

RES3DINVx64 ver. 3.13
Basic and Professional versions
with multicore and 64-bit support

for Windows XP/Vista/7/8/10

Rapid 3-D Resistivity & IP inversion
using the least-squares method
(For 3-D surveys using the pole-pole,
pole-dipole, dipole-dipole, rectangular, Wenner,
Wenner-Schlumberger and non-conventional arrays)
On land, aquatic, cross-borehole
and time-lapse surveys

Geoelectrical Imaging 2-D & 3-D
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1 Introduction

RES3DINVx64 is a computer program that will automatically determine a three-dimensional (3-D) resistivity model for the subsurface using the data obtained from a 3-D electrical imaging survey (Li and Oldenburg 1992, White *et al.* 2001). Ideally, the electrodes for such a survey are arranged in a rectangular grid (**Figure 1a**). However, in practice (depending on the available equipment, surface topography, survey time and budget), different types of survey procedures have been used. More details on the practical use of the pole-pole, pole-dipole, dipole-dipole and other arrays for 3-D surveys are given in the free ‘Tutorial notes on electrical imaging’ (Loke 2016). On a computer with 8 GB RAM, the RES3DINVx64 Basic program can handle survey grids with about up to about 16000 electrodes. The RES3DINVx64 Professional program can access up to 192GB RAM and support survey grids with up to 200000 electrodes. On a modern multi-core Windows-based microcomputer, the data inversion takes from less than a minute for small surveys with 100 electrodes in a flat area to several hours for large surveys with 6000 electrodes in rugged terrain. The inversion of a data set with 198 electrode positions (BLOCKS_22x9-ws.dat file) just takes about 17 seconds on a PC with a hex-core i7 CPU. A variety of survey configurations are supported, from simple rectangular grids (Figure 1a,b), to non-rectangular grids (Figure 1c), to even data sets collated from survey lines in different directions (Figure 1d).

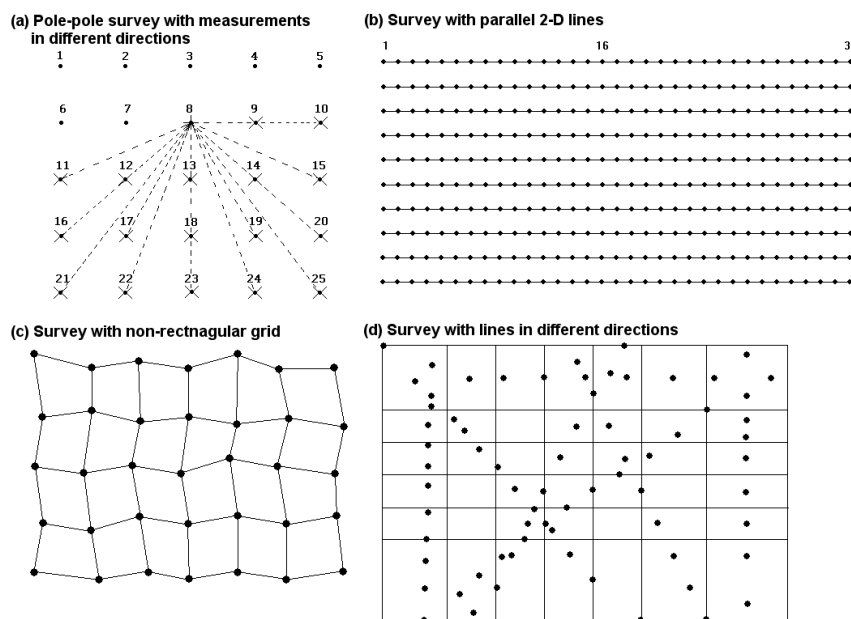


Figure 1. Some possible layouts for 3-D surveys.

2 Computer system requirements

RES3DINVx64 is a 64-bit program that will run under a 64-bit version of Windows XP/Vista/7/8/10. You will need a microcomputer with a multi-core Intel CPU to run this program. It is recommended that you use a PC with an Intel (rather than an AMD) CPU as the RES3DINVx64 program has options that are optimized for this type of CPU that can significantly reduce the calculation time for large data sets.

RES3DINVx64 comes in two versions, Basic and Professional, depending on the license the license you have purchased. RES3DINVx64 Basic replaces the older 32-bit RES3DINVx32 as 32-bit Windows is obsolete. While RES3DINVx32 is limited to 2 GB RAM, RES3DINVx64 Basic allows the use of up to 8 GB RAM. RES3DINVx64 Professional can access up to 192 GB RAM. The following section has more details on the differences between the Basic and Professional versions.

RES3DINVx64 requires at least 4 GB RAM. You will also need at least 32 GB of free hard-disk space that the program can use to store temporary swap files. If you have more than one hard-disk drive, the program will automatically select the drive with the largest amount of free space as the drive to store the swap files. For computer systems with more than 12 cores (including logical cores using the Intel hyper-threading technology), the remaining bottleneck is probably the speed of the hard-disk which the program uses to store temporary files. The time taken to write and read the temporary files can be significantly reduced by using a Solid State Drive (SSD). The amount of free hard-disk space should be at least 8 times the RAM.

There should not be any background programs running (such as word processors, CAD programs, etc.) when executing the RES3DINV program. Please shut down other programs to free the memory for this program. This will reduce memory to hard-disk swapping that slows down the program. In Windows XP/Vista/7/8/10, the active programs are usually listed on the Start bar at the bottom of the screen.

On some versions of Windows it might be necessary to configure the program to run as an Administrator so that it is allowed to create temporary files in the hard-disk. This can be done by right-clicking the program icon on the Windows desktop and select the 'Run as Administrator' label.

This program attempts to make full use of the computer CPU and hard-disk storage when processing a large data set. It is designed for standalone PCs, and it is recommended that it should not be used with a PC in a network (used as a network server) when carrying out the inversion of a very large data set with more than 100,000 data points or model cells. We cannot guarantee that it will run smoothly on such network PCs for the inversion of very large data sets and models. Also, it should not with PCs having a dual operating system such as Windows and Linux.

2.1 Differences between RES3DINVx64 Basic and Professional

RES3DINVx64 Basic is mainly intended as a replacement for the older 32-bit RES3DINVx32 as 32-bit Windows is obsolete. The version of RES3DINVx64 that the user is allowed to use depends on the license the software has. The main differences between the two versions are as follows.

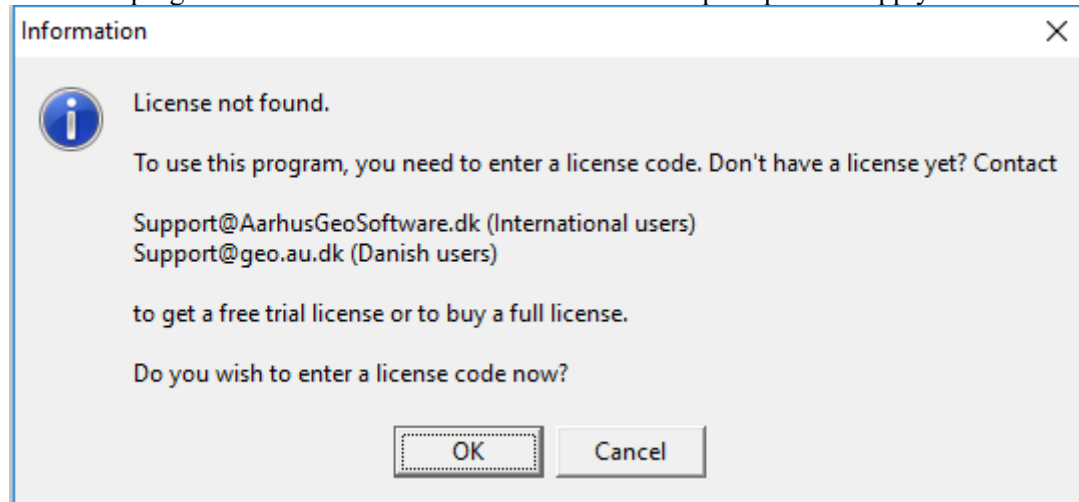
- 1). Res3dinvx64 Basic is limited to 8 GB RAM memory space while Res3dinvx64 Professional can access up to 192GB RAM.
- 2). Only Res3dinvx64 Professional supports 3-D time-lapse inversion. The Basic version does not support this type of data.
- 3). Res3dinvx64 Basic is limited to a finite-difference/element mesh model with a maximum of 1.4 million nodes. In Res3dinvx64 the maximum mesh size depends on the computer RAM. With 128GB, it supports up to about 12 million nodes.

RES3DINVx64 Basic is probably sufficient for medium size surveys with up to several thousand electrodes positions. RES3DINVx64 Professional is recommended for more complex survey arrangements (particularly for mineral exploration) with very large surveys grids with tens of thousands of electrodes positions, data points and model cells, or for time-lapse surveys.

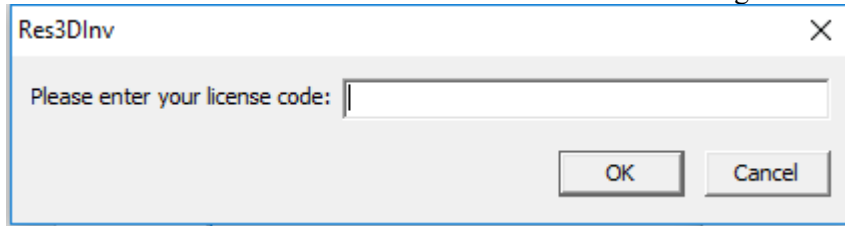
3 Copy protection

The program uses the Aarhus Geosoftware Internet based digital copy protections system for copy protection. Without the digital license, you can use the program to invert data sets with up to 200 electrodes (with a limit of 4 iterations in the inversion routine). If you had purchased the license for the 2-D resistivity/IP inversion program (RES2DINV) only, you can process data sets with up to 1100 electrodes (with a limit of 5 iterations) using the license provided. With a license that has the RES3DINVx64 software license, the restrictions are removed.

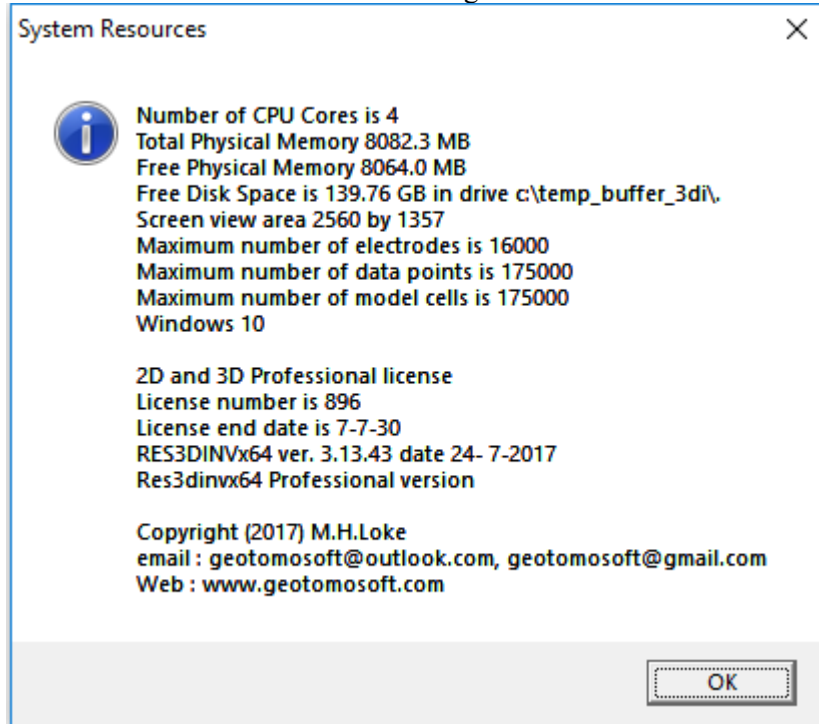
When the program is launched for the first time the user is prompted to supply a license code:



If “Cancel” is selected the program continues in demo mode with limited functionality. If “OK” is selected the user need to enter the license code in the following window and press “OK”.



If the license code is valid the following screen with information about the PC and the license is seen:

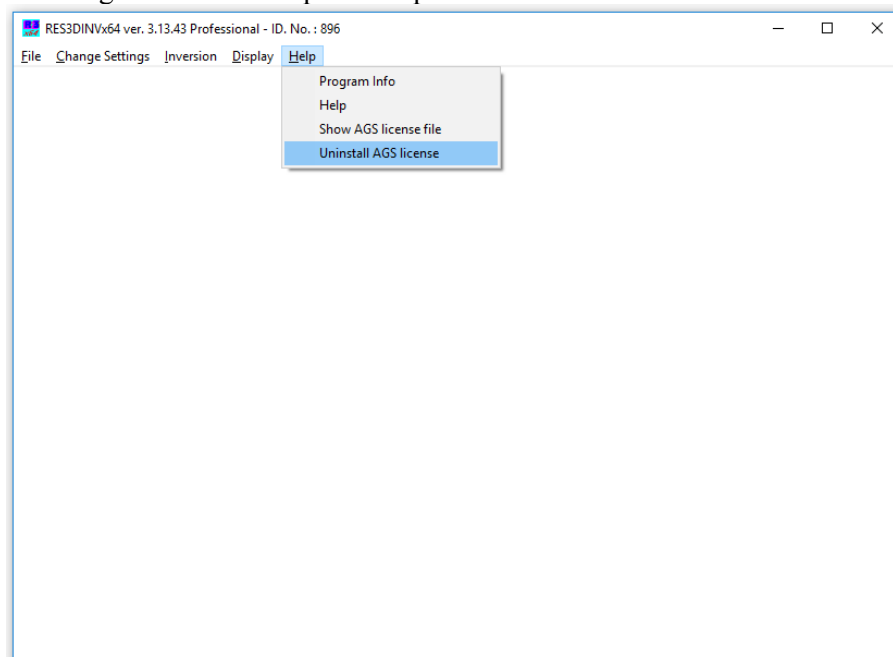


It is also possible to see the license information in Help -> show AGS license file.

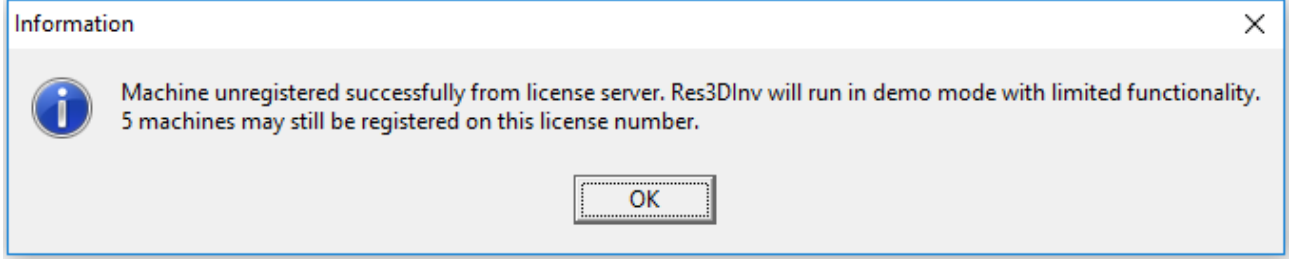
To unregister a license for use on another pc

The license can be unregistered to be moved to another PC, always remember to do this before uninstalling the software as the computer will still take up the license if this is not done.

To unregister the license press Help -> Uninstall AGS license as seen below:



The following info box will be shown with information about the available number of licenses on the code



4 Theory

The inversion routine used by the program is based on the smoothness-constrained least-squares method (deGroot-Hedlin and Constable 1990, Sasaki 1992, Loke *et al.* 2003). The basic smoothness-constrained least-squares method is based on the following equation.

$$(\mathbf{J}^T \mathbf{J} + \lambda \mathbf{F}) \Delta \mathbf{q}_k = \mathbf{J}^T \mathbf{g} - \lambda \mathbf{F} \mathbf{q}_k, \quad (4.1)$$

where $\mathbf{F} = \alpha_x \mathbf{C}_x^T \mathbf{C}_x + \alpha_y \mathbf{C}_y^T \mathbf{C}_y + \alpha_z \mathbf{C}_z^T \mathbf{C}_z$

$\mathbf{C}_x, \mathbf{C}_y$ = horizontal roughness filters

\mathbf{C}_z = vertical roughness filter

\mathbf{J} = Jacobian matrix of partial derivatives

\mathbf{J}^T = transpose of \mathbf{J}

λ = damping factor

\mathbf{q} = model perturbation vector

\mathbf{g} = data misfit vector

One advantage of this method is that the damping factor and roughness filters can be adjusted to suit different types of data. This program uses the Gauss-Newton method that recalculates the Jacobian matrix of partial derivatives after each iteration (Loke and Dahlin 2002). Besides the above basic smoothness-constrained method, other variations are also available. One example is a robust model (L_1 norm) inversion method that tends to produce models with sharper boundaries (Loke *et al.* 2003). The choice of inversion method to use should be guided by the nature of the known geology of the survey area. The inversion program divides the subsurface into a number of rectangular prisms, and attempts to determine the resistivity values of the prisms so as to minimize the difference between the calculated and observed apparent resistivity values, subject to selected constraints. One possible arrangement (Loke and Barker 1996) is shown in Figure 2. Here each block in the top layer has an electrode in each corner at the surface of the model. The optimization method tries to reduce the difference between the calculated and measured apparent resistivity values by adjusting the resistivity of the model blocks. A measure of this difference is given by the root-mean-squared (RMS) error. However, the model with the lowest possible RMS error can sometimes show large and unrealistic variations in the model resistivity values and may not always be the "best" model from a geological perspective. In general, the most prudent approach is to choose the model at the iteration after which the RMS error does not change significantly. This usually occurs between the 4th and 5th iterations.

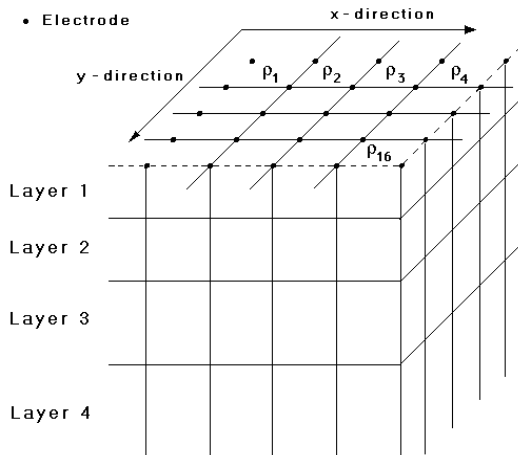


Figure 2. A simple discretization model used in the inversion program with electrodes at the surface corners of each block in the top layer.

5 Software installation

You can download the programs from the www.aarhusgeosoftware.dk. The RES3DINVx64 package comes in a single compressed installation file SETUP.EXE. It is a Windows-based installation program that will install the program files. The default folder for the program is C:\Program Files (x86)\Geotomo_Software\Res3dinvx64. In this folder, you will also find a number of example data files with a DAT extension. **Table 1** has a partial list of the example data files.

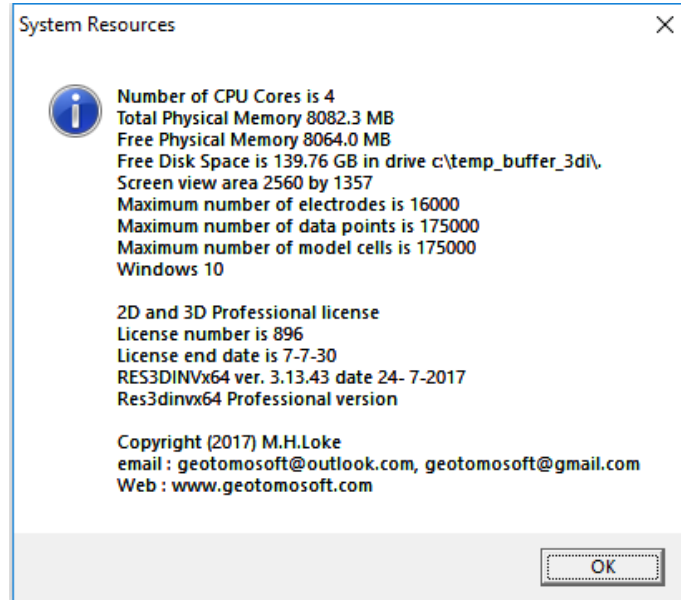
Depending on the type of field equipment you are using, the manufacturer of the equipment will probably also supply you with supplementary programs and example files to convert the raw data files obtained with the instrument into the format required by this program.

Table 1. Some example data files installed with the RES3DINV program.

