do not correspond to the stated criteria, the program corrects either the grid size X_max, Y_max or Z_max or modifies Dx, Dy, or Dz.

Ohm-m - the colour scale of the resistivity.

A single click on a coloured square box activates that colour; activation is indicated by a marker on the left side of the square. The lowest square box in the sky-blue colour is used for the air resistivity; it is applied when modelling a surface relief. We do not recommend changing the colour or resistivity (10000 Ohm-m) of this box.

Double clicking the square box opens a standard colour dialogue, which allows the colour of any box to be changed.

Double clicking on the <**Ohm-m**> heading sets the max/min scale resistivities.

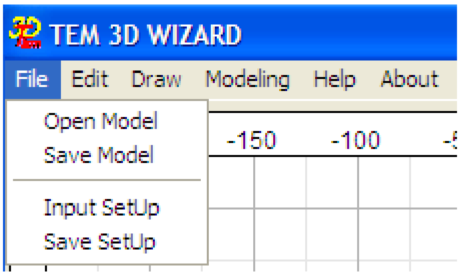
Depth Layer – set the number and upper and lower boundaries of the layer, i.e., the layer shown in the XY map at the moment

X=979 m Y=-697 m – the coordinates of the cursor position on the XY map

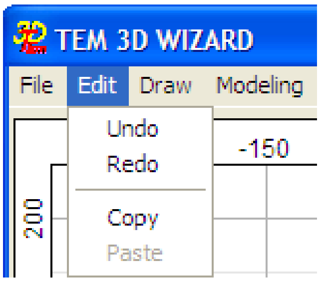
X-Z Section – the switch for opening the section along the X-axis

Y-Z Section – the switch for opening the section along the Y-axis

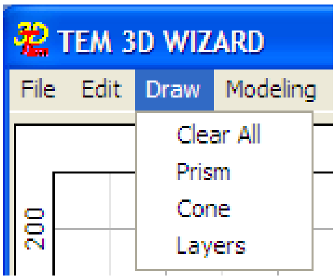
The triangle markers on the left hand side of the XY map indicate the locations of the X-Z and Y-Z sections. The markers can be moved either using the mouse (keeping the left button pressed) or with the arrows (→) (←) (↓) (↑) on the keyboard. The **Page Down** and **Page Up** keys change the position of the XY plane along the Z-axis (change of depth).



Open Model - load a model created earlier and saved to file *.3Dm
Save Model - load the current model to a file *.3Dm
Input SetUp - load the parameters of the grid created earlier and saved in file *.stp
Save SetUp - save the current parameters of the grid in a file *.stp



Undo-Redo - restore the design one step back or ahead
Copy - copy the current design
Paste - insert the copied design in the specified position

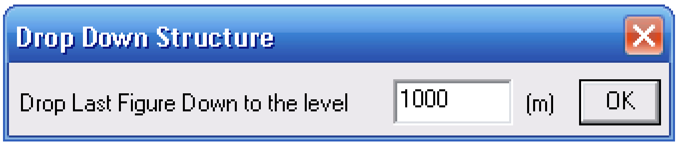


Clear All – clear the entire XYZ block
Prism - insert a prism
Cone - insert a cone
Layers - insert a layered model
Modelling - open the window for field calculations in the created model of the medium
Help - help and information
About - program serial number

Drawing a model on the XY map

1. Set the layer for drawing (**Depth Layer**).
2. Single click the cell to set the cell colour according to the current palette
3. "press→move→release" with the left mouse button to draw a line. All the cells intersected by the straight line connecting the first and last points are painted over.
4. Continuously pressing the Shift button with "press→move→release", use the left mouse button to paint the cells inside the drawn rectangle.
5. Clicking the right mouse button on the map allows the last drawn object (line, cell or rectangle) to be copied to the underlying layers.

Example: To paint over the entire map with any colour (draw a rectangle), press the right mouse button, and you will see the window:



Press the OK box, and the whole model up to h≤1000 m depth is filled by the selected colour, i.e., a uniform half-space is created.

XZ and YZ Sections

1D is the mode for drawing horizontal layers. Clicking on any cell creates a horizontal layer filled with the current colour. When you hold down the **Ctrl** button, the horizontal layer flows around the cell that was previously filled with any colour - Fig. 1.2.

2D is the mode for drawing quasi two-dimensional structures. Like drawing on the horizontal XY map, it is possible to draw a plane figure on the *XZ* or *YZ* maps. When the mouse key is released, the distance along the Y-axis that should reach the figure is requested (Y Length (m)) - Fig. 1.3.

3D is the mode for drawing 3D structures; only "plane" cells lying on the XZ or YZ maps are painted. As in the **2D** mode, lines and rectangles can be drawn.

2-d Screen – Open a window with an additional screen.

All the possible functions are defined in **Help.**
In particular:
Insert - key to insert the selected layer (active) of resistivity ρ (here ρ=31 Ohm-m) at a depth corresponding to the position indicator of the depth (here h=175 m);
Delete - key to remove a layer at a depth corresponding to the position indicator of the depth (here h=175 m).

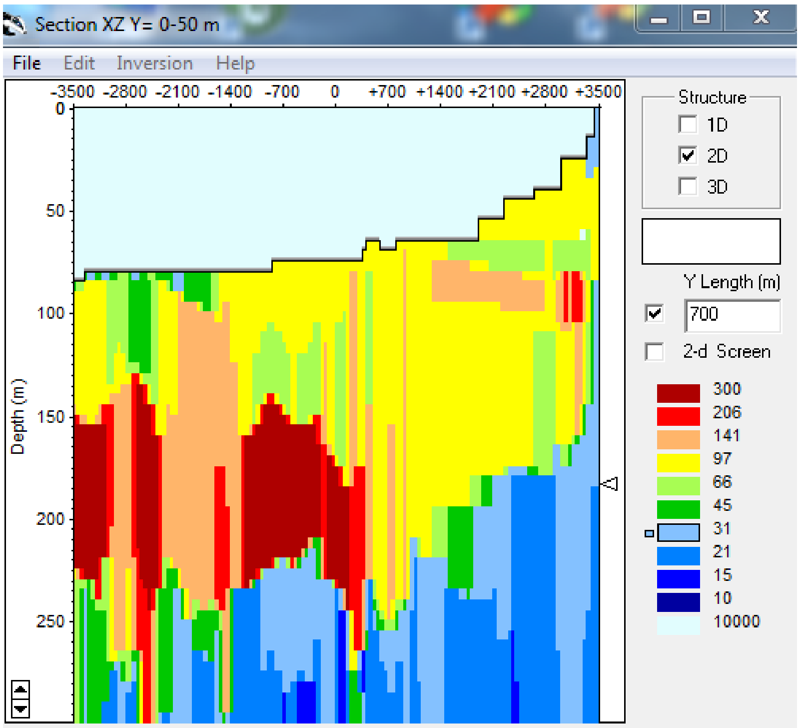


Fig. 1.2. The *XZ* section (Y=-0-50 m) of a 3D model with a day surface relief constructed from experimental TEM responses

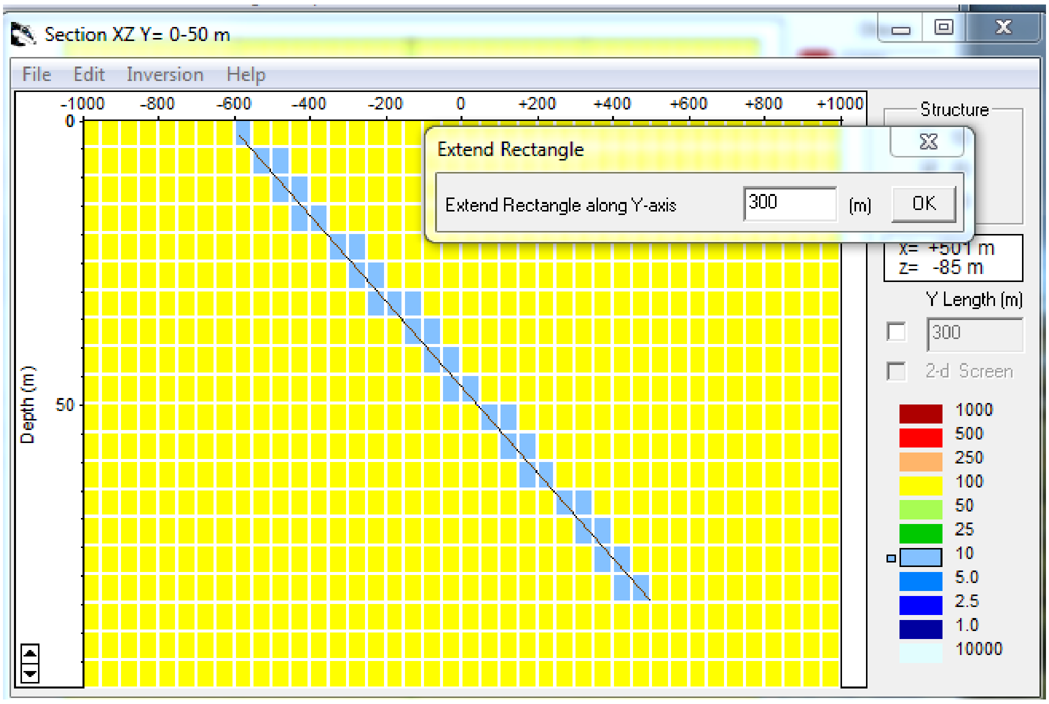


Fig. 1.3. Design of a sloping dike with ρ=10 Ohm-m and length L=300 m along the strike (axis Y).

Help window in the XZ Section

VERTICAL SCALE

Page Up/Down - Adjust Scale

Double click <Ohm-m> - Switch Resistivity-to-Signal

Z-SLIDE POSITION

Up Arrow   to Shift UP

Down Arrow to Shift Down

1D STRUCTURE MODE

Left_button Click   --> fill selected Area with current color

Left_button+CTRL Click --> fill selected Area but save living structures

2D STRUCTURE MODE

Left_button and Move cursor --> Draw Line

Shift+Left_button and Move cursor --> Draw Rectangle

Y-Length Window --> Extend Last rectangle along Y-axis

Switch ON   to Define Y-Length Before Drawing

Switch OFF to Define Y-Length After   Drawing

2D THRUST AND FAULT

Mark Start point over the surface by Left button

Move cursor Down and Release button at Finish point

Define Displacement (shift) by Fault and Active Block of Section

ACTIONS

Alt+S - Use/Ignore Surface topography

Alt+G or Click Right button - switch Grid mode

Alt+L - Connect/Disconnect profile sets

Alt+E - Hide/Show Error bars

Alt+T - Hide/Show All Controls to copy screen

Alt+A or Double Click on <Y-axis> - switch Depth/Altitude mode

Alt+Y   - Rotate Model by 90 degrees

Alt+N   - Hide/show Time Labels

Double Click at <Time label> to Hide Response

Alt+1,2,3 or 4 - Hide/Show Profile data

F1-F9 and Alt+0 - Hide/Show Responses No 1-10

Alt+[>] - Shift Profile data to the Right

Alt+[<] - Shift Profile data to the Left

Double Click area 'Distance' - to start x-scale labels from'0'

Alt+X - Change x-scale style

Insert key - Insert layer

Delete key - Delete layer

PROFILING and INVERSION

Alt+M - Calculate 3D Profile responses

Alt+C or Right button Click at model - Calculate 1D Profile responses

Alt+W - 1D Inversion the Whole of Selected Area

Alt+P - Make 1D Point Inversion for Profile

Alt+I - Make 1D Point Global Inversion for Profile

ALT+D - Show investigation depth

ALT+@ - Show TR-Rec antennas position

ALT+# - Show antennas labels (names)

Double Click on <Profile point> - Show Response vs time

Double Click+Shift on <Profile point> - Calculate 3D Model

Double Click+Ctrl on <Profile point> - Make 3D INVERSION

Alt+%   - Hide/show RMS error

ALT+(- Labels: Use () style or Comma style

ALT+O   - Use Greek Omega in (Ohm-m)

In this case, the figure has been stretched from -150 m to +150 m along the Y=0 axis in the XY plane. The strip appears in the layer h=50-55 m (Fig. 1.4):

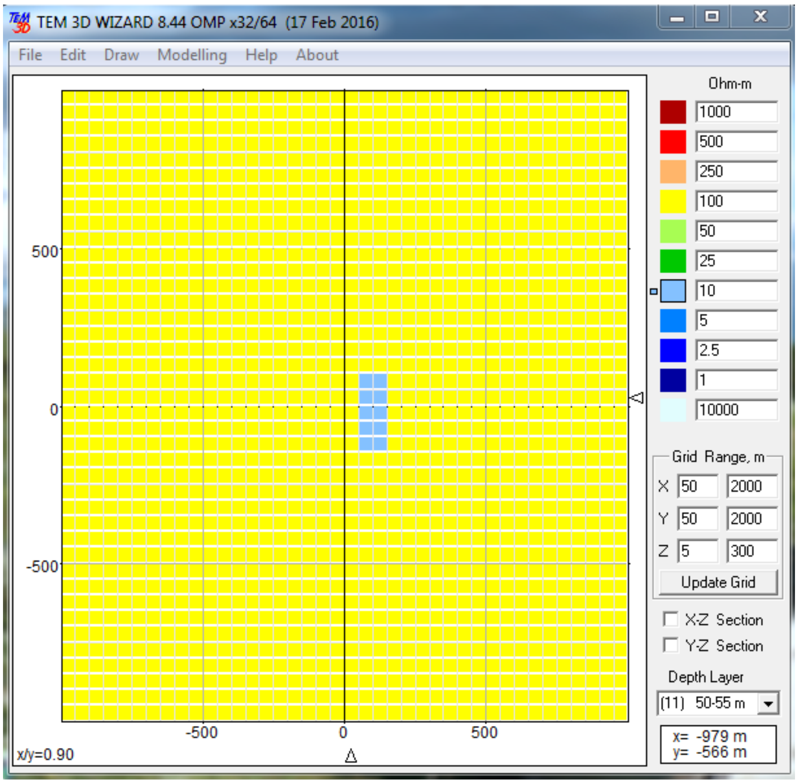


Fig. 1.4. The projection of the inclined dike (Fig. 1.3) on the horizontal XY plane (h=50-55 m for the layer).

The parameters **Y Length** or **X Length** can be fixed in the box so the program will not ask again for this option when drawing a regular structure.

The painted figures "stretch" along the axis perpendicular to the plane of the plate (XZ or YZ) and span the interval [-Y_length +Y_posit, +Y_length +Y_posit] or [-X_length +X_posit, +X_length +X_posit], where X_posit and Y_posit is the cut position defined by the triangular markers on the XY map.

The vertical scale can be changed using the **Page Up** and **Page Down** keys or using the buttons on the bottom left of the window.

To view the sections in the XY plane, change the position of the triangle depth marker on the left side of the map using the ↑↓ arrows. Occasionally, for better viewing, it is expedient to hide the grid; you can achieve that using the key combination **Alt+G** or by pressing the right mouse button.

Drawing slips and faults

Draw the start (top) and end (bottom) points of the slip on the XZ or YZ section using the mouse cursor as shown in Fig. 1.5.

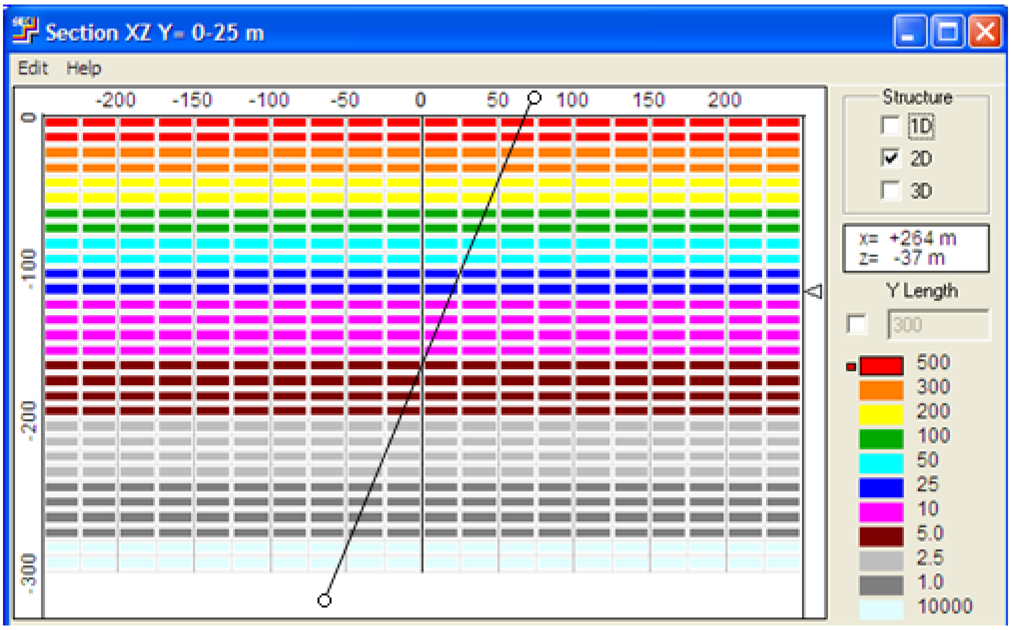


Fig. 1.5. Drawing slips and faults

Release the mouse button, and the window shown in Fig. 1.6 will request the additional parameters.

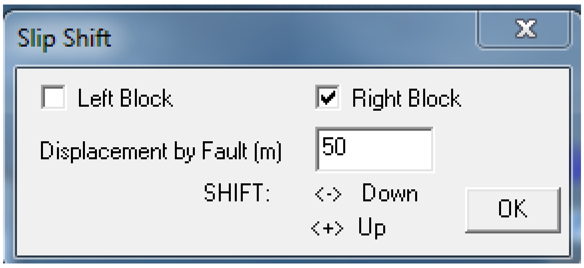


Fig. 1.6

The sign <+> in the "Slip Shift" window shifts the selected block **Up**, and < - > shifts it **Down**. After pressing OK, the right side of the slip (fault) is shifted up along the slip; the result appears on the screen (Fig. 1.7).

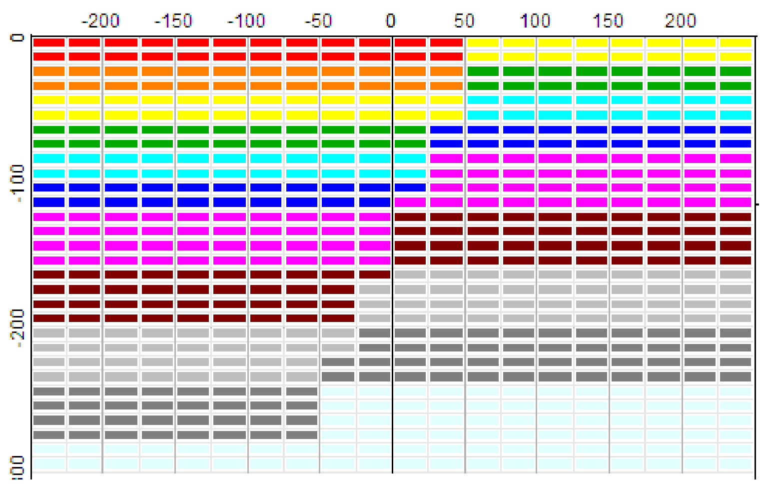


Fig. 1.7. A horizontally layered section with a fault

Drawing layered structures

Draw→Layer opens the window (Fig. 1.8) for drawing layered structures.

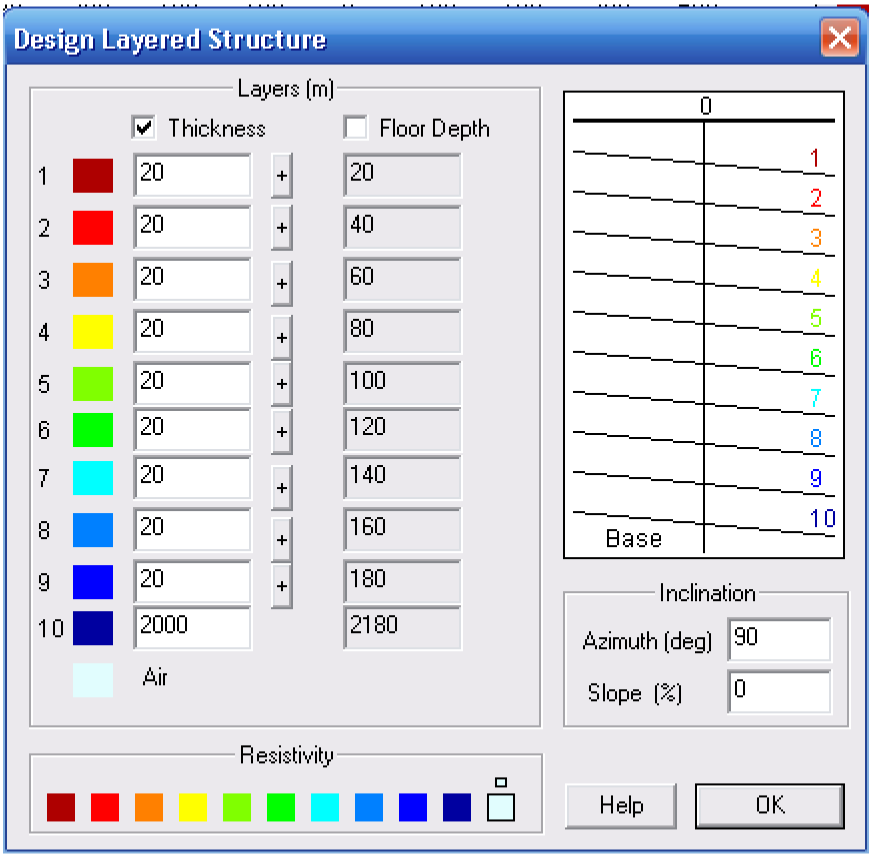
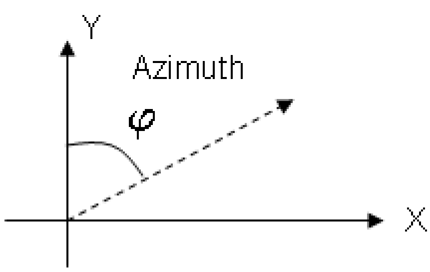


Fig. 1.8. Drawing layered structures

One can change the colour of the layer; choose a colour from the “Resistivity” scale (the colours of the markers denote the corresponding position) and click on the colour rectangle in the vertical layer scale.

The style of setting the layers’ parameters according to their thickness or depth can be changed. The inclination of the layers is determined by the **Slope (%)** and **Azimuth (deg)** parameters.



Drawing prisms and cones.

Draw→Prism or **Draw→Cone** opens the window for drawing prisms and cones.

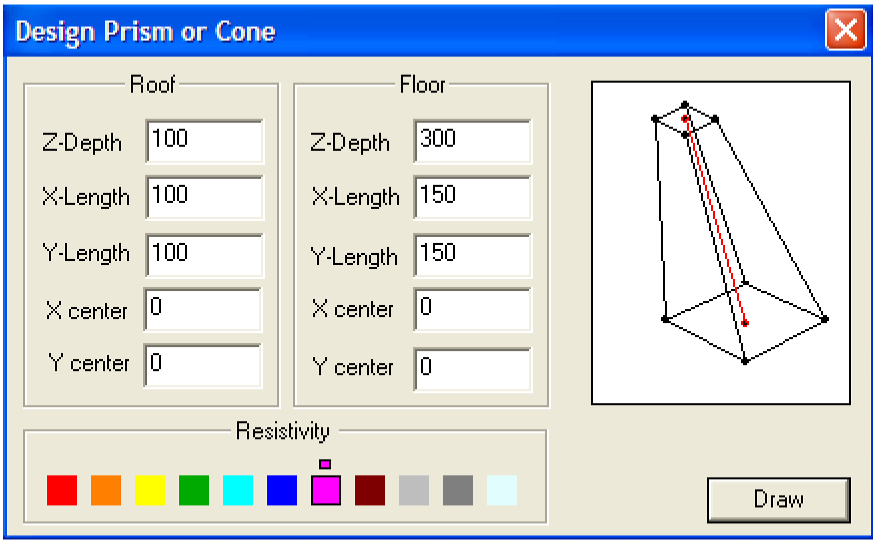


Fig. 1.9. Drawing prisms and cones

The colour of the created figure is determined by the **Resistivity** rectangle scale (purple in Fig. 1.9). The quality of the drawn figure depends on the grid's parameters. When **Draw** is pressed**,** the figure is superimposed on the existing model in the workspace XYZ.

For example (Fig. 1.10), a vertical rectangular prism with a resistivity of 5 Ohm-m is "inserted" in the section with inclined layers (at the section, the grid is hidden using **Alt + G**).

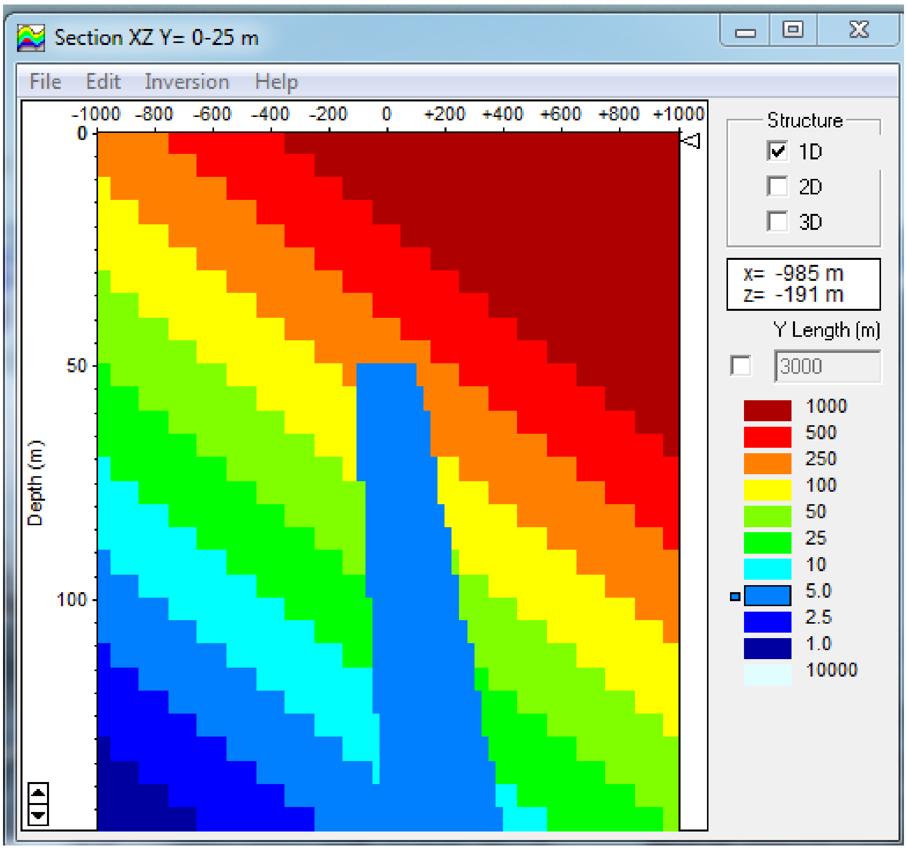


Fig. 1.10. A prism with ρ=5 Ohm-m in a layered inclined structure.

Constructing medium models from experimental data

2D structures

To construct 2D models of the medium, it is necessary to first create 1D inversion files (int-files) from the experimental data (tem-files) and either a **TEM-RESEARCHER** (**TemRes**) program or transformations files (psc). In Tem-Res v. 8 (2008 or later), one can create a *.sec file that combines -tem, -psc and -int files (see the description of the TEM/INT/PSC/SEC formats in **TemRes**).

In the **Section XZ** window, it is necessary to open the **File→Input Observed Data** menu and select the file that contains information on the research profile or territory. It can be a PSC, SEC or INT file; a map of the location of the sounding points will be shown on the screen (Fig. 1.11).

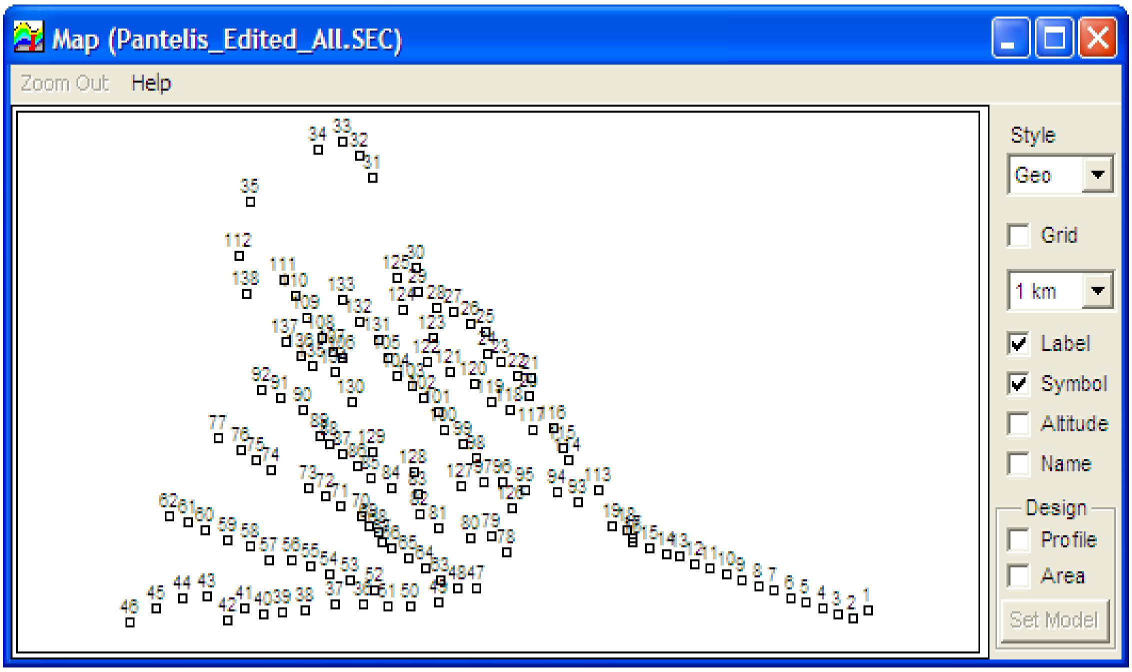


Fig. 1.11. TEM-FAST sounding point location map (*.psc, *.int and *.sec files)

Activate the **Profile** switch in the **Design** section and mark the points on the map that should be included in the analysed section (click the left mouse button on the square that denotes the TEM-FAST antenna loop). To complete the construction of the profile, double-click any blank space on the map; the selected points are coloured red.

You can also use another method. Using the mouse cursor, draw a broken line that passes as close as possible to the desired points on the map (Fig. 1.12A). Each line segment begins and ends by pressing the left mouse button. As soon as the last line segment is finished, double-click the left mouse button, and the profile is displayed on the map in red, as shown in Fig. 1.12B.

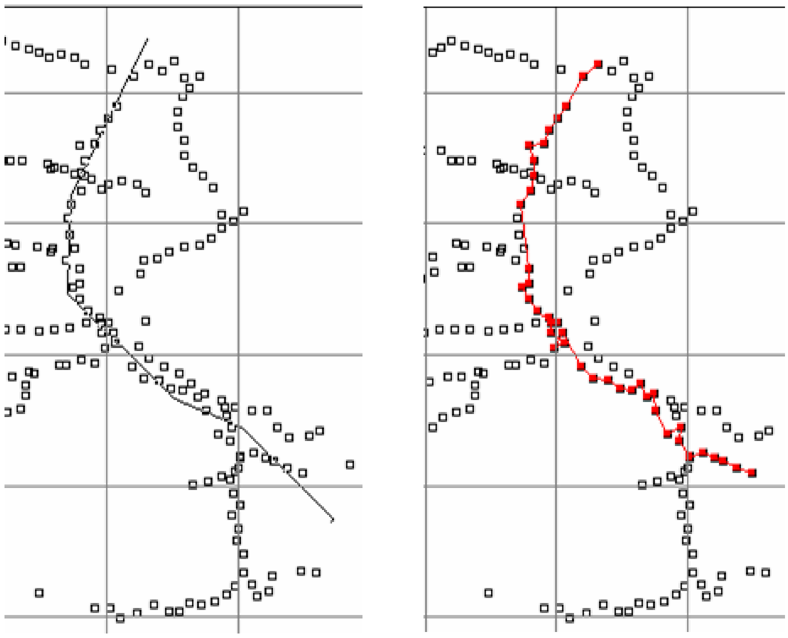


Fig. 1.12. Construction of a profile along a broken line

The program automatically "captures" all the measurement within a radius of 10 pixels (!) from the drawn broken line (use **ZOOM** to increase the resolution in the profile construction - see the **Help** window).

If all the necessary points are included in the profile, press the **Set Model** button. If the attempt was unsuccessful (which is often the case for complex configurations), you must **turn** the **Profile** switch **off**, then **turn** it **on** again and make another attempt.

At a relatively simple location of the sounding points, the program will automatically construct the profile, including all the points (Fig. 1.13).

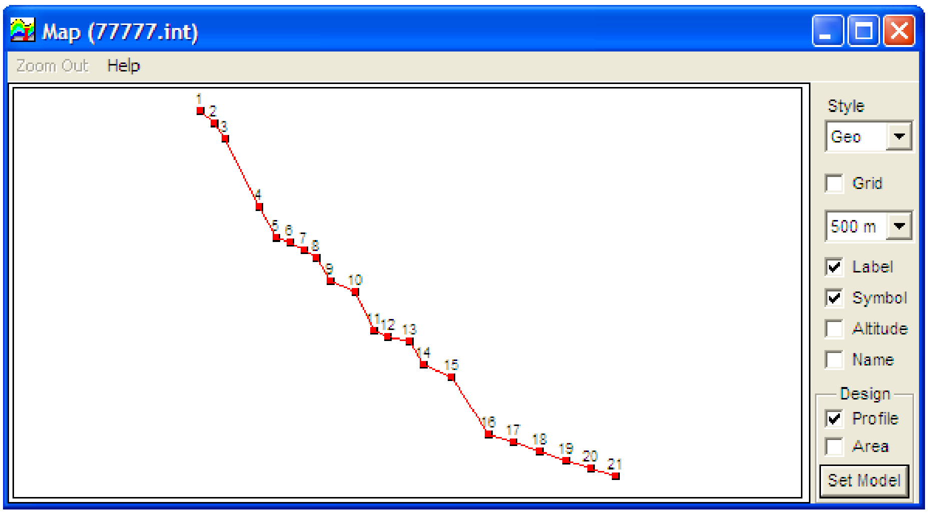


Fig. 1.13. Automatic construction of the profile after turning the **Profile switch on**. The numbers on the points correspond to the number of the sets in the initial files. By activating the **Label**, **Altitude** and **Name** checkboxes, the captions of the sets can be changed.

After successfully constructing the profile and clicking the **Set Model** button, the window **Section XZ** appears (Fig. 1.14).

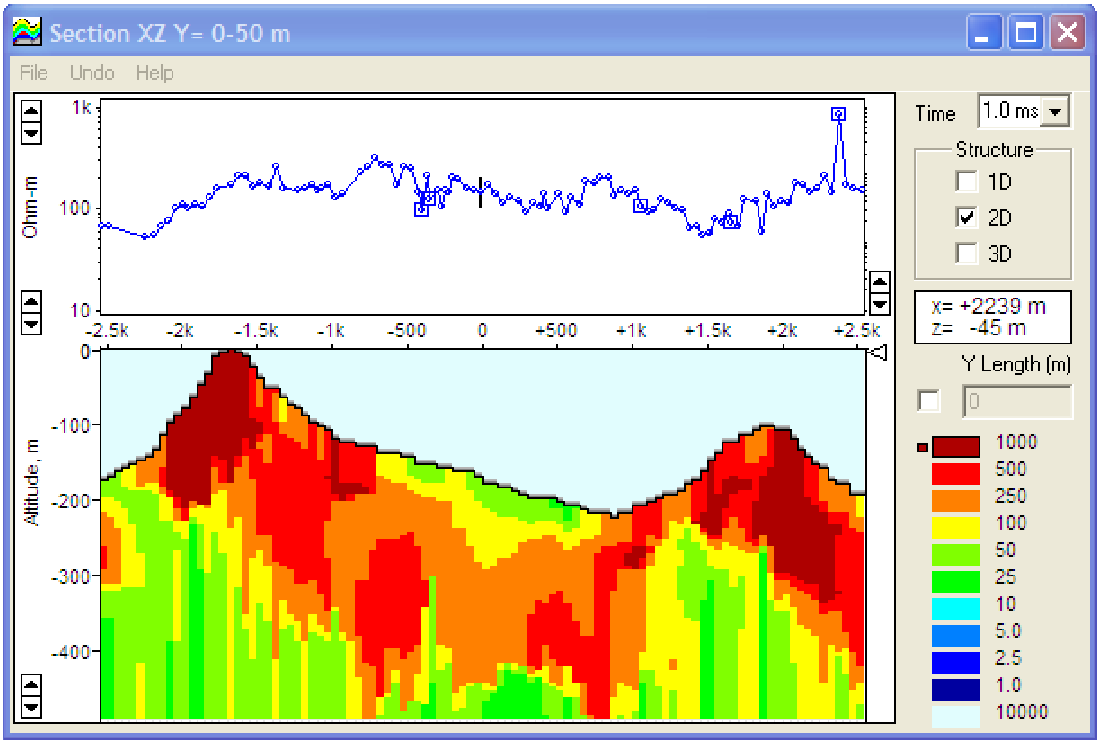


Fig. 1.14. The section **Section XZ** with the model based on experimental data (1D inversion - int files)

When working with an SEC-file that contains transformation data and the results of a 1D inversion, one must remember that the section will use the transformation if the menu file dialog is set to «**Transformation *.psc *sec"**. If «**Inversion * .int * sec"** is selected, the model will be built according to the 1D inversions.

If you open a TEM-file or PSC-file that does not contain the 1D inversion data, the program will be ready to make the transformation $\rho(h)$ itself and will ask for the parameters for this procedure, as shown in the window in Fig. 1.14-1.

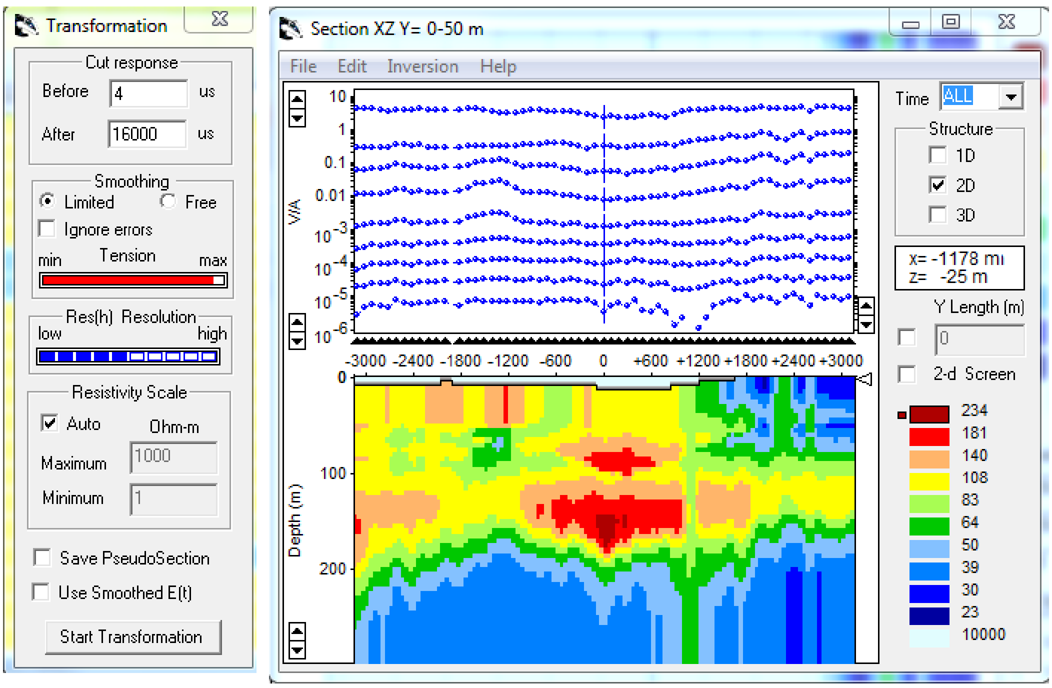


Fig. 1.14-1. TEM data transformation parameters (when opening PSC and TEM files) and a profile built on the transformation $\rho(h)$.

These parameters are set like those in the **Tem-Researcher** program. In addition, there is an opportunity to save the TEM smoothed data to a file and use them for further analyses.

On the right panel in Figure 1.14-1, a 2D section of a 3D model is shown, which was constructed from the "raw" TEM (or PSC) data.

As seen in Figs. 1.14 and 1.14-1 the experimental data are transformed to the discrete model grid, and the cell's size (Grid) and the gradation of the resistivity are defined in the main window. If the profile is very long and the number of cells exceeds the permissible limit (Nx>300 or Nz>300), the program will automatically resize the cell.

The relief of the day surface is indicated by the black line, and the air space is demarcated by the sky-blue colour. The highest point on the profile is taken as the zero altitude. To obtain data on the actual altitude, press **Alt + A**.

The resistivity scale **Ohm-m** or the signal scale **V/A** is located in the window's top panel. Double clicking the scale caption switches the apparent resistivity scale to the signal level. In the upper right corner, the **Time** window is used to select the delay time **t** used to construct the *E(t)/I* profile or *ρ(t)*. Negative values of *E(t)/I* or *ρ(t)* are bordered by squares.

The 2D model of the medium that has been constructed can be edited using the previously described methods.

Profile calculations are performed in the **Modeling** window, and the results are displayed in the **Profile** and **Section XZ** windows. Thus, we can compare the 3D modelling results with the experimental data (Fig. 1.15).

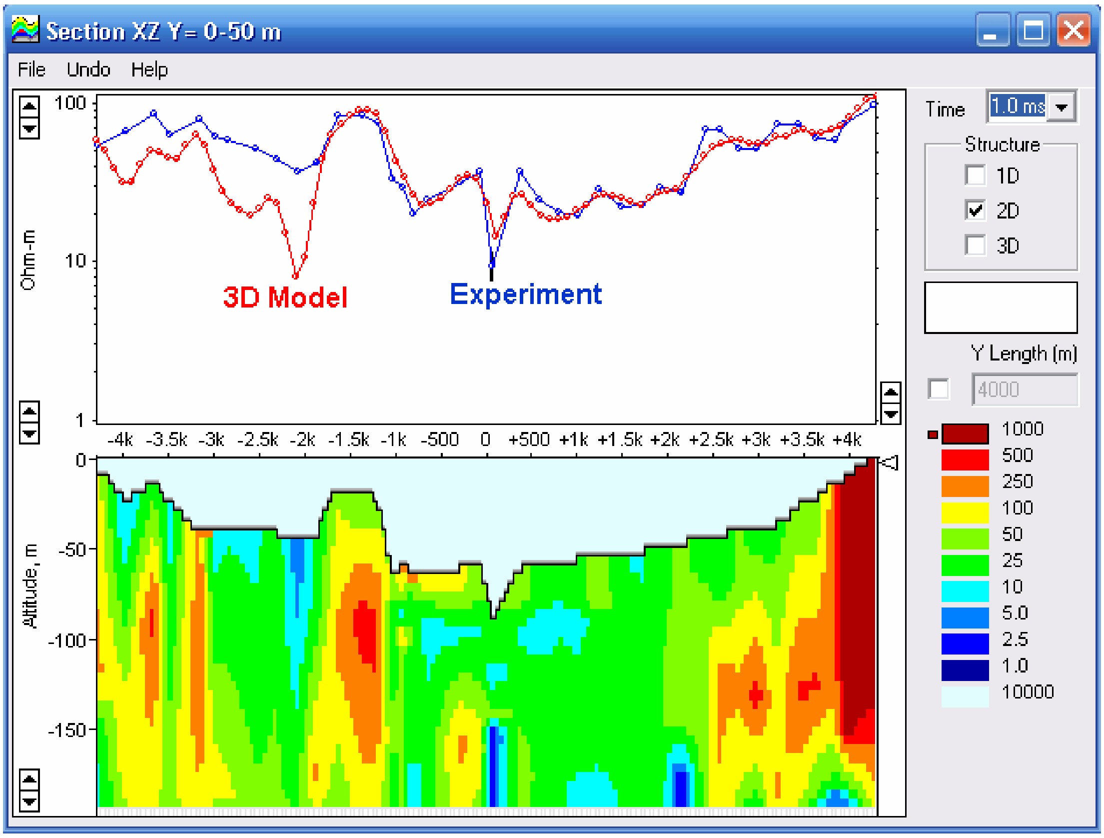


Fig. 1.15. The medium model constructed using the experimental data and the profile of the experimental (blue curve) and model (red) data in the form of the apparent resistivity *ρ(t)* at time *t*=1 ms

The **Section XZ** menu contains the following commands:

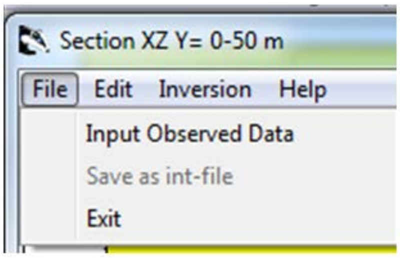


Fig. 1.16. Section XZ menu

Input Observed Data – load the experimental data. The possible formats of the data are
TEM-FAST data (*.tem, *.int,*.sec,*psc)
Transformation data (*.psc, *sec)
Inversion data (*.int, *sec)
Save as int-file (TR format) – save the inversion data in an int-file
Edit - return one step back or one step forward when drawing a model
Inversion – open the Inversion window

To compare the experimental and model $\rho(t)$ or $E(t)/I$ responses, click twice on a corresponding marker (point) in the upper graph (Fig. 1.17).

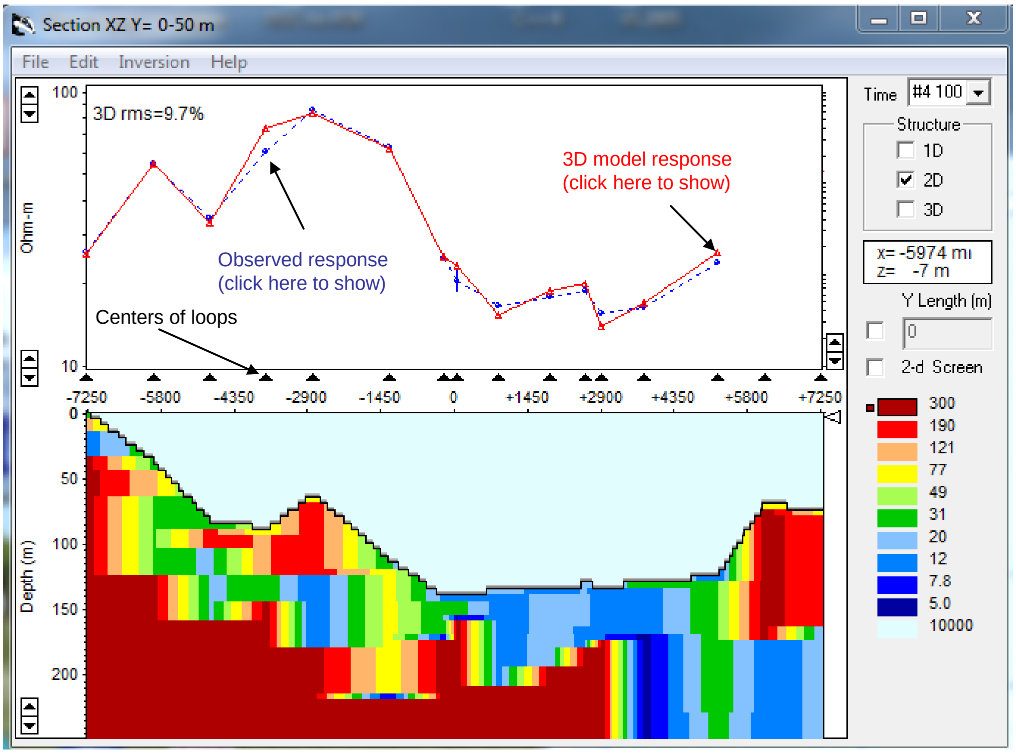


Fig. 1.17. The experimental and model data comparison window (transient TEM responses vs. time)

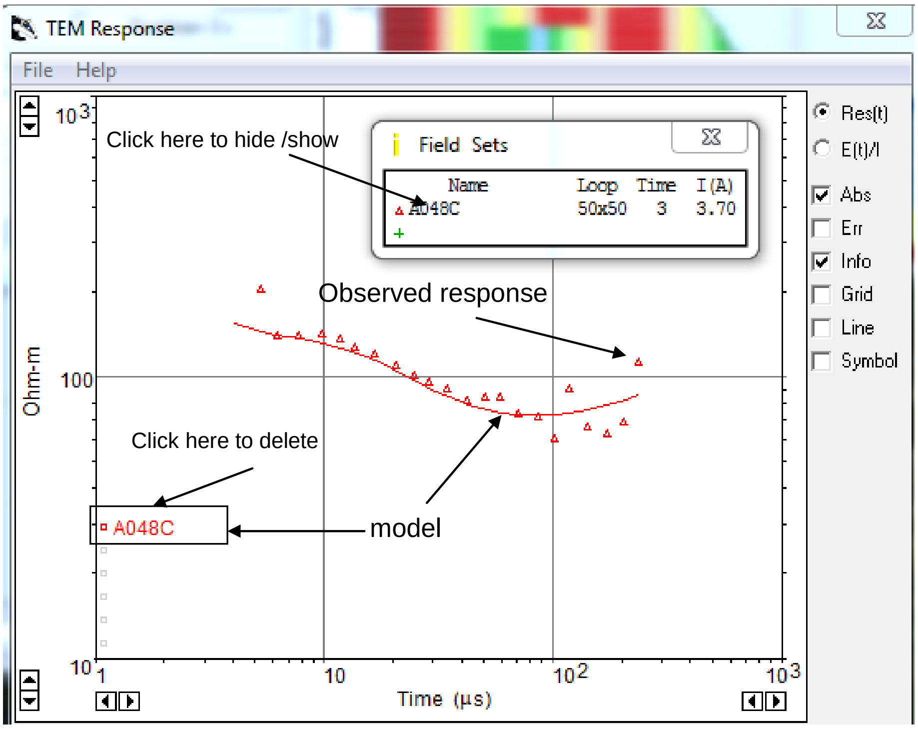


Fig. 1.18. The experimental and model transient TEM responses

3D structures

If you have array data in the form of TEM-INT-PSC-SEC files, you can construct a 3D model of the medium. After loading the corresponding file, select the **Area** option in the **Design** section and mark a rectangle to determine the X-Y boundaries of the 3D structure (*draw while holding the left mouse button down*). After clicking the **RIGHT mouse button**, the data sets are painted a red colour, and the **Set Model** box becomes active (Fig. 1.19). To select all the sounding points, press **Alt+A.**

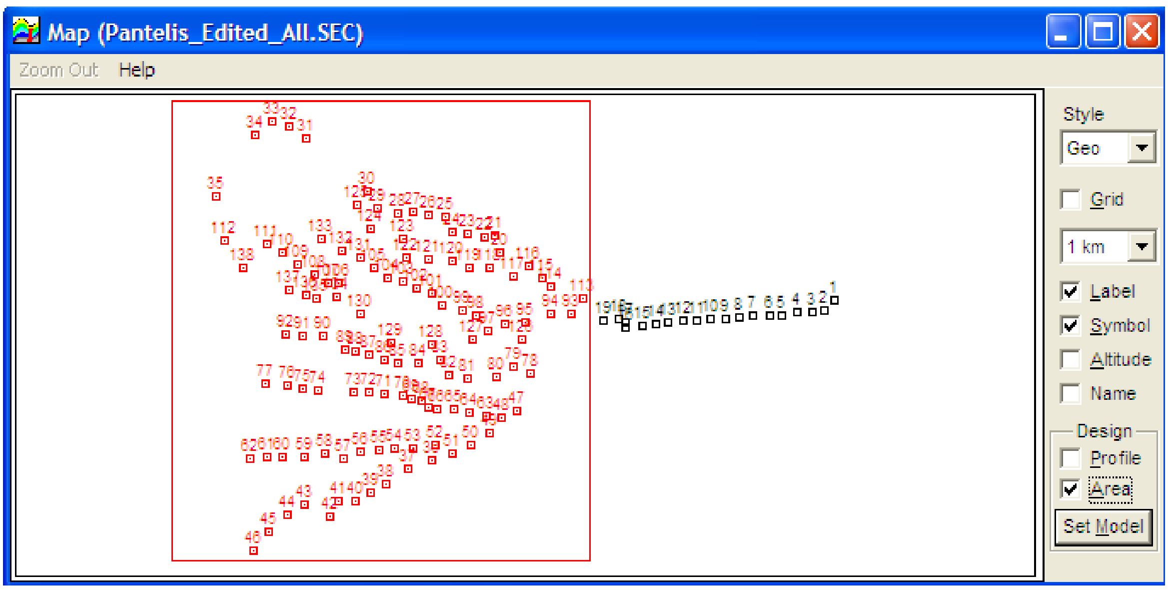


Fig. 1.19. Construction of a 3D model using experimental data. Selection of the area.