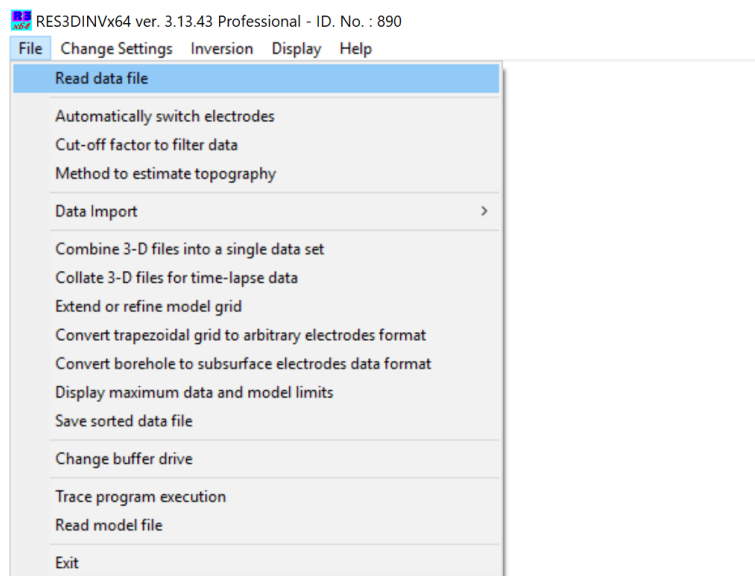
ROOTS7.DAT	A small field data set with a 7-by-7 survey grid.
PIPE3D.DAT	Data from a field survey over an underground pipe with an 8-by-9 grid.
EKEBODA.DAT	Field data set from a landfill site survey
GRID7X7.DAT	A synthetic data set with a 7-by-7 grid with all the possible measurements. (Pole-pole array).
BLK15PPL.DAT	A synthetic data set with a 15-by-15 grid. (Pole-pole array).
Block17x15ip_PDP.DAT	A synthetic data set with a 17-by-15 grid containing I.P. data. (Pole-dipole array).
BLK15DDP.DAT	A synthetic data set with a 15-by-15 grid. (Dipole-dipole array).
3d_mixed_arrays.dat	Example of data file with mixture of different arrays using the general array data format.
MODEL3IP.DAT	An example data file with resistivity and I.P. data.
GRID8X8.DAT	A small synthetic data set with an 8-by-8 grid. (Pole-pole array).
MOD3DFIX.DAT	An example data file with where the resistivity of a section of the model is fixed by the user.
BLOCK26W.DAT	Example data set for the Wenner array
BLOCK26S.DAT	Example data set for the Wenner-Schlumberger array
Blocks 95x33 2p5m dd.dat	A large data set with a 95-by-33 grid.
BLOCK11T.DAT	Example input data file with topography.
BLOCK11T List.DAT	Same data as above but with topography given as an unstructured list.
TRAPEZOIDAL.DAT	Example data files with electrodes arranged in a trapezoidal grid.
BLOCK12x11_points.dat	Example data file with electrodes at arbitrary locations.
Subsurface_point_elects.dat	Example data file with subsurface electrodes at arbitrary locations.
Block11x12_pp_boundary.dat	Example data file with a user specified boundary.
Water_Float_19x12.dat	Example data file for a survey with floating electrodes with water layer modeled by a sharp boundary.
BLOCKS 22x9-ws.dat	Example data file with 196 electrodes
BLOCK11x12_time_3.dat	Example time-lapse data set
Combine-3-time.txt	Example script file to create time-lapse data set
L5N Resistivity Global.dat	Example of data file with true coordinates and inclined survey lines.
L5N Resistivity Local.dat	Example of data file after rotation to reduce grid size.
BLOCK12x11_points_compressed.dat	Example of data in arbitrary electrodes data format with compressed format for coordinates of electrodes.
Tank Model.dat	Example with sides of tank specified.
Ekeboda.dat	Example landfill survey data set.

6 Using the program – a quick start

After installing the program, just click the RES3DINVx64 icon to start the program. The program will first check the computer system to ensure that it has the necessary resources that is required. It will check for the available memory and hard-disk space. If the program displays a warning, you should quit from the program and make the necessary changes. As an example, below is a typical initial information box displayed by the RES3DINVx64 program.



After checking the computer configuration, the program will then display the following Main Menu bar near the top of the screen.



You can select an option by clicking it with the mouse cursor. If this is the first time you are using the program, try reading in one of the smaller files such as ROOTS7.DAT provided with the program. Click the File choice, followed by the “Read data file” menu choice. After that, if necessary, navigate to the folder where the RES3DINVx64 program is installed. After reading in the file, go to the “Inversion” option, and then choose the “Carry out inversion” option. The inversion subroutine will start. Wait for about a minute for the data to be inverted. If you need to stop the inversion routine at any time, just press the “Q” key or click the 'Next' sub-window at the bottom-right of the screen, and wait for a short while. By default, the program will carry out 6 iterations that can be increased if necessary.

After the inversion process has been completed, click the “Display” and then the “Display inversion model” sub-option. You will then be asked to select the iteration number, type of model slice (horizontal or vertical) and type of contour intervals. After you have made the appropriate choices, the program will then display the model slices.

7 Data file format

When you select the “Read data file” menu choice as described in the previous section, a list of files in the current folder that has an extension of DAT will be displayed. It is assumed that the files follow the format required by this program. If not, you will have to convert the raw data files using the conversion program for the particular resistivity meter system. Some field equipment systems, such as the ABEM SAS and IRIS Syscal systems, come with a utility program to convert the raw data into the format required by the RES2DINVx64 and RES3DINVx64 programs. Many 3-D data sets are collated from a number of parallel 2-D survey lines. The RES2DINVx64 program has an option to combine the data from a number of 2-D survey lines into a 3-D data set with the format required by the RES3DINVx64 program (please refer to the manual for the RES2DINVx64 program). The apparent resistivity values are given in a text file. You can use any general purpose text editor, such as the Windows NOTEPAD program, if you are creating the data file manually. The data are arranged in an ASCII delimited manner where a comma or blank space or LF/CR is used to separate different numerical data items. If there is a problem in running this program, one possible cause is that the input data is arranged in a wrong format. The following sections describe the data format for the different survey electrode grid arrangements shown in **Figure 1**.

7.1 Survey grid types

This section describes the types of survey grids supported.

7.1.1 Uniform rectangular survey grid

The arrangement of the electrodes is shown in **Figure 3**. The electrodes are arranged in a rectangular grid with a constant spacing between the electrodes in the x-direction (as well as the y-direction). However, the spacing between the electrodes in the x-direction can be different from that in the y-direction.

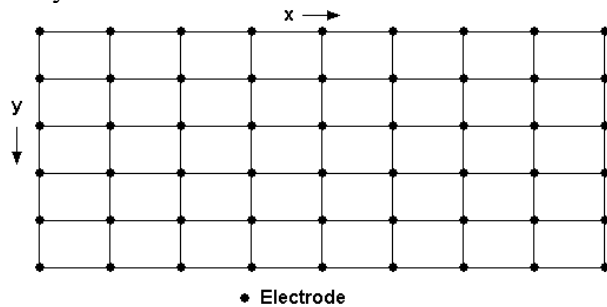


Figure 3. Uniform rectangular grid.

A description of the data format is given below using the ROOTS7.DAT data file an example is given in Table 2. The first data line gives the name of the survey line. The next two lines give the number of electrodes in the x- and y-directions in the survey grid. This is followed by the 4th and 5th data lines that give the spacing between adjacent electrodes in the x- and y-directions. In this example, the number of electrodes as well as the unit electrode spacings in the x- and y-directions are the same. However, they need not be the same. The EKEBODA.DAT file is an example field data set collated from 10 parallel 2-D lines that are spaced 10 meters apart with 61 electrodes positioned 5 meters apart along each line. However, the unit electrode spacing in both directions are set at 5 meters in the data file to reduce banding effects (Loke and Dahlin 2010).

The 6th data line gives the array type number. The different types of arrays with the number codes are listed in Appendix A. The 7th data line gives the number of data points. The following section lists the x- and y-positions of the electrodes used in each measurement followed by the apparent resistivity value.

Table 2. Example data format for a regular rectangular survey grid.

<i>ROOTS7.DAT file</i>	<i>Comments</i>
garden-square-0.5m	<i>Title</i>
7	<i>Number of electrodes in x-direction</i>
7	<i>Number of electrodes in y-direction</i>
0.5	<i>x unit electrode spacing</i>
0.5	<i>y unit electrode spacing</i>

2	<i>Array type, 2 for pole-pole</i>
467	<i>Number of data points</i>
0.00 0.00 0.50 0.00 350.46	<i>For each data point, enter x- and y-location of current electrode, x- and y-location of potential electrode, apparent resistivity value</i>
0.00 0.00 1.00 0.00 398.05	
0.00 0.00 1.50 0.00 424.08	
0.00 0.00 2.00 0.00 413.83	
0.00 0.00 2.50 0.00 373.76	
.	<i>Repeat for all data points</i>
.	
.	
0	<i>Followed by a few 0's: these are flags for other options, such as topography</i>
0	
0	
0	

The example in Table 2 is for the pole-pole array where only the positions of two electrodes, the current electrode (C1) and the potential electrode (P1), are listed. It is assumed that the second current (C2) and potential (P2) electrodes are sufficiently far from the survey grid so that they do not influence the measurements.

The data file Block17x15_PDP.DAT in Table 3 is an example of a pole-dipole data set. The pole-dipole array has 3 active electrodes. Thus in the data file the positions of the one current (C1) and two potential (P1 and P2) electrodes are listed.

Table 3. Example of a pole-dipole array data set.

<i>Block17x15_PDP.DAT file</i>	<i>Comments</i>
FOUR BLOCKS	<i>Title</i>
17	<i>Number of electrodes in x-direction</i>
15	<i>Number of electrodes in y-direction</i>
1.0	<i>x unit electrode spacing</i>
1.0	<i>y unit electrode spacing</i>
6	<i>Array type, 6 for pole-dipole</i>
8523	<i>Number of data points</i>
0.000 0.000 1.000 0.000 2.000 0.000 55.845	<i>For each data point, enter x- and y- locations of the C1 elec., P1 and P2 electrodes, apparent resistivity value</i>
0.000 0.000 2.000 0.000 3.000 0.000 51.324	
0.000 0.000 3.000 0.000 4.000 0.000 50.402	
0.000 0.000 4.000 0.000 5.000 0.000 50.181	
.	<i>Repeat for all data points</i>
.	
.	
.	
0	<i>Followed by a few 0's: these are flags for other options, such as topography</i>
0	
0	
0	

As an example of an array with 4 active electrodes, we look at the data format for the dipole-dipole array in the example file BLK15DDP.DAT in Table 4. For each measurement, the x- and y-locations of the C1, C2, P1 and P2 electrodes must be given.

The number of electrodes used in the array is fixed for the conventional arrays. In some cases, a non-conventional array may be used or the data has a combination of measurements from different arrays (such as the dipole-dipole and gradient arrays). For such data sets, the number of electrodes used for each measurement must be specified. The file 3d_mixed_arrays.dat is an example with measurements from the dipole-dipole (with 4 electrodes) and the pole-dipole (with 3 electrodes). It is always assumed that the data is in apparent resistivity for surveys carried out with conventional arrays. However, for non-conventional arrays, the data can also be given as resistance values. A description of the data format is listed in Table 5. Note that an array number of 11 is used followed by the sub-array number. As this data

set consists of a mixture of data measured with different arrays, a sub-array number of 0 is used to indicate a non-specific array. The next data line after the sub-array number is a header for the type of data. For a general array type, the user can enter the apparent resistivity value or the resistance value. The type of data is given in the next data line, 0 for apparent resistivity and 1 for resistance. The next data line after the data type flag is the number of data points. This is followed by the data measurements information. Note that each data line starts with the number of electrodes used for the measurement. This is not required for the conventional arrays described earlier as the number of electrodes is fixed. Next the x- and y-positions of each electrode are listed followed by the apparent resistivity or resistance value. The positions of the electrodes are always arranged in the order C1, C2, P1 and P2 (if the C2 and P2 electrodes are used).

Table 4. Example of a dipole-dipole array data set.

<i>BLK15DDP.DAT file</i>	<i>Comments</i>
FOUR BLOCKS	<i>Title</i>
15	<i>Number of electrodes in x-direction</i>
15	<i>Number of electrodes in y-direction</i>
1.0	<i>x unit electrode spacing</i>
1.0	<i>y unit electrode spacing</i>
3	<i>Array type, 6 for pole-dipole</i>
3360	<i>Number of data points</i>
1.0 0.0 0.0 0.0 2.0 0.0 3.0 0.0 49.9643	<i>For each data point, enter x- and y-locations of the C1, C2, P1 and P2 electrodes, apparent resistivity value</i>
1.0 0.0 0.0 0.0 3.0 0.0 4.0 0.0 50.1541	
1.0 0.0 0.0 0.0 4.0 0.0 5.0 0.0 50.6451	
.	<i>Repeat for all data points</i>
.	
.	
.	
.	
0	<i>Followed by a few 0's: these are flags for other options, such as topography</i>
0	
0	
0	

Table 5. Example of a data set with mixed arrays.

<i>3d mixed arrays.dat file</i>	<i>Comments</i>
<i>Mixed dipole-dipole and pole-dipole data</i>	<i>Title</i>
10	<i>Number of electrodes in x-direction</i>
10	<i>Number of electrodes in y-direction</i>
1.0	<i>x unit electrode spacing</i>
1.0	<i>y unit electrode spacing</i>
11	<i>11 for general array, and 0 for no fixed sub-array type</i>
0	
Type of data (0 = apparent resistivity, 1 = resistance)	<i>Extra header needed for general array format</i>
0	<i>0 for apparent resistivity</i>
2480	<i>Number of data points</i>
4 1.0 0.0 0.0 0.0 2.0 0.0 3.0 0.0 29.968	<i>For each data point, enter number of electrodes used, followed by x- and y- locations of the electrodes used, and the apparent resistivity value</i>
4 1.0 0.0 0.0 0.0 3.0 0.0 4.0 0.0 30.096	
4 1.0 0.0 0.0 0.0 4.0 0.0 5.0 0.0 30.438	
4 1.0 0.0 0.0 0.5 0.0 0.0 6.0 0.0 30.810	
4 1.0 0.0 0.0 0.0 6.0 0.0 7.0 0.0 31.034	
.	<i>Rest of the dipole-dipole data points</i>
.	
.	
3 0.0 0.0 1.0 0.0 2.0 0.0 29.964	<i>Pole-dipole data points with 3 electrode positions</i>
3 0.0 0.0 2.0 0.0 3.0 0.0 30.022	
.	<i>Repeat for all data points</i>
.	
0	<i>Followed by a few 0's: these are flags for other options, such as topography</i>
0	
0	
0	

7.1.2 Non-uniform rectangular survey grid

In some areas, it may not be possible to place the survey lines at the same distance apart. One possible situation is shown in Figure 4 where the inner survey lines are 0.5 meters apart while the lines at the edge are 1.0 meters apart. To handle such a situation, the x- and y-location of each survey line must be specified. The file NUGRID.DAT is an example data file with a non-uniform survey grid. The first part of the file with comments is as follows.

Table 6. Example of a non-uniform rectangular grid data format.

<i>NUGRID.DAT file</i>	<i>Comments</i>
2 BLOCKS	<i>Title</i>
9	<i>Number of electrodes in x-direction</i>
9	<i>Number of electrodes in y-direction</i>
Nonuniform grid	<i>Header to indicate non-uniform grid</i>
x-location of grid-lines	<i>Header for x-location of grid lines</i>
0.0 1.0 1.5 2.0 2.5 3.0 3.5 4.0 5.0	<i>x-location of grid lines</i>
y-location of grid-lines	<i>Header for y-location of grid lines</i>
0.0 1.0 1.5 2.0 2.5 3.0 3.5 4.0 5.0	<i>y-location of grid lines</i>
2	<i>Array type, 2 for pole-pole</i>
992	<i>Number of data points</i>
0.000 0.000 1.000 0.000 29.934	<i>First data point</i>
0.000 0.000 1.500 0.000 29.918	<i>Second data point</i>
.	<i>Format of the rest of the data file is the same as for a uniform grid described earlier</i>
.	
.	
.	<i>Repeat for all data points</i>
.	
.	
0	<i>Followed by a few 0's: these are flags for other options, such as topography</i>
0	
0	
0	

Note the main difference in the data from that of a uniform rectangular grid is that instead of the unit electrode spacings in the x- and y-directions, the section contains the positions of each individual survey grid line. This allows the spacing between the grid lines to vary across the survey area. One situation this survey grid format is useful is in accommodating the gradient array where the C1 and C2 current electrodes are usually placed at the edges of the survey area. The distances of the current electrodes are usually much larger compared to the survey spacing within the main survey area. The non-uniform grid option can be used to add extra survey grid lines to include the remote C1 and C2 electrodes into the survey grid. In this case, the spacing between the grid lines should be gradually increased until the last grid line reaches the outer electrodes. If the survey was carried out with crooked or non-parallel lines, the trapezoidal (section 7.1.3) or arbitrary electrode positions (section 7.1.4) data format can be used.

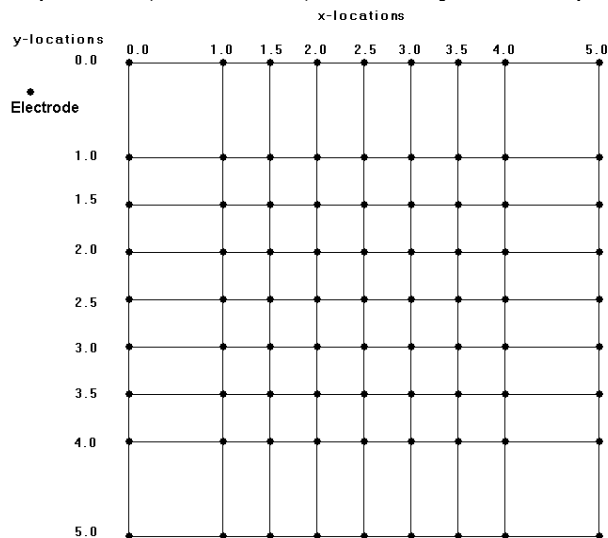


Figure 4. Non-uniform rectangular grid.

7.1.3 Trapezoidal survey grid

In areas with rugged and forested terrain, it is frequently not possible to place the survey lines in a perfectly rectangular grid. This option allows moderate departures from a rectangular arrangement of the electrodes. Figure 5 gives a sketch of a possible electrode arrangement that deviates from a rectangular grid and effectively forms a trapezoidal grid. Along each survey line, the number of electrodes must still be the same. The example has a 7-by-5 grid, so there must still be 7 electrodes in each row. The survey lines need not be orthogonal, but deviations greater than 30 degrees are not be advisable. When the RES3DINVx64 program reads in the data file, it will check for trapeziums that have small angles or are degenerate (section 9.2.7). The finite-element method used might not give reasonable results if degenerate trapeziums are present. For cases with larger deviations, the arbitrary electrodes format might be better (see the following section).

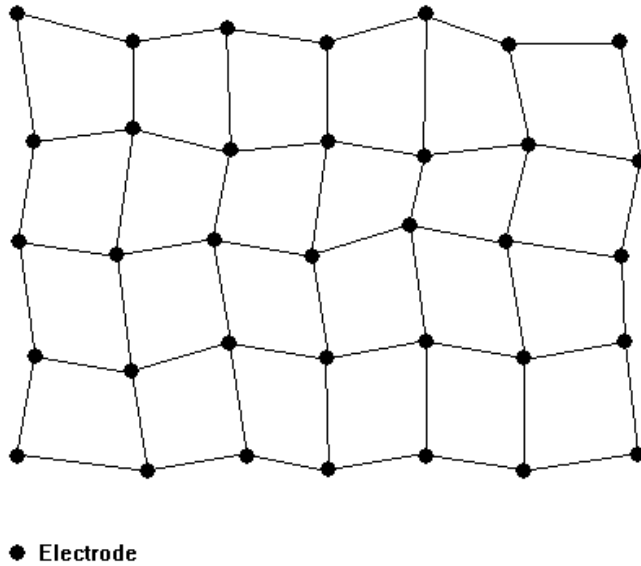


Figure 5. Example of a trapezoidal survey grid.

In the data file, the x-, y- and z-coordinates of each electrode in the grid must be given. The x- and y-coordinates must be the true horizontal coordinates, and not distances along the ground surface, while the z-coordinate is the elevation. The file TRAPEZOIDAL.DAT listed in **Table 7** gives an example of the data format used.

One possible ambiguity when the ground surface is not flat is in the geometric factor used, i.e. whether it is calculated using the horizontal coordinates alone or linear distances where the z-coordinate is also used in the calculation of the distance between the electrodes. The type of geometric factor is probably not important, but the program must use the same geometric factor as that used in calculating the apparent resistivity value from the resistance (potential divided by current) values. In the data format, the type of geometric factor used must be specified to avoid any ambiguity. Most surveys will probably calculate the distance between the electrodes using the (x,y) coordinates only, which can usually be derived from GPS readings. In the above example, a value of 0 is used to indicate that the geometric factor is calculated using horizontal distances. Another possibility is to use the linear distance between the electrodes by using the (x,y,z) coordinate (value of 1 in the above data format) of each electrode.

In some surveys, the geometric factor may be calculated using the distance along the ground surface, or some other criteria. To accommodate for this possibility, a user-defined option is available. In this case the value of the geometric factor must be entered into the data file after the apparent resistivity value (or after IP value if present) for each data point. The file BLOCKS_TRAP.DAT is an example with a user defined geometric factor (actually calculated using the surface distance).