It is possible to edit a 3D modelling region by activating the **Area** box and clicking on the sounding set point; the change in its colour indicates that the set has joined or been deleted from the modelling area.

After activating **Set Model,** the program begins to construct the 3D structure; this procedure requires some computational time. The interpolation of the resistivity $\rho(h)$ from the INT or PSC files conforms to the following rules.

1. The interpolation is produced over the layers $i \cdot dz \geq z > (i+1) \cdot dz$, $(i=0,1,2,\ldots,N_z-1)$.

For any (x,y) point with coordinates of the model grid $\boldsymbol{R}$ lying within layer z, the three nearest points with coordinates (x_1,y_1), (x_2,y_2), and (x_3,y_3) and resistivities $\rho_1(x_1,y_1)$, $\rho_2(x_2,y_2)$, and $\rho_3(x_3,y_3)$ are selected.

In the 3D space ($\boldsymbol{X}$, $\boldsymbol{Y}$, $\boldsymbol{\rho}$), the plane $\rho = A*x+B*y+C$ passing through the three points ρ_1, ρ_2, ρ_3 is determined. The resistivity in the (x,y) cell is calculated according to the foregoing formula when the point $\boldsymbol{R}(x,y)$ lies within the triangle defined by (x_1,y_1), (x_2,y_2), and (x_3,y_3). In the cells that remain “empty”, the resistivity is calculated according to item 3 as the mean of the nearest “filled” cells.

2. The surface relief is determined according item 3, but in the (X, Y, Z) space. On the surface the resistivity of the model is interpolated over the surface relief between the sounding points (because all the points have the same altitudes).

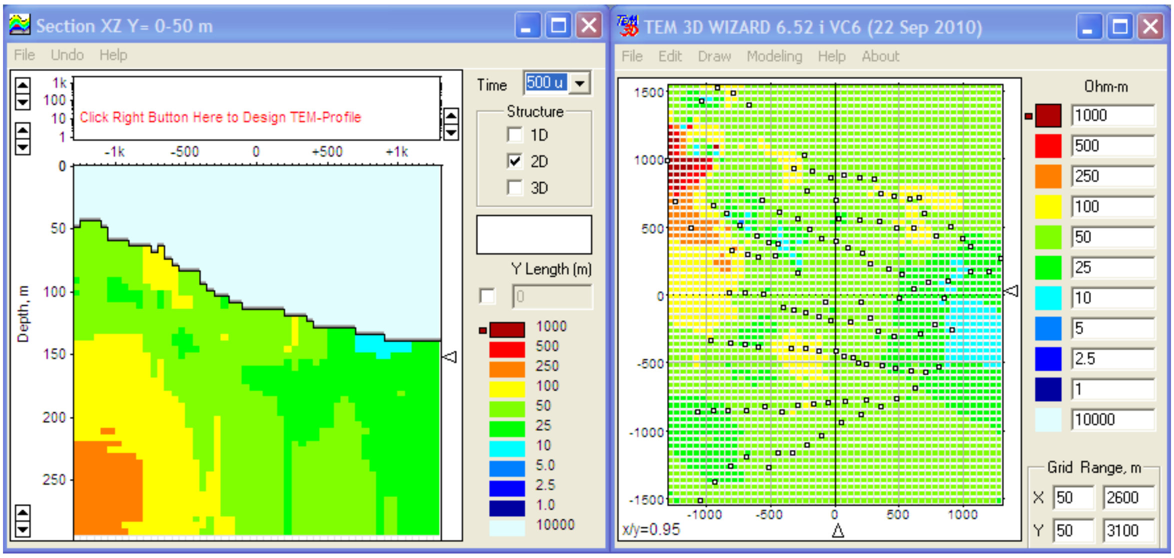


Fig. 1.20. 3D model constructed using array experimental data.

The right panel (XY-plane) corresponds to a horizontal section at a depth of 150 m (triangle depth indicator on the left panel). The squares show the location of the sounding antenna. The left window, which is labelled **Section XZ** in the left panel, shows that the TEM data are absent because that profile was not chosen. An experimental data profile can be selected by pressing the right mouse button on the panel (Fig. 1.21).

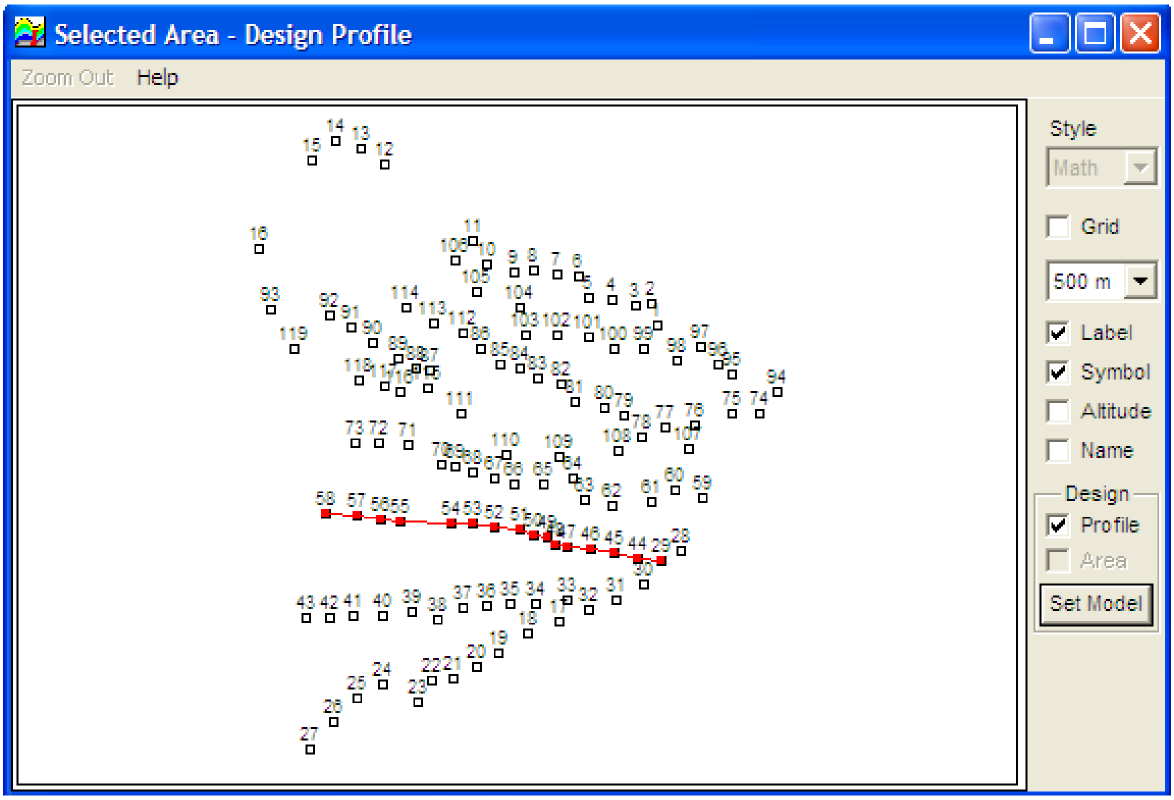


Fig. 1.21. Selecting an experimental data profile of a 3D structure

After pressing the mouse button on the **Set Model** function, the 3D structure rotates around the centre of the area so that the selected profile passes through a horizontal axis (the X-axis in Fig. 1.22).

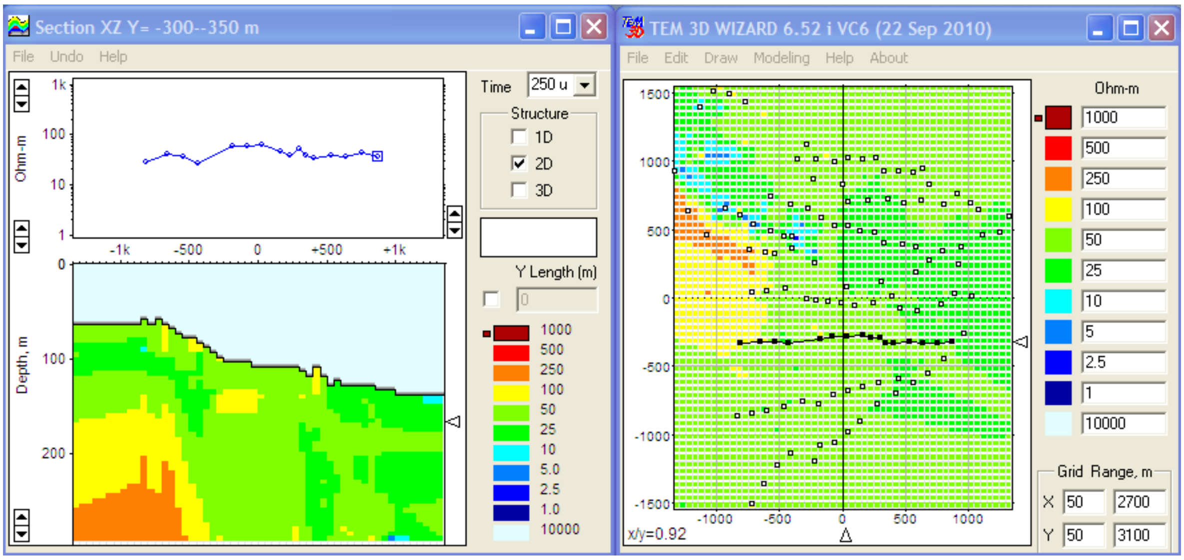


Fig. 1.22. 3D structure and profile of experimental data

Because soundings sets, as a rule, do not lie on straight lines, the profile of the experimental data in the **Section XZ** window is projected onto the horizontal X-axis. The selected profile is marked in the XY plane by a black broken line. The profile location indicator (the triangle on the vertical Y-axis of the XY window) must be placed close to a selected profile (in our case, Y=-350 m). Now, the 3D model and X-profile are ready for calculations in the **Modeling** window (Fig. 1.23).

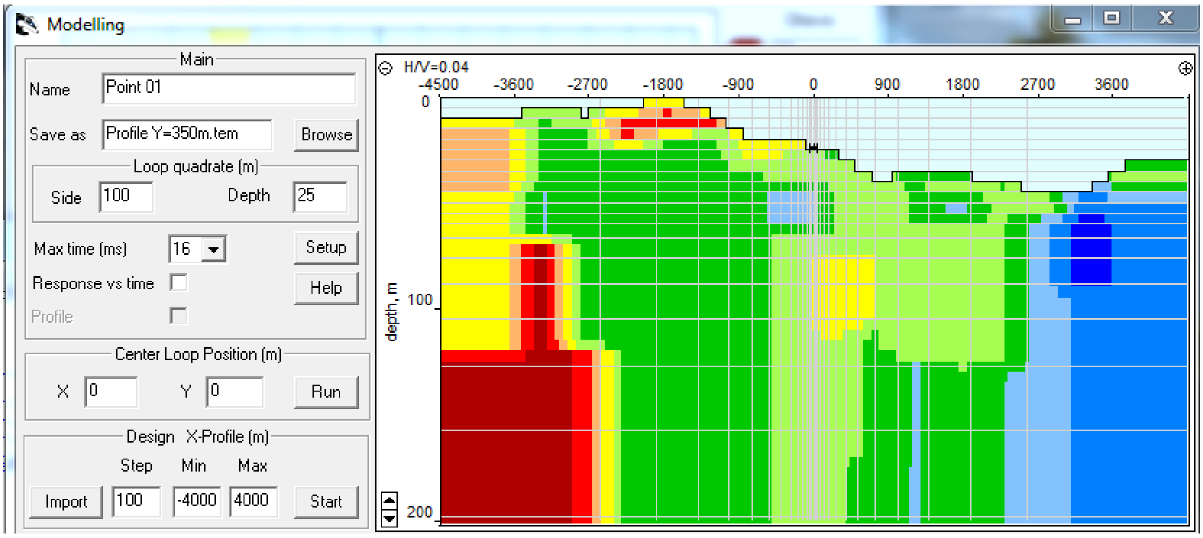


Fig. 1.23. Profile along the X-axis at Y=-350 m

To select another profile, it is necessary to again click the right mouse button on the upper panel of the **Section XZ** window.

Occasionally, it is convenient to delete the surface relief from a model (to make a plane surface). This procedure is activated by pressing **Alt+S**. All the possible manipulations of a 3D model are described in the **Help** window.

3D models can be constructed. Open a data file (**Input Observed Data**) in the **Section XZ** window, turn on the Area switch and select the area with the data (Fig. 1.23.1A).

Click the right mouse button and activate the **Set Model** function, which appears after clicking the window shown in Fig. 1.23.1B. Click the right mouse button on the top panel as shown in the figure, and open the window to select the profile or area (Fig. 1.23.1C).

In this window, turn on the **Area** switch and select the area with data. Clicking the right mouse button activates the **Set Model** function. After pressing the button, the 3D model is constructed, and the data from the central profile with the coordinate Y = 0 appear in the upper panel of the **Section XZ** window. By changing the position of the pointer of the latitude (Latitude) coordinate of the profile (i.e., changing Y) into the main frame (X-Y plane), one can select the desired profile (cross-section) that crosses the created 3D model.

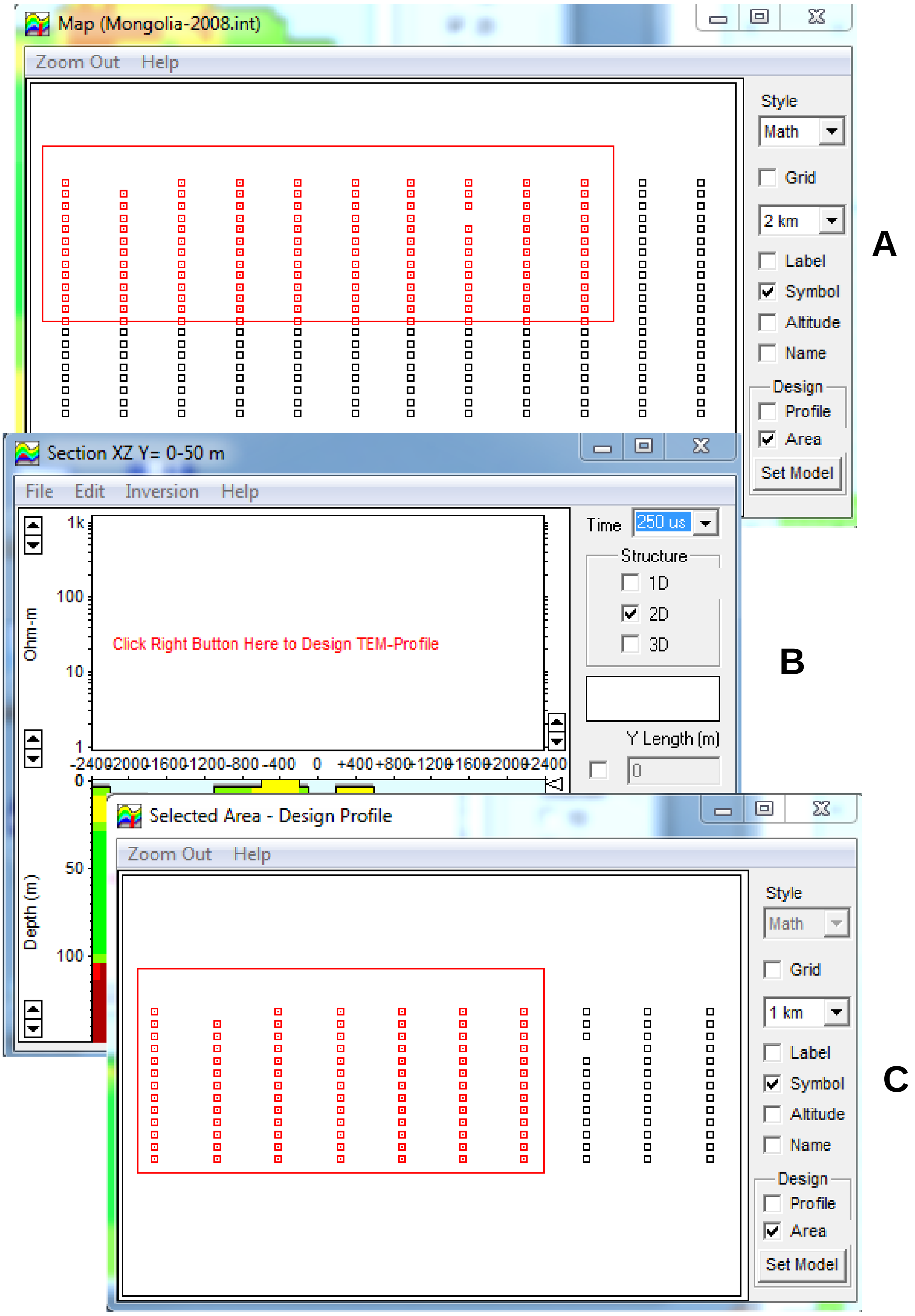


Fig. 1.23.1. Construction of a 3D model with the option of changing the Profile position of the cross-section (coordinate Y).

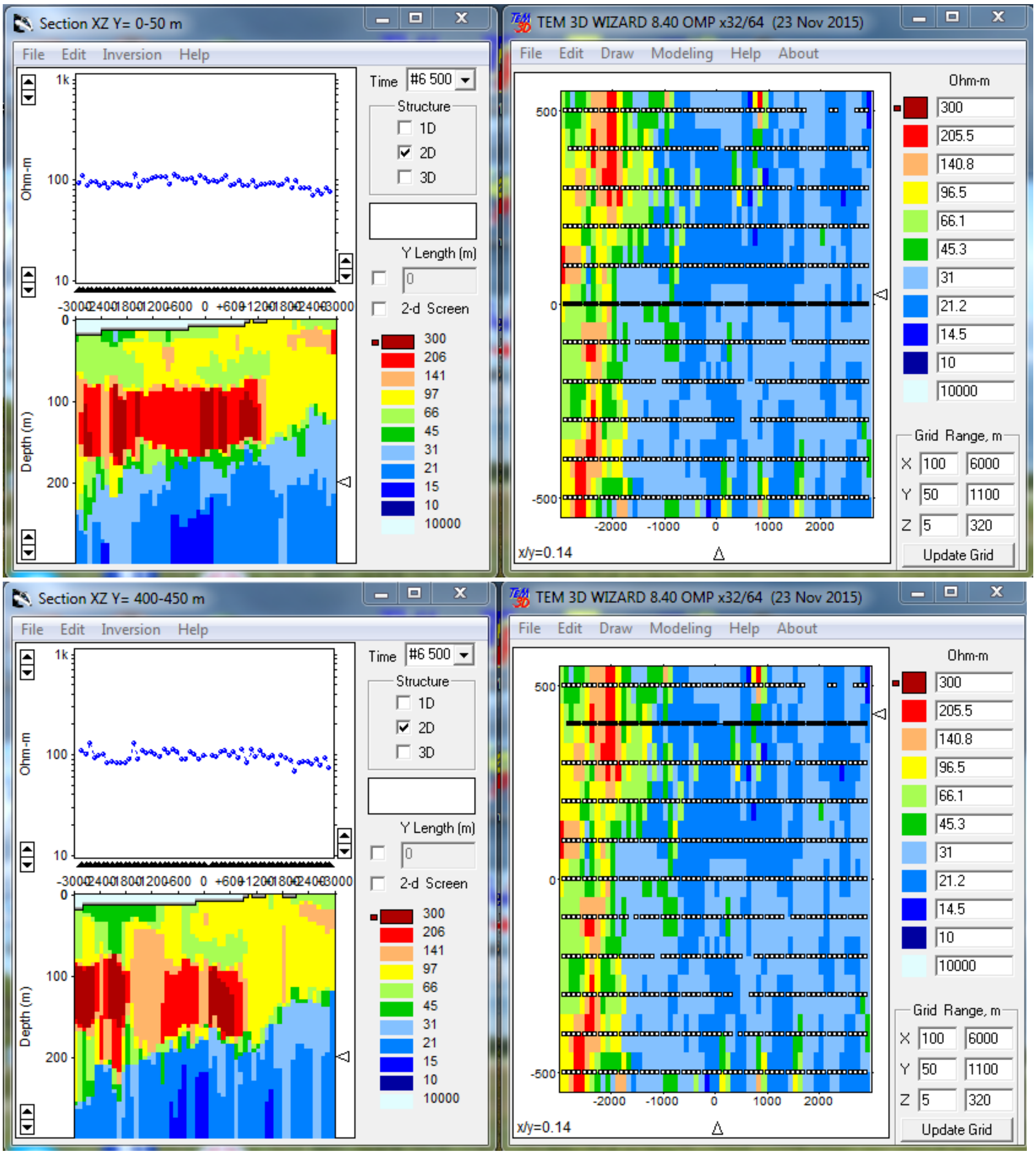


Fig. 1.23.2. 3D resistivity model sections along two profiles with latitudinal coordinates Y=0-50 m and Y=450-450 m. The latitudinal position of the profile is controlled by the latitude indicator in the main window (right panel, triangular indicator on the Y- axis). The depth of the section is controlled by the indicator (left panel, triangular indicator on the Z-axis (z=200 m)).

In the main window (right panel of Fig. 1.23.2), you can save the 3D models of the medium layer-by-layer in a text file. Press **Alt+S**, specify a filename XXX.txt, and the coordinates (X and Y) of the model's cell and the corresponding resistivity $\log_{10}(\rho)$ and ρ (Ohm-m) will be saved in the file. In addition, the coordinates of the Loop X and Loop Y points are recorded. The altitudes of the top and bottom of the horizontal section (layer) model are recorded in the filename, for example, XXX_Depth_100-105 m (the depth is specified in the **Depth Layer**).

X(m)	Y(m)	log10(Ohm-m)	(Ohm-m)	Loop X(m)	Loop Y(m)	Loop ALT(m)	Name
-2100.0	+1200.0	+2.11461	130.200	+1951.5	-1149.0	-114.0	-08
-2100.0	+1150.0	+2.26221	182.900	+1853.5	-1091.0	-112.0	-007
-2100.0	+1100.0	+2.40976	256.900	+1695.5	-1007.0	-109.0	-006
-2100.0	+1050.0	+2.40976	256.900	+1505.5	-907.0	-107.0	-005

Extrapolating the resistivities in the space outside the work zone X×Y×Z

The modelling grid is irregular and covers a space far beyond the size of model grid parameters specified in the main menu.

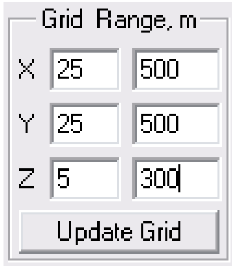


Fig. 1.24. Setting the model grid

The rule for extrapolating the resistivity is as follows. Outside a work area covered by cells, the resistivity is horizontally layered using the resistivities at the corresponding edges. This rule is illustrated in Fig. 1.25.

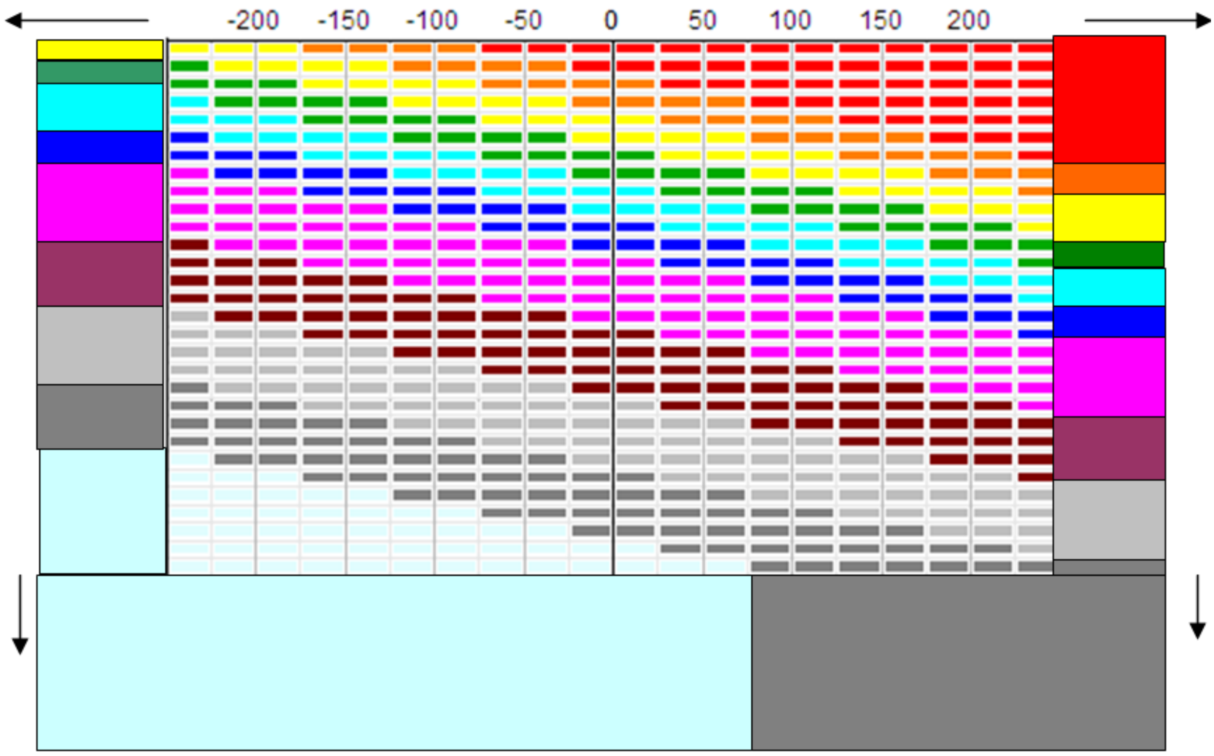


Fig. 1.25. Extrapolation of the resistivities outside the work area

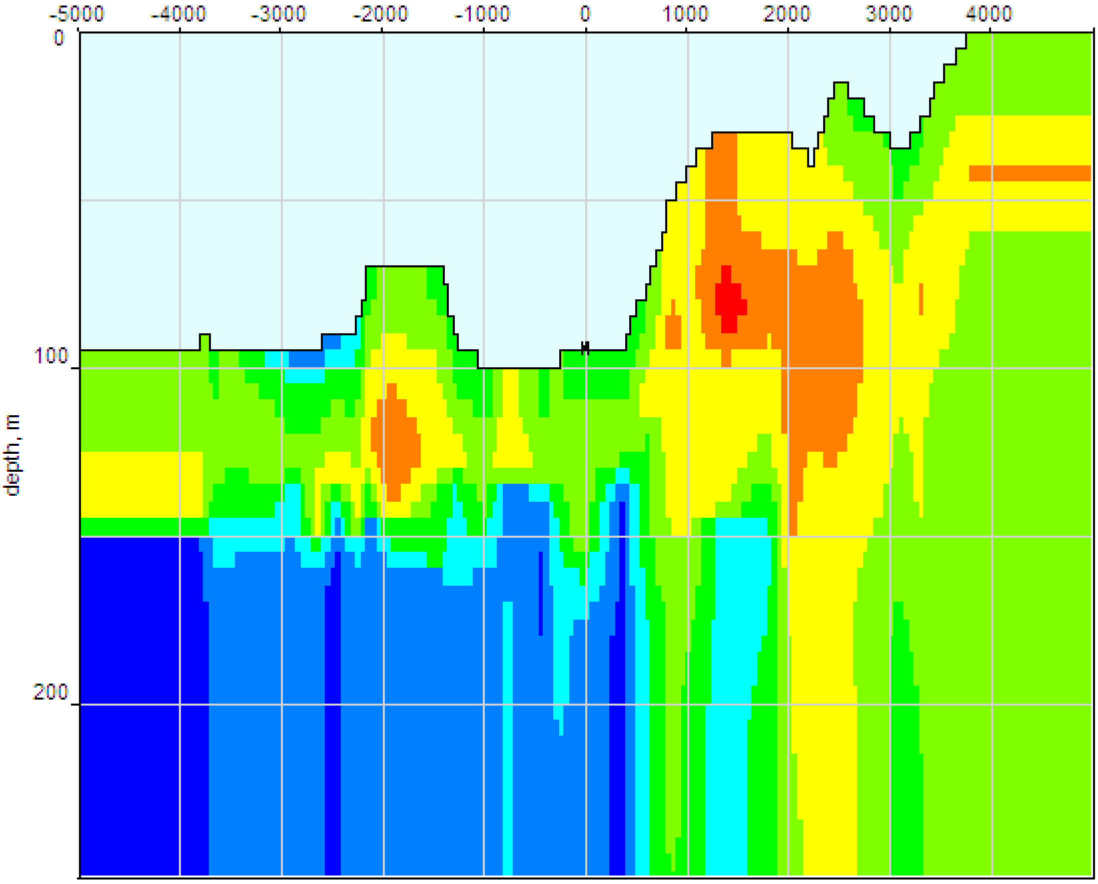
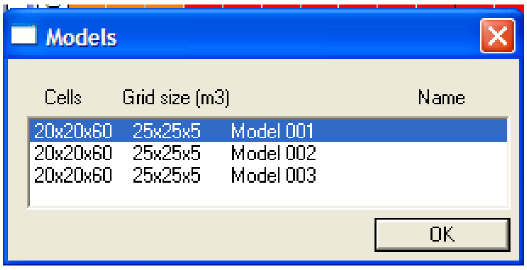


Fig. 1.26. The 2D-model is complemented outside the border |x|>4000 m by horizontal layers with resistivities that correspond to the boundaries of the model grid at |x|=4000 m.