In the TRAPEZOIDAL.DAT file, the elevation of the electrodes is set at 0.0 in which case there is actually no topography. If topography is present, the elevation is given as the z-coordinate of the electrode, as in the example BLOCKS_TRAP.DAT file.

Table 7. Example data file with trapezoidal grid format.

<i>TRAPEZOIDAL.DAT file</i>	<i>Comments</i>
2 BLOCKS with Shifted Y lines	<i>Title</i>
14	<i>Number of electrodes in x-direction</i>
14	<i>Number of electrodes in y-direction</i>
Trapezoidal Grid used	<i>Header to indicate trapezoidal grid</i>
Location of electrodes given line-by-line	<i>Header</i>
Line 1	<i>Header for Line 1</i>
0.0,0.0,0.0	<i>(x,y,z) coordinate of 1st electrode on Line 1</i>
3.0,0.0,0.0	<i>(x,y,z) coordinate of 2nd electrode on Line 1</i>
6.0,0.0,0.0	<i>Same for other electrodes on Line 1</i>
9.0,0.0,0.0	
12.0,1.0,0.0	
15.0,1.0,0.0	
18.0,1.0,0.0	
21.0,0.0,0.0	
24.0,0.0,0.0	
27.0,0.0,0.0	
30.0,0.0,0.0	
33.0,0.0,0.0	
36.0,0.0,0.0	
39.0,0.0,0.0	<i>(x,y,z) coordinate of last electrode on Line 1</i>
Line 2	<i>Header for line 2</i>
0.0,3.0,0.0	<i>(x,y,z) coordinate of 1st electrode on Line 2</i>
3.0,3.0,0.0	<i>(x,y,z) coordinate of 2nd electrode on Line 2</i>
.	<i>Similar information is given for other electrodes and survey lines until last line</i>
.	
36.0,39.0,0.0	<i>(x,y,z) coordinate of 2nd last electrode</i>
39.0,39.0,0.0	<i>(x,y,z) coordinate of last electrode</i>
Type of geometric factor (0=horizontal, 1=linear, 2=user defined)	<i>Header</i>
0	<i>0 to indicate horizontal distance used to calculate geometric factor</i>
2	<i>Array type, 2 for pole-pole</i>
1274	<i>Number of data points</i>
0.00, 0.00 0.00, 3.00 101.4090	<i>Location of electrodes and apparent resistivity. The format for the rest is the same as before for rectangular grids.</i>
0.00, 0.00 0.00, 6.00 102.4530	
0.00, 0.00 0.00, 9.00 103.3240	
.	
.	

7.1.4 Electrodes at arbitrary positions

In some surveys, the positions of the electrodes cannot fit into a simple rectangular or even trapezoidal grid. This situation occurs because of physical obstructions such that straight survey lines cannot be used (for example in very rugged terrain), or the data is collated from surveys over different periods. This is particularly common in mineral exploration surveys where there are different survey phases, usually using a series of quasi-parallel 2-D survey lines. One possible situation is shown in Figure 6. In this example, a series of 2-D surveys lines were carried out at different times, with different electrode spacings and orientations. It is not possible to fit the lines into a rectangular or trapezoidal grid pattern. To allow such a situation, the model grid specifying the boundaries of the model blocks is made independent of the positions of the electrodes. This is different from the normal rectangular and trapezoidal grid data formats where the electrodes are located at the corners of the model block. The model block discretization (which is independent of the electrodes positions) used is the non-uniform rectangular grid.

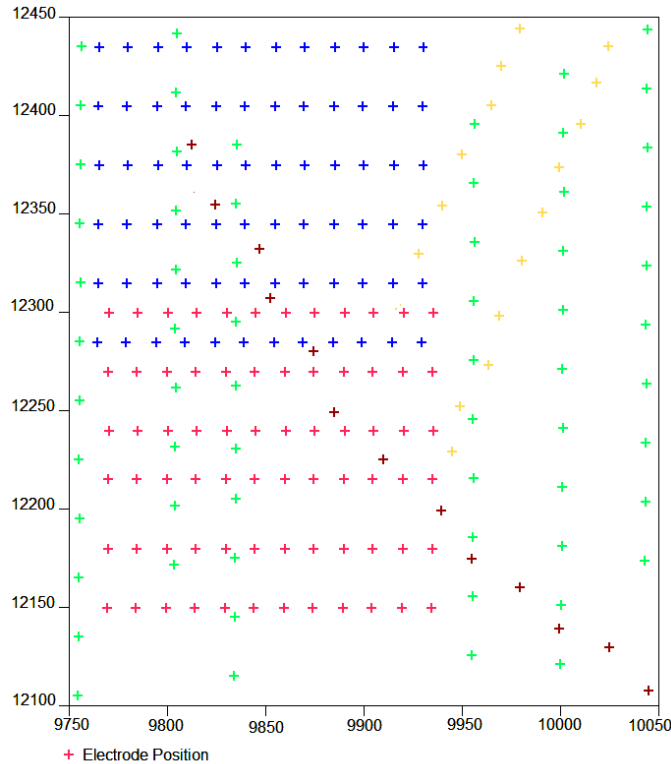


Figure 6. Survey with electrodes at arbitrary positions. Map showing positions of electrodes from different survey phases (marked by different colors). The different survey lines can have different electrode spacings and orientations.

The positions specified for the model grid lines need not correspond to actual electrode positions but are only used to specify the boundaries of the model blocks. In the example shown in Figure 6, the spacings between the electrodes in the survey lines range from 15 to 30 meters. Thus, a convenient model block width would be about 10 to 20 meters.

Another constraint is the minimum distance between two electrode positions used in the same array in the data set. There should be at least 2 (preferably 3) nodes in the finite-difference or finite-element mesh between the two electrode positions. The program automatically subdivides each model block by 4 mesh lines in the x - and y -directions. Thus, if the minimum spacing between two electrode positions is 5 meters, the block width should not be more than 10 meters. The survey area in Figure 6 is about 300 by 350 meters. If model blocks with 10 meter widths are used for the entire region, this would be a model grid with 29-by-34 blocks (or 986 blocks) for each model layer. Since the program uses 4 mesh lines in both horizontal directions, this results in a huge finite-difference or finite-element mesh that requires a large amount of computer memory to implement. The computer system used to process such data sets should have at least a dual-core CPU with 8 GB RAM.

An example of a data set with some electrodes at arbitrary positions is the BLOCK12x11_points.dat file. A description of the new format details to specify electrodes at arbitrary positions is given in **Table 8**. For this synthetic example data set, some of the electrodes used in the listed

data points fall on the rectangular grid nodes, while a few are located at arbitrary positions. For some field data sets, all of the electrodes might be in the point electrodes list.

If the data set has topography, the z-coordinate of the electrode gives the elevation. The topography information can also be entered after the section with the data points, as in the normal non-uniform grid data format (see following section).

The non-uniform data format allow the spacing between the model grid lines to be different. This feature can be used to reduce the model grid size (in terms of the number of model blocks) by using wider spacings in areas where the electrodes are further apart. In Figure 6, the electrodes are further apart between x-locations of 9950 to 10050. A wider spacing between the model grid lines (for example 15 to 20 meters) can be used to reduce the model grid size (and thus the computer time and memory required).

Table 8. Data format with arbitrary point electrodes.

<i>BLOCK12x11 points.dat file</i>	<i>Comments</i>
Model with 3 blocks	<i>Title</i>
12,11	<i>Specifies 12 by 11 model grid</i>
Nonuniform grid	<i>Header to specify non-uniform grid format</i>
x-location of grid-lines	<i>Header</i>
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00 11.00	<i>x-location of model grid lines</i>
y-location of grid-lines	<i>Header</i>
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00	<i>y-location of model grid lines</i>
2	<i>Electrode number (pole-pole in this case)</i>
Point Electrodes outside grid present	<i>Header to specify electrodes at arbitrary positions present</i>
Number of point electrodes	<i>Header</i>
5	<i>Specifies number of these electrodes</i>
Point Electrode 1	<i>Header for first electrode at arbitrary position</i>
Coordinates of electrode	<i>Header</i>
2.00,1.50,0.00	<i>Gives x, y, z position of electrode. If topography is present, the z coordinate gives the elevation</i>
Point Electrode 2	<i>Header for second electrode</i>
Coordinates of electrode	<i>Header</i>
6.50,7.40,0.00	<i>Gives x, y, z position of second electrode.</i>
.	<i>Similar info for other point electrodes</i>
.	
.	
9316	<i>Number of data points</i>
0.00 0.00 1.00 0.00 99.481	<i>First data point</i>
0.00 0.00 2.00 0.00 99.366	<i>Second data point</i>
.	<i>Other data points</i>
.	
.	
9.40 9.00 4.60 8.60 98.694	<i>Last data point</i>
0	<i>Ends with a few zeros</i>
0	
0	
0	

7.1.5 Remote electrodes

Although for the pole-pole array only the locations of two electrodes (the C1 and P1) are given in the data file, in practice all measurements are made using four electrodes. To minimize the effects of the C2 and P2 electrodes, it is generally recommended that the distance of these two electrodes from the C1 and P1 electrodes must be at least 10 times (preferably 20 times) the maximum C1-P1. In some cases, when large spacings between the C1 and P1 electrodes are used, this requirement is not met for all measurements. This could lead to distortions in the inversion model (Robian *et al.* 1997). To overcome this problem, the RES3DINV program allows the user to incorporate the effects of the C2 and P2 electrodes in the inversion. The data file roots7_remote.dat gives an example where the C2 and P2 electrodes are included.

There are two options for the geometric factor used to calculate the apparent resistivity values. If only the positions of the C1 and P1 electrodes are used, the header 'Approximate geometric factor used' must be used. If the positions of 'all the four electrodes are used, the header 'Exact geometric factor used' must be used. For the pole-dipole array, only the location of the C2 electrode is given as a remote electrode.

Table 9. Example data file with remote electrodes specified.

<i>roots7_remote.dat file</i>	<i>Comments</i>
garden-square-0.5m	<i>Title</i>
7	<i>Number of electrodes in x-direction</i>
7	<i>Number of electrodes in y-direction</i>
0.5	<i>x unit electrode spacing</i>
0.5	<i>y unit electrode spacing</i>
2	<i>Array type, 2 for pole-pole</i>
Remote electrodes included	<i>Header to indicate remote electrodes positions are given</i>
C2 remote electrode X, Y, Z location	<i>Header for C2</i>
-25.00,0.00,0.00	<i>x, y and z location of C2 electrode</i>
P2 remote electrode X, Y, Z location	<i>Header for P2</i>
-24.00,13.00,0.00	<i>x, y and z location of P2 electrode</i>
Approximate geometric factor used	<i>Indicates type of geometric factor</i>
467	<i>Number of data points</i>
0.00 0.00 0.50 0.00 350.46	<i>First data point</i>
0.00 0.00 1.00 0.00 398.05	<i>The format is the same as that used for normal data sets.</i>
0.00 0.00 1.50 0.00 424.08	
0.00 0.00 2.00 0.00 413.83	
...	

If the 'remote' electrodes are too close to the other electrodes and cannot be considered as truly remote (or more than one position is used for the C2 or P2 electrodes) the array can no longer be considered as a pole-pole array but should be treated as an array with four electrodes. The C2 and P2 electrodes can be incorporated by extending the model grid using the non-uniform grid data format (section 7.1.2) until the outer limits of grid reaches these electrodes. A wider spacing between the model grid lines can be used beyond the main survey area towards the C2 and P2 electrodes to minimize the mesh size. The apparent resistivity should be calculated using the exact geometric factor.

7.1.6 Arbitrary positions versus trapezoidal and non-uniform grids

The finite-difference and finite-element methods give the most accurate results with rectangular meshes with the same mesh spacing in the x and y directions (i.e. square model cells) near the electrode locations. In some surveys, the layout of the electrodes might differ greatly from a regular rectangular grid. While it is possible to use the trapezoidal or non-uniform grid data format to accommodate such surveys, it might result in highly distorted model grid. The trapezoidal grid format could have highly skewed model cells, or the non-uniform rectangular grid might have cells with widely different widths next to each other. Both types of distortions can greatly reduce the accuracy of the finite-difference and finite-element forward modeling routines. It is recommended that the arbitrary electrodes format be used for such highly non-uniform electrodes layouts so that model cells of relatively uniform sizes can be used

where the electrode are located. Please refer to section 8.9.2 of the “Tutorial : 2-D and 3-D electrical imaging surveys” notes on methods to optimize the use of the arbitrary electrodes positions data format.

7.2 Topography information

This section describes the format for topography information used by the different survey grid types.

7.2.1 Rectangular grids

This covers the uniform and non-uniform rectangular grids described in sections 6.1.1 and 6.1.2. The elevation of each electrode in the grid is entered in the data file after the section with the apparent resistivity measurements. The data file BLOCK11T.DAT is an example with topography which has an 11-by-11 grid of electrodes. The bottom part of the file with comments is given in **Table 10**. The word ‘Topography’ must be entered in the file immediately after the last apparent resistivity data point. Next, the value ‘2’ in the above example indicates that the x- and y-coordinates given earlier are distances along the ground surface and not the true horizontal distances. This is probably the normal case where a cable with a constant separation between the takeouts is used. If a value of ‘1’ is given, it indicates that the x- and y- coordinates given earlier are the true horizontal distances. Next the height of each electrode in the grid is given, row-by-row in the x-direction. For example, the values in the first row are the heights of the electrodes in the line at y equals to 0 meters. In this example, since there are 11 electrodes in the x-direction, there are 11 values in each row. This is followed by the heights for the second row of electrodes, and similarly for all the rows. A simpler and less rigid format for the topography information by listing the (x,y) coordinates of selected points with the elevation values can also be used (section 7.2.4).

Table 10. Example topography information for the rectangular grid format.

<i>BLOCK11T.DAT file</i>	<i>Comments</i>
...	<i>The upper part of the file follows the same format as described earlier</i>
8.000 10.000 10.000 10.000 113.3131	<i>Last two resistivity data points</i>
9.000 10.000 10.000 10.000 102.7262	
Topography	<i>Header to indicate topography present</i>
2	<i>Indicates surface distance used, 1 for true horizontal distances</i>
0.00 0.00 0.00 -0.50 -1.00 -1.50 -1.00 -0.50 0.00 0.00 0.00	<i>Elevation at survey grid points</i>
0.00 0.00 0.00 -0.50 -1.00 -1.50 -1.00 -0.50 0.00 0.00 0.00	
0.00 0.00 0.00 -0.50 -1.00 -1.50 -1.00 -0.50 0.00 0.00 0.00	
0.00 0.00 0.00 -0.50 -1.00 -1.50 -1.00 -0.50 0.00 0.00 0.00	

If the data set contains topography, the inversion subroutine will automatically incorporate the topography into the inversion model by using the finite-element method (Silvester and Ferrari 1990).

7.2.2 Trapezoidal grids

The elevation of each electrode in a trapezoidal grid must be specified together with the x- and y-locations. Thus, the topography information is automatically included in the section of the data file with the list of the electrodes.

7.2.3 Electrodes at arbitrary locations

If the data set has topography, the z-coordinate of the arbitrary electrode in the list gives the elevation. The topography information can also be entered after the section with the data points, as in the normal non-uniform grid data format (section 7.2.4), that gives the elevation at the nodes of the rectangular model grid or as an unstructured list.

7.2.4 Topography data in an unstructured list

In this format, the elevations at a number of positions are listed, possibly including locations that are not covered by the electrodes actually used in the survey. The program then interpolates the elevation

at the surface of the model grid used from the topography data points listed in the file. **Table 11** shows an example of the data format used in the example data file BLOCK11T_List.dat.

The example in **Table 11** uses a flag value of '2' to indicate surface distances are used for the (x,y) coordinates. A value of '1' is used for true horizontal distances which is normally used for data in the arbitrary electrodes format.

This option is useful for the data format with electrodes at arbitrary locations where the number of electrodes listed in the data file is much less than the model grid size. This results in some sections of the model grid that are far from an electrode so the topography is not accurately defined. This option is also useful when a model grid that is finer than the survey grid is used for 3-D data sets with topography to reduce banding effects (Loke and Dahlin 2010). The same topography data section can be used for the data set but with different model grid sizes. Note this option cannot be used for data with the trapezoidal grid format. You need to convert such data into the arbitrary point electrodes format (section 8.9).

Table 11. Example topography information given as an unstructured list.

<i>BLOCK11T_List.dat file</i>	<i>Comments</i>
...	<i>The upper part of the file follows the same format as described earlier.</i>
8.000 10.000 10.000 10.000 113.3131	<i>Last two resistivity data points</i>
9.000 10.000 10.000 10.000 102.7262	
Topography	<i>Header to indicate topography present</i>
2	<i>Indicates surface distance used in this example</i>
Topography in unstructured list	<i>Extra header to indicate topography data given as a list</i>
Number of points in list	<i>Header</i>
121	<i>Number of topography points</i>
List of topography data points (index,x,y,z)	<i>Header with format used</i>
1 0.0 0.0 0.00	<i>1st topography data point</i>
2 1.0 0.0 0.00	<i>2nd topography data point</i>
..	
60 4.0 5.0 -1.00	
61 5.0 5.0 -1.50	
..	
121 10.0 10.0 0.00	<i>Last topography data point</i>
0,0,0,0	<i>End with a few zeros</i>

7.3 I.P. data

The data collected from I.P. (Induced Polarization) surveys consists of two sets, the normal apparent resistivity measurements and an apparent I.P. data set. The file MODEL3IP.DAT is an example data file with both resistivity and IP data. This program supports three different types of I.P. data; (i) time domain chargeability measurements, (ii) frequency domain percent frequency effect or phase angle measurements and (iii) metal factor I.P. values. The file MODEL3IP.DAT has the IP data as chargeability values. The first part of the file with comments is listed in **Table 12**.

The word *IP*, placed after the data line with the number of data points, is used to indicate the data set contains I.P. measurements. This is followed by the type of I.P. data. The word *Chargeability* shows that the I.P. data is given in terms of chargeability. Many I.P. instruments measure the chargeability by integrating the area under the I.P. decay curve. In this case, the unit is in msec (millisecond). The chargeability value obtained by this method is normally calibrated to the Newmont M₍₃₃₁₎ standard (Summer 1976) so that the chargeability value in msec has the same numerical value as the chargeability given in mV/V. The chargeability in mV/V is defined as the ratio of the secondary voltage immediately after the current is cut off to the primary DC voltage. The next line gives the type of I.P. unit, in this case in mV/V. If the I.P. measurement was made in msec, then the word 'msec' should be used. Finally, two parameters relevant to the IP measurement are given. For time-domain chargeability measurements, these are the delay and the integration time.

I.P. values that are given in other units are converted into chargeability values internally by the program during the inversion process. The relevant conversion equations may be found in the papers by Van Voorhis et al. (1973) and Nelson and Van Voorhis (1973).

Table 12. Example I.P. data file.

<i>MODEL3IP.DAT file</i>	<i>Comments</i>
RESISTIVITY & IP MODEL	<i>Title</i>
8	<i>Number of electrodes in x-direction</i>
8	<i>Number of electrodes in y-direction</i>
1.0	<i>x unit electrode spacing</i>
1.0	<i>y unit electrode spacing</i>
2	<i>Array type, 2 for pole-pole</i>
712	<i>Number of data points</i>
IP present	<i>Word 'IP' to indicate IP is present</i>
Chargeability	<i>Type of IP data</i>
mV/V	<i>IP unit</i>
0.1,1.0	<i>Delay and integration times</i>
0.000 0.000 1.000 0.000 10.0544 0.3702	<i>For each data point, enter x- and y-locations of the C1 and P1 electrodes, apparent resistivity and apparent IP values</i>
0.000 0.000 2.000 0.000 10.1311 0.8952	
0.000 0.000 3.000 0.000 10.1860 1.3004	
0.000 0.000 4.000 0.000 10.1808 1.3179	
.	<i>Repeat for all data points</i>
.	
.	
0	<i>Followed by a few 0's: these are flags for other options, such as topography</i>
0	
0	
0	

For frequency domain measurements, the I.P. value is usually given in Percent Frequency Effect (PFE). This is given as

$$\text{PFE} = 100 (\rho_{\text{DC}} - \rho_{\text{AC}}) / \rho_{\text{AC}}$$

where ρ_{DC} and ρ_{AC} are the apparent resistivity values measured at low and high frequencies. For such measurements, the format would be as in **Table 13**.

Table 13. I.P. data given as percent frequency effect.

<i>Data file contents</i>	<i>Comments</i>
Chargeability	<i>Type of IP data</i>
PFE	<i>IP unit</i>
0.3,5.0	<i>Lower and upper measurement frequencies</i>

I.P. values are also given as phase angles. In this case, the unit normally used is milliradians (mrad). The I.P. data section would be given as in **Table 14**.

Table 14. I.P. data given as phase angles.

<i>Data file contents</i>	<i>Comments</i>
Phase angle	<i>Type of IP data</i>
Mrad	<i>IP unit</i>
0.0,5.0	<i>Lower and upper measurement frequencies</i>

I.P. data is sometimes given as a metal factor (MF) value. The MF value can be calculated from either time domain or frequency domain measurements. In the time domain, the metal factor is value is given by

$$\text{MF} = 1000 M / \rho_{\text{DC}}$$

where the chargeability M is given in terms of millisecond (Witherly and Vyselaar 1990). In the frequency domain, it is given as

$$\text{MF} = 100000 (\rho_{\text{DC}} - \rho_{\text{AC}}) / \rho_{\text{AC}}^2$$

An example format for metal factor measurements is given in **Table 15**.

Table 15. I.P. data given as metal factor.

<i>Data file contents</i>	<i>Comments</i>
Metal factor	<i>Type of IP data</i>
0.001 ms/ohm.m	<i>IP unit</i>
0.1,1.0	<i>Delay and integration time for time-domain measurements</i>

The inversion program tries to minimize the difference between the observed and calculated equivalent apparent chargeability values. I.P. values in percent frequency effect and phase angles are directly proportional to the equivalent chargeability values. However, the metal factor value also involves a resistivity value. The model which gives a minimum RMS error for the chargeability values sometimes does not give a minimum RMS error for the metal factor values. However, the actual effect on the inversion model is usually very small.

7.4 Fixed regions

In some cases, the true resistivity of a section of the subsurface might be known, for example from borehole resistivity measurements. This program allows you to fix the resistivity of up to 4000 sections of the subsurface. The shape of the section to be fixed must be rectangular.

The data to fix the model resistivity values are entered into the input data file after the section with the topography information (if topography is present). As an example, part of the example data file MOD3DFIX.DAT is listed in Table 16.

Table 16. Example data file with a fixed region.

<i>MOD3DFIX.DAT</i>	<i>Comments</i>
7.000 9.000 8.000 9.000 9.8828	<i>Last three data lines</i>
7.000 9.000 9.000 9.000 9.8237	<i>Note no topography information in this example</i>
8.000 9.000 9.000 9.000 9.9337	
FIXED REGIONS	<i>Header to indicate model has fixed regions</i>
1	<i>Number of regions to be fixed</i>
R	<i>Shape of fixed region, R for rectangular</i>
2.0,4.0,0.7	<i>X, Y, Z coordinates of top-left-back corner</i>
6.0,7.0,1.5	<i>X, Y, Z coordinates of bottom-right-front corner</i>
1.0	<i>Resistivity of fixed region</i>
2.0	<i>Damping factor weight for fixed region</i>
0,0,0,0	<i>A few zeros to end the data file</i>

The first item is the header 'FIXED REGIONS' to indicate that the model has at least one region where the resistivity is to be fixed. This is followed by the number of fixed regions (1 in the above example). Next, the shape of the region is given, which is R for rectangular. For the rectangular region, the x-, y- and z-coordinates of the top-left-back and bottom-right-front corners of the rectangular prism are given, as shown in Figure 7. The next data item is the resistivity of the region. After that, the damping factor weight for the resistivity of the region is needed. This parameter allows you to control the degree to which the inversion subroutine can change the resistivity of the region. There is usually some degree of uncertainty in the resistivity of the region. Borehole measurements can only give the resistivity of a very limited zone near the borehole. Thus, it is advisable that the program should be allowed (within limits) to change the resistivity of the region. If a damping factor weight of 1.0 is used, the resistivity of the region is allowed to change to the same extent as other regions of the subsurface model. The larger the damping factor weight used, the smaller is the change allowed in the resistivity of the 'fixed' region. Normally, a value of about 1.0 to 2.0 is used. If a relatively large value is used, for example 10.0, the change in the resistivity of the region would be very small during the inversion process. Such a large value should only be used if the resistivity and shape of the region is accurately known.

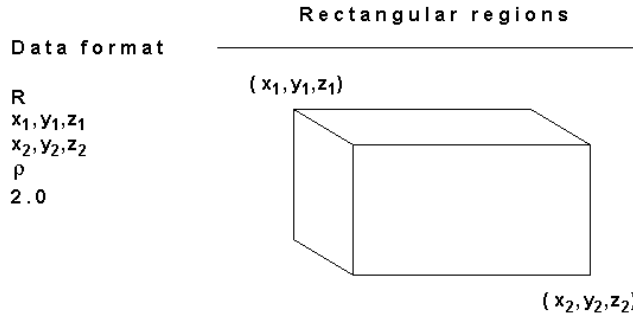


Figure 7. Fixing the resistivity of a rectangular region in the inversion model.

7.5 Incorporating a known boundary

In some cases, the depth of a boundary between two layers with very different resistivity values is known from other sources such as borehole data or seismic refraction surveys. Very frequently, there is a rapid and sharp change across the boundary, such as between a clay and sand layer. If the depth to the boundary is known, this information can be incorporated into the inversion so that the resistivities of the layers can be more accurately determined.

The example data file Block11x12_pp_boundary.dat (Table 17) shows the data format for a surface survey data set with a sharp boundary specified. The sharp boundary settings are placed after the main data section with the apparent resistivity values. If topography, fixed regions or water layer data is present, they should be placed after the main data section and before the sharp boundary data section. Note that this example data file does not have topography or fixed regions or water layer data, so the sharp boundary data section follows immediately after the last data point. For each point on the boundary, the x , y and z coordinates are given. The z value is the depth below the surface. The file Block11x12_pp.dat has the same data set, but without the boundary specified. Figure 8 shows the inversion model for the two data sets. The inversion model with the sharp boundary specified shows a more distinct boundary between the two layers at a depth of 4.8 meters.

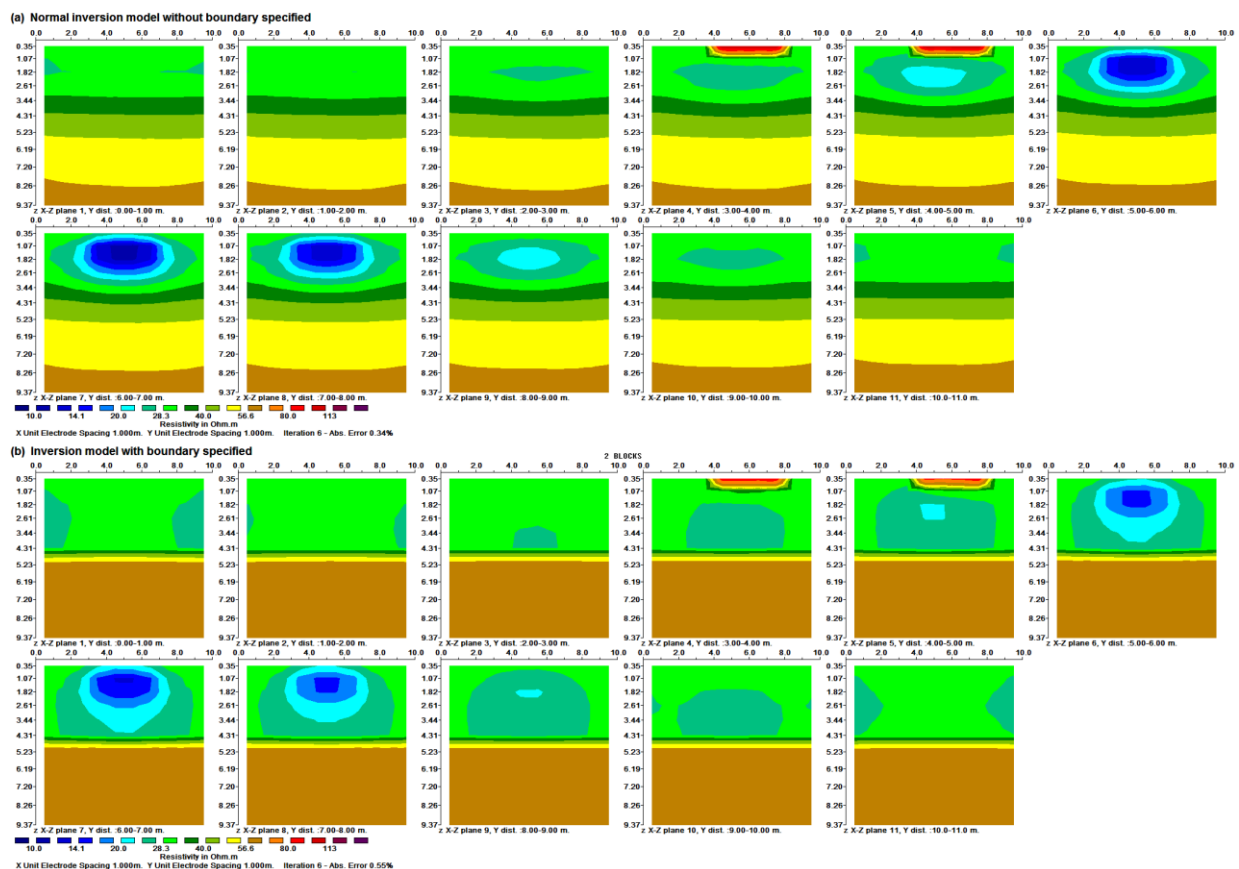


Figure 8. Inversion models for a surface survey, with and without a sharp boundary specified in the data file. The data was created from a synthetic model with a boundary at 4.8 meters between two layers with resistivities of 30 ohm.m and 60 ohm.m.

A special case of a sharp boundary situation is an aquatic survey using floating electrodes on the water surface. The electrodes are usually on a streamer floating on the water surface that is dragged behind a boat. A bathymetric survey is usually carried out simultaneously with the resistivity survey, and frequently, the water resistivity is measured. In most cases, there is a fairly small variation in the resistivity of the water layer throughout the survey area. A modification of the sharp boundary option is available where the resistivity of the first layer can be specified. This is similar to the fixed regions option in section 7.4 except the entire first layer becomes the fixed region. An example data file with a fixed first layer is the Water_Float_19x12.dat file. **Table 18** has a description of the data file format. Note the extra section to indicate the resistivity of the first layer is specified.

Table 17. Data format for a known boundary.

<i>Block11x12 pp boundary.dat</i>	<i>Comment</i>
..	<i>Initial part of file</i>
9.000 11.000 10.000 11.000 33.915	<i>Last data point</i>
Sharp layers present	<i>Header to indicate sharp boundary present</i>
Number of boundaries	<i>Header</i>
1	<i>1 boundary in this example</i>
Boundary 1 parameters	<i>Header</i>
Boundary type	<i>Header</i>
Layer	<i>Type of boundary</i>
Group weight	<i>Header</i>
1.0	<i>Enter 1.0 here</i>
Number of points on boundary	<i>Header</i>
132	<i>Same as number of electrodes in surface grid</i>
x and y and z coordinates of points	<i>Header</i>
0.0,0.0,4.8	<i>First point on first line y = 0.0</i>
1.0,0.0,4.8	<i>Second point on first line</i>
.	
.	
10.0,0.0,4.8	<i>Last point on first line</i>
0.0,1.0,4.8	<i>First point on second line y = 1.0</i>
1.0,1.0,4.8	<i>Second point on first line</i>
.	
.	
10.0,1.0,4.8	<i>Last point on second line</i>
0.0,2.0,4.8	<i>First point on third line y = 2.0</i>
.	
.	
10.0,10.0,4.8	<i>Last point on 11th line y = 10.0</i>
0.0,11.0,4.8	<i>First point on last line y = 11.0</i>
.	
.	
9.0,11.0,4.8	<i>Second last point on last line</i>
10.0,11.0,4.8	<i>Last point on last line</i>
0,0,0	<i>End with a few zeros</i>

Table 18. Floating electrodes survey with the water layer model as a known boundary.

<i>Water Float 19x12.dat</i>	<i>Comment</i>
...	<i>Initial part of file</i>
18.0 5.0 18.0 2.0 18.0 8.0 18.0 11.0 15.413	<i>Last data point</i>
Sharp layers present	<i>Header to indicate sharp boundary present</i>
Number of boundaries	<i>Header</i>
1	<i>1 boundary in this example</i>
Boundary 1 parameters	<i>Header</i>
Boundary type	<i>Header</i>
Layer	<i>Type of boundary</i>
Group weight	<i>Header</i>
4.0	<i>Enter 1.0 here</i>
Fixed resistivity of model cells above boundary (0=No.1=Yes)	<i>Extra header to indicate resistivity of layer given</i>
1	<i>1 for Yes</i>
Resistivity value	<i>Header</i>
10.0	<i>Resistivity of first layer</i>
Number of points on boundary	<i>Header</i>
228	<i>Same as number of electrodes in surface grid</i>
x and y and z coordinates of pts	<i>Header</i>
0.0,0.0,0.86	<i>First point on first line y=0.0</i>
1.0,0.0,0.86	<i>Second point on first line</i>
.	
.	
18.0,11.0,0.86	<i>Last point for boundary</i>
0,0,0,0	<i>End with a few zeros</i>

7.6 Underwater surveys

This section describes the data format for a survey where some, or all, of the electrodes are underwater. In such a survey, it is important that the effect of the water layer is accurately accounted for by the inversion program. The elevation of all the electrodes, as well as the water surface, must be measured. In addition, the resistivity of the water layer must be accurately measured. This is usually done with a portable conductivity meter that frequently also measures other physical variables such as the temperature and water pH. The file WATER3D.DAT gives an example of the data format used. Sections of the file with comments are given in Table 19.

Firstly, note that the format for the initial section of the data file, covering the apparent resistivity measurements and the topography sections, is the same as that used for normal land surface surveys. The only additional section is towards the end of the file where the parameters of the water layer are given. The most important parameters are the water resistivity and elevation of the water surface.

In many surveys, all the electrodes are underwater. However, this program will also handle a situation where some of the electrodes are above the water level. The program determines this by comparing the elevation of the electrodes as given in the topography section with the elevation of the water surface. The data format also requires the minimum and maximum x- and y-coordinates of the water-covered section. However, this information is at present not used by the inversion program, but is included for possible new options in future.

If the data file has a 'Fixed' regions section (section 7.4), the information for the fixed regions should be given after the topography information section but before the underwater survey information. The present version of RES3DINV requires the topography information section for an underwater survey. This is probably not a significant problem since the river/lake/sea bottom usually has some height variations. The file WATER3D.INV gives the inversion model for the WATER3D.DAT data set. A plot of the vertical sections across the model with the topography is shown in the Figure 9.

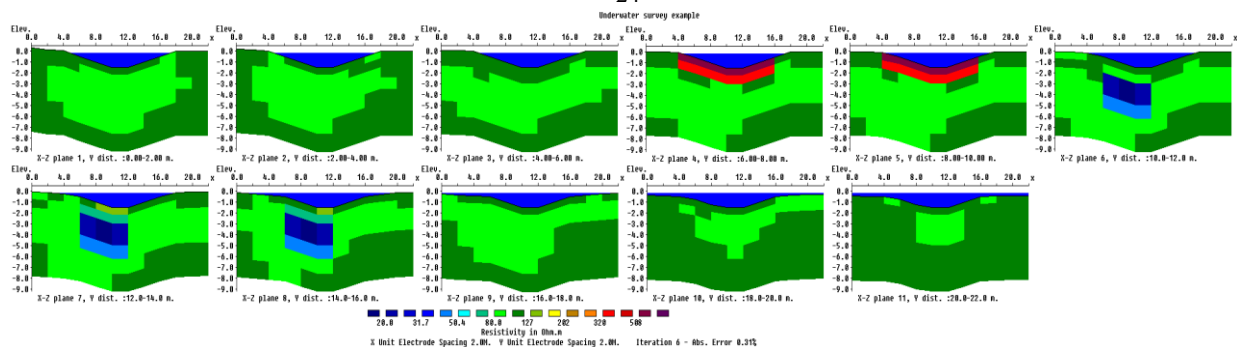


Figure 9. Example model from a survey with underwater electrodes. Plot of the model sections with topography from the WATER3D.INV file. The water layer is indicated by the blue zone at the top part of the sections. Note that some of the electrodes are above the water level, i.e. this data set has electrodes below as well as above the water layer.

Table 19. Example data file with underwater electrodes.

<i>WATER3D.DAT file</i>	<i>Comments</i>
1 BLOCK	<i>Title</i>
12	<i>x surface grid size</i>
12	<i>y surface grid size</i>
2.0	<i>x unit electrode spacing</i>
2.0	<i>y unit electrode spacing</i>
3	<i>Array type, 3 for dipole-dipole</i>
1440	<i>Number of data points</i>
2.0 0.0 0.0 0.0 4.0 0.0 6.0 0.0 106.811	<i>x- and y-locations of C1, C2, P1, P2 electrodes, followed by the apparent resistivity value</i>
2.0 0.0 0.0 0.0 6.0 0.0 8.0 0.0 84.895	
2.0 0.0 0.0 0.0 8.0 0.0 10.0 0.0 97.331	
...	<i>Note same format as land survey</i>
...	<i>Other data points</i>
22.0 10.0 22.0 4.0 22.0 16.0 22.0 22.0 97.808	<i>Last data point</i>
Topography	<i>Header for topography</i>
2	<i>Type of x- and y- coordinate</i>
0.5 0.0 0.1 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 0.0 0.0 0.0	<i>Elevation of electrodes</i>
0.3 0.2 0.0 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 0.0 0.0 0.0	<i>Given row by row</i>
0.2 0.1 0.0 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 0.0 0.0 0.0	
...	<i>Elevation for other rows</i>
-0.5 -0.5 -0.5 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 -0.5 -0.4 -0.4	<i>Last row</i>
Underwater survey parameters	<i>Header to indicate underwater survey</i>
Resistivity of water layer	<i>Header</i>
50.0	<i>Resistivity of water layer</i>
Rectangular limits of water layer	<i>Header</i>
0.000,0.000	<i>Minimum x- and y-coordinates of water covered area</i>
22.000,22.000	<i>The maximum x- and y-coordinates</i>
Elevation of water surface	<i>Header</i>
-0.2	<i>The elevation of the water surface</i>
Type of geometric factor (1=surface,0=exact)	<i>Header</i>
1	<i>1 to indicate surface geometric factor</i>
0,0,0,0	

7.7 Borehole, subsurface and long electrodes data format

The resolution of electrical surveys carried out with electrodes on the ground surface decreases exponentially with depth. One method to obtain better resolution at depth is by making measurements with the electrodes in boreholes. Cross-borehole surveys are much less frequently carried out compared to surface based surveys, so unlike surface surveys, there are at present no common standards with regards to the arrangement of the electrodes. The surface electrodes can be arranged in one of the grid formats described in section 7.1. The program divides the subsurface into a number of hexahedral blocks. The x- and y-locations of the boundaries of the blocks are set using the surface grid. The vertical positions of the boundaries are set at the depths where the borehole electrodes are located.

Borehole electrodes format

The file BOR9ALL.DAT is an example data file with cross-borehole measurements using the pole-pole array. A description of the format used is given below in Table 20. Note that in this example, the measurements are made with the pole-pole array where only the C1 and P1 electrodes are used. This example has a 9-by-9 surface grid and 4 boreholes with 8 electrodes in each borehole. Thus, the total number of electrodes is 123.

The file BORHOLE3D.DAT gives an example where the pole-dipole array is used (Table 21). The format for the initial section is the same as for the above example, the only difference is the x-, y- and z-locations of the P2 electrode is also entered in the data section. Part of the data section is shown with comments in Table 21. If 4 electrodes are used in a measurement, the x-, y- and z-locations of the C1, C2, P1 and P2 electrodes are given in that order. The array number is 12 for cross-borehole survey data with the measurements given as apparent resistivity values. You can also enter the data as resistance measurements, in which case the array number is 13. This might be more convenient as most resistivity meters give the readings as a resistance value in ohm, and furthermore the geometric factor for arrays with subsurface electrodes is different from the geometric factor for conventional surface arrays.

If I.P. data is present, the format is similar to that used for normal surface surveys. The type of I.P. information is entered after the number of data points and before the apparent resistivity and I.P. values. For a computer system with 4GB RAM, the maximum number of boreholes allowed is 1500. The maximum total number of borehole electrodes is 25000. The borehole data format described has several important limitations. All the boreholes must have the same number of electrodes, and the depths of the electrodes in the different boreholes must be the same. Also, only vertical boreholes are supported.

Subsurface electrodes format

This is a modification of the arbitrary electrodes option that allows subsurface arbitrary electrodes and removes these limitations for borehole electrodes. The data format described in section 7.1.4 is for surface surveys where all the arbitrary electrodes are on the ground surface. The depths of the model layers boundaries are set by the user and do not necessary coincide with the depths where the subsurface electrodes are located.

The example data file Subsurface_point_elec.dat shows the data format for subsurface arbitrary electrodes. A description of the data format is given in Table 22. There are several important modifications from the data format given in Table 8. Firstly, note the extra header 'Subsurface point electrodes present' to indicate that the electrode might be below the ground surface. Next, the header 'Compressed format used for point electrodes coordinates' indicates that a more compact format is used for the positions of the arbitrary electrodes. This avoids the need to enter two extra header lines for each electrode. In this compressed format, the first value is the electrode number in the list. This is followed by the x- and y-locations and the elevation of the ground surface at this location. The last value on each data line is the depth of the electrode below the ground surface.