Saving the medium models

Created models can be saved in a file with the extension *.3Dm using (**File→Save Model**) and opened later using (**File→Open Model**). The **File→Open Model** operation is used to open a *.3Dm file by selecting the required model (by name and size) and loading it into the program.



The structure of 3Dm - file

```
<3D MODEL (TEM-3D-WIZARD)  Date: Tue Dec 15 15:12:14 2009
Name: 3D Model 001 (simple model)
Reamrk1: demo version
Remark2: no comment now
DX (m)=      25.0
DY (m)=      50.0
DZ (m)=       5.0
Nx= 20
Ny=  4
Nz= 11
Codes  Resistivity [Ohm-m]
0=     500.000
1=     300.000
2=     200.000
3=     100.000
4=      50.000
5=      25.000
6=      10.000
7=       5.000
8=       2.500
9=       1.000
A=   10000.000
#  R    G    B  Resistivity Colors
 1  255    0    0
 2  255  127    0
 3  255  255    0
 4    0  170    0
 5    0  255  255
 6    0    0  255
 7  255    0  255
 8  127    0    0
 9  190  190  190
10  127  127  127
11  225  253  254
 Resistivity Maps (X-Y) [20x4 bricks] [500x200 m*m]
Layer # 1:    0.0-   5.0 m
55555555555555555555
55555555555555555555
55555555555555555555
55555555555555555555
Layer # 2:    5.0-  10.0 m
33333333333333333333
………………………..
 ……………………….
```

Saving and loading the model grids (Grid Setup)

For this, use **File→Save SetUp** and **File→Input SetUp**.

Example of an st p- file:

```
<<TEM-3D-WIZARD STEUP  Date: Fri Dec 18 12:10:16 2009
DX (m)=      25.0
DY (m)=      25.0
DZ (m)=       5.0
Nx= 20
Ny= 20
Nz= 60
Codes  Resistivity [Ohm-m]
0=     500.000
1=     300.000
2=     200.000
3=     100.000
4=      50.000
5=      25.000
6=      10.000
7=       5.000
8=       2.500
9=       1.000
A=   10000.000
#    R     G     B  Resistivity Colors
 1  255    0     0
 2  255   127    0
 3  255   255    0
 4    0   170    0
 5    0   255  255
 6    0     0  255
 7   255    0  255
 8   127    0    0
 9   190  190  190
10   127  127  127
11   225  253  254
#  Code   Thickness(m)
 1   0        20.00
 2   1        20.00
 3   2        20.00
 4   3        20.00
 5   4        20.00
 6   5        20.00
 7   6        20.00
 8   7        20.00
 9   8        20.00
10   9        20.00
11   10       20.00
```

Part 2. Modelling the TEM responses

After constructing the medium model, it is possible to begin modelling the transient processes. Activating the **Modeling** menu opens the window shown in Fig. 2.1.

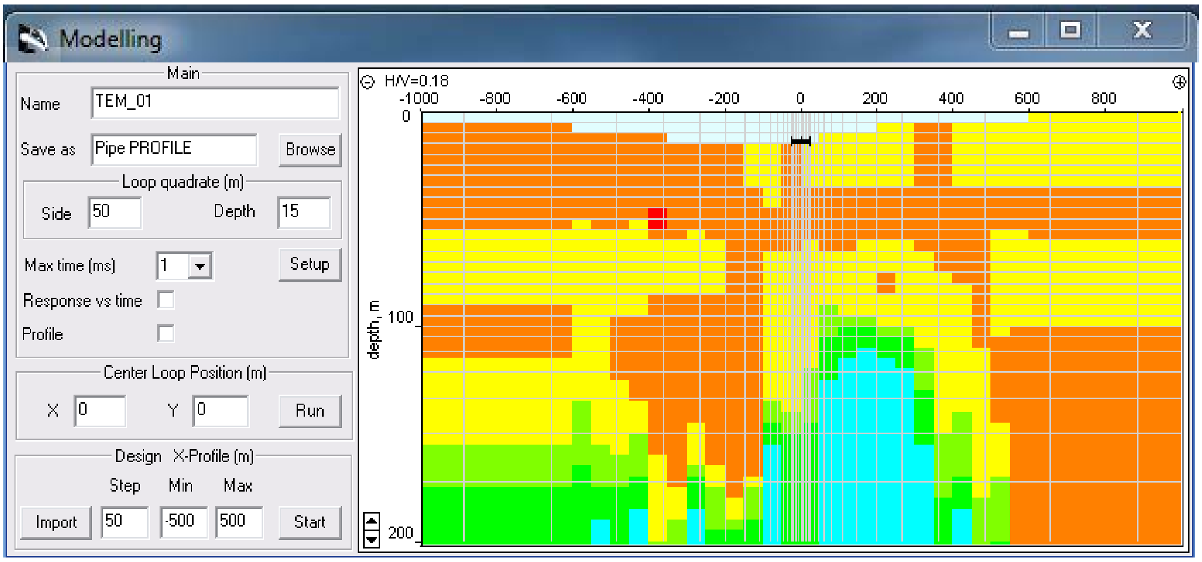


Fig. 2.1. Modelling window

In the right part of the window, a section of a 3D model is shown in the XZ plane at Y=0 together with its extrapolation outside the work zone XYZ (-600 m≥X≥+600 m). The scale of the picture can be changed using the (-) (+) (↓) (↑) control elements.

H/V=0.18 is the ratio of the horizontal scale to the vertical scale. The horizontal and vertical scales are given in meters.

A 50×50 m^2 projection of the coincident transmitter-receiver antenna is shown on the surface of the medium at the point X=0 (because parameter X in the **Center Loop Position (m)** section is equal to zero).

The altitude of the antenna is automatically determined by the surface relief (more precisely, according to the base of the sky-blue layer denoted as air).

The extension of the space grid used for the calculations of the EM field is shown on the section. Using the **Alt+G** combination, the numerical grid can be hidden.

The grid parameters are specified in the **Grid Setting** window (**Setup** button).

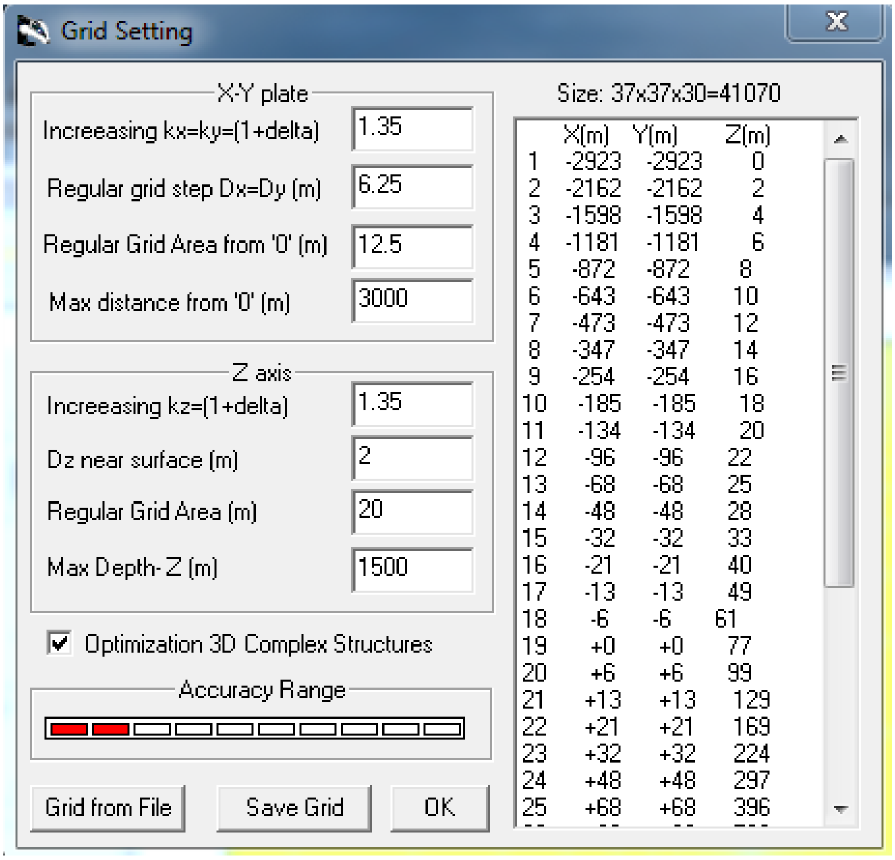


Fig. 2.2. **Grid Setting** window for setting the grid parameters used for the calculation of the TEM responses

The grid step is determined by the **Regular grid step Dx=Dy (m)** parameter**.** Within the square antenna's contour, the grid is regular in the x and y directions (dx=dy). The size of regular grid area is specified by the **Regular Grid Area from "0"(m)** parameter.

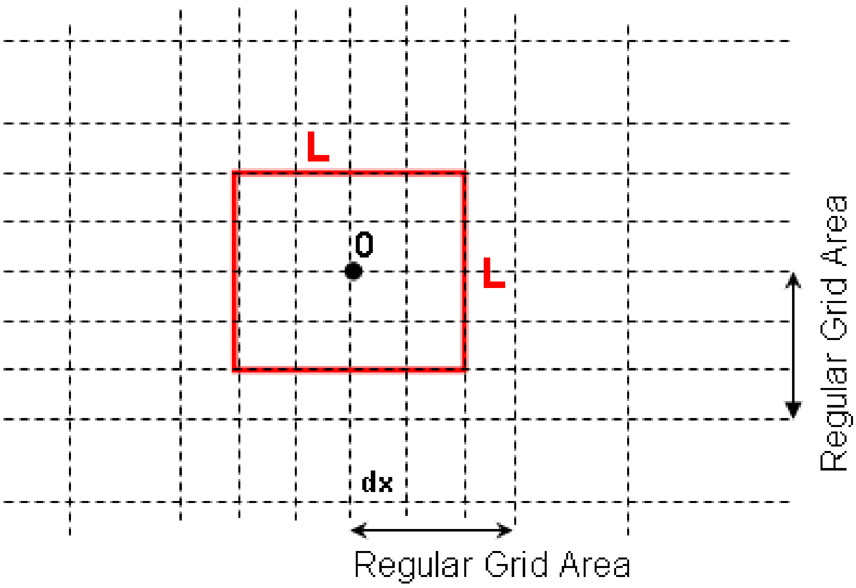


Fig. 2.2A. The grid configuration inside and outside transmitter-receiver antenna (dx=dy)

The **Increasing kx=ky=(1+delta)** parameter sets the coefficient of the grid's extension outside the **Regular Grid Area**. If $x_i<x_{i+1}<x_{i+2}$ are sequential X-coordinates, then $x_{i+2}-x_{i+1}=kx*(x_{i+1}-x_i)$. At kx=1, the grid is regular over the entire calculation area.
The program has the following limitations.

L/dx must be an even number (**L** is the length of the square antenna's side) and

(Regular Grid Area)/dx is an integer number.

The **Max distance from "0"** parameter sets the boundaries of the computational grid (by default, it is ±3000 m along the X and Y-axes). There are analogous parameters for the Z-axis.

Increasing kz=(1+delta) specifies the coefficient of the grid's extension outside of **Regular Grid Area**.

Max Depth specifies the boundary of the grid along the Z-axis (by default, it is 1500 m).

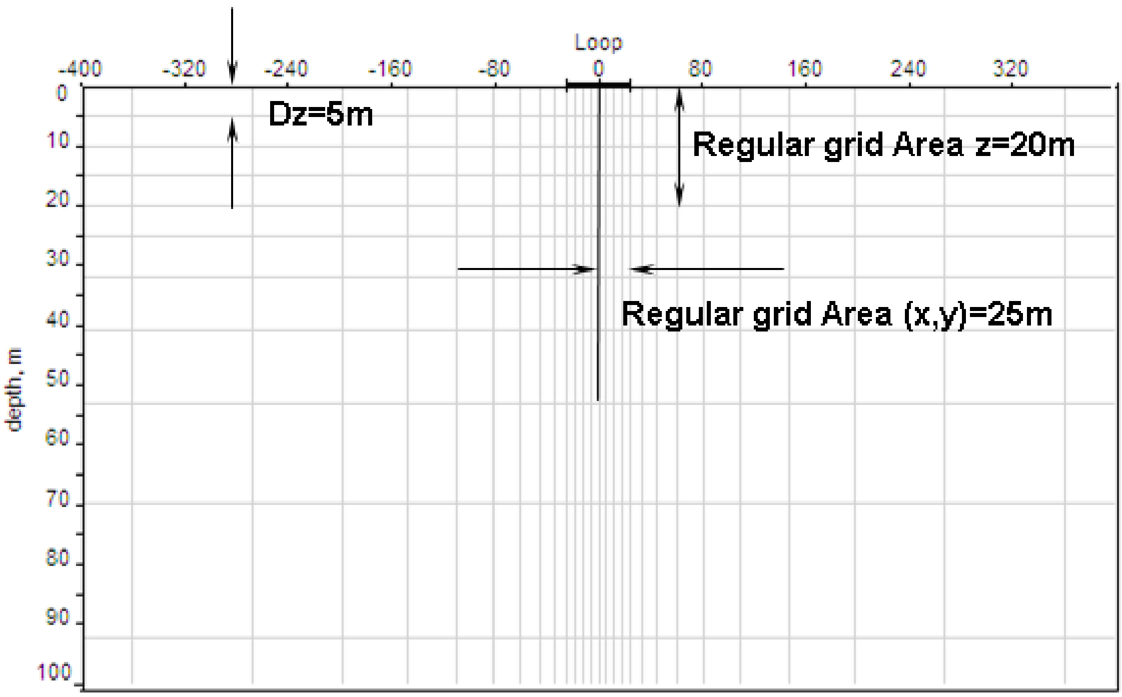
Dz near surface fixes the regular step of the grid near the day surface (z=0).

Regular Grid Area sets the boundary of the regular grid along the Z-axis.

(**Regular Grid Area**)/dz must be an integer number.

The table of the grid's nodes is shown in the right part of the window in Fig. 2.2.
The total number the nodes in the example shown is (37×37×30=41,070).
The computational time is proportional to the number the nodes.

Fig. 2.2B illustrates the numerical grid parameters.



The accuracy calculation scale of the TEM signals, **Accuracy Range,** which is conditionally divided into 10 levels, appears in the lower part of the window (Fig. 2.2). The calculation time is proportional to the **Accuracy Range** value.

The **Save Grid** window is used to save the grid's parameters in a ***.ini** file**,**

Grid from File is used to set a grid from a ***.ini** file.

Three examples are now used to demonstrate the influence of the grid's parameters on the accuracy of the TEM calculations. The two-layer model parameters are ρ_1=100 Ohm-m, h=50 m and ρ_2=1 Ohm-m.

Example 1.

The apparent resistivity curves presented in Fig. 2.3 were calculated with the following parameters for different values of **Accuracy Range:** 2, 4 and 6:

L=50 m,
dx=dy=3.125 m,
dz=5 m,
kx=kz=1.35,
Regular Grid Area (xy)=25 m, and
Regular Grid Area z=50 m.

The black curve corresponds to a 1D layered model calculated using the TEM-RESEARCHER program.

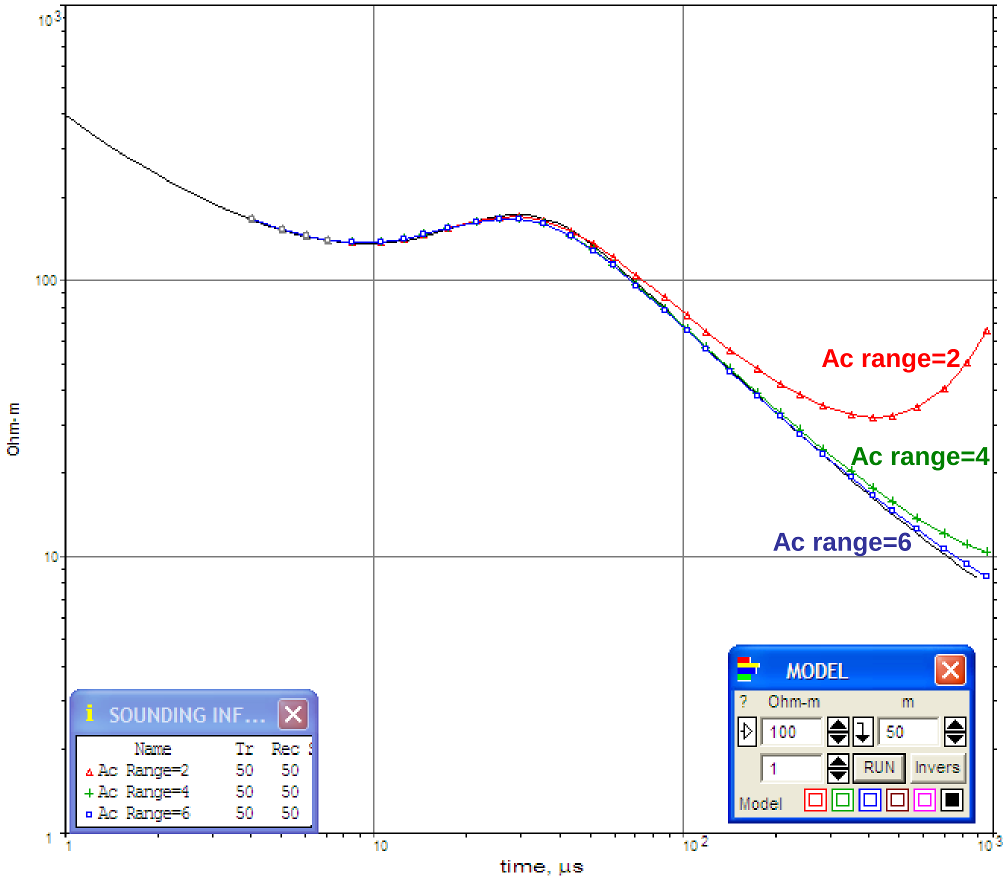


Fig. 2.3. Estimation of the influence of the **Accuracy Range** value on the accuracy of the TEM calculations

Increasing the **Accuracy Range** parameter essentially influences the accuracy of the calculations in both the near and far zones of the transmitter (late stage of the transient process).

Example 2

The apparent resistivity curves presented in Fig. 2.4 were calculated using the following parameters:

L=50 m,
dz=5 m,
kx=kz=1.35,
Regular Grid Area (xy)=25 m,
Regular Grid Area z=50 m, and
Accuracy Range= 6.

The black curve corresponds to a 1D layered model calculated using the TEM-RESEARCHER program. Only the dx and dy parameters were varied (**dx=dy=2.5, 3.125, 6.25** and **12.5 m)**.

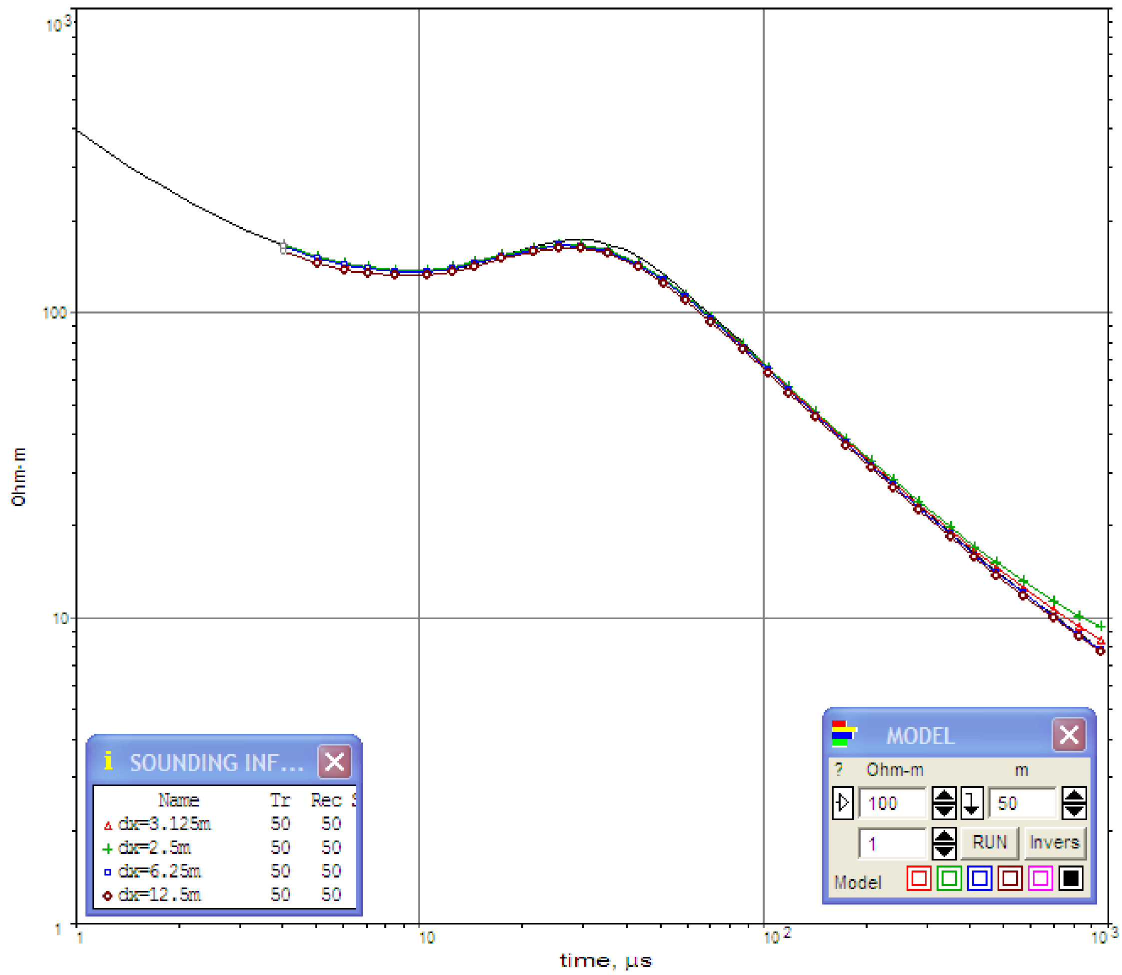


Fig. 2.4. Estimation of the influence of the dx parameter on the TEM response accuracy

Increasing the dx parameter within 2.5-12.5 m does not significantly affect the accuracy of the calculation of the transient responses in the near and far zones of the transmitter.

Example 3

The apparent resistivity curves shown in Fig. 2.5 were calculated using the following model parameters:

L=50 m,
dx=dy=6.25 m,
kx=kz=1.35,
Regular Grid Area (xy)=25 m,
Regular Grid Area z=50 m, and
Accuracy Range= 6.

The black curve corresponds to a 1D layered model calculated using the TEM-RESEARCHER program. Only the dz parameter was varied (**dz=2.5, 5** and **10 m).**

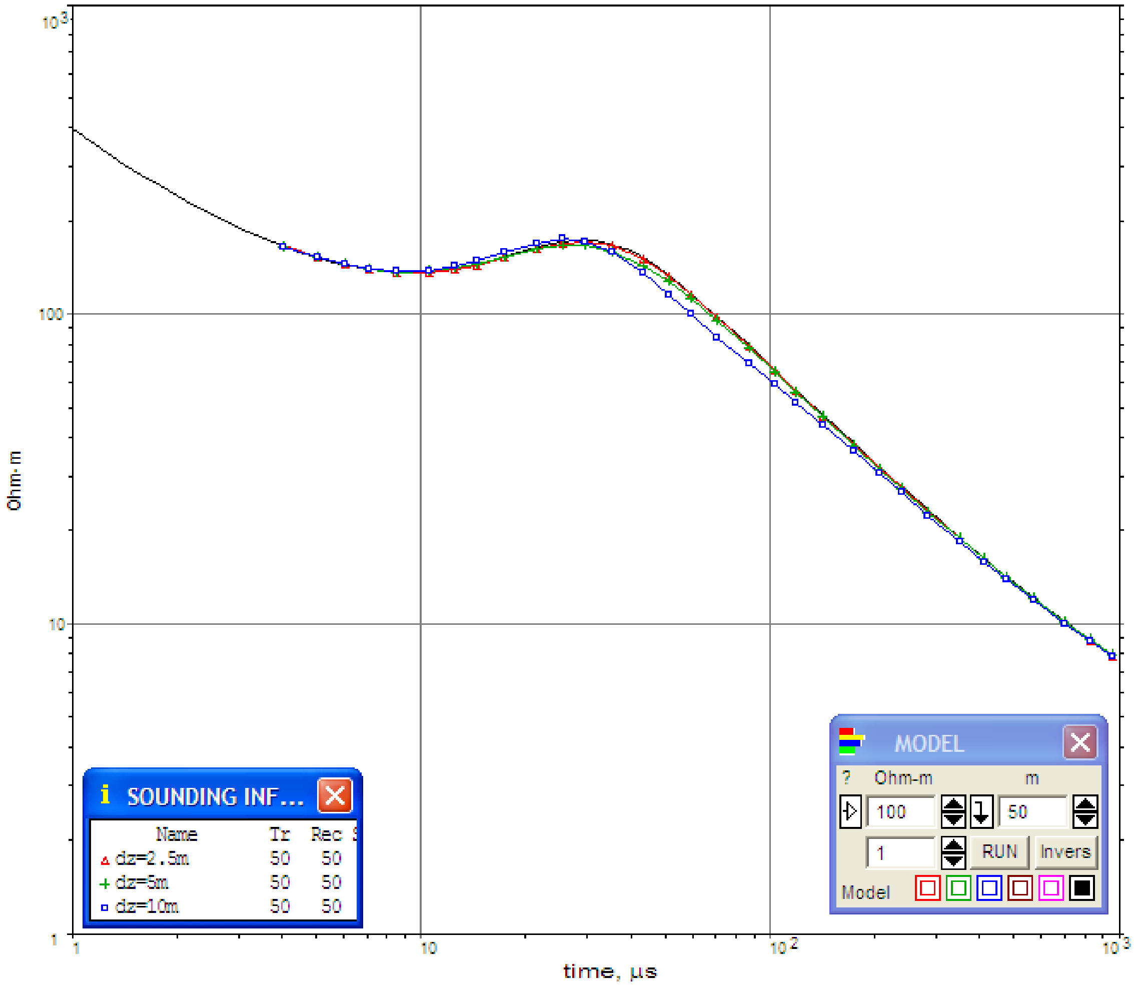


Fig. 2.5. Estimation of the influence of the dz parameter on the TEM response accuracy

Increasing dz from 2.5-5 m had no effect on the accuracy of the calculation of the transient processes; however, at *dz*≥10 m (blue curve), a 15% distortion occurred in the intermediate zone of the transient. There were no distortions in the early (*t*<10 μs) and late stages of the transient process (*t*>500 μs).

It should be noted that even essential changes in the **kx**, **kz, Max distance from "0"** and **Max depth** parameters essentially had no effect on the accuracy of the calculations.

A model of a medium and a computational grid

As previously defined, the grid used to construct the models is regular along the X-, Y-, and Z-axes, whereas the grid used to calculate the TEM responses logarithmically expands in space. It is therefore impossible to accurately match the boundary lines of the model blocks and computational grid everywhere.

For example, if a medium is horizontally layered, to obtain accurate calculations, it is necessary to match the nodes of the computation grid along the Z-axis with the layer boundaries. However, this matching is possible only by concentrating the grid nodes along the vertical axis. When the z-nodes do not match the grid boundaries, the TEM signal calculations are somewhat inaccurate because the model used for the calculations differs from the initial model (Fig. 2.6).

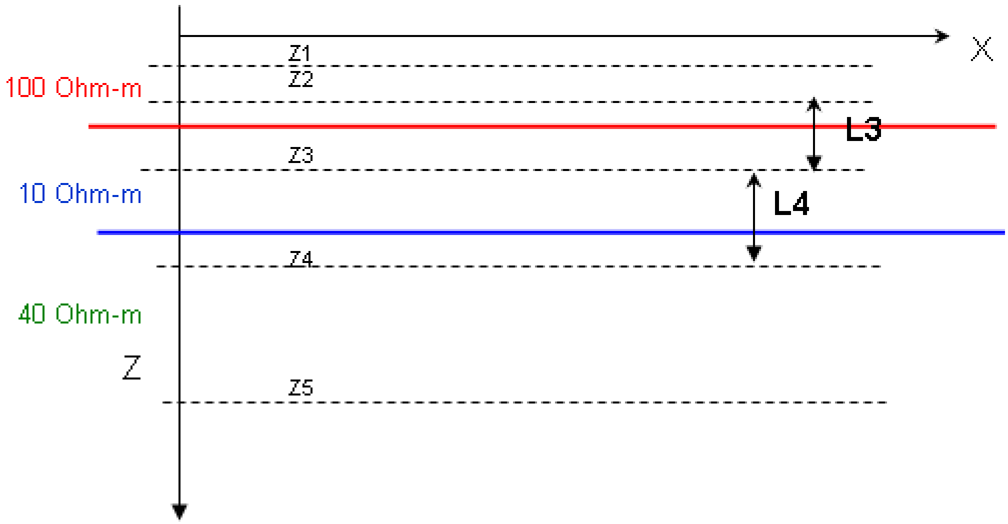


Fig. 2.6. The grid and horizontally layered medium boundaries

Within the limits of the nodes of grid $z_2>z>z_3$ (L3) and $z_3>z>z_4$ (L4), the resistivity does not coincide with the resistivities of the first, second and third layers. The resistivities in such border layers are calculated using a special algorithm that accounts for the resistivity of the cell model in three orthogonal directions (the cell model is considered to be anisotropic with respect to the resistivity ρ_x, ρ_y, and ρ_z). Evidently, a universal algorithm that can provide a precise calculation of the fields for an arbitrary model does not exist. Inaccuracies will always result from the "substitution" of an initial model of the medium using a calculation model corresponding to the given parameters of the grid. The resulting errors decrease as the nodes (and lines) of a calculation grid approach the contrast boundaries of a model.

As a rule, superficial horizontal model boundaries can be easily combined with the computation grid lines by fitting **dz** and the **Regular Grid Area z** parameters, and deep lying boundaries (not all, but the most important) can be combined by manipulating the **kz** coefficient. The vertical boundaries along the X- and Y-axes can be treated in a similar way.

There is no universal method for constructing the grid for any medium's model. However, a user can independently find an acceptable solution to this problem in the process of working with this program.

The next example demonstrates the fact that even in a rather complicated situation close to the real one, the value of the **Regular Grid Area** parameter (over the depth z) insignificantly affects the modelling results.

Fig. 2.6A depicts the results of the calculations for a medium model that contains an inclined high conductivity dike. The calculations were fulfilled for the grid with two different parameters (at depth): **Regular Grid Area**=150 m and 50 m. When the **Regular Grid Area** equals 150 m, all the vertical boundaries of the inclined dike coincide exactly with the boundaries of the grid, whereas when the **Regular Grid Area** equals 50 m, none of them coincide with the computational grid. Nevertheless, the results of the calculations practically coincide (the difference is less than 2%).

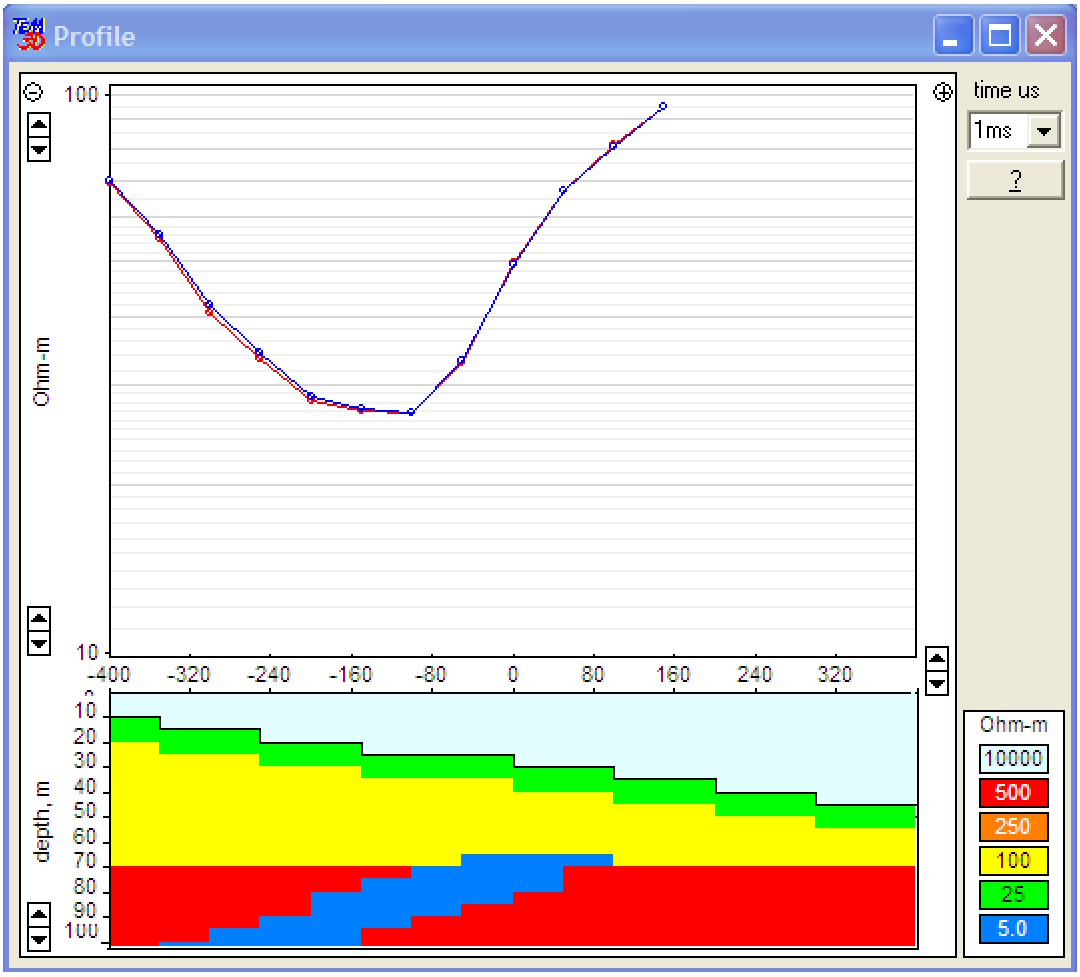


Fig. 2.6A. The profile crossing the inclined dike: the calculations. The red curve corresponds to calculations with the following parameters: dz=5 m, **Regular Grid Area (z)=150 m,** (~90,000 cells, and the calculation time is ~4 s)**;** blue curve dz=5 m, **Regular Grid Area (z)=50 m,** (~50,000 cells, and the calculation time is approximately 2 s).

Fig. 2.6B presents the TEM responses at point x=0 for the profile shown in Fig. 2.6A. The calculations were made with two different grids, the parameters of which are presented in the lower panel of Fig. 2.6B.

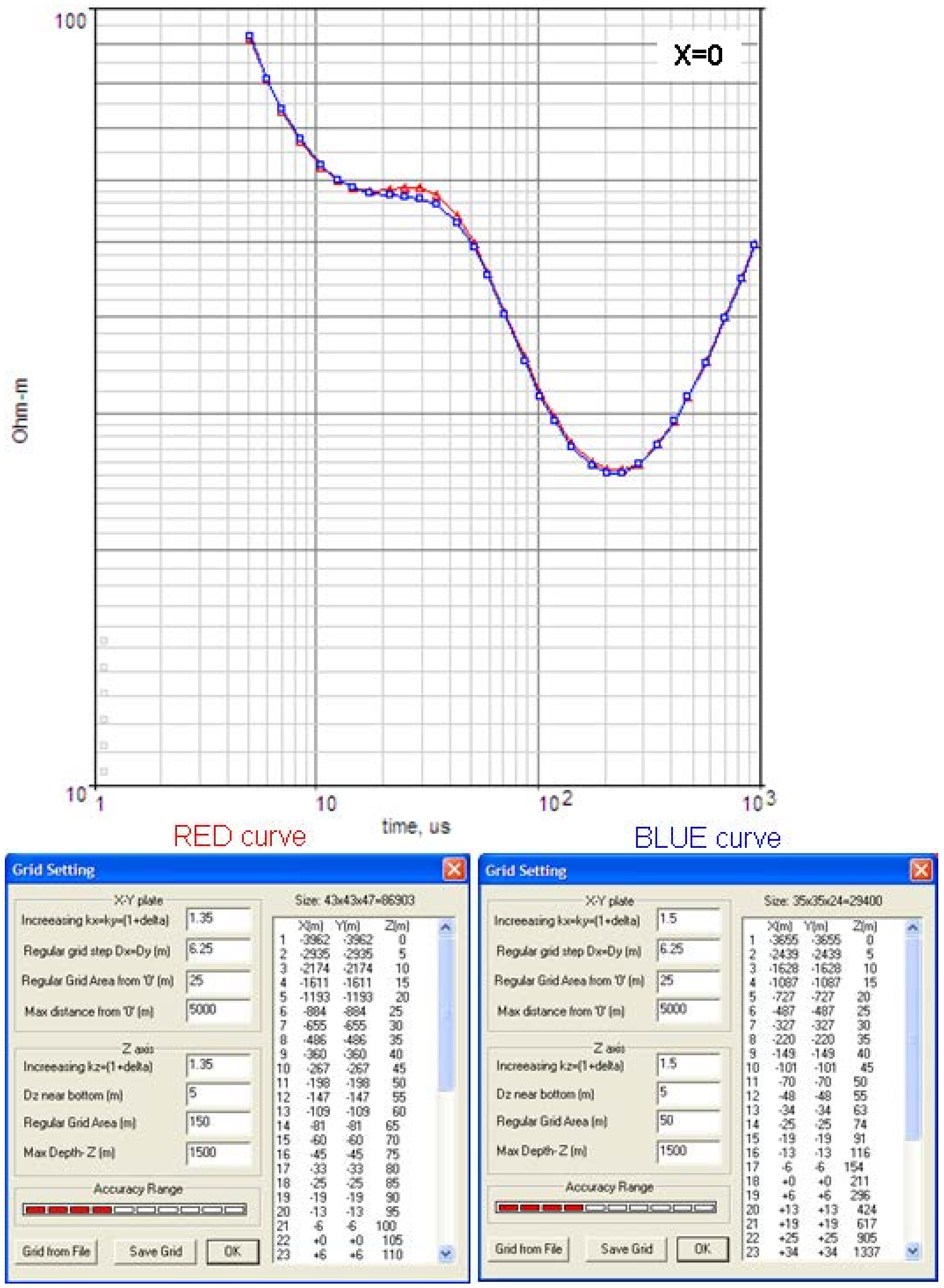


Fig. 2.6B. TEM responses in the normalization of the apparent resistivity, corresponding to the point x=0 in the profile (see Fig. 2.6A). The bottom panel shows the parameters of the calculated grids for the red and blue ρ(t) curves.

Although the computational grid corresponding to the blue curve is ~3 times less dense than that for the red curve, the difference is less than 3.5% in the middle stage of the TEM process.

Let us return to the main modelling window.

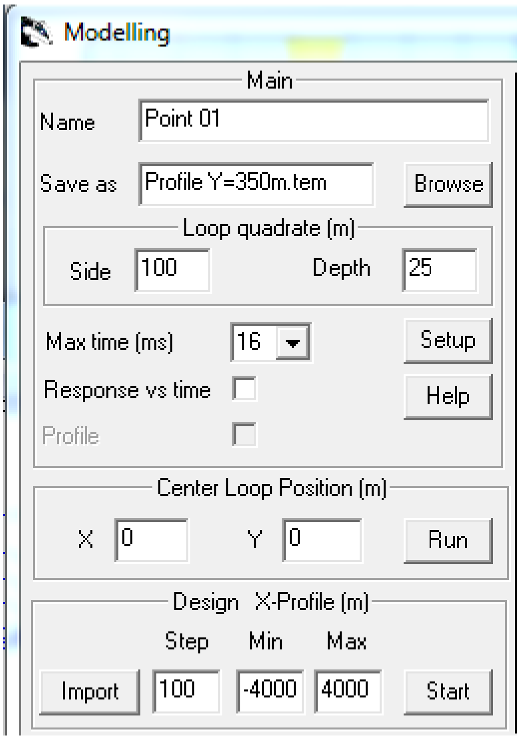


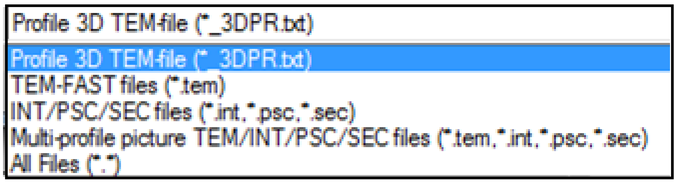
Fig. 2.7. Modelling window

Name – set name that should be written in the TEM file
Browse - Save as - name of the TEM file for the saved results of the calculations
Side ≥ **1** - length of the side of a square coincident antenna (loop) in meters
Depth ≥ **0** - depth of the antenna (counted from z=0) in meters
Max time (ms) - maximum time of the TEM response (1/4 – 16 ms)
Setup - activate the window for setting the calculation grid parameters
Response vs. time - activate the window for the $\rho(t)$ or $E(t)/I$ graphs
Profile - activate the window of the model medium and the graphs of $\rho(t)$ or $E(t)/I$ along a profile.
The window becomes active after the calculation or loading of profile data (**Import**).
Center Loop Position (m) - set the antenna position
Run - start the TEM response calculation for a given position of the antenna (XY)
Design X-Profile (m) - section for setting the parameters for the profile calculations
Step – step along the profile (meters), **Step**>0
Min – initial position of the antenna centre on the profile (meters)
Max - final position of the antenna centre on the profile (meters) (**Max>Min)**

Start - start the profile calculations. The set's names correspond to the antenna location on the X-axis. The profile data are saved in two text files that have the same name but have *.tem and *_3DPR.txt extensions as specified in the **Save as** window. The model parameters are written in the last file.

Import - function for loading the profile data and previously calculated model saved earlier in *3DPR.txt and *.tem files. After loading, the model can be recalculated using other grid parameters, or the model can be changed.

Data Type in menu **Import**:



- **Profile 3D** - enter the profile data (txt-file) and configure the appropriate model (the previously loaded model will be replaced!) – Fig. 2.7A.
- **TEM-FAST file** - enter the TEM data (observed or calculated)
- **INT/PSC/SEC** - enter the TEM input data format (-int, -psc, -sec)
- **Multi-Profile picture** - enter the data in the -tem, -int, -psc, and -sec formats to build multiple profile pictures (6 profiles on the same panel from 6 different TEM files) - Fig. 2.7A.

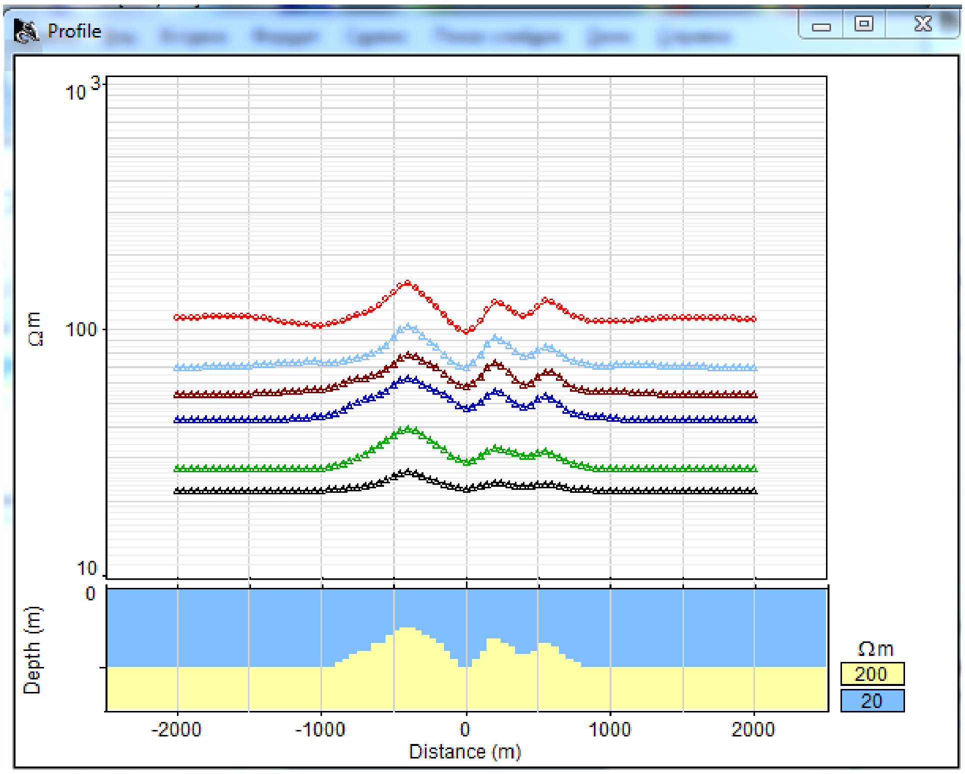


Fig. 2.7A. Window **Profile**. An example of a multiple profile picture (responses at a fixed time *t*=1 ms from 6 different TEM files). The medium models differ by the thicknesses of their upper layers (ρ=20 Ohm-m).

*Format the text file *.3DPR.txt that contains the profile data:*

<ADVANCED 3D MODELING NT= 24
<NSET= 11
Voltage [V/Amp] Loop= 25.0x 25.0 m*m Rec= 25.00x25.00 m*m turn= 1.000

#	LAT(m)	LONG(m)	time (us)	time (us)	time (us)	time (us)	time (us)	time (us)
			4.05612	5.0659	6.06912	7.07705	8.5172	10.529
1	-500	0	1.58E-01	9.41E-02	6.14E-02	4.25E-02	2.72E-02	1.63E-02
2	-400	0	1.58E-01	9.41E-02	6.14E-02	4.25E-02	2.72E-02	1.63E-02
3	-300	0	1.58E-01	9.37E-02	6.08E-02	4.19E-02	2.66E-02	1.57E-02
4	-200	0	1.44E-01	8.07E-02	5.00E-02	3.36E-02	2.14E-02	1.36E-02
5	-100	0	1.44E-01	8.06E-02	4.99E-02	3.34E-02	2.12E-02	1.33E-02
6	0	0	1.44E-01	8.06E-02	4.99E-02	3.34E-02	2.12E-02	1.33E-02
7	100	0	1.44E-01	8.06E-02	4.99E-02	3.34E-02	2.12E-02	1.33E-02
8	200	0	1.44E-01	8.06E-02	4.99E-02	3.34E-02	2.12E-02	1.33E-02
9	300	0	1.44E-01	8.06E-02	4.99E-02	3.34E-02	2.12E-02	1.33E-02
10	400	0	1.44E-01	8.07E-02	5.00E-02	3.36E-02	2.14E-02	1.36E-02
11	500	0	1.58E-01	9.37E-02	6.08E-02	4.19E-02	2.66E-02	1.57E-02

Apparent Resistivity [Ohm-m]

1	-500	0	111.94	109.25	107.51	106.27	105.03	103.88
2	-400	0	111.94	109.25	107.51	106.28	105.03	103.89
3	-300	0	112.04	109.56	108.15	107.35	106.77	106.43
4	-200	0	119.04	121.05	123.25	124.39	123.32	117.37
5	-100	0	119.06	121.14	123.47	124.86	124.27	118.99
6	0	0	119.06	121.14	123.47	124.86	124.27	119
7	100	0	119.06	121.14	123.47	124.86	124.27	119
8	200	0	119.06	121.14	123.47	124.86	124.27	119
9	300	0	119.06	121.14	123.47	124.86	124.27	118.99
10	400	0	119.04	121.05	123.25	124.39	123.32	117.37
11	500	0	112.04	109.56	108.15	107.35	106.77	106.43

```
****************************** ADVANCED 3D-MODEL ******************************************************************************
 Ohm-m
0 -    1000.000
1 -     500.000
2 -     250.000
3 -     100.000
4 -      50.000
5 -      25.000
6 -      10.000
7 -       5.000
8 -       2.500
9 -       1.000
A -   10000.000
Nx= 40 Dx=    50.000
Nz= 60 Dz=     5.000
Ny= 40 Dy=    50.000
<<******************************  COMPLETE 3D MODEL ***********************************
 Resistivity Maps (X-Y) [40x40 bricks] [2000x2000 m*m]
Layer # 1:    0.0-   5.0 m
   5555555555555555555555555555555555555555555555555
   5555555555555555555555555555555555555555555555555
   3333355555555553333333333333333333355555555555555
   3333333333333333333333333333333333333333333333333
   3333333333333333333333333333333333333333333333333
   1111111111111111111111117774444444444444444444444
   1111111111111111111111117744444444444444444444444
   1111111111111111111111177744444444444444444444444
   1111111111111111111111177744444444444444444444444
   1111111111111111111111177444444444444444444444444
   1111111111111111111111777444444444444444444444444
   1111111111111111111111777444444444444444444444444
   1111111111111111111111774444444444444444444444444
   1111111111111111111117774444444444444444444444444
   1111111111111111111117774444444444444444444444444
   1111111111111111111117744444444444444444444444444
   1111111111111111111117744444444444444444444444444
   1111111111111111111177444444444444444444444444444
   1111111111111111111177444444444444444444444444444
   1111111111111111111177444444444444444444444444444
   1111111111111111111774444444444444444444444444444
   1111111111111111111774444444444444444444444444444
```

.ini format of the computation grid's configuration file

NAME: TEM_01
Regular Step Dx=Dy= 6.250
kx=ky=1.350
Max distance (X,Y)= 5000.000
Area XY with regular grid= 25.000
kz=1.350
Regular Step Dz=5.000
Loop= 50.000
Depth of loop= 0.000
Max Depth=1500.000
Area Z with regular grid=20.000

TEM Response *window*

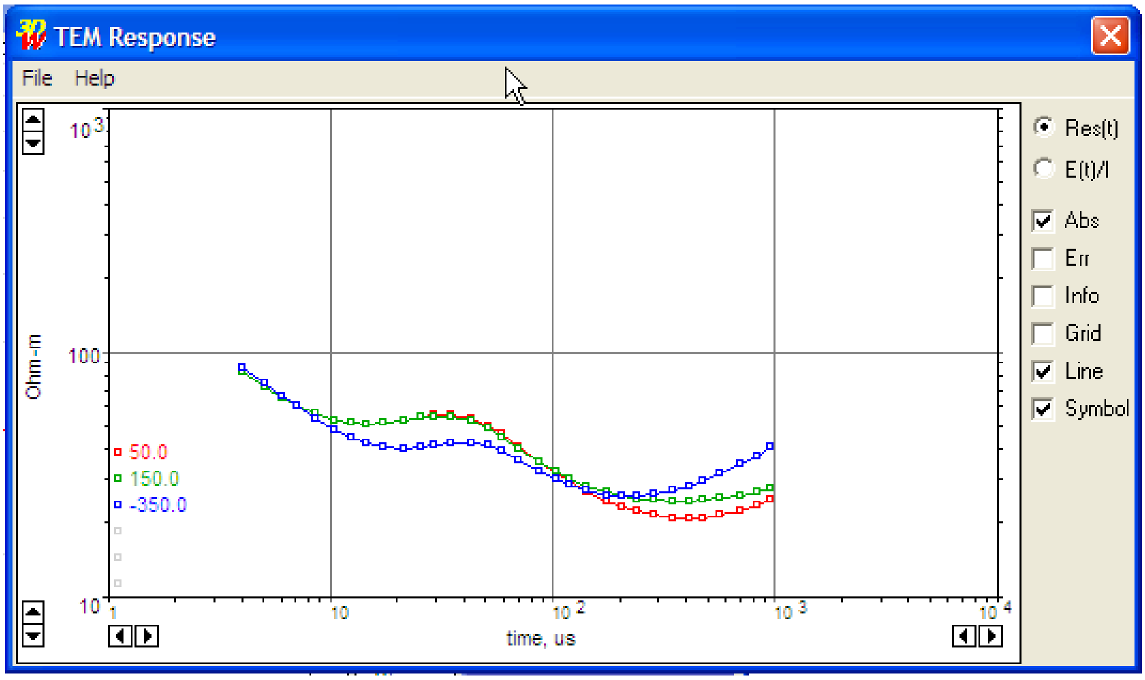


Fig. 2.8. Apparent resistivity curves $\rho(t)$ corresponding to different locations of the antenna along the profile.