The first four point electrodes have values of 0.0 for the depth, indicating that they are actually on the ground surface. The last four electrodes have non-zero values to indicate they are below the ground surface. As an example, the fifth electrode is located 0.35 meters below the ground surface. Note this value is given relative to the ground surface at the given x- and y-location.

Long electrodes format

In some areas, existing wells or pipes with metal casing can be used as 'long' electrodes to provide more information at depth than would be possible with only surface electrodes (Rucker *et al.* 2010). For 'normal' electrodes, the length of the electrode in contact with the ground is much shorter than the spacing between the electrodes so they are effectively assumed to be 'point' electrodes in the modeling of the data. If the length of the electrode is significant, its length must be taken into account

when calculating the measured potentials associated with the electrode. An example of the data format is given in the BLOCK12x12_long.dat data file is given in Table 23. If the measurements are given as apparent resistivity values, the standard geometric factor used for normal point electrodes should be used to convert the potential values into apparent resistivity values.

Table 20. Example cross-borehole data file using the pole-pole array.

<i>BOR9ALL.DAT file</i>	<i>Comments</i>
1 BLOCK	<i>Title</i>
9	<i>x surface grid size</i>
9	<i>y surface grid size</i>
1.0	<i>x unit electrode spacing</i>
1.0	<i>y unit electrode spacing</i>
12	<i>array number 12 for borehole survey</i>
Number of boreholes	<i>Header</i>
4	<i>The number of boreholes</i>
Borehole 1	<i>Header</i>
8	<i>Number in electrodes in borehole 1</i>
2.0 2.0 1.0	<i>x, y and z location of 1st electrode in borehole</i>
2.0 2.0 2.0	<i>x, y and z location of 2nd borehole electrode</i>
.	<i>Repeat for other borehole electrodes</i>
.	
2.0 2.0 8.0	<i>x, y and z location of last electrode in borehole</i>
Borehole 2	<i>Header for 2nd borehole</i>
8	<i>Number of electrode in 2nd borehole</i>
6.0 2.0 1.0	<i>The following section gives the x, y and z locations of the borehole electrodes starting from the first borehole electrode.</i>
6.0 2.0 2.0	
6.0 2.0 3.0	
.	
.	
6.0 2.0 8.0	<i>Last electrode in second borehole</i>
Borehole 3	<i>Header for 3rd borehole</i>
8	<i>Number of borehole electrodes</i>
6.0 6.0 1.0	<i>x, y and z location of 1st borehole electrode</i>
...	<i>Repeat the same for other borehole electrodes</i>
6.0 6.0 8.0	<i>Last electrode in 3rd borehole</i>
Borehole 4	<i>Header for 4th borehole</i>
8	<i>Number of electrodes in 4th borehole</i>
2.0 6.0 1.0	<i>x, y and z location of first electrode</i>
...	
2.0 6.0 8.0	<i>Last electrode in 4th borehole</i>
6328	<i>Number of data points</i>
2 0.0 0.0 0.0 1.0 0.0 0.0 99.39	<i>For each data point, the first parameter is the number of electrodes used (2 for pole-pole). This is followed by the x, y and z location of the current electrode C1, and then the x, y and z locations of the potential electrode P1.</i>
2 0.0 0.0 0.0 2.0 0.0 0.0 98.50	
2 0.0 0.0 0.0 3.0 0.0 0.0 97.63	
2 0.0 0.0 0.0 4.0 0.0 0.0 97.14	
2 0.0 0.0 0.0 5.0 0.0 0.0 97.23	
...	<i>Repeat for other data points</i>
...	
2 2.0 6.0 7.0 2.0 6.0 8.0 99.38	<i>Last data point</i>
0, 0, 0, 0	<i>End with a few zeros</i>

Note the long electrodes information is placed after the array type information. If both long and point electrodes at arbitrary positions are present, the long electrodes information should be placed before the point electrodes information. The file Grid11x8_long_point.dat is an example with both point and subsurface point electrodes. The type of long electrodes supported in the program is limited to vertical long electrodes with the top on the surface. More details about modeling with long electrodes can be found in section 8.8 of the 'Tutorial Notes' by Loke (2016) and the paper by Rucker *et al.* (2010).

Table 21. Example cross-borehole data file using the pole-dipole array.

<i>BOREHOLE3D.DAT file</i>	<i>Comments</i>
..	<i>Initial section</i>
2642	<i>Number of data points</i>
3 0.0 0.0 0.0 1.0 0.0 0.0 2.0 0.0 0.0 100.273	<i>The format for each data point is number of electrodes used in measurement; x-, y- and z-locations of C1 electrode; x-, y- and z-locations of P1 electrode; x-, y- and z-locations of P2 electrode; apparent resistivity value.</i>
3 0.0 0.0 0.0 2.0 0.0 0.0 3.0 0.0 0.0 100.255	
3 0.0 0.0 0.0 3.0 0.0 0.0 4.0 0.0 0.0 99.094	
3 0.0 0.0 0.0 4.0 0.0 0.0 5.0 0.0 0.0 96.780	
3 0.0 0.0 0.0 5.0 0.0 0.0 6.0 0.0 0.0 94.732	
3 0.0 0.0 0.0 6.0 0.0 0.0 7.0 0.0 0.0 93.977	
3 0.0 0.0 0.0 7.0 0.0 0.0 8.0 0.0 0.0 94.352	
3 0.0 0.0 0.0 0.0 1.0 0.0 0.0 2.0 0.0 100.273	
3 0.0 0.0 0.0 0.0 2.0 0.0 0.0 3.0 0.0 100.254	

Table 22. Example data file with arbitrary subsurface point electrodes.

<i>Subsurface point elecs.dat file</i>	<i>Comments</i>
Model with surface and subsurface point electrodes	<i>Title</i>
12,12	<i>x and y surface grid size</i>
Nonuniform grid	<i>Header for non-uniform rectangular model grid</i>
x-location of grid-lines	<i>Header</i>
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0	<i>x grid lines positions</i>
y-location of grid-lines	
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0	<i>y grid lines positions</i>
11	<i>General array data format</i>
2	<i>Pole-pole sub-array type</i>
Type of measurements (Resistivity=0,Resistance=1)	<i>Header</i>
0	<i>Apparent resistivity values</i>
Point Electrodes outside grid present	<i>Header for arbitrary point electrodes</i>
Number of point electrodes	<i>Header</i>
8	<i>Number of arbitrary point electrodes</i>
Subsurface point electrodes present	<i>Extra header to indicate subsurface electrodes present</i>
Compressed format used for point electrodes coordinates	<i>Extra header to indicate compact format used for arbitrary electrodes</i>
1 2.0000,1.5000,0.0,0.0000	<i>For each electrode, enter point electrode number, x-location, y-location, elevation, depth below the surface</i>
2 6.5000,7.5000,0.0,0.0000	
3 0.5000,0.5000,0.0,0.0000	
4 9.5000,9.0000,0.0,0.0000	
5 0.5000,0.5000,0.0,0.3500	
6 0.5000,0.5000,0.0,4.4160	
7 0.1250,0.5000,0.0,8.5180	
8 5.1200,6.9000,0.0,0.5500	
11468	<i>Number of data points</i>
2 0.000, 0.000, 0.000 1.000, 0.000, 0.000 101.090	
2 0.000, 0.000, 0.000 2.000, 0.000, 0.000 99.922	
...	

Table 23. Example data file with long electrodes.

<i>Grid12x12 long_elecs.dat file</i>	<i>Comments</i>
Blocks with long electrodes	<i>Title</i>
12,12	<i>x and y surface grid size</i>
Nonuniform grid	<i>Header for non-uniform rectangular model grid</i>
x-location of grid-lines	<i>Header</i>
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0	<i>x grid lines positions</i>
y-location of grid-lines	
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0	<i>y grid lines positions</i>
11	<i>General array data format</i>
2	<i>Pole-pole sub-array type</i>
Type of measurements (Resistivity=0,Resistance=1)	<i>Header</i>
0	<i>Apparent resistivity values</i>
Long Electrodes Present	<i>Header to indicate long electrodes present</i>
Number of long electrodes	<i>Header</i>
2	<i>Number of long electrodes</i>
Long Electrode 1	<i>Header for 1st long electrode</i>
Top Location	<i>Header for top of electrode</i>
2.5000,1.5000,0.0000	<i>x,y and z location of top end</i>
Bottom Location	<i>Header for bottom of electrode</i>
2.5000,1.5000,3.8679	<i>x,y and z location of bottom end</i>
Resistivity and cross-sectional area	<i>Header</i>
0.0100,0.25000	<i>Resistivity and cross-section</i>
Long Electrode 2	<i>Header for 2nd long electrode</i>
Top Location	<i>Header for top of electrode</i>
6.5000,7.5000,0.0000	<i>x,y and z location of top end</i>
Bottom Location	<i>Header for bottom of electrode</i>
6.5000,7.5000,4.7613	<i>x,y and z location of bottom end</i>
Resistivity and cross-sectional area	<i>Header</i>
0.0100,0.25000	<i>Resistivity and cross-section</i>
10585	<i>Number of data points</i>
2 0.000 0.000 1.000 0.000 99.790	<i>Standard format for data points</i>
2 0.000 0.000 2.000 0.000 96.351	
...	

7.8 Tank boundaries

This data format is intended for measurements made within a rectangular laboratory tank with non-conducting boundaries. Experiments are frequently conducted using a tank as the resistivity and shape of the materials are known, and also can be easily changed, to test the usefulness of different survey layouts. As the current cannot penetrate beyond the tank walls, they have a significant effect of the apparent resistivity measured values. The effect of the tank walls must be incorporated into the forward modeling routine which normally assumes the subsurface boundaries extended to infinity. Note that only arrays with four electrodes can be used for measurements within a tank. Table 24 shows the data format used to include the tank boundaries. The header to indicate tank boundaries are present is placed after the section with the array type. In this example, it is a standard dipole-dipole array so only one line in the data file is used to list the array type. If it is a general or mixed array, all the four information lines for this array format must be given. The left and right x and y boundaries locations must be given. Note for the z boundary, only the depth to the bottom of the tank is needed. It is assumed that the surface of the tank medium is flat, i.e. it has no topography.

Table 24. Example data file with tank boundaries.

<i>Tank Model.dat file</i>	<i>Comments</i>
Tank Model	<i>Title</i>
14,12	<i>x and y surface grid size</i>
Nonuniform grid	<i>Header for non-uniform rectangular model grid</i>
x-location of grid-lines	<i>Header</i>
0.0 2.0 4.0 6.0 8.0 10.0 12.0 14.0 16.0 18.0 20.0 22.0 24.0 26.0	<i>x grid lines positions</i>
y-location of grid-lines	
0.0 2.0 4.0 6.0 8.0 10.0 12.0 14.0 16.0 18.0 20.0 22.0	<i>y grid lines positions</i>
3	<i>Dipole-dipole array indicator</i>
Tank Model	<i>Header to indicate tank data</i>
Boundary positions	<i>Header</i>
x boundary positions (-x,+x)	<i>Apparent resistivity values</i>
-4.000,30.000	<i>Header to indicate long electrodes present</i>
y boundary positions (-y,+y)	<i>Header</i>
-6.000,28.000	<i>Number of long electrodes</i>
z boundary position	<i>Header for 1st long electrode</i>
40.000	<i>Header for top of electrode</i>
1980	<i>Number of data points</i>
2.0 0.0 0.0 0.0 4.0 0.0 6.0 0.0 99.042	<i>Standard format for data points</i>
2.0 0.0 0.0 0.0 6.0 0.0 8.0 0.0 95.386	
...	

7.9 Time lapse survey data format (RES3DINVx64 Professional)

This data format is intended for survey measurements made at different times using the same survey grid (Loke *et al.* 2014a). The data file Model_123-n15.dat in Table 25 shows the data format used. The first five lines follow the normal format used by a survey using the simple rectangular grid setup (section 7.2.1) in this example. However, other survey arrangements such as the non-uniform rectangular grid, trapezoidal and arbitrary electrodes arrangements can also be used. The section with the time-lapse survey information is given after the line with the number of data points. The header 'Time lapse data' is used to indicate this is a data set with time-series data. The next header 'Type of time lapse data' is used to indicate whether it is assumed the subsurface resistivity does not change during the time it takes to make a single set of measurements (static), or whether the resistivity changes during that time (dynamic). At present, only the 'static' option is supported. The following sections list the number of time-series measurements (3 in this example) and the time-interval from the first measurement.

In the main data section, the initial part is similar to a normal data file with the x and y positions of the electrodes are first listed in each data line. This is followed by the apparent resistivity value from the first, second and third measurements using the same array configuration. Note in this case, it is stated that the dipole-dipole array is used in line 4 of the data file. If a general array format is used (Table 5), the number of electrodes used in the measurement should be listed at the beginning of each data line.

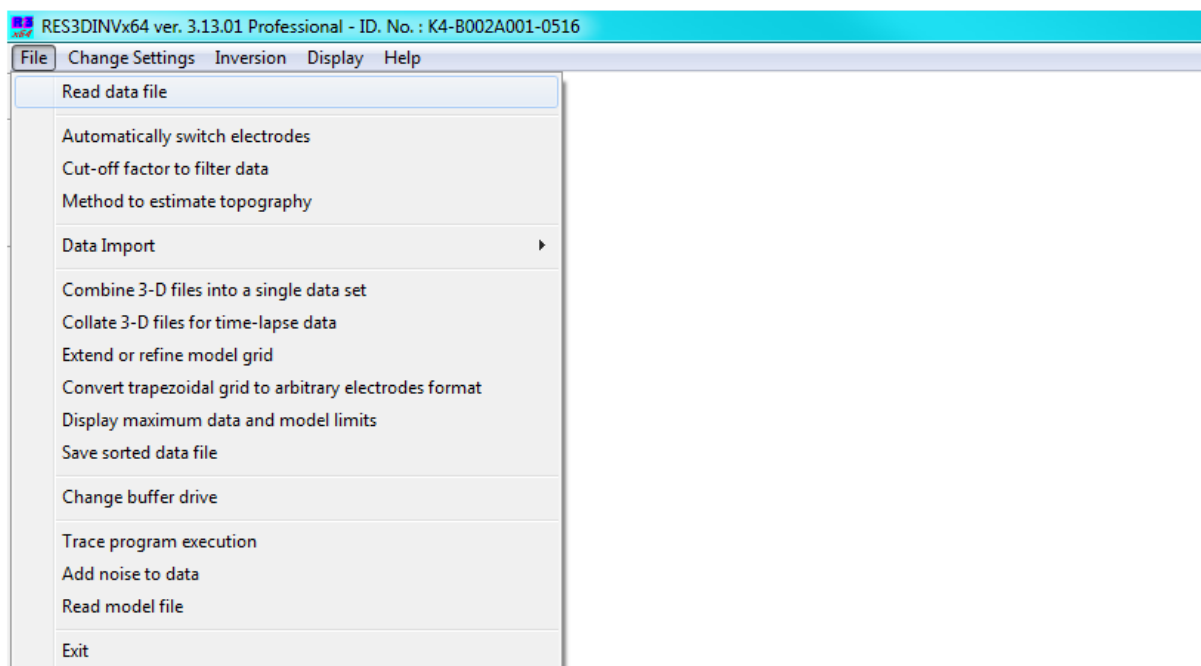
Table 25. Example time-lapse data file.

<i>Model_123-n15.dat file</i>	<i>Comments</i>
Blocks Model with 3 time series	<i>Title</i>
16,12	<i>x and y surface grid size</i>
1.00,1.00	<i>Unit electrode spacing in x and y directions</i>
3	<i>Array type, dipole-dipole</i>
2604	<i>Number of data points</i>
Time lapse data	<i>Header to indicate time-lapse data</i>
Type of time lapse data (0=static,1=dynamic)	<i>Time-lapse measurement type, always 0 for now</i>
0	<i>Dipole-dipole array indicator</i>
Number of time sections	<i>Header</i>
3	<i>Three time series for this example</i>
Time unit	<i>Header</i>
Hours	<i>Type of time unit</i>
Second time section interval	<i>Header</i>
1.0	<i>Time from first set of measurements</i>
Third time section interval	<i>Header</i>
2.0	<i>Time from first set of measurements</i>
1.0,0.0 0.0,0.0 2.0,0.0 3.0,0.0 101.885,101.934,101.877	<i>Data points.</i>
1.0,0.0 0.0,0.0 3.0,0.0 4.0,0.0 101.120 ,101.176,101.236	
...	

For each data point in the example in Table 25, the x and y locations for the C1, C2, P1, P2 electrodes are first given, followed by the apparent resistivity values of the first second and third time-series.

8 File menu options

This section describes the series of sub-options under the 'File' menu option, as shown below.

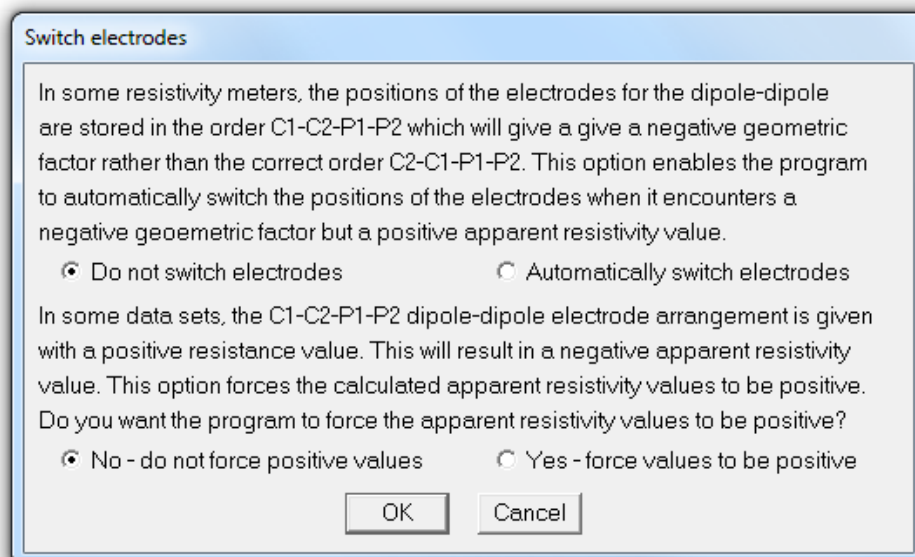


8.1 Read data file

This option reads in a data file in the RES3DINV 'dat' format, as described earlier in section 6.

8.2 Automatically switch electrodes

Clicking this option will bring up the following dialog box.



This option allows the user to automatically switch the positions of the electrodes so that the geometric factor of the array is positive. The data from some surveys are recorded as resistance values. A problem arises when the sign of the resistance values are not recorded, i.e. they are all listed as positive. This results in an inconsistent value when the geometric factor for the array is negative and it should also have a negative resistance value. The second option automatically corrects this error.

8.3 Data cut-off factor

Clicking this option will bring up the following dialog box.

Cutoff value to filter data

To avoid possibly very noisy readings, the program will automatically eliminate readings where the potential values are likely to be very small. The parameter used is the ratio of the smallest to the largest potential reading. This ratio is usually between 0.01 to 0.0001 (i.e. a ratio of 100 to 10000 times). If you wish to change the cutoff value, please enter the new value below.

This cutoff value will not be used to eliminate readings if the data is given as resistance values, and the user does not select the option to change the data into apparent resistivity values.

For the offset type of arrays where the electrode are on different lines, using the geometric factor alone might not be sufficient to identify the unstable arrays. Setting a cutoff value for the geometric factor relative error can identify most of the unstable arrays not removed by the geometric factor cutoff.

Do you want to use the geometric factor relative error as well to filter arrays?

☐ No - do not use relative error ☒ Yes - use geometric factor relative error

Cutoff factor for geometric factor relative error to use (3.0 to 15.0) :

This option allows the user to automatically filter out data points with very large geometric factors that are likely to be noisy. The cutoff value is set as the ratio of the smallest to the largest geometric factor, i.e. approximately the dynamic range of the system used to measure the potential due to the current injected into the ground. As an example, if a value of 0.00001 is used, this will filter out data points where the geometric factor is more than 10,000 times higher than the smallest geometric factor in the data set. For surveys that use an offset type of array, where the current and potential electrodes are on different survey lines, the geometric factor relative error (Loke *et al.*, 2014b) can be used to filter out arrays that are likely to be unstable.

8.4 Method to estimate topography

This option is only relevant for data with arbitrary point electrodes (section 7.1.4) that has topography as well. The program has two methods to estimate the topography for the model grid, as shown by the following dialog box.

Type of method to estimate topography

This option is only relevant to data with arbitrary point electrodes and topography. For some data sets, large areas of the model grid might be far away from the nearest point electrode. At such locations, the topography using the nearest 4 point electrodes might not be accurate enough and have a jagged variation. For such data, the option to use all the point electrodes to estimate the topography will produce a smoother variation in the topography.

☐ Use nearest 4 point electrodes ☒ Use all point electrodes

If the point electrodes are uniformly distributed across the survey area, using the nearest 4 electrodes is usually sufficient. However, when there are large areas with poor coverage (such as the bottom left region in Figure 10), together with large variations in the topography, the estimated topography can have a very jagged contours. To avoid this, the second method that uses all the point electrodes to estimate the topography should be used.