Control functions:

Res(t) - depict the TEM response as the apparent resistivity $\rho(t)$
E(t)/I - depict the TEM response as the voltages on the antenna's terminals
Abs - the absolute values of $|\rho(t)|$ or $|E(t)/I|$
Err - depict the confidence intervals for the experimental TEM responses
Info - brief information on the experimental TEM responses
Grid - set the details of the logarithmic grid
Line - connect the experimental TEM responses with lines and dots
Symbol - denote the dots on the model TEM responses using square boxes

The labels **50.0, 150.0,** and **350.0** corresponding to the first three of the last six calculation sets (responses) are highlighted in the lower left corner. Double clicking the mouse button removes the corresponding graphs from the screen.

Menu:

File→Input Field Set - activate the loading sets of experimental data from a TEM file (including the binary files from a Nomad (handheld) computer)

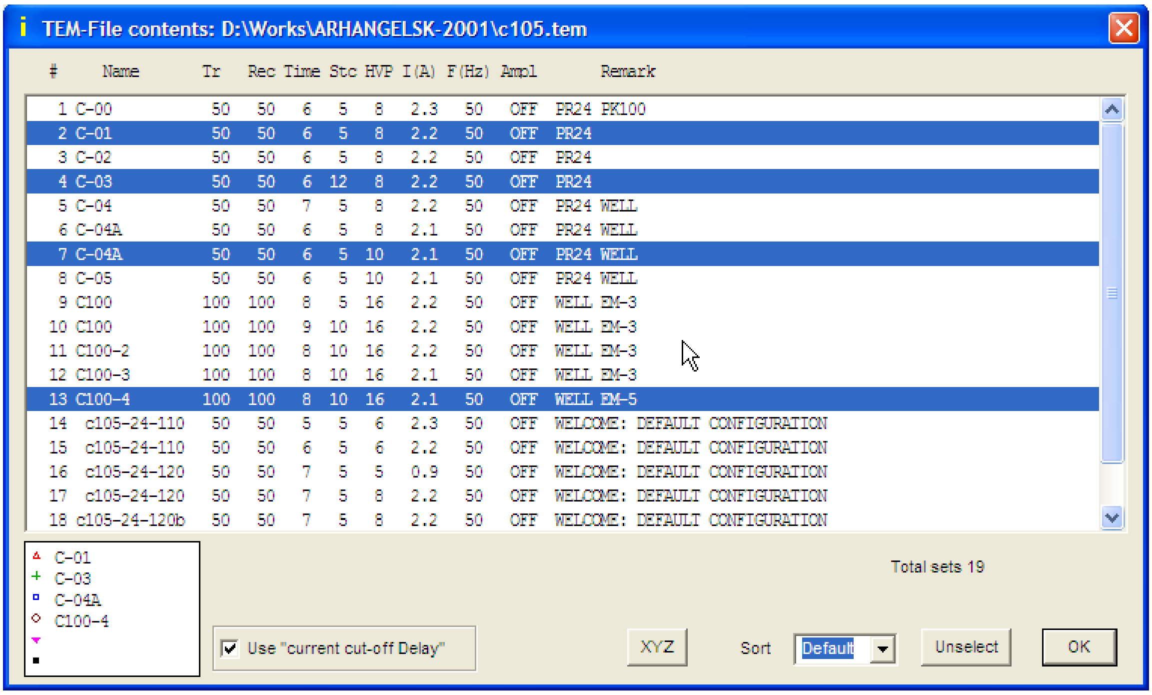


Fig. 2.9. The window for loading experimental data. The four selected sets are ready to be loaded.

Use “current cut-off Delay” - activate the automatic correction of the experimental TEM responses, taking into account the real switch-off ramp of the electric current in the antenna

ATTENTION:

When using model data, the Use “current cut-off Delay” function must be “Off”.

XYZ - view the coordinates of the data sets

Sort - sort the data according to different criteria

Unselect - cancel the current set selection

OK - load the selected data sets (≤ 6)

If the data stack (the window in left low corner) is occupied by already loaded data, double clicking on an unnecessary set removes it.

Thus, you can simultaneously process 6 models and 6 experimental TEM responses (Fig. 2.10).

Double click on the model set name result in deleting of this set.

Thus, using the **TEM Response** window (Fig. 2.8), one can set 6 models and 6 experimental TEM responses simultaneously.

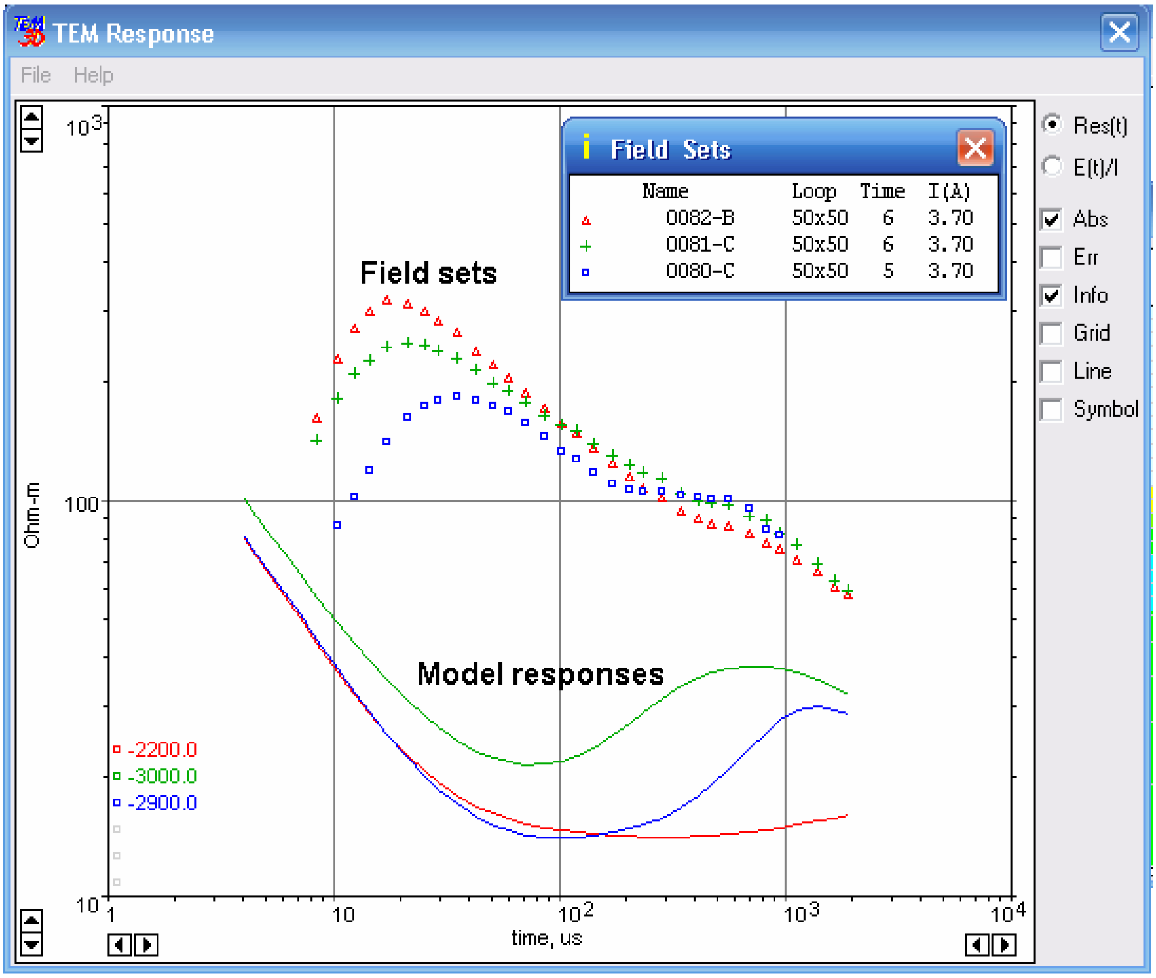


Fig. 2.10. TEM Response window. The names of the model sets are in the lower left corner, and information on the experimental sets is in the **Field Sets** window.

Double click on the name of the model set to delete the set.
Double click on the name of the experimental set in the Field Sets window to delete the set.

Profile window

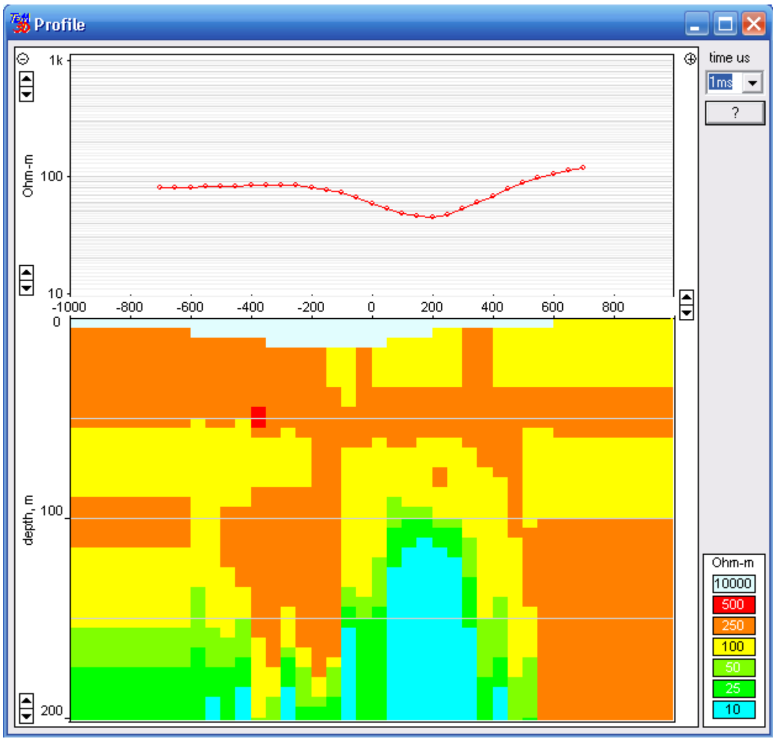


Fig. 2.11. The medium model and the results of the calculations of the apparent resistivity $\rho(t)$ along the profile at a time delay t=1 ms.

The possible manipulations in the “**?**” window are listed in Fig. 2.12.

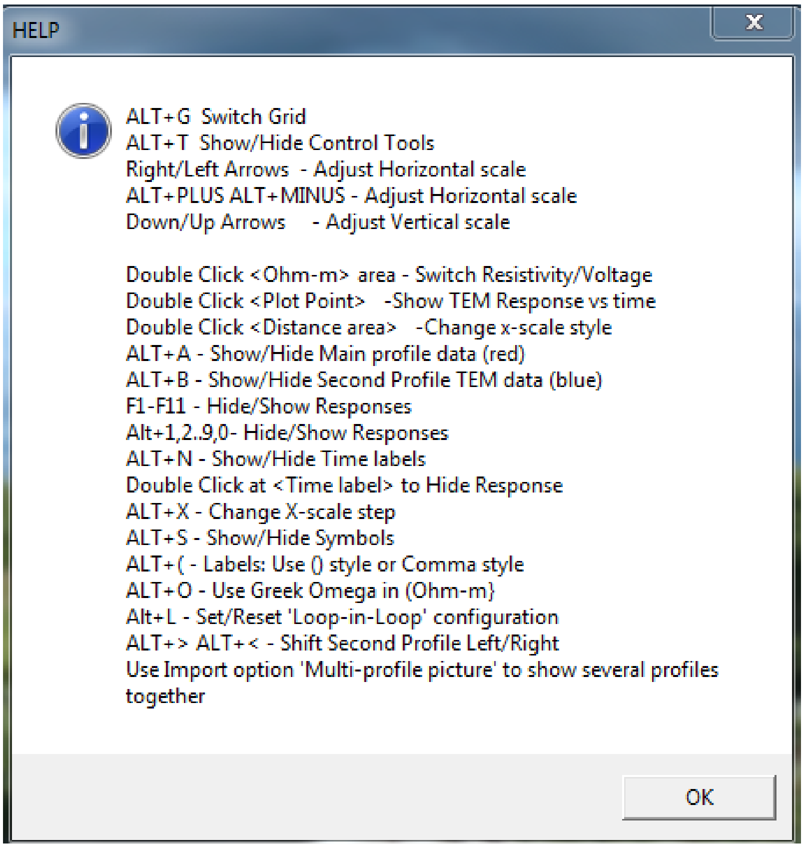


Fig. 2.12. List of commands in the “?” window

Double clicking any graph point makes a copy of the TEM response in the **TEM Response** window.

Double clicking the left vertical axis (on the **V/A** or **Ohm-m** names) changes the Resistivity ↔ Voltage regimes.

The (-) (+) (→) (←) (↓) (↑) control elements can be used to change the scale of the picture.

Press **Alt+T** to delete all the control elements from the map (Fig. 2.13).

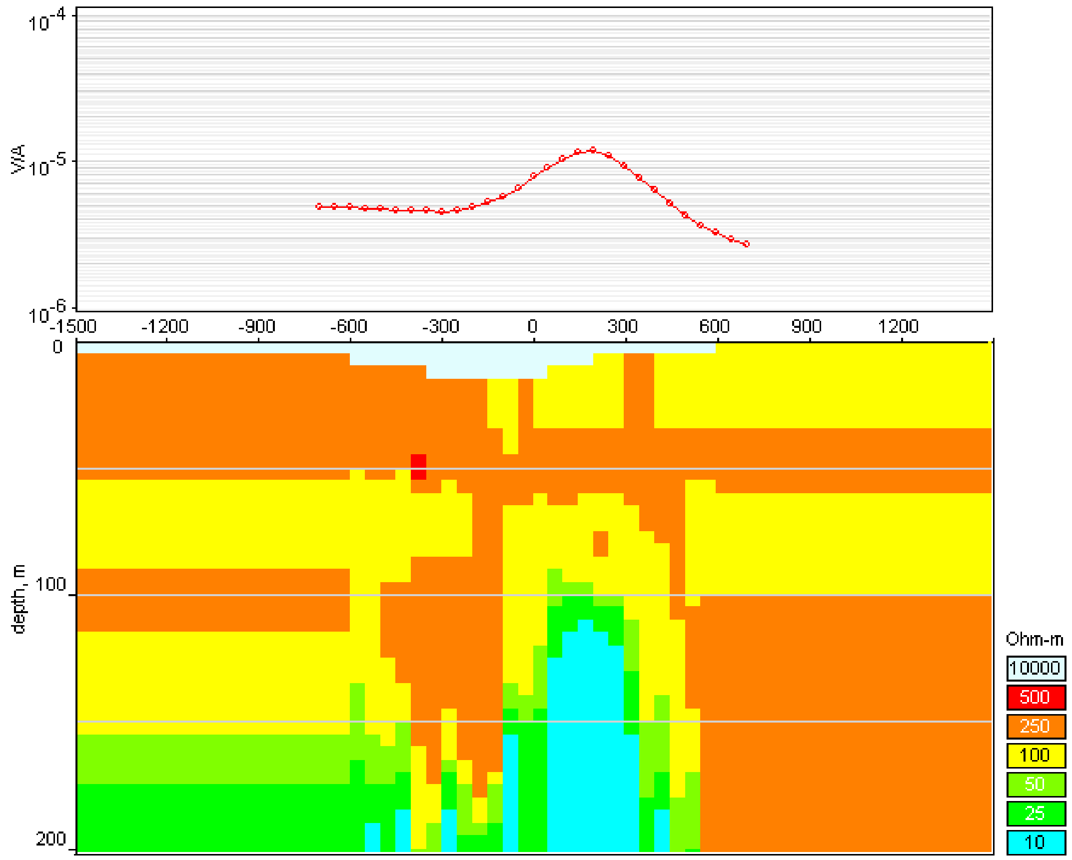


Fig. 2.13. The **Profile** window after pressing **Alt+T**. This window is convenient for cropping and inserting files and presentations into a text.

The **Modelling** window in the **Design X-Profile** section allows profile model data (*3DPR.txt) and experimental data from TEM, PSC, INT or SEC (Fig. 2.14) files to be loaded.

Fig. 2.14

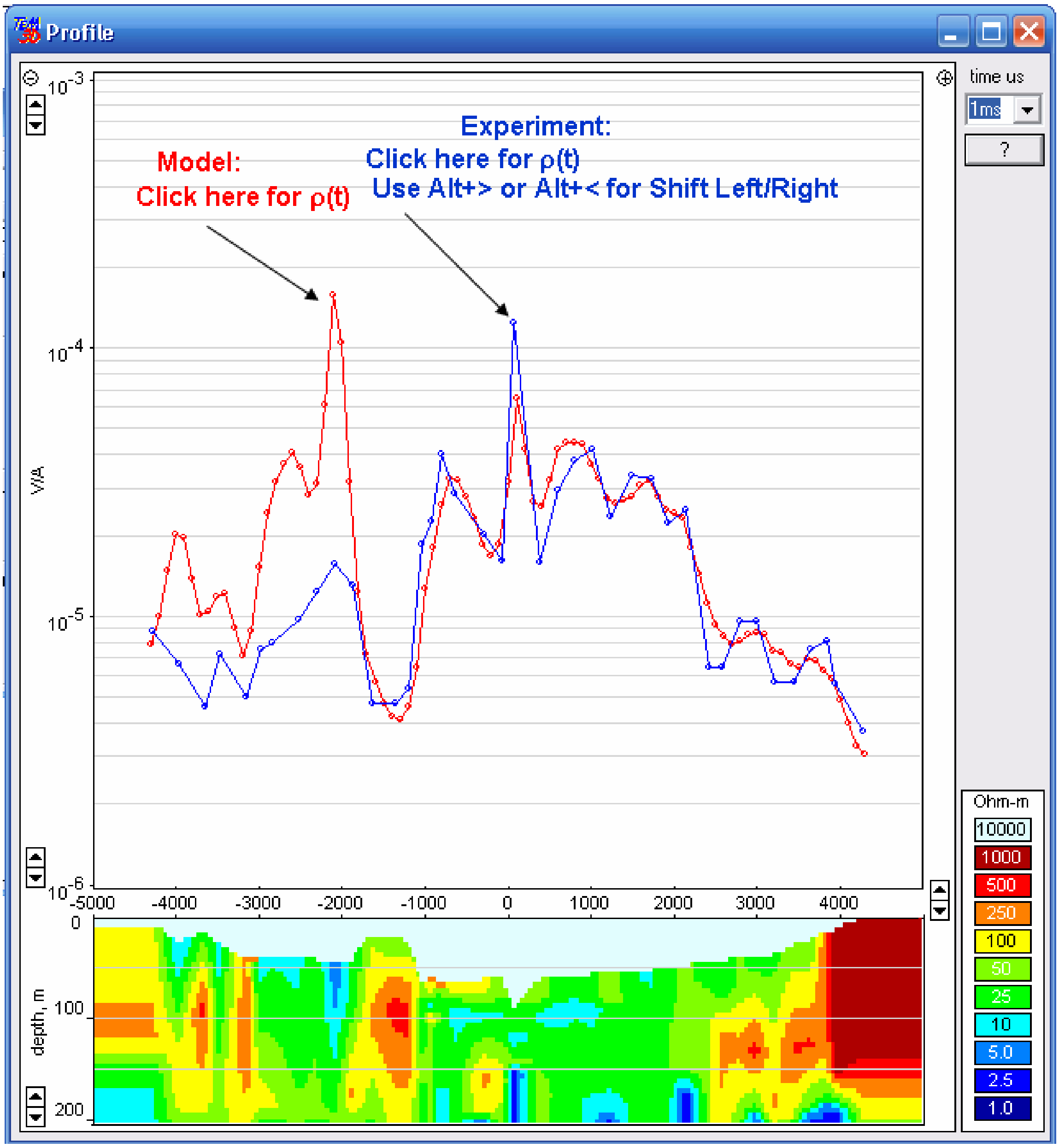


Fig. 2.15. Model of the medium and corresponding experimental (blue) and model (red) curves of *E(t)/I*, t=1 ms

Occasionally, 3D modelling is carried out to evaluate the TEM-FAST resolution under different geological conditions. In that case, the calculated TEM responses for models with identical geometries and different resistivities are of interest; for example, for the investigation of an anomalous target of different resistivity embedded in a layered section.

A 3D model of a kimberlite intrusion constructed by transforming experimental data is shown in Fig. 2.16.

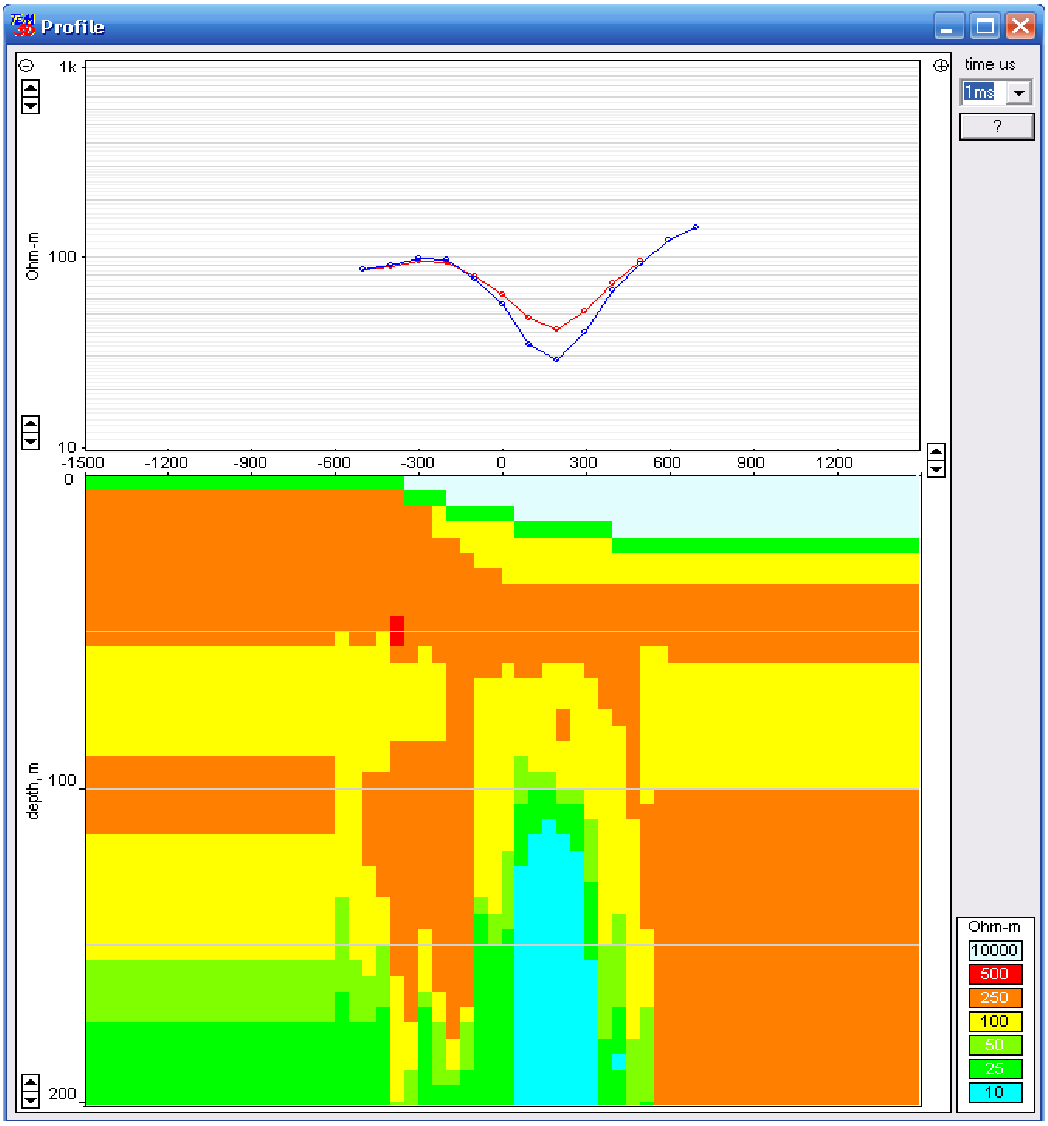


Fig. 2.16. The model of a kimberlite intrusion with TEM responses that correspond to two variants of the kimberlite body's resistivity: ρ=10 Ohm-m (red) and ρ=3 Ohm-m (blue).

The red curve and model were constructed using the 3D-model file loaded from PIPE_10 Ohm-m_3DPR.txt, and the blue curve was constructed after loading the TEM file PIPE_3 Ohm-m.tem.

Fig. 2.17 shows the field measurement data together with the 3D modelling results along a profile that crosses the kimberlite pipe. The pipe model is the same as that in Fig. 2.16.