8.5 Data import

This contains a series of sub-options that handle the import of data from different resistivity meter systems. Most systems come with a utility program that converts the raw field data into the format used by the RES2DINV/RES3DINV programs. Please refer to the documentation for your field system. Many 3-D field data sets are collated from a series of parallel 2-D survey lines. The RES2DINV program contains an option to combine data from different 2-D surveys lines into a single 3-D data file in the format used by the RES3DINV program.

8.6 Combine 3-D files into a single data set

Please refer to Appendix I for the details on this option.

8.7 Collate 3-D files for time lapse data

This option allows the user to combine separate 3D data files using the same survey grid but measured at different times into a single time-lapse data file. On selecting the batch mode inversion option, you will be prompted for a script file that contains the list of files to be combined into a single file. An example of the format for the script file is shown in Table 26. Note the RES3DINVx64 Professional version is required to carry out the inversion of a time-lapse data set.

Table 26. Example script file to combine 3-D data files into a single time-lapse file.

<i>Combine-3-time.txt file</i>	<i>Comments</i>
Collate 3 data files	<i>Title of this set of files</i>
Time unit	<i>Header</i>
Hours	<i>Indicates time intervals are in hours</i>
Number of files	<i>Header</i>
3	<i>Indicates three files in this example</i>
Name of first file	<i>Header for first file</i>
d:\temp\Model_1_n5.dat	<i>Data file name including drive and folder</i>
Time of measurement	<i>Header</i>
0.0	<i>Time of measurement, usually 0.0 for first file</i>
Name of second file	<i>Header for start of second file</i>
d:\temp\Model_2_n5.dat	<i>Name of second file</i>
Time of measurement	<i>Header</i>
1.0	<i>Time since first set of measurements</i>
Name of third file	<i>Header for start of third file</i>
d:\temp\Model_3_n5.dat	<i>Name of third file</i>
Time of measurement	<i>Header</i>
2.0	<i>Time since first set of measurements</i>
Name of output time-series data file	<i>Header for output combined file</i>
d:\temp\Model_123_n5.dat	<i>Name of time-lapse data file</i>
End file	<i>Indicates end of batch file</i>

8.8 Extend or refine model grid

This option uses the non-uniform rectangular grid data format (section 7.1.2) to extend the model grid in the x- and y-directions so that 1 or 2 extra rows of model blocks surrounds the original grid using the dialog box below. As an example, if the original grid has 11-by-12 electrode locations, this option can extend it to a 13-by-14 grid. This is useful if there are structures just outside the area covered by the survey grid that have a significant influence on the measurements. These external structures can be included in the inversion model by extending the model grid. The second option divides the model grid spacing by half in the x or y direction. This is useful when the distance between the survey lines is two or more times the inline electrode spacing.

Extend or refine model grid

This option extends the model grid in the x and y directions. It reduces artifacts due to structures outside the survey area.

Distance to extend x-grid (0, 1 or 2) :-

Distance to extend y-grid (0, 1 or 2) :-

This option reduces the size of the model cells in the x or y directions by half, so that near-surface anomalies can be more accurately modeled. Enter a value of 0 for no model grid refinement, 1 to refine grid.

Refine model x-grid (0 or 1) :-

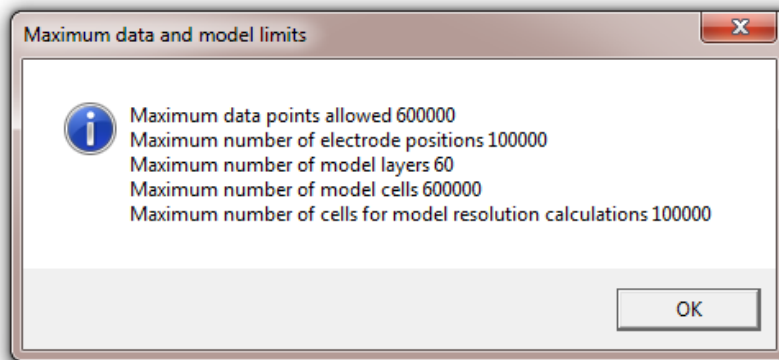
Refine model y-grid (0 or 1) :-

8.9 Convert trapezoidal grid to arbitrary electrodes format

This option converts a data file in the trapezoidal grid format (section 7.2.2) into the arbitrary electrodes data format (section 7.2.3). First read in the file with the trapezoidal grid format, and then select this option. The program will check through the electrodes positions listed and will flag cases where some of the electrodes in the trapezoidal grid format are dummy electrodes inserted to satisfy the format requirements. The user can choose to remove such unused electrodes before saving the data in the arbitrary electrodes format. If the unused electrodes are left out of the list of point electrodes, they are included as topography data points in an unstructured list after the main data section that are used to estimate the elevations at the model grid positions.

8.10 Display maximum model and data limits

This option display the maximum number of data points and model cells allowed depending on the software license and the computer memory available. Below is an example of the output with the RES3DINVx64 program on a computer with 64 GB RAM.



8.11 Save sorted data file

If this option is enabled, the program will save the data file after it is read in. The output data file will have the data points rearranged according to the positions of the current and potential electrodes. If you intend to filter out data points with large geometric factors or geometric factor relative errors (section 8.3), it is recommended you select this option before you read in the data file. Then after you read in the data file, save the filtered data in a new file. After that, carry out the inversion using the new file with the filtered data.

8.12 Change buffer drive

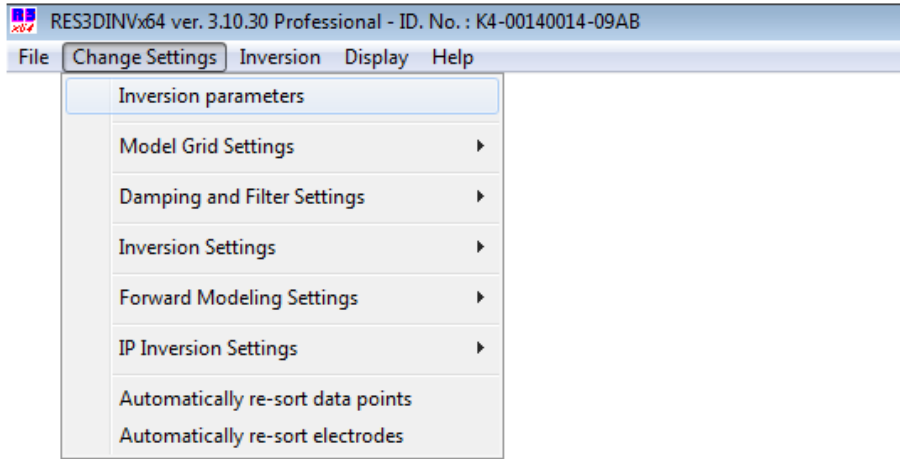
The program will automatically select the hard-disk drive with the largest amount of free space as the buffer drive to store temporary files used in the inversion routine. This option allows the user to change the buffer drive, such as to a faster SSD drive.

8.13 Trace program execution

When this option is enabled, the program will dump information into a R3DTRACEX64.TXT file during the inversion process. This is mainly used to trace problems in the program if it is unable to read or invert a data file.

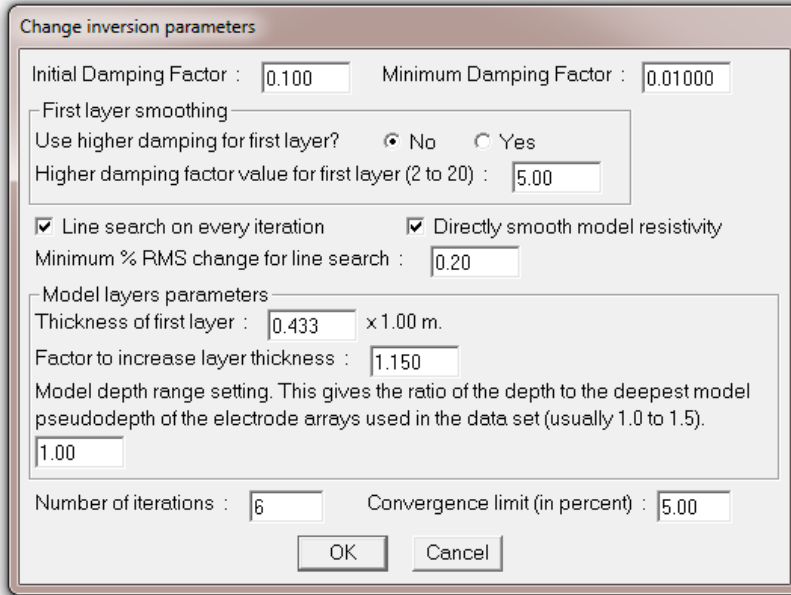
9 Change Settings

This menu option has a number of sub-options where the user can modify the inversion settings used by the program.



9.1 Change inversion parameters

This option will bring up the following dialog box where some commonly used inversion settings can be easily modified.



Initial and minimum damping factors : The first two options set the damping factor λ used in the least-squares equations (4.1). The inversion routine starts by using the initial damping factor (about 0.1 to 0.3) that is then progressively reduced after each iteration. However, to avoid instability in the model values due to a damping factor value that is too small, a minimum limit for the damping factor is used (usually about one-tenth the initial value). If the data set appears to be very noisy, and unusually high or low model resistivity values are obtained with the default values, use larger values for the damping factors.

First layer smoothing: This option allows the user to set a higher damping factor for the first model layer. It can be useful in some situations to avoid unusually large resistivity variations in the top layer (Loke and Dahlin 2010).

Directly smooth model resistivity: This option uses the following variation of the least-squares equation (4.1)

$$(\mathbf{J}^T \mathbf{J} + \lambda \mathbf{F}) \Delta \mathbf{q}_k = \mathbf{J}^T \mathbf{g}_k, \quad (8.1)$$

if the option 'Directly smooth model resistivity' is not selected. Note this equation forces the change in model resistivity to be smooth ($\Delta \mathbf{q}$) but does not ensure that the model resistivity is smooth.

Line search on every iteration: The least-squares equation (4.1) usually provides a good estimate of the magnitude in the change of the model resistivities in order to reduce the data misfit subject to the smoothness constraint used. This option tries to find the optimum magnitude for the change in the model

parameters using a local line search. In connection with this option, the user can specify the minimum change in the data misfit for a line search to be carried out.

Model layers parameters: These settings controls depths to the layers used in the inversion model.

Thickness of first layer - This gives the ratio of the first layer thickness to the unit electrode spacing in the x-direction.

Factor to increase layer thickness - The thickness of each subsequent deeper layer is usually increased since the resolution of the resistivity method decreases with depth. This setting controls the rate of increase of the layer thickness.

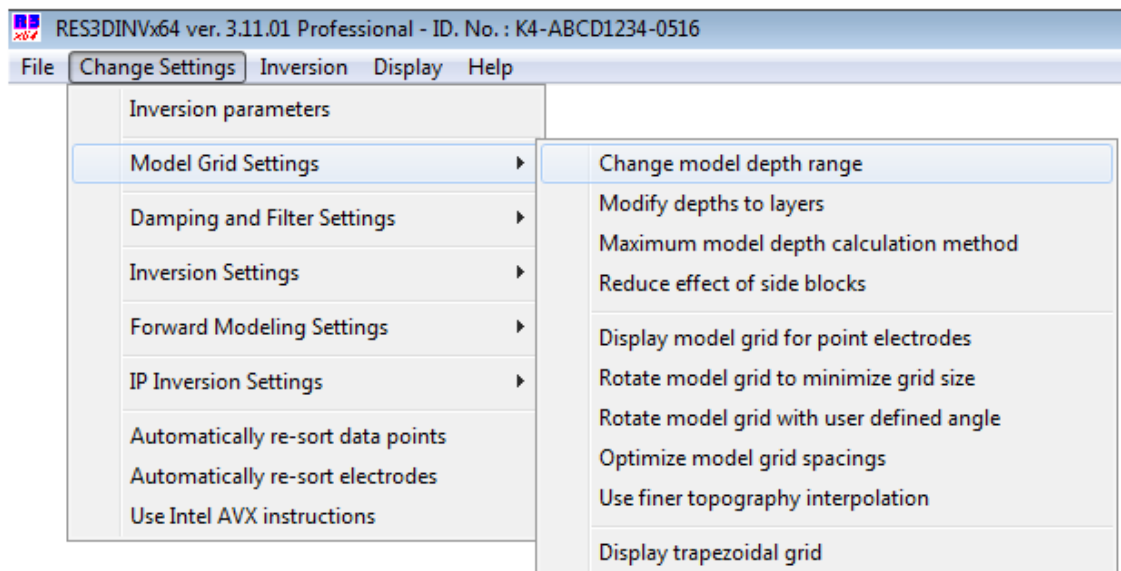
Model depth range setting - This sets the maximum depth of the deepest layers. Normally the program sets the deepest layer at about the maximum depth of investigation (Edwards 1977) of the arrays used in the data set. This option allows the user to extend the depth range of the model.

Number of iterations: This sets the maximum number of iterations the program uses before it automatically stops. However, the program does not end the inversion but will ask the user whether additional iterations are to be used. Normally 4 to 8 iterations are used.

Convergence limit: This sets the percentage data misfit in the inversion of the apparent resistivity data where the program will stop. Normally a value of between 2% and 5% should be used, depending on the quality of the data. In this program, the relative change in the RMS error, rather than an absolute RMS value, is used to accommodate different data sets with different degrees of noise present.

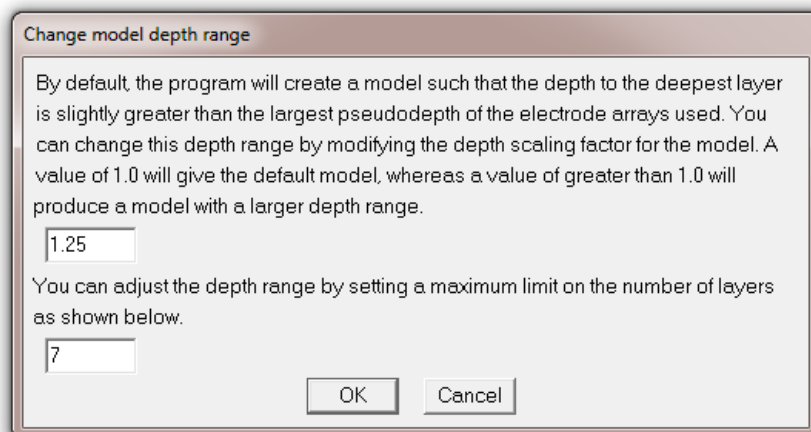
9.2 Model Grid Settings

This is a group of options that control the discretization of the subsurface into layers and blocks used as the inversion model. The following list of sub-options is listed when this menu option is selected.



9.2.1 Settings for model layers depths and sides

Change model depth range: Selecting this option brings up the following dialog box.



The first option that sets the maximum depth range for the model is the same as that discussed earlier in section 9.1. If a very large value is used for the depth range, together with thin layers, the model may end up with a very large number of layers. The second option puts a maximum limit on the number of layers in the inversion model.

Modify depths to layers: This option allows the user to directly change the depth to the model layers. This can be useful to directly set the depth to a layer to coincide with a known boundary. The figure below shows an example dialog box using this option. Here the user can type in the new depth values.

Layer	New Depth	Present Depth	Layer	New Depth	Present Depth
1	1.02	1.02	21		None
2	2.19	2.19	22		None
3	3.53	3.53	23		None
4	5.08	5.08	24		None
5	6.86	6.86	25		None
6	8.91	8.91	26		None
7	11.3	11.3	27		None
8	14.0	14.0	28		None
9	17.1	17.1	29		None
10		None	30		None
11		None	31		None
12		None	32		None
13		None	33		None
14		None	34		None
15		None	35		None
16		None	36		None
17		None	37		None
18		None	38		None
19		None	39		None
20		None	40		None

Maximum model depth calculation method: By default, the program uses the median depth of investigation method (Edwards 1977) to estimate the maximum depth range for the model. This option allows the user to use the maximum array length to set the model depth range.

Reduce effect of side blocks: In the finite-difference or finite-element mesh used to calculate the apparent resistivity values, the resistivity of the model cells at the sides and bottom extend to the edges of the mesh. The distance to the mesh edges can be more than 10 times the maximum array length, so the side cells have sizes much larger than the interior blocks. This causes the sensitivity (Jacobian matrix) values associated with the side cells to be much larger than the neighboring interior cells. In some cases, this can cause the resistivity values of the side cells calculated by the inversion method to have unusually high or low values. This option allows the user to trim the sensitivity values for the side cells by differing amounts, as shown by the dialog box below. A better way to incorporate effects of structures outside the survey grid is to extend the model grid slightly beyond the immediate survey area (section 8.8).

Reduce effect of side blocks

Do you want to reduce the effect of the model cells at the sides of the model? In some cases this can reduce the occurrence of unusually high or low resistivity values at the corners of the model.

Reduce effect of side model cells?

☐ None
 ☐ Slight
 ☐ Moderate
 ☒ Severe
 ☐ Truncate

9.2.2 Settings for data in arbitrary electrode format

The following options are only used for data sets in the arbitrary point electrodes format.

Display model grid for point electrodes: This option displays the model grid together with the positions of the electrodes for a data file with the arbitrary electrodes format (section 7.1.4). It will highlight electrodes used in the same array that might be too close together (less than 2 mesh nodes). The user can add or remove the model grid lines in this display so as to optimize the model grid to achieve a balance between a sufficiently fine mesh and a minimum number of model cells. An example of a plot showing the model grid and the electrodes is shown in Figure 10.

Rotate model grid to minimize grid size: This option rotates the model grid automatically to find the minimum model grid that can accommodate all the electrode positions. In some cases, the survey lines are aligned at a significant angle to the true North-South and East-West directions, particularly those collated from a series of 2-D survey lines using the RES2DINVx64 program. This results in a large model with empty spaces at two corners. The example (in the file L5N_Resistivity_Global.dat) shown in Figure 11 has inclined lines with large areas without data in the North-West and South-East sections of the model grid. For this data set, after a rotation of 20 degrees (in the file L5N_Resistivity_Local.dat), the x-axis of the model grid is aligned along the direction of the survey lines (Figure 12). The rotation of the model grid reduces the model grid from 68x45 to 64x26 model mesh lines. This reduces the number of model cells by about half. The finite-element mesh size used in the inversion routine is also reduced by a similar factor. The reduction in the grid size reduces the computer time and memory required by more than half. When this option is selected, the program automatically calculates the angle of rotation that will give a minimum model grid size. It will then prompt the user for the name of the file to save the data set with the modified model grid and data coordinates. Note the x and y coordinates in the data set will be changed to local coordinates. However, the true coordinates are also stored in the data file so that the results can be translated back into the original coordinates when saving the inversion model values into the XYZ format (section 11.1) or displayed on the screen (section 11.3).

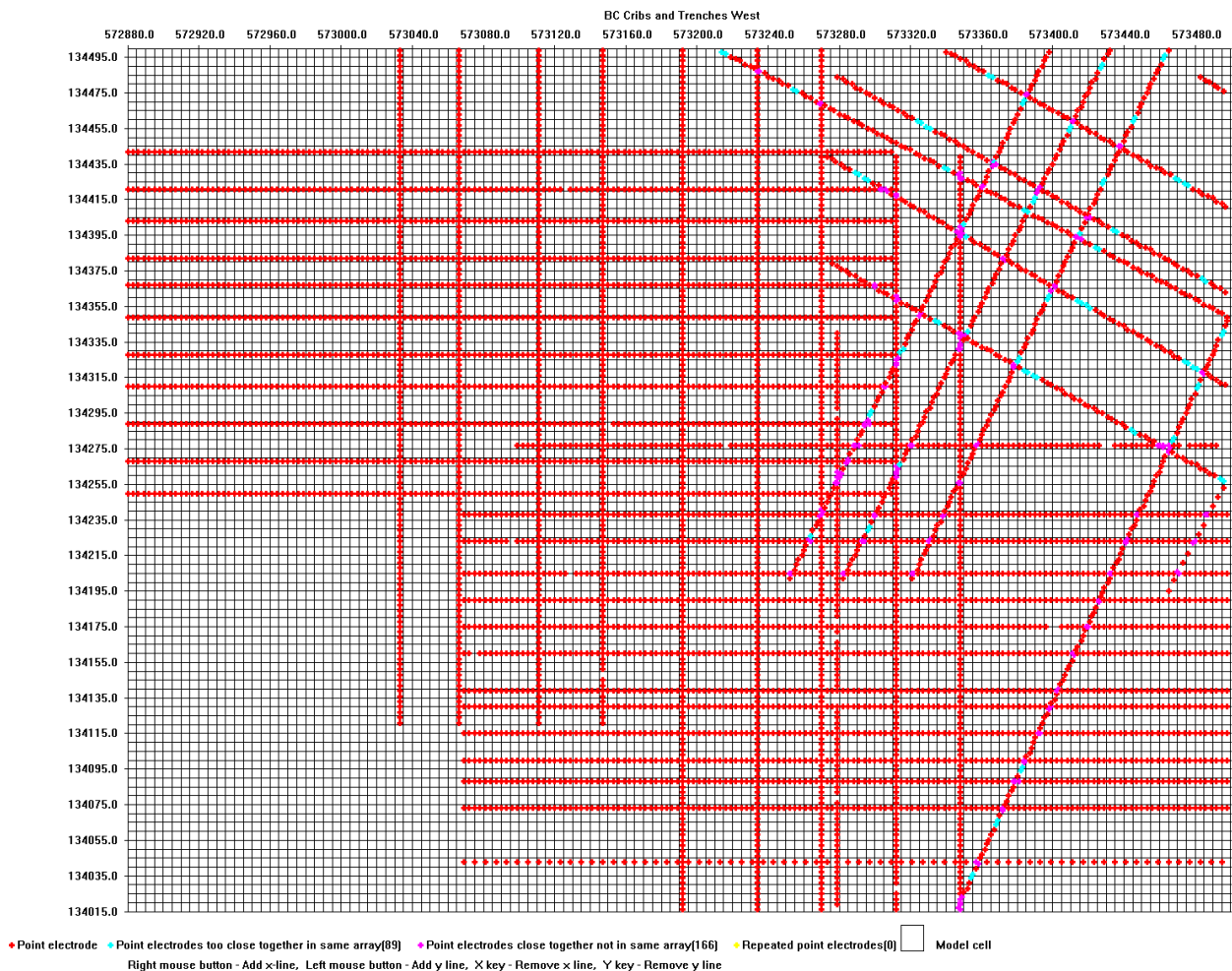


Figure 10. Example display of a model grid with arbitrary point electrodes.

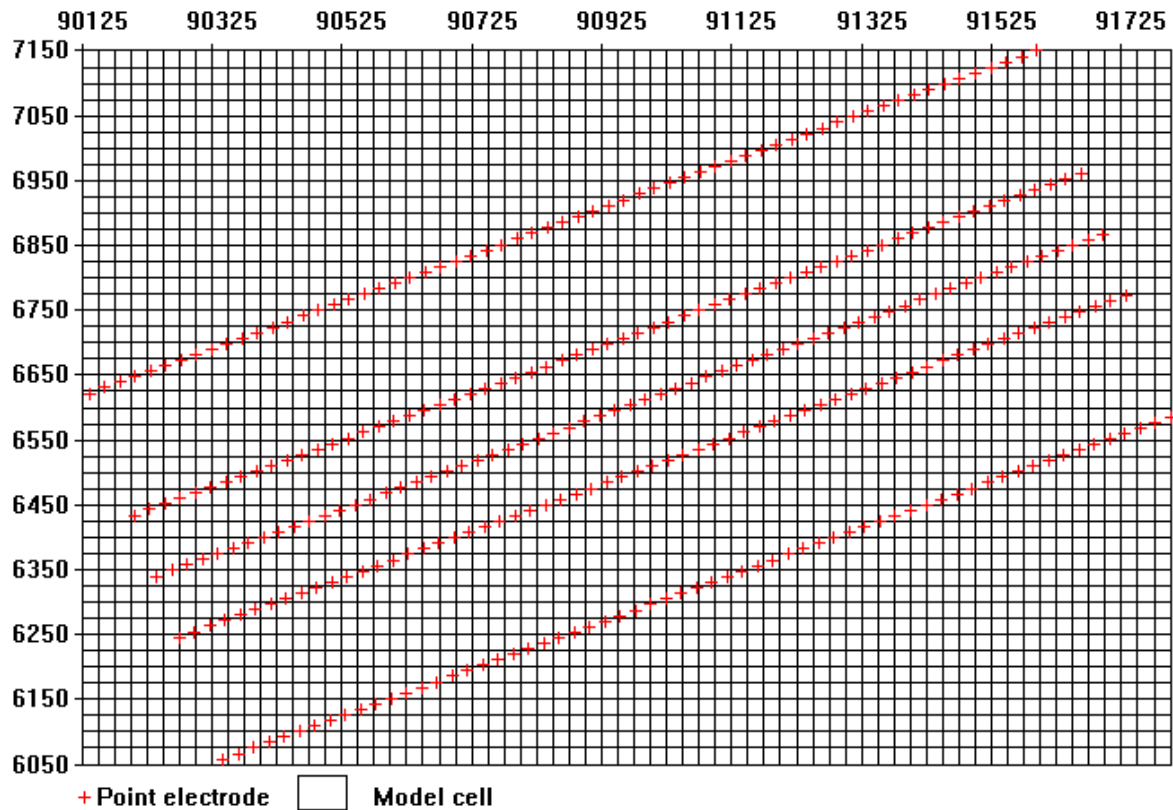


Figure 11. Example a model grid with inclined survey lines resulting in large empty spaces at the top-left and bottom-right two corners.

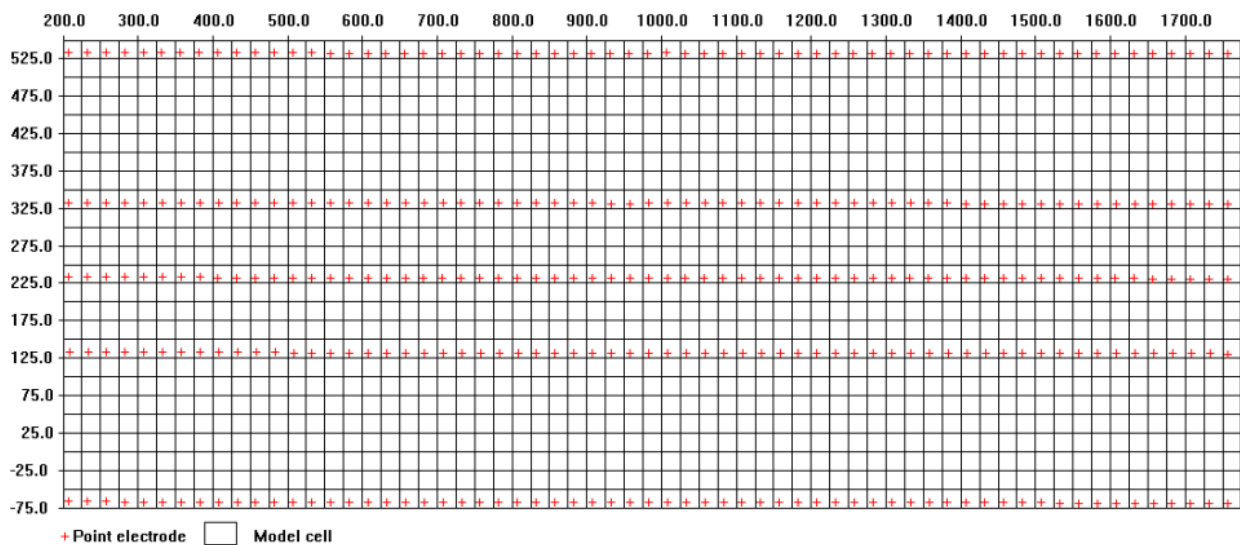
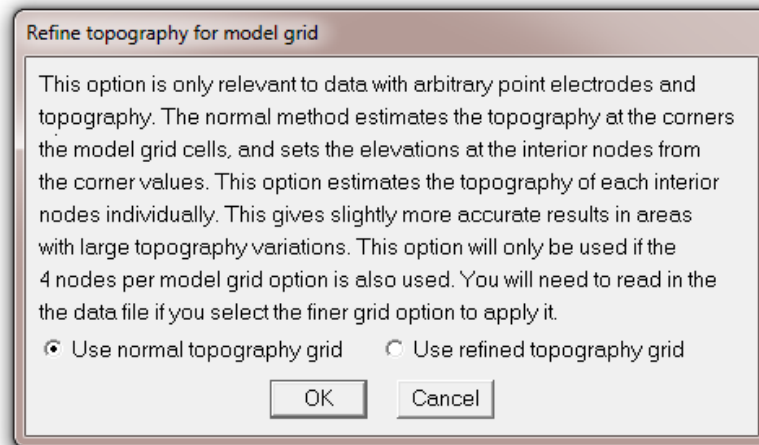


Figure 12. Model grid after a rotation of 20 degrees so that the model grid axis is aligned along the direction of the survey lines.

Rotate model grid to with user defined angle: This option also automatically rotates the model grid to minimize the grid size using an angle selected by the user. This might be useful in some cases to align the x or y grid direction to the main direction of the survey lines.

Optimize model grid spacings: This option automatically adjusts the spacings between the model grid lines to minimize the number of model cells. It will generally use wider spacings in areas with few electrode positions. This might be useful for very large survey grids to reduce the computer time and memory required to process the data set. However, it is recommended that a uniform model grid should be used where possible.

Use finer topography interpolation: The program normally estimates the elevations at the corners of the model grid using the topography values at the point electrodes (and an unstructured topography data list if available). From the elevations at the corners of the model grid, it calculates the elevations at the surface nodes of the 4x4 finite-element mesh within each model cell using linear interpolation. This option calculates the elevation at each node individually so that non-linear topography variations located within each model cell can be taken into account.



9.2.3 Settings for data in trapezoidal grid format

Display trapezoidal grid

This option display the x-y model grid (Figure 13) used for data sets in the trapezoidal grid format (section 7.1.3). It will highlight sections of the grid that have trapeziums with small interior angles (Figure 14c), or degenerate trapeziums (Figure 14d). The finite element method assumes the trapeziums in the model grid are convex (Figure 14b). If the grid has trapeziums that are degenerate, the finite element method might not give reasonable results. Even if the trapezium is mathematically convex, it might still be numerically degenerate due to the finite accuracy of the finite element method. The program will consider a trapezium to be degenerate if one side has zero length (i.e. two electrodes in the grid fall at the same place) or an interior angle is less than 1 degree or more than 179 degrees. In such cases, it would be better to use the arbitrary electrodes data format (section 7.1.4) so that the model cells are rectangular regardless of the distribution of the electrodes used in the survey.

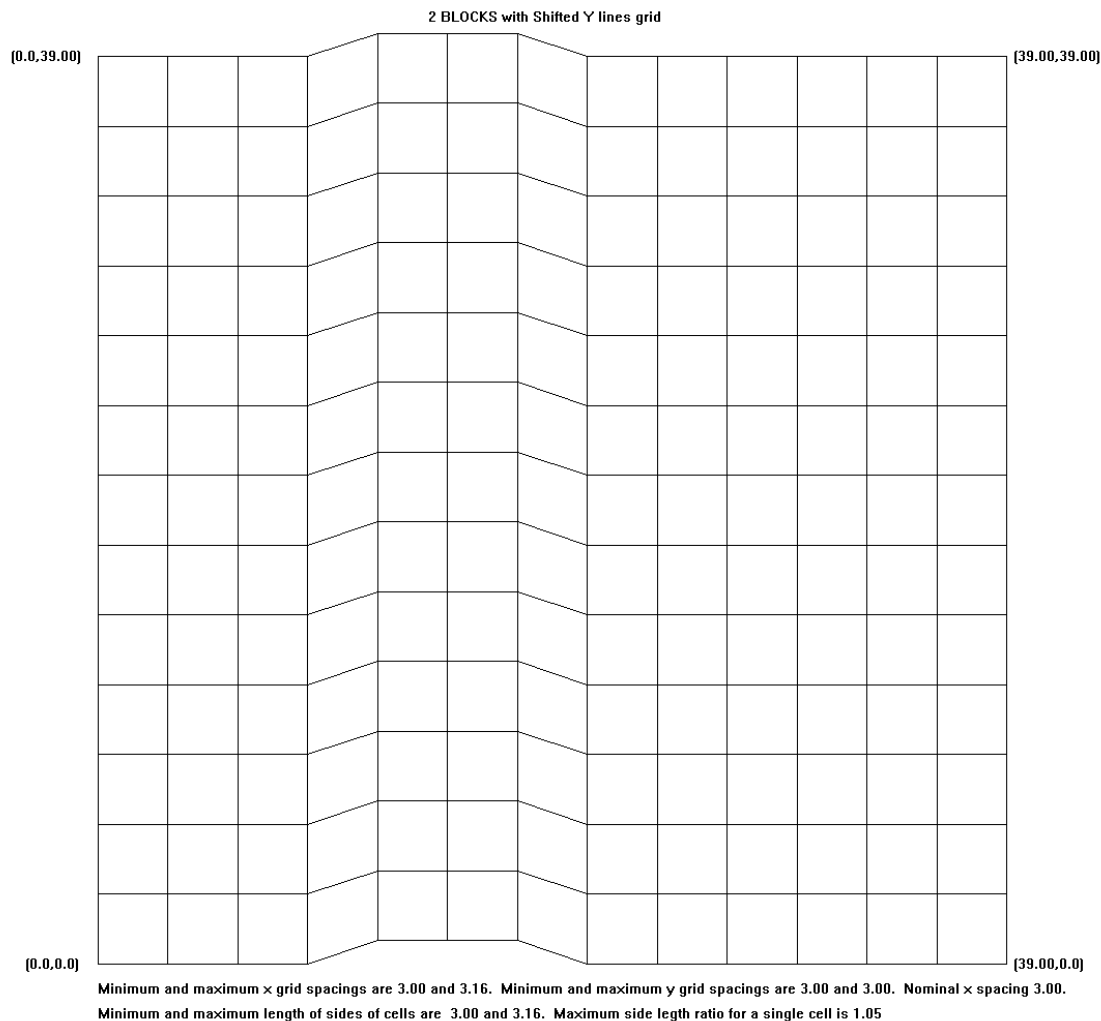


Figure 13. Example trapezoidal grid display.

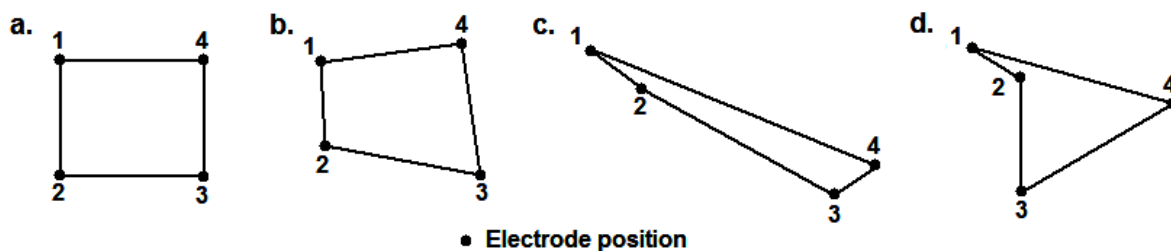
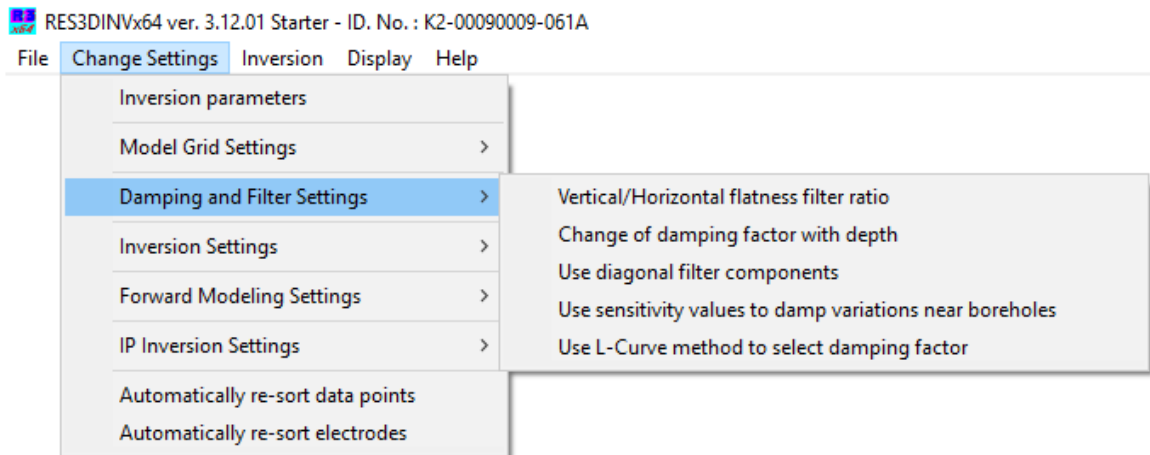


Figure 14. Type of model grid elements. (a) Rectangular element. (b) Convex trapezoidal element. (c) Almost degenerate trapezoidal element. (d) Degenerate concave trapezoidal element.

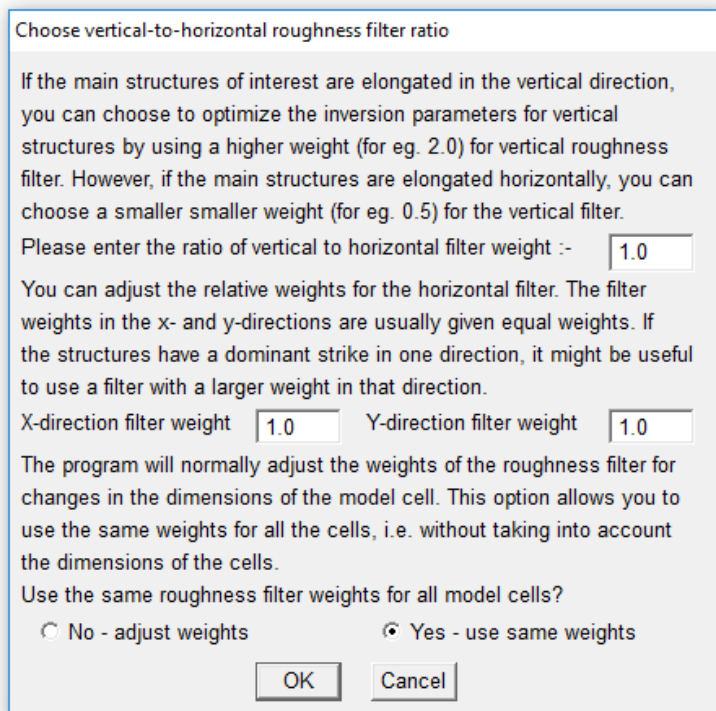
9.3 Damping and filter settings

This group of options controls the damping factors and roughness filters used in the smoothness-constrained least-squares method. The following list of sub-options is listed when this option is selected.



9.3.1 Vertical/Horizontal flatness filter ratio

You can select the ratio of the relative weights given to the damping factor for the vertical flatness filter (C_z) and horizontal flatness filters (C_x and C_y). By default, the same damping factor is used for all of them. However, if the anomalies in the pseudosection are elongated vertically, you can force the program to produce models that are also elongated vertically by selecting a higher value (for example 2.0) for the ratio of the vertical flatness filter. For anomalies that are elongated horizontally, choose a smaller value (e.g. 0.5).



This option also allows the user to use different weights in the x and y directions.

9.3.2 Change of damping factor with depth

Since the resolution of the resistivity method decreases exponentially with depth, the damping factor used in the inversion least-squares method is normally also increased with each deeper layer. This is done in order to stabilize the inversion process. Normally, the damping factor is increased by 1.05 times with each deeper layer, but you can change it. Use a larger value if the model shows unnatural oscillations in the resistivity values in the lower sections. This will help to suppress the oscillations. You can also select the choice to allow the program to determine the value to increase the damping factor with depth automatically. This might be a good choice if the thickness of the layers is much thinner than the default values.

9.3.3 Use diagonal filter components

The normal 3-D roughness filter used in the least-squares inversion method has components in the x-, y- and z-directions only. It has a tendency to produce structures with boundaries that are aligned along these horizontal and vertical directions, particularly if the L1-norm inversion method is used (Farquharson 2008). One method to reduce this effect is to include components in the diagonal directions as well. Selecting this option will display the following dialog box.

Use diagonal filter components

The normal roughness filter has vertical and horizontal components only. This option allows you to use filter components in the diagonal directions in the horizontal and vertical planes.

Do you want to use the xy horizontal diagonal roughness filter? ☒ Yes ☐ No

Do you want to use the xz and yz vertical diagonal roughness filter? ☐ Yes ☒ No

Do you want to use the xyz vertical cross-diagonal roughness filter? ☐ Yes ☒ No

Normally the diagonal filter components have the same weight (1.0) as the horizontal and vertical

You can change the weight for the diagonal components by setting the value below.

Weight for diagonal components (0.5 to 2.0) :

Do you want to use a higher damping for the first model layer? This is normally used together with the diagonal horizontal roughness filter to reduce near-surface artefacts in the inversion model for 3-D data sets that are collated from parallel 2-D survey lines.

☒ Yes - use higher damping for first layer ☐ No - use same damping as other layers

Higher damping factor value for first layer (2 to 20) :

Do you want to extend the range of the horizontal filters to the nearest 2, 3 or 4 model cells? This might be useful if the survey consists of 2-D lines with separations of more than twice the inline electrode spacing.