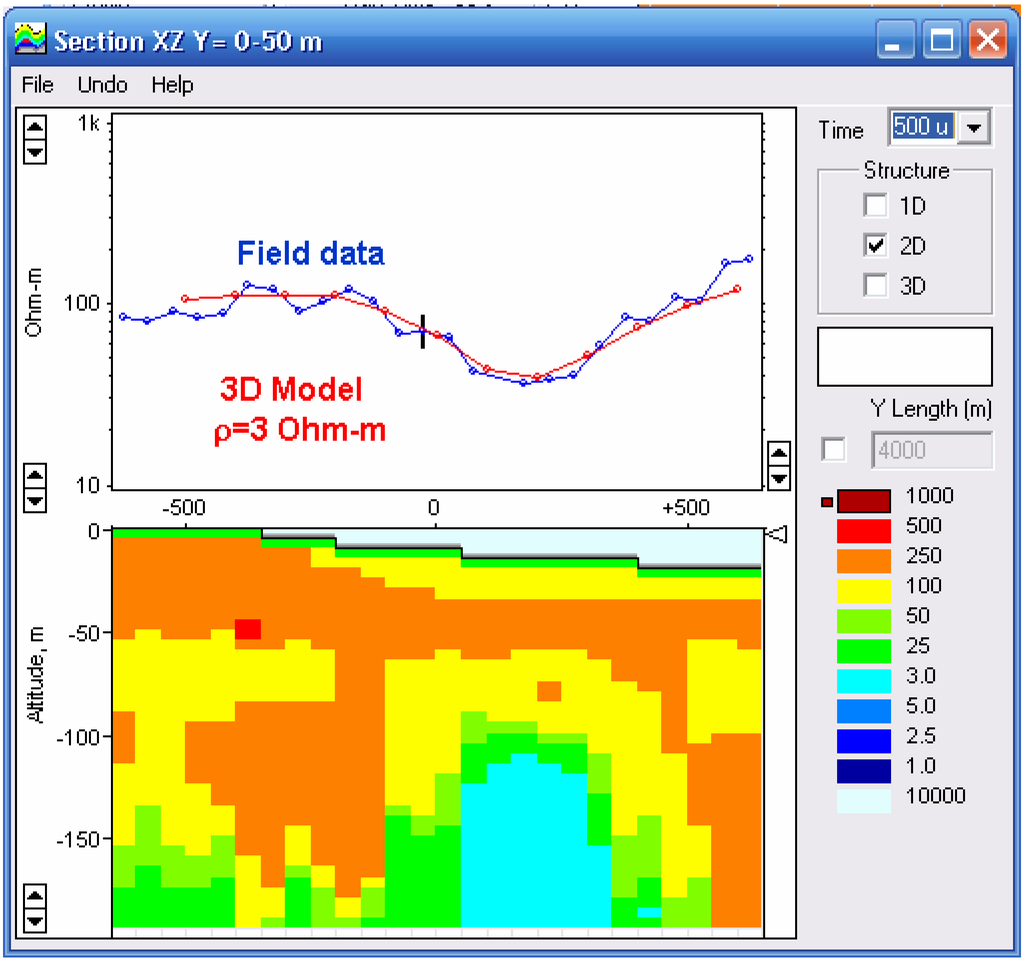


Fig. 2.17. The model of the kimberlite intrusion and graphs of the TEM responses: red - 3D model for the kimberlite resistivity ρ=3 Ohm-m, blue - experimental data

Part 3: Inversion of the observed data

The **Inversion** window can be activated in the **Section XZ** menu (Fig. 3.1).

Once the user has downloaded the experimental data measured along the profile or the area and the program builds a 2D or 3D model of the medium, the Inversion Setting window (Fig. 3.1) in **Section XZ** becomes available.

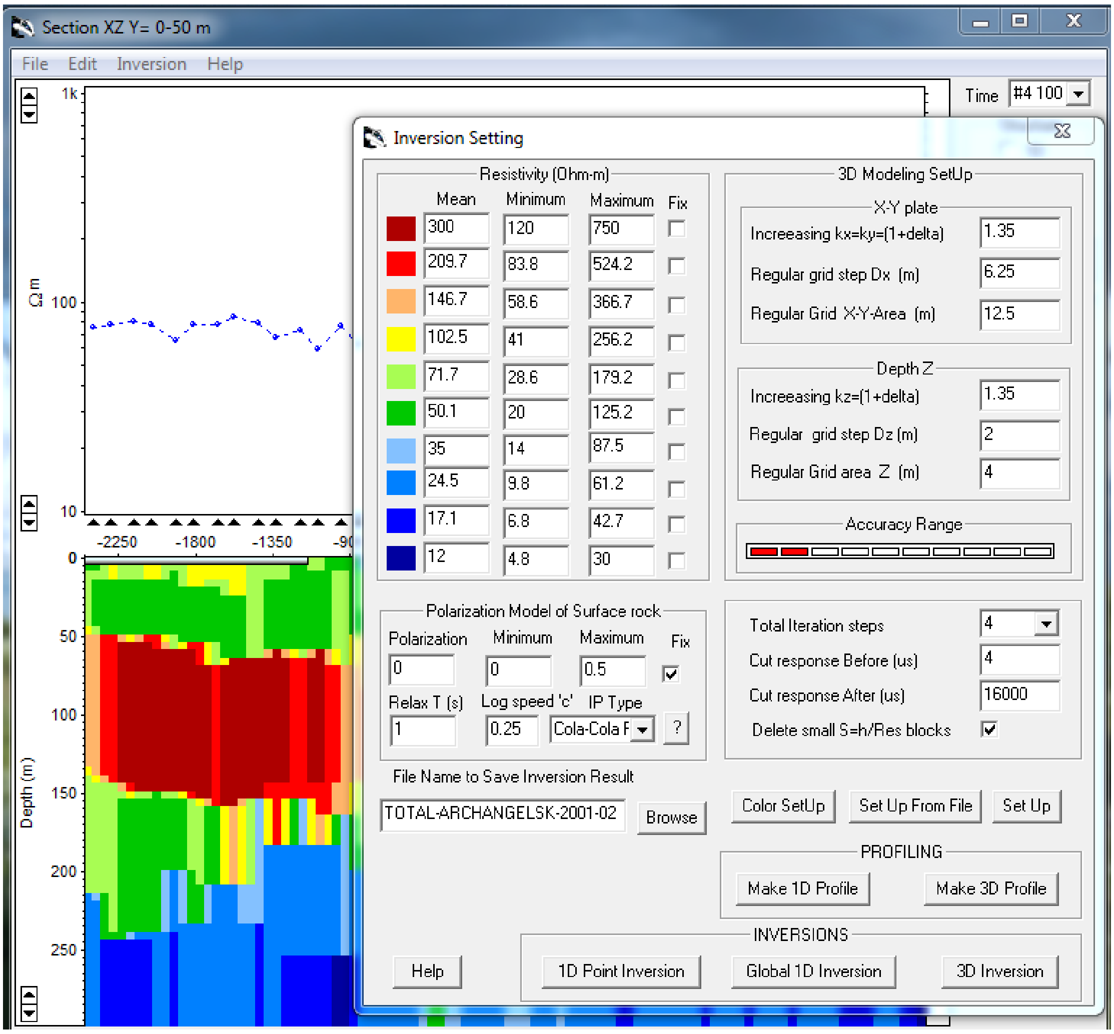


Fig. 3.1. The **Inversion Setting** window in **Section XZ**

The **3D Modelling SetUp** section completely duplicates the **Setup** section of the **Modelling** window. It sets the grid parameters for the calculation of the 3D model.

The **Make 1D Profile** button activates the pointwise calculation of the TEM responses of the 1D models constructed for each profile point; at each point of the profile where there are observed data, a fragment of the 3D model is replaced by the 1D layered model, and the responses are calculated (the number of layers and their thicknesses are determined by the model grid parameter dz).

The **Make 3D Profile** button activates the calculation of the TEM responses of the 3D models for all the "active" points of the profile. The active points are denoted by triangles on the horizontal axis of the **Section XZ** panel (the deactivation/activation of a set is fulfilled by a double click on the triangle, and a global deactivation/activation by pressing **Alt+@**).

The **1D Point Inversion** button begins the 1D pointwise inversion of the observed data for all the points on the profile. The result of the inversion at each point of the profile does not depend on the results of inversion on the adjacent points. The initial resistivity values as well as their maximum and minimum values can be specified in the **Resistivity Ohm-m** section. In the case of a 1D inversion, fixing the resistivity (**Fix** switches) is not valid.

Because the inversion at each point of the profile is carried out with respect to the resistivity of the multilayer 1D model (up to 30 layers with fixed thicknesses h=dz, which is determined in the **Grid Range** main menu), in some cases thin layers with high resistivities and small conductances $S=h/\rho$ (power/resistivity) can appear. These layers do not contribute to the calculated response but significantly distort the model of the medium. To eliminate such layers, the option **Delete small S=h/Res blocks** is applied.

Figure 3.2 shows the inversion results for two identical models of the medium that were built from the same observational data. Both models have been artificially "distorted" by introducing several thin layers with h=5 m and resistivity ρ=1000 Ohm-m (S=0.005 Ohm^{-1}). The left panel shows the results of the **1D Point Inversion** with the **Delete small S=h/Res blocks** option deactivated, and the right panel shows the results with the option activated.

Delete small S=h/Res blocks =OFF **Delete small S=h/Res blocks** =ON

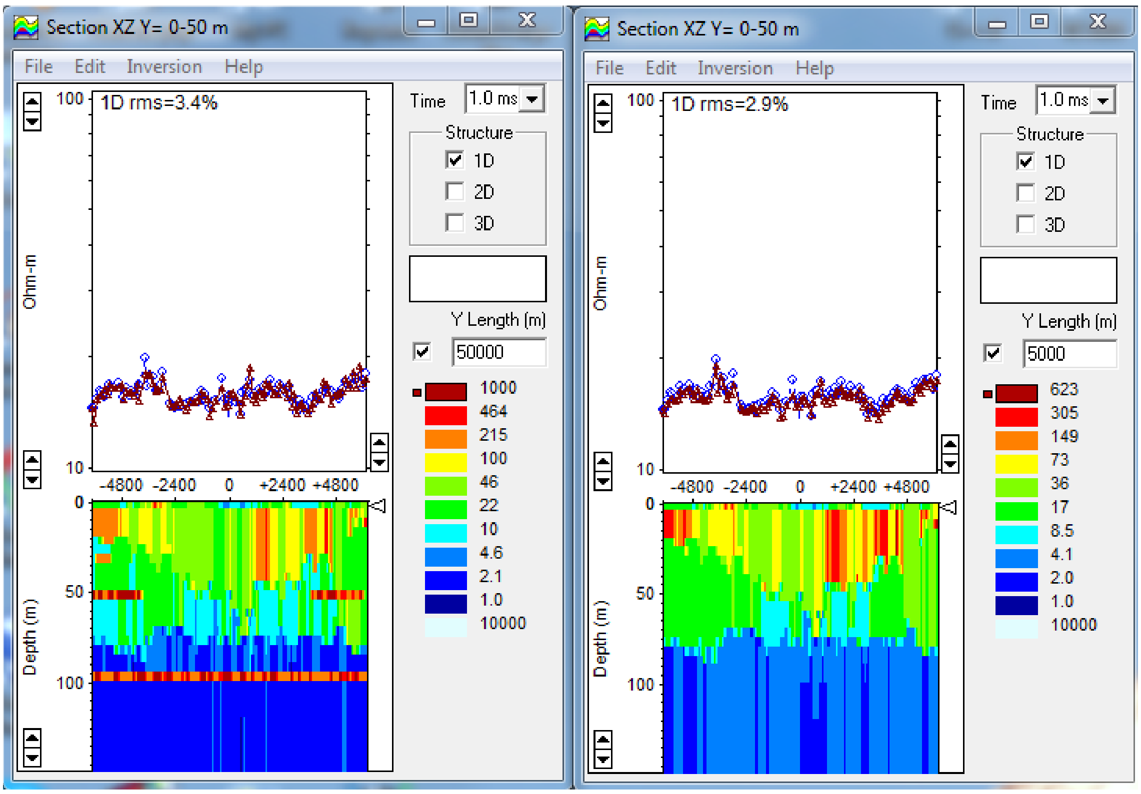


Fig. 3.2. Inversion results with the **Delete small S=h/Res blocks** option enabled and disabled**.**

If the source data are complicated by Induced Polarization (IP) effects, the average, maximum and minimum values of the polarizability can be set in the **Polarization Model of Surface rock** section. The polarization effect is calculated only for the first surface layer.

The **Global 1D Inversion** button activates a 1D pointwise inversion of the observed data for all points on the profile simultaneously. The program selects the combination of the resistivity that minimizes the discrepancy between the experimental and calculated data across a given array of TEM responses.

The **3D Inversion** button starts the 3D inversion of the measured data for all the active points on the profile (shaded triangles in Fig. 3.2.1).

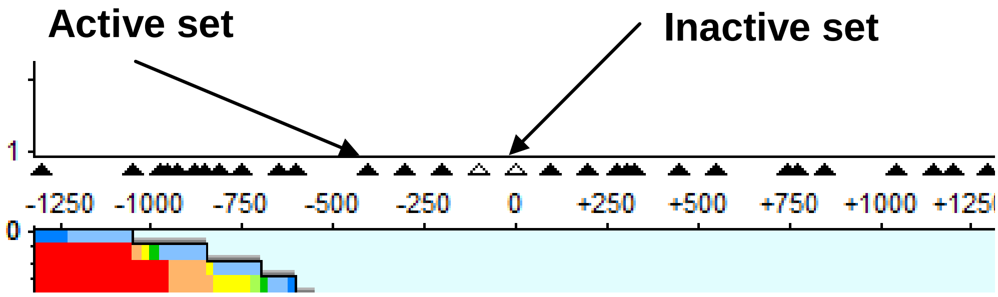


Fig. 3.2.1. The fragment of Section XZ window with location of the sounding antennas centres

Before starting this function, you must specify the mean (**Mean**), minimum (**Minimum**) and maximum (**Maximum**) resistivities. The **Fix** column is necessary to fix the resistivity so that it will not change during the data inversion (**Resistivity Ohm-m** section).

The procedure of a full 3D inversion with respect to a set of 10 resistivities can be extremely time consuming and does not always lead to acceptable final results because the inversion is performed with respect to blocks of resistivity whose boundaries are not changed during the inversion. Therefore, in the preliminary stage, we recommend using pointwise 1D inversions and several preliminary calculations of the 3D responses (**Make 3D Profile**) and “manually" choosing (drawing) an acceptable geometry of the model’s blocks.

When starting the **Make 3D Profile** and **3D Inversion** procedures, it is necessary to specify the file name where the results of the calculations will be recorded. For example, after you set a file named XXX and after the calculation, the files will have the following names:

XXX_INV_ (15-27).ini - file with the estimated parameters of the grid,

XXX_INV_ (15-27).3DPR.txt - file with the relevant TEM data,

XXX_INV_ (15-27).3Dm - file with the data model of the environment, and

XXX_INV_ (15-27).tem - file with the TEM data for all the points of the profile will arise.

The creation time (hours-minutes) of the files is indicated in parentheses.

Fig. 3.3 shows the results of the preliminary data inversion. The preliminary model is based on “raw” TEM data that have been transformed into psc-data on loading (left panel). The model is clarified on the basis of the 1D pointwise inversion.

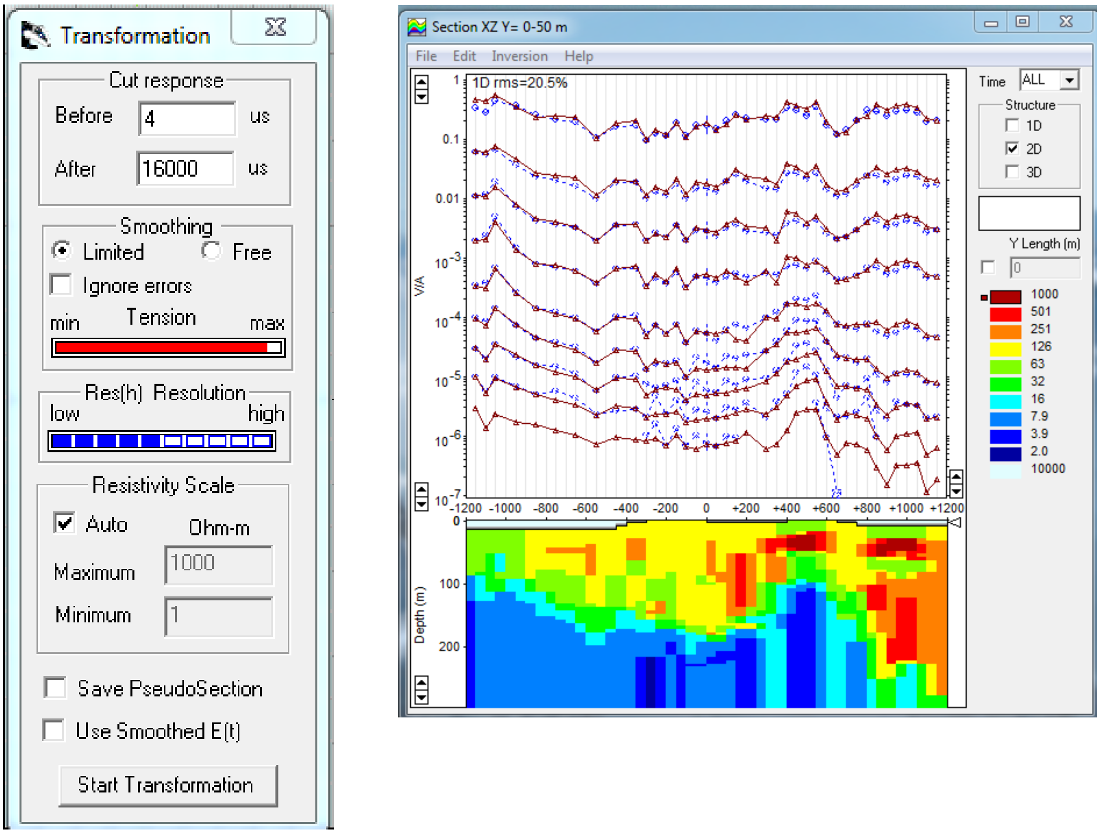


Fig. 3.3. Smoothing and transformation parameters in the left pane and the observed data (blue) and model (brown) in the right pane.

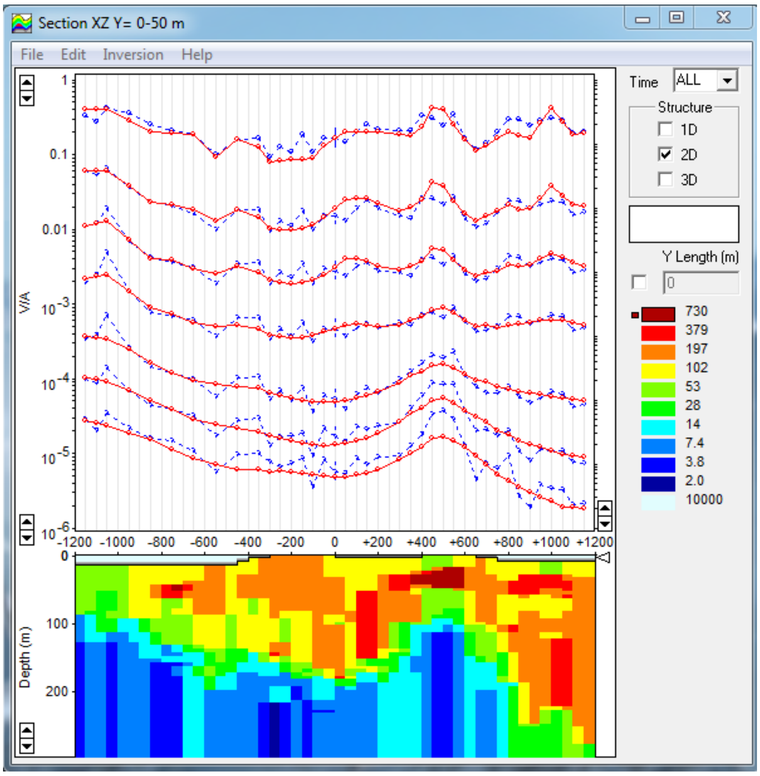


Fig. 3.4 The observed data (blue) and TEM responses (red), calculated (function **Make 3D Profile**) for the 3D model based on the 1D inversion data (Fig. 3.3).

Fig. 3.4 shows that in the area of the points with coordinates x=400-500 m, it is necessary to correct the model because there is significant difference between the observed and calculated responses at later times.

Using the results of a "manual" correction of the model, the TEM responses (normalized apparent resistivities) at time t=1 ms are shown in Fig. 3.5. The discrepancy between the observed and model responses (rms) is ~24%. If you need more detail in the "drawing" model, you can continue the correction. However, in this example, the anomaly associated with the kimberlite pipe (x=450-550 m) was interpreted in sufficient detail and does not require further correction.

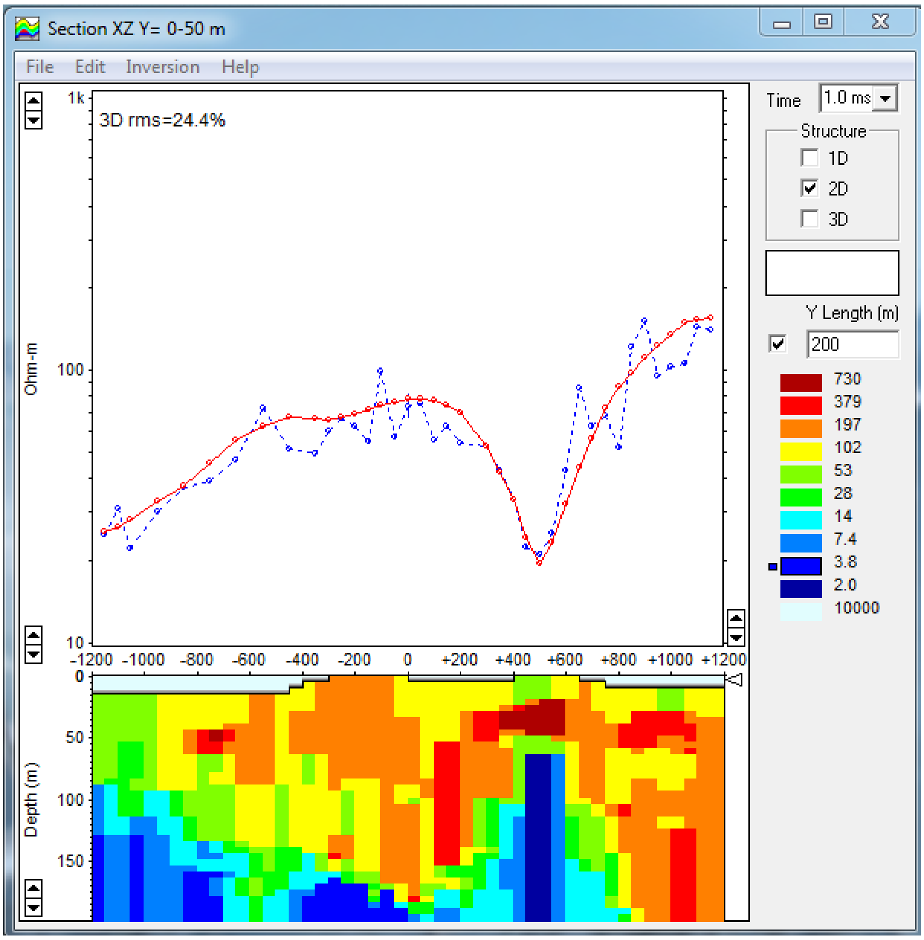


Fig. 3.5. The observed and calculated 3D TEM responses expressed as the apparent resistivity at time t=1 ms. The local anomaly corresponds to a kimberlite pipe with a resistivity ~ 3.8 Ohm-m and a horizontal section of ~100×100 m^2.

Inversion of the profile data in the "manual mode"

After loading the TEM profile data (INT-data, from the 1D **TEM-RESEARCHER** inversion program), the geoelectric section is shown in the **Section XZ** window, as seen in Fig. 3.6.

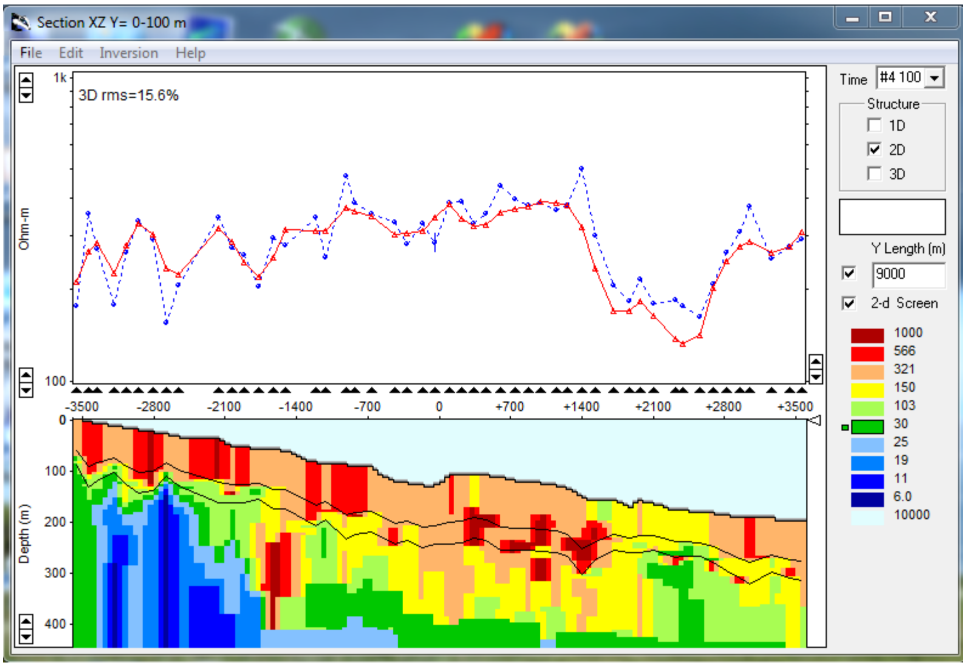


Fig. 3.6. 2D geoelectric section constructed on the base of 1D inversions

The key combination **ALT+D** displays the ranges of the depths corresponding to the selected time (where t=100 μs) using black lines. On the distance axis, the centres of the sounding antennas are denoted by triangles. The sounding points can be deactivated and activated by double clicking the left mouse button on the corresponding triangle. In this example, the observed data at these points did not disappear; however, during the calculation of the model responses, the "inactive" points are ignored, which significantly saves calculation time.

When working in "manual mode", it is convenient to use a second screen (**2-d Screen button**), as shown in Fig. 3.7.

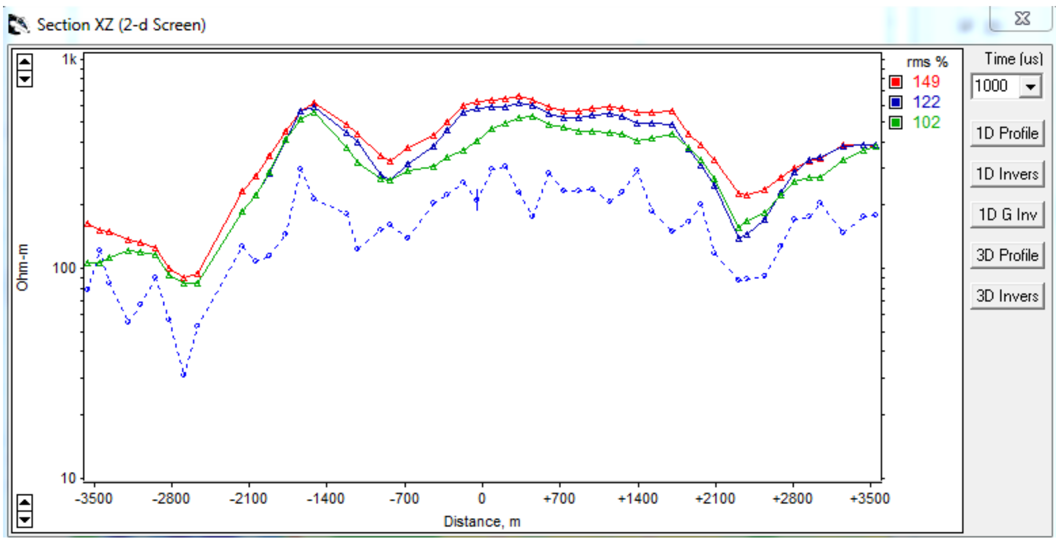


Fig. 3.7. Additional **2-d Screen**, opened in the **Section XZ** window.

Whenever the **3D profile** calculations are performed, the TEM-responses corresponding to the selected medium model are mapped on an additional screen. In the upper right corner, the discrepancies between the model and the observed responses (rms %) for the selected time (where *t*=1000 μs) are shown. Thus, using the "designing" geoelectric section (by introducing new blocks or editing existing blocks) in **Section XZ** on the second screen, one can control the changes in the model responses ("history" does not contain more than 6 responses).

The researcher can return to the best (from his point of view) model variant using the menu's Edit->Undo/Redo function.

Occasionally, in a small section of a long profile, the discrepancy between the experimental and model data is unacceptable (for example, Fig. 3.8).

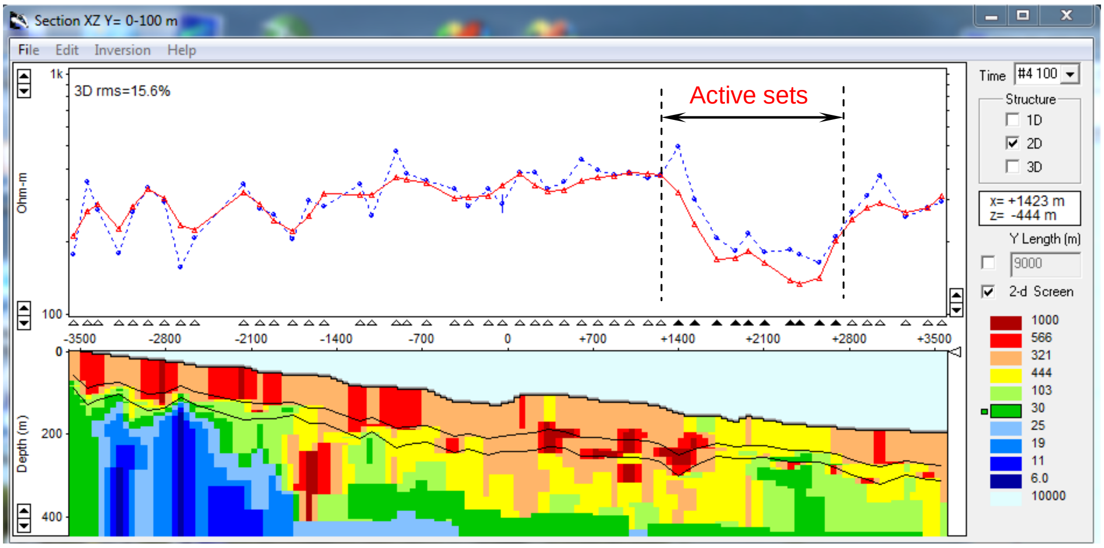


Fig. 3.8 Profile of TEM responses at time t=100 μs with a selected area of active soundings sets.

To correct the geoelectric section in the selected area, you must activate all the profile points (**ALT+@**) and then double-click the mouse to activate the desired sets. You can then edit the resistivity section in the selected interval and check the results of the model design by starting **3D Profile** from **2-d Screen** (Fig. 3.9).

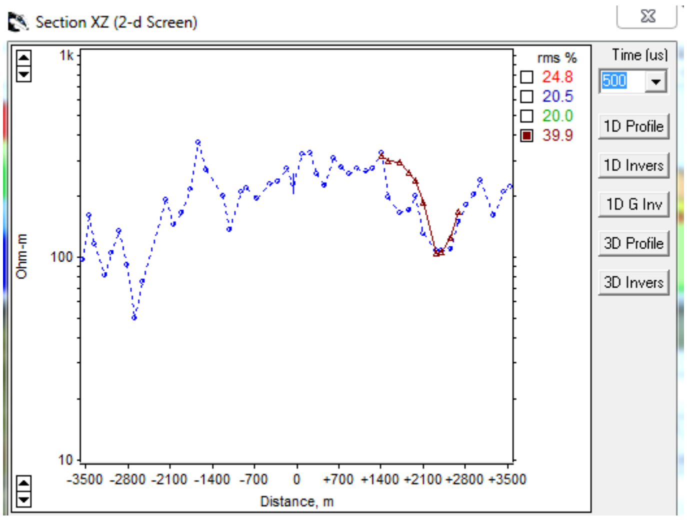


Fig. 3.9. Results of the TEM response calculation in the highlighted range of the profile shown in Fig. 3.8.

The 13 steps of a 3D inversion

Based on our experience with 3D inversions of experimental data, we propose the following stages (steps) of interpretation.

1. Using the TEM-RESEARCHER (TemRes) filter, eliminate soundings sets that are distorted by noise, induced polarization effects (IP) or superparamagnetic effect (SPM).

2. Run a 1D inversion on the filtered area or profile data in TemRes. At this stage, you have to set geologically reasonable limits for changes in the layers' resistivities and thicknesses. All the area or profile data with the edited **X-Y-Z** coordinates must be in the same **sec** or **int**-file.

3. In the main window, set the size of the model grid (**Grid**) along the Z-axis based on the characteristics of the geological problem to be solved (approximately dz~L/20, where L is the size of the antennas). The sizes of the cells in the X and Y directions (dx=dy) and the size of the model (Range) are automatically determined when the data are loaded.

4. Load the int-file (the window **Section XZ**, **File->Input Observed data** type of files when loading **- Inversion data**) Fig. 3.10A, switch on **Design Profile** and mark the needed profile. Click the right mouse button on any point on the tablet; the marked area is coloured red (Fig. 3.10B). Press the **Set Model** button, and the 2D model of the medium is ready (Fig. 3.10C).

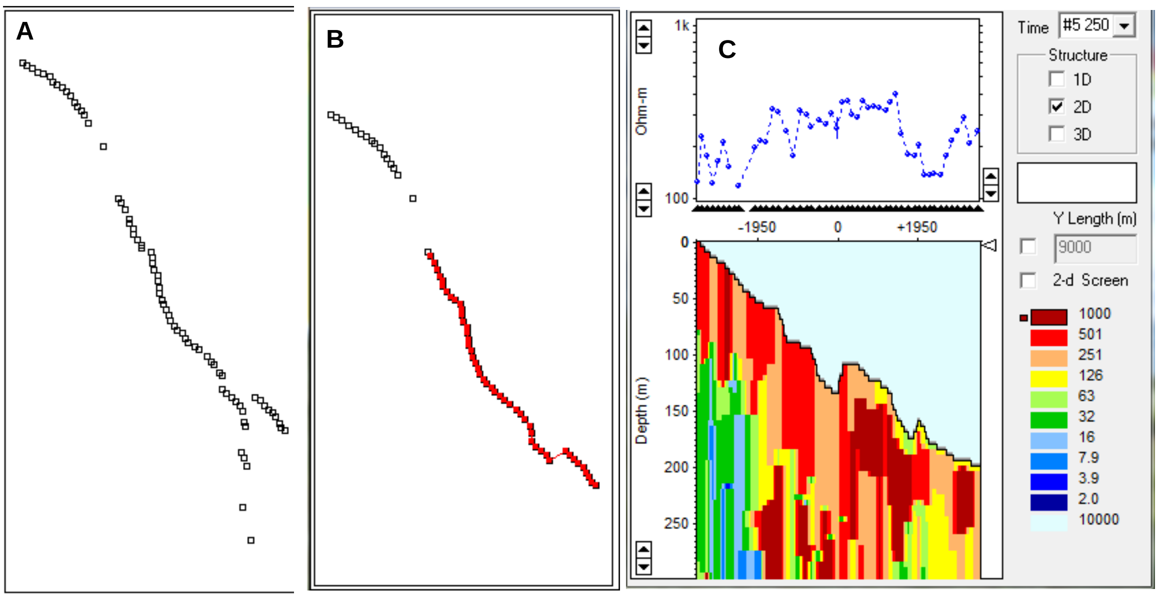


Fig. 3.10. The sequence for constructing a 2D model: int-input data (A), marking all (or part) of the profile (B), construction of the 2D models, taking into account the earth's surface relief (C).

5. If there are area data, and you want to build a 3D model, you must perform the following actions: enter the data in the **int**-or **sec**-file (Fig. 3.11A), turn the **Design Area** switch on, mark the area (check box with the left mouse button) and click the right button in an arbitrary place on the tablet; the selection area will then be marked in red (Fig. 3.11B). Click the **Set Model** button and build a 3D model without marking profiles (Fig. 3.11C). Next, right click on the top bar of the window (Fig. 3.11C) and remark the area (or profile). This results in a 3D model and highlights the central area of the profile (y=0) (Fig. 3.12.). Now, run the 1D inversion process for the entire built model (**Alt+W**).

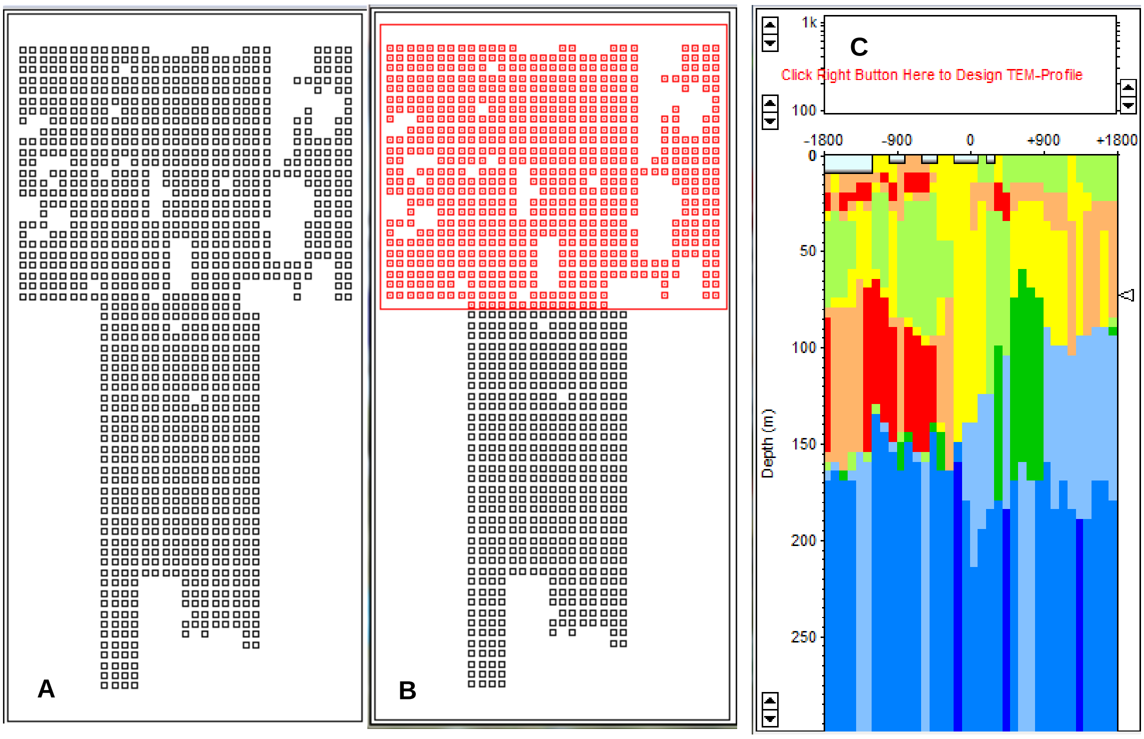


Fig. 3.11. The sequence of building a 3D model: int-data input (A), mark all (or part of) the area (B), build the 3D model, taking into account the relief of the earth's surface without marking the profile (C).

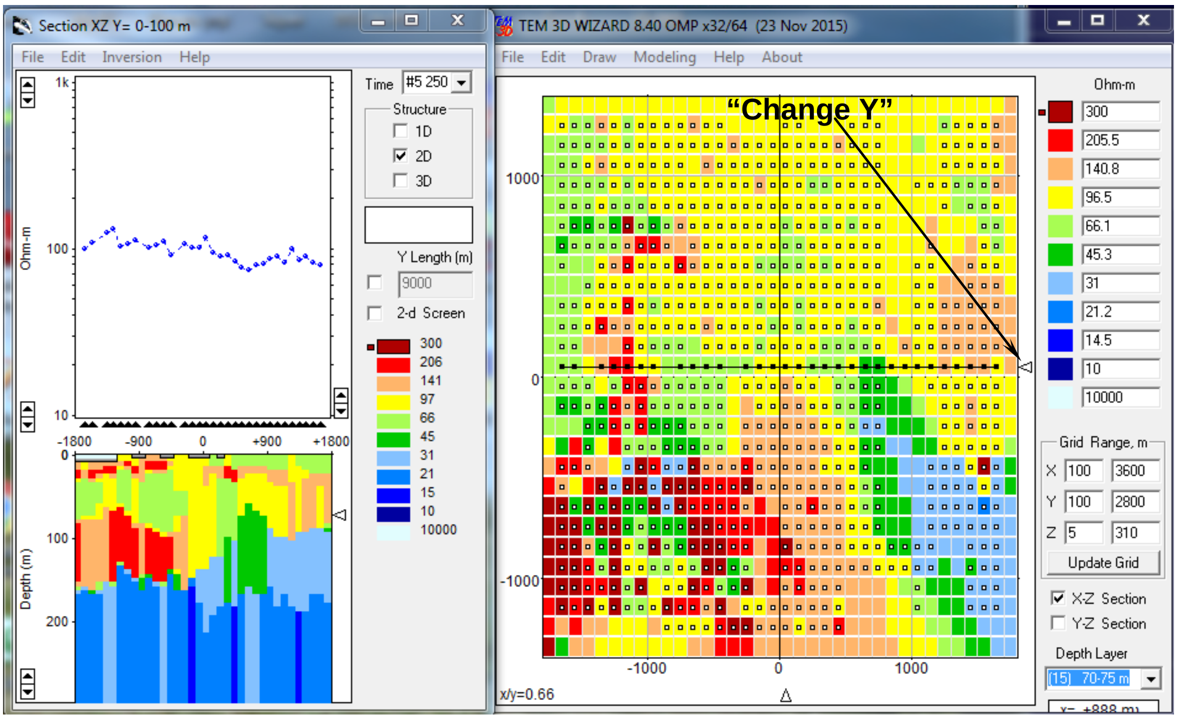


Fig. 3.12. The results of constructing the 3D model. The isolated central part of the profile for (y=0). By moving the mouse pointer in the latitudinal direction «Change Y», you can select the desired profile, and the TEM data will appear in the **Section XZ** window.

If you want to draw a profile in any direction, then, at the step shown in Fig. 11c, activate the **Design Profile** switch and mark the desired sets (Fig. 3.13).

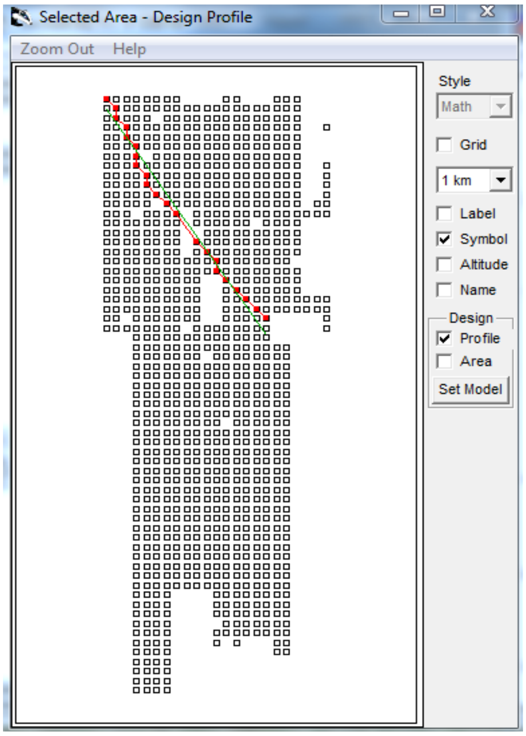


Fig. 3.13 Marking the profile in an arbitrary direction.

After clicking **Set Model,** a model that is expanded such that the selected profile is similar in The X-axis direction is displayed (Fig. 3.14).

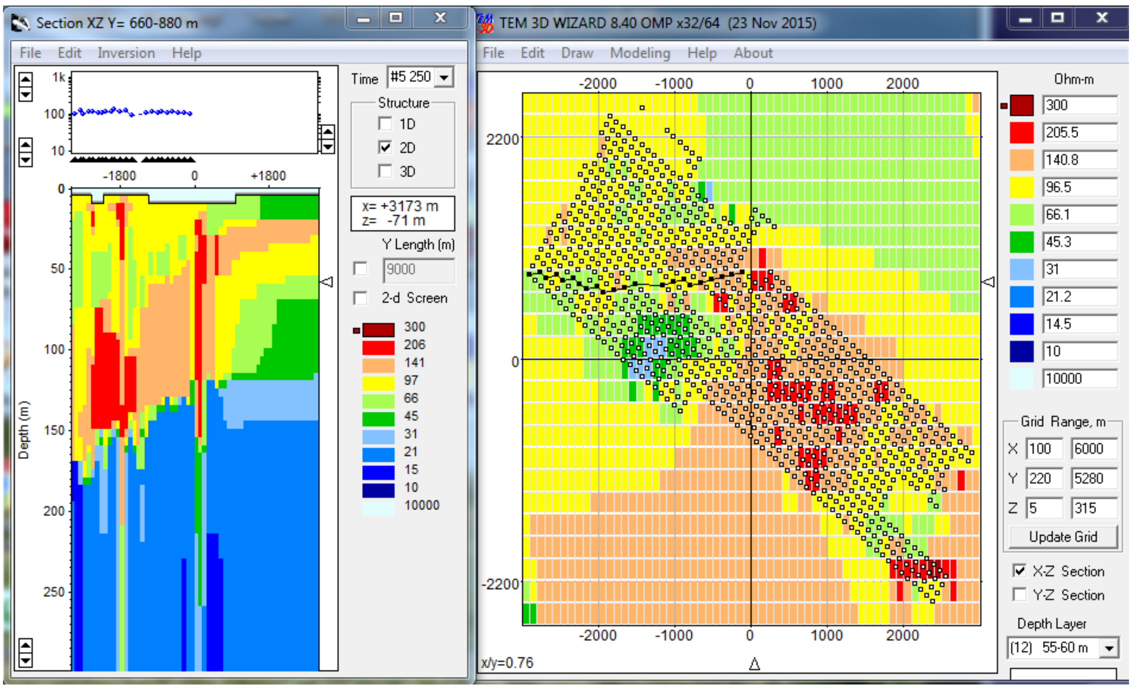


Fig. 3.14. 3D model that is unfolded to an arbitrary angle, based on TEM areal data.

6. Set the necessary inversion parameters in the **Section XZ->Inversion** window (1D and 3D) and leave this window using the **Set Up** (button) command.

7. Activate an additional screen using **2d Screen** in the **Section XZ** window.

8. Start the **1D Invers** process. The model responses are drawn on the top panel in a brown colour.

9. Start the **1D G Inv** (global 1D inversion) process to optimize the scale of the resistivities. In this process, the colour palette of the section does not change; only the resistivities that correspond to each scale colour change. After the inversions, if the value of the residual does not exceed 10-15% for all the TEM response times, this procedure has only slightly corrected the resistivity levels.

10. Set the optimum (in terms of the geological problem to be solved) grid parameters and calculation level of accuracy (**Accuracy Range**). To do that, open the **Modelling** window and then the **Setup** window. On the **Modelling** panel, you can see how the calculated net "covers" the analysed model of the medium.

11. Start the **3D Profile** procedure, which will produce results like those shown in Fig. 3.15.

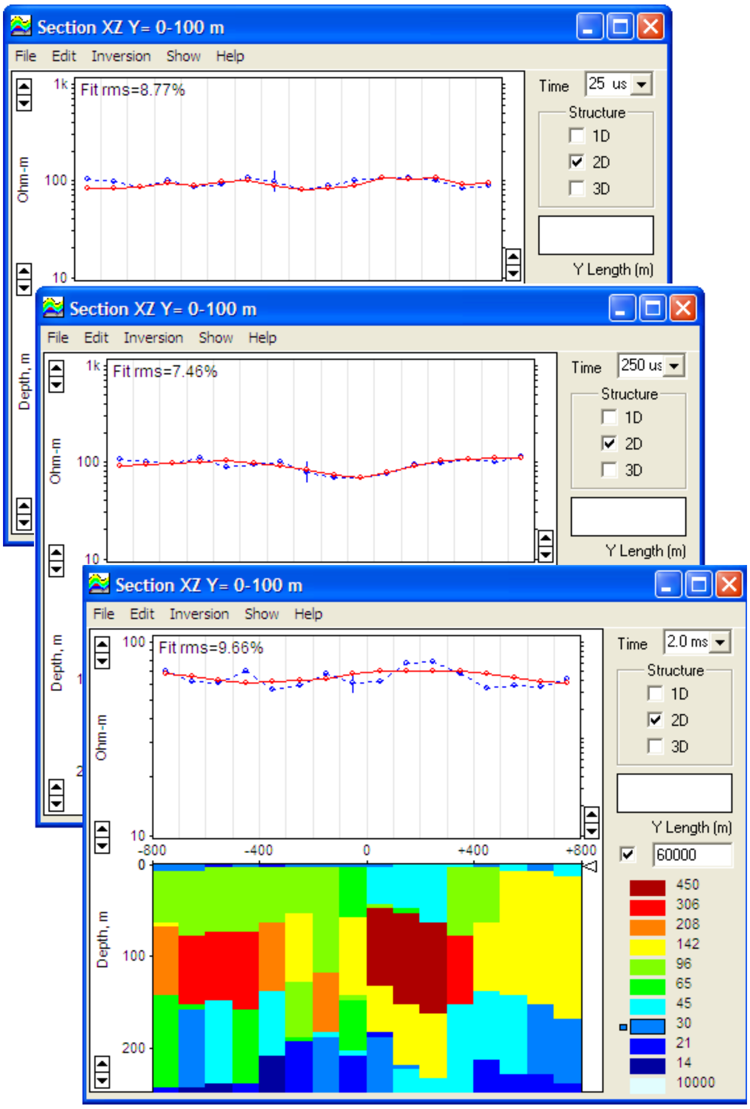


Fig. 3.15. TEM responses calculated using the **3D Profile** procedure for a profile crossing the 3D model. Blue - observed data, red - 3D model responses for three different times: *t*=25 μs, 250 μs and 2 ms.

For each point on the profile, you can estimate the degree of closeness of the model and observed responses. For that, double-click the left mouse button on any blue and red symbol on the graphs (Fig. 3.15) to open the **Response vs. time** window (Fig. 3.16).

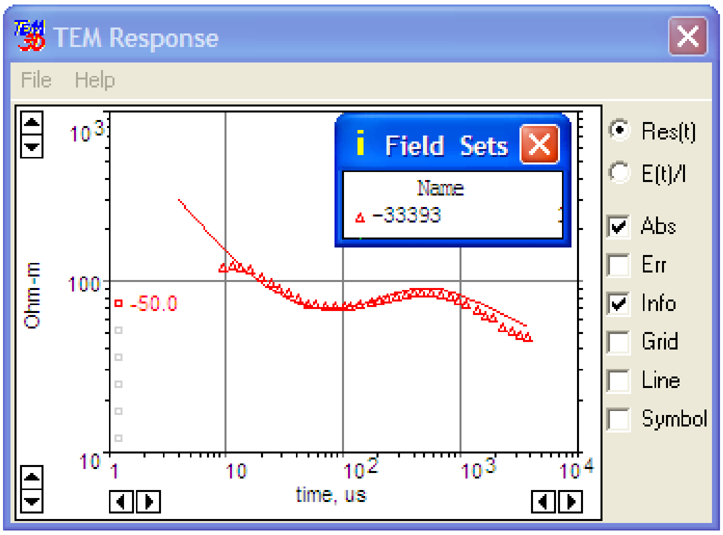


Fig. 3.16. Apparent resistivity curves of the observed (triangles) and model responses (solid line) for the point on the profile labelled “**33393**”. The label **-50.0** is the name of the model response.

12. A user can edit the medium model interactively. The possible actions are described above in the “**Inversion of profile data in the manual mode**” section.

13. After editing the model by pointwise fitting the experimental and model responses, limit and fix the model resistivities as needed and run the **3D Inversion** procedure. Keep in mind that that the time required to perform a 3D inversion is proportional to the product of the number of points on the profile (or array) and the number of *unfixed* resistivities.

During operation, the program saves intermediate results in the following files:

***.3Dm** – file containing information on the 3D model,

*.ini - file containing the estimated grid parameters,

*.int - file containing the 1D inversion data,

*.tem - Standard TEM file with the model responses, and

*3DPR.txt - file containing the responses for the 3D profile.

References

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Barsukov P.O., Fainberg E.B., Khabensky E.O. 2015. Shallow investigations by TEM-FAST technique: methodology and examples. // Electromagnetic sounding of the Earth's interior: theory, modeling, practice, Elsevier, Ed. Spichak V.V., Chapter 3, 2005, P. 47-77

Notice

The ability to competently perform three-dimensional data inversions of TEM soundings is the apex of an interpreter’s professionalism. The proposed program provides a great opportunity; for the novice, do not be confused by the difficulty required to master this program - the loss of time spent in training will pay off handsomely during its application.

Forward - and good luck to you!