☒ Normal 1 cell ☐ Extend 2 cells ☐ Extend 3 cells ☐ Extend 4 cells

In the first option, 'Horizontal roughness filter', you can choose to apply the diagonal components in the horizontal directions only in the x-y plane. The second option, 'Vertical roughness filter', will apply the diagonal components in the x-z and y-z vertical planes as well. The diagonal components are normally given the same weights as the normal horizontal and vertical components. However, the weights given to the diagonal components can be modified by the user. Many 3-D data sets are collated from a number of parallel 2-D survey lines. The inversion models for such data sets sometimes have prominent banded anomalies aligned in the x- and y-directions (Johansson *et al.* 2007) in the near-surface layers. One method to reduce such artifacts is to use a higher damping factor for the top model layers (the bottom option in the dialog box) together with the x-y diagonal filter (Loke and Dahlin 2010). If the lines are separated by more than twice the inline electrode spacing (Figure 12) the artifacts can be further reduced by extending the range of the roughness filter by 2 or 3 model cells.

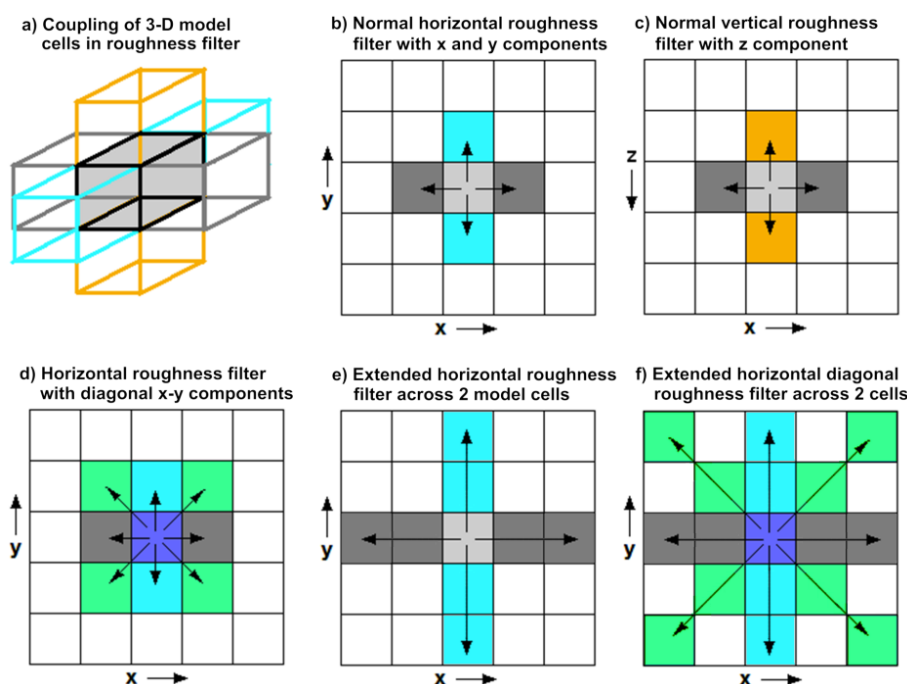


Figure 15. 3-D roughness filters with different components.

9.3.4 Use sensitivity values to damp variations near electrodes

On selecting this option, the following dialog box is shown. In some surveys with subsurface electrodes, prominent artifacts are observed near the subsurface electrodes (Loke et al. 2015). This option basically applies a higher damping factor for model cells with higher sensitivity values to suppress this artifact.

Reduce variations near electrodes using sensitivity values

To reduce the resistivity variations near the borehole electrodes, you can use the sensitivity values. This is more useful in cases where not all the boreholes electrodes are used, for example when the subsurface electrodes are actually arranged along a horizontal line.

Do you want to use the sensitivity values to set the damping factors?

☒ Yes - use the sensitivity values ☐ No - do not use the sensitivity values

You can set the degree in which the variations near the electrodes are reduced by changing the value below. A larger value will result in smaller variations near the electrodes.

Damping factor increase to reduce variations :-

You can also control the degree the variations near the electrodes are suppressed depending on the sensitivity value. A smaller value will result in a greater reduction in the resistivity variations in parts of the model that have higher sensitivity values.

Rate of damping factor reduction with sensitivity :-

Only model cells above a set cutoff sensitivity value will be subject to a higher damping factor.

Cutoff sensitivity values to set higher damping factor :-

9.3.5 Use L-curve method to select damping factor

If you select this option, the program will attempt to find the optimum damping factor λ in equation (4.1) using the L-curve method (Farquharson and Oldenburg 2004; Loke et al. 2014a). For very large data sets with more than 10000 data points and/or model parameters, the time taken in each iteration could be significantly increased as it is necessary to solve the least-squares equation many times per iteration.

Use L curve method

You can select the L curve method to estimate the optimum damping factor for each iteration.

Use L curve method?

☒ No, do not use ☐ Yes, use L curve

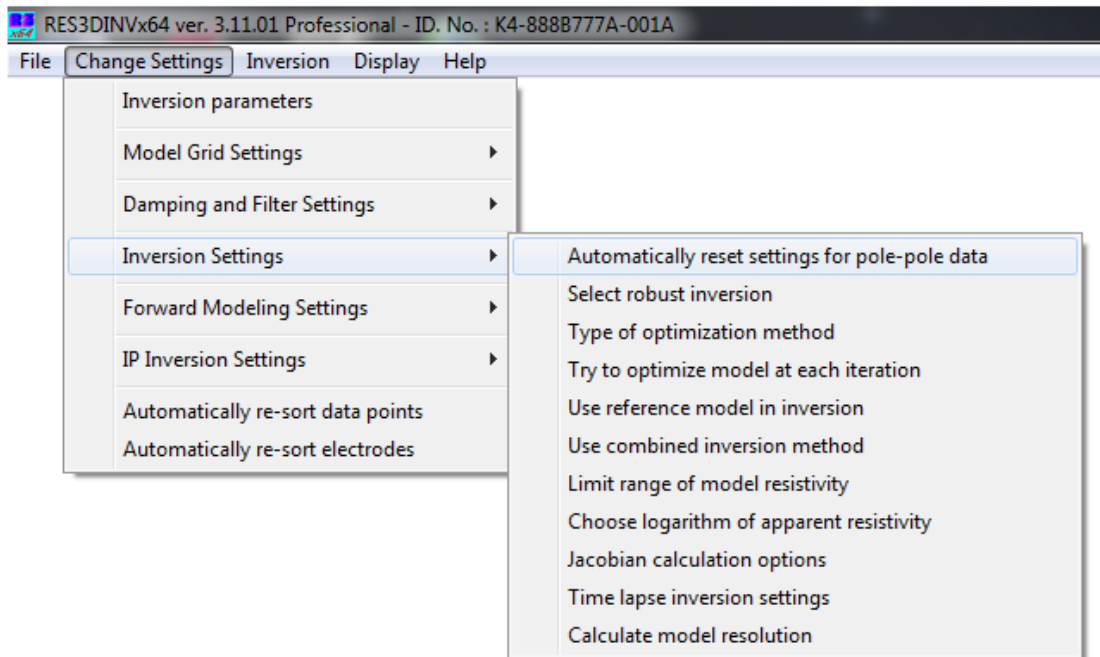
Use same norm for L curve calculation as in the data inversion?

☒ No, always use L2 ☐ Yes, use same norm

The first option selects the L-curve method. In some cases, where the L1-norm is selected in the data and model inversion (section 9.4.2), it can result in a curve that is not smooth. The second option calculates the equivalent L-curve for the L2-norm, even if the L1-norm is selected.

9.4 Inversion settings

This is a group of settings that control various aspects of the optimization method used. The following list of menu sub-options is displayed upon selecting this item.

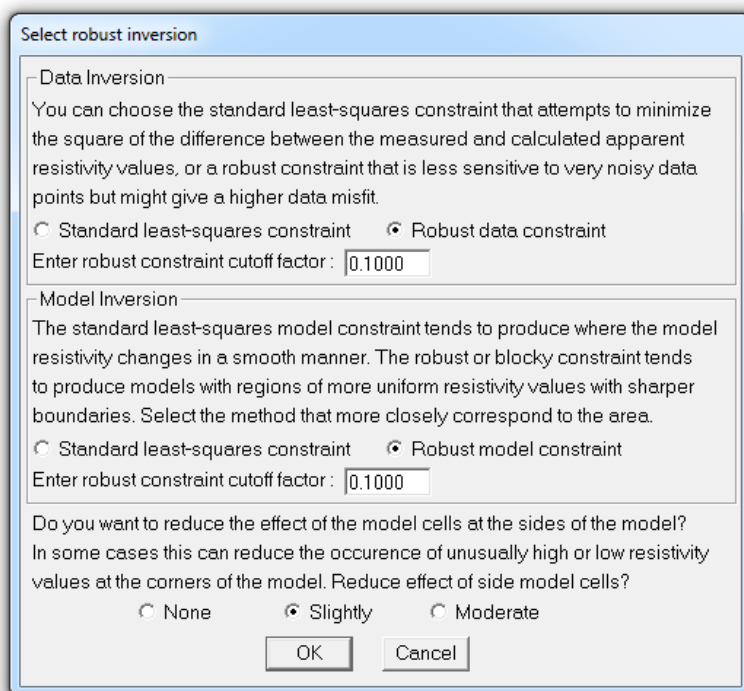


9.4.1 Automatically reset settings for pole-pole

This option allows the user to use a different set of inversion settings for data collected with the pole-pole array. If this option is enabled, the program will automatically read in the settings from a file, POLEPOLE.IVP stored in the same folder as the RES3DINVX64 program.

9.4.2 Select robust inversion

This option is used to select between the normal smoothness-constrained (L2 norm) and robust or blocky (L1 norm) inversion method (Loke *et al.* 2003). The following dialog box appears when this option is selected.



The conventional least-squares method will attempt to minimize the *square* of the difference (L2 norm) between the measured and calculated apparent resistivity values. The 'Robust data constraint' option will attempt to minimize the *absolute* difference (or the *first* power, L1 norm) between the measured and

calculated apparent resistivity values (Claerbout and Muir 1973). This method is less sensitive to very noisy data points. In a similar way, the ‘Robust model constraint’ option will attempt to produce where absolute spatial changes in the model resistivity values is minimized, compared to the normal smoothness-constrained method where the square of the changes is minimized. This robust model option tends to produce a model with sharper boundaries. Both the model and data robust constraints have a cutoff factor value. This value determines the extent the L1 norm constraint is used in contrast to the L2 norm constraint. If a large value is used, the method becomes effectively the L2 norm method. The robust model constraint can sometimes produce models with unusually high or low values at the edges. This effect can be reduced by reducing the effect of the side model blocks (section 9.2).

9.4.3 Type of optimization method

This option allows you to choose two different methods to solve the least-squares equation (4.1). On selecting this menu option, the following dialog box will be shown.

Optimization method : The ‘Standard Gauss-Newton’ least-squares method uses a direct method to solve the least-squares equation where an exact solution is obtained. In theory, this produces the most accurate results but the computer time increases with the cube of the number of model blocks. If the number of data points and/or model cells is large (more than 10000), the time taken to solve the least-squares equation could be the most time-consuming part of the inversion process. To reduce the inversion time, an alternative method that calculates an approximate solution of the least-squares equation (the ‘Incomplete Gauss-Newton’ method) using an iterative linear conjugate-gradient method. The user can set the accuracy of the solution. For most data sets, an accuracy of about 1% (i.e. a convergence limit of 0.01 in the above dialog box) seems to provide a solution that is almost the same as that obtained by the ‘Standard Gauss-Newton’ method. Setting a higher accuracy, for example 0.5%, will in theory give a result that is even closer to the ‘Standard Gauss-Newton’ method but this is at the expense of a longer inversion time.

Data compression and scaling : For very large data sets and models (over 20000 data points/model blocks), a “data compression” option is provided with the ‘Incomplete Gauss-Newton’ method when the entire Jacobian matrix is larger than the computer memory. The fast wavelet transform method developed for this program is probably one to two orders of magnitude faster than standard wavelet transform methods for large 3-D models. The data compression method has a cut-off where Jacobian matrix values (or its transform) that are less than the limit set are not used. Normally a value of 0.001 (0.1%) to 0.01 (1%) of the maximum value is used. Setting a higher cut-off value will reduce the memory required by the compressed Jacobian matrix at the cost of lower accuracy. The default value of 0.003 is probably sufficient for most data sets. The time taken by the iterative solution method can be significantly reduced by scaling the diagonal elements of the Jacobian matrix product.

Gauss-Newton numerical precision : If the ‘Standard Gauss-Newton’ method is chosen, the program normally solves the matrix equation using double-precision calculations. This option enables the user to carry out the calculations in single-precision which is about twice as fast. For most data sets, the difference in the results is usually small.

9.4.4 Try to optimize model at each iteration

This is the same as the line search option discussed earlier in section 9.1.

9.4.5 Use reference model in inversion

The least-squares equation (4.1) minimizes a combination of the model smoothness and the data misfit. Sometimes, an additional constraint is used where the model must be 'close' to some reference model as shown below.

$$(\mathbf{J}^T \mathbf{J} + \lambda \mathbf{F} + \mu \mathbf{I}) \Delta \mathbf{q}_k = \mathbf{J}^T \mathbf{g} - \lambda \mathbf{F} \mathbf{q}_k - \mu (\mathbf{q}_k - \mathbf{q}_m)$$

An additional damping factor μ that controls the degree where the inversion model is 'close' to a reference model \mathbf{q}_m is used. The reference model is usually a homogeneous half-space model. The following dialog box shows the settings that can be selected by the user.

Use reference model constraint

In this option, you can constrain the model so that the deviation of the model resistivity from a homogenous reference model is limited.

Use this reference model constraint? ☒ Yes ☐ No

Please enter the damping factor value for reference model. A larger damping factor value will result in a model with less variations from the reference model.

Damping factor value (0.01 to 1.00):

You can choose to use the default reference resistivity value (usually the average of the apparent resistivity) or a user defined reference value by changing the the value given below.

Value of user defined reference resistivity:

You can use a constant reference model damping factor for all the model cells or use an adaptive damping factor that adjusts for deviations from the reference.

Use adaptive reference damping factor? ☐ Yes ☒ No

For an I.P. data set, you can use the same reference damping factor for the I.P. model or a different damping factor.

Use same damping factor for I.P. model? ☒ Yes ☐ No

If you choose to use a different I.P. reference damping factor, enter the value.

I.P. damping factor value (0.01 to 1.00):

The average apparent I.P. value in mV/V is :- 0.37

You can select to use this reference I.P. model value or set it to zero.

☒ Use average apparent I.P. value ☐ Use zero reference I.P. value

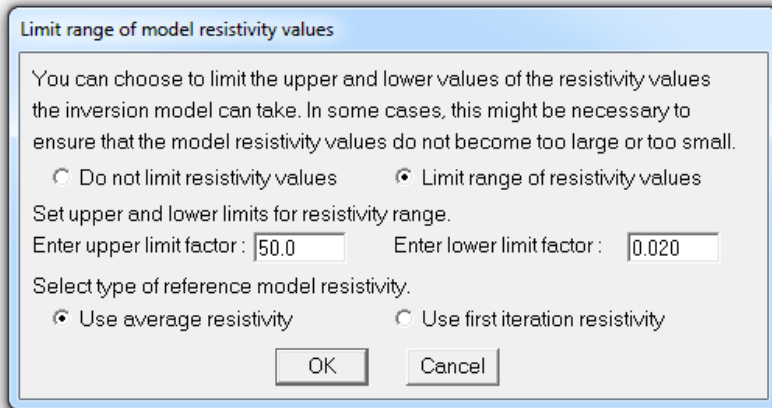
The reference resistivity value is normally set at the average of the apparent resistivity values. The user can also set the reference resistivity value. A constant value for the reference damping factor μ is normally used for all the model cells. The 'adaptive damping factor' option allows a non-uniform damping factor that depends on the sensitivity of the model cells and deviations from the reference model to be used. If the data set has I.P. measurements the user can also select to use a value of zero, instead of the average apparent I.P. value, for the reference I.P. model value. This is the I.P. value for rocks without any polarizable minerals.

9.4.6 Use combined inversion method

This option is intended for unusual situations where the data sensitivity values of the model blocks are significantly distorted by large resistivity variations. In some situations, such as a survey over a very low resistivity body, the current paths could be distorted such that parts of the subsurface are not well-mapped and have very low data sensitivity values in the inversion model. This could lead to large distortions just below the low resistivity body. By combining the Marquardt (or ridge regression) and Occam (or smoothness-constrained) inversion methods, the distortions in some cases might be reduced. This option should be used as a last resort if everything else fails! It seems to give better results in resolving compact structures where the width and thickness are slightly smaller than the depth, such as a cave or ore-body whose size is just slightly less than its depth. In theory, it is possible to just use the Marquardt (or ridge regression) method alone. However, it has been found that this method is unstable when the data contains noise if a model with a relatively large number of model parameters is used.

9.4.7 Limit range of model resistivity

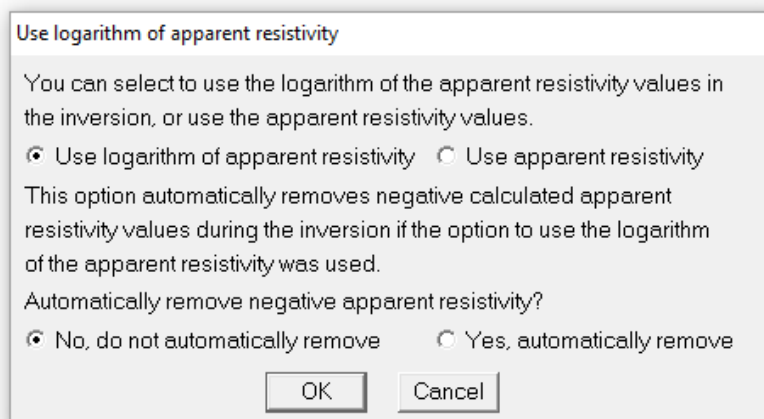
When you select this option, the following dialog box will be shown.



This option allows you to limit the range of resistivity values that the inversion subroutine will give. In the above example, the upper limit for is 20 times the average model resistivity value while the lower limit is 0.05 times (i.e. 1/20 times). The program uses “soft” limits that allow the actual resistivity model values to exceed the limits to a certain degree. However, this option will avoid extremely small or large model resistivity values that are physically unrealistic. The user can also choose to use the inversion model obtained at the first iteration as the reference model.

9.4.8 Choose logarithm of apparent resistivity

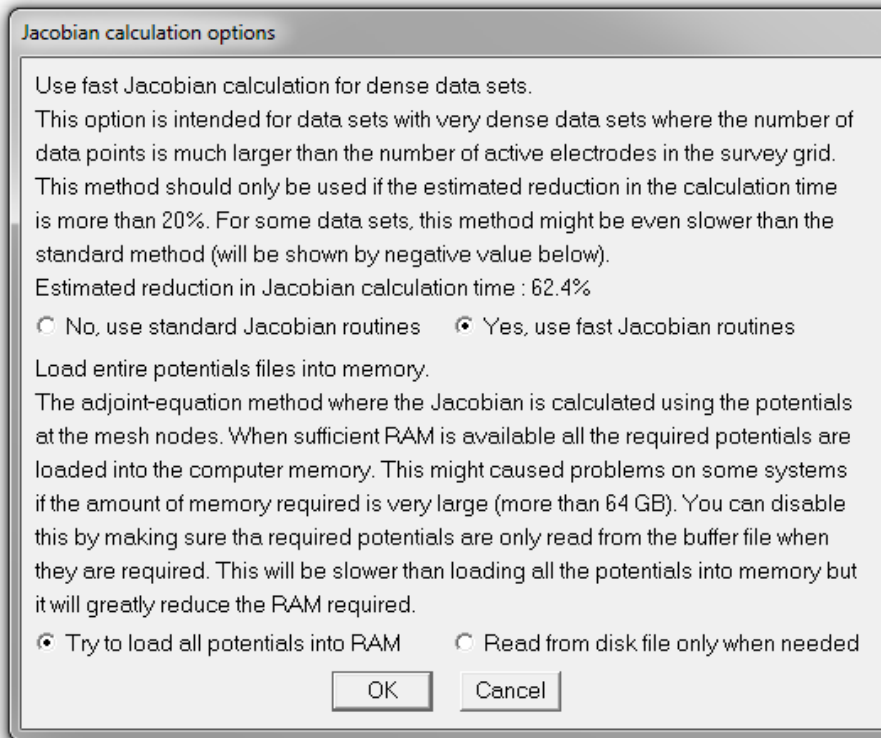
By default, the program will use the logarithm of the apparent resistivity values as the data parameter when carrying out the inversion. For most cases, this gives the best results. In some cases, for example with negative or zero apparent resistivity, this is not possible. This option enables the apparent resistivity value by itself to be used for such situations.



In some cases, particularly with arrays that have large geometric factors or skewed arrays with large geometric factor relative errors, the forward modeling routine might give negative calculated apparent resistivity values for some data points that have a positive measured apparent resistivity. This will cause the program to stop the inversion if the logarithm of the apparent resistivity is used. The second set of options allows the program to automatically remove such data points from the inversion process instead of stopping. At the end of the inversion, the user has a choice to save the data points into a new file after trimming the arrays that gave negative calculated apparent values during the inversion. Appendix H has a discussion on a strategy to handle data sets with potentially unstable arrays.

9.4.9 Jacobian calculation options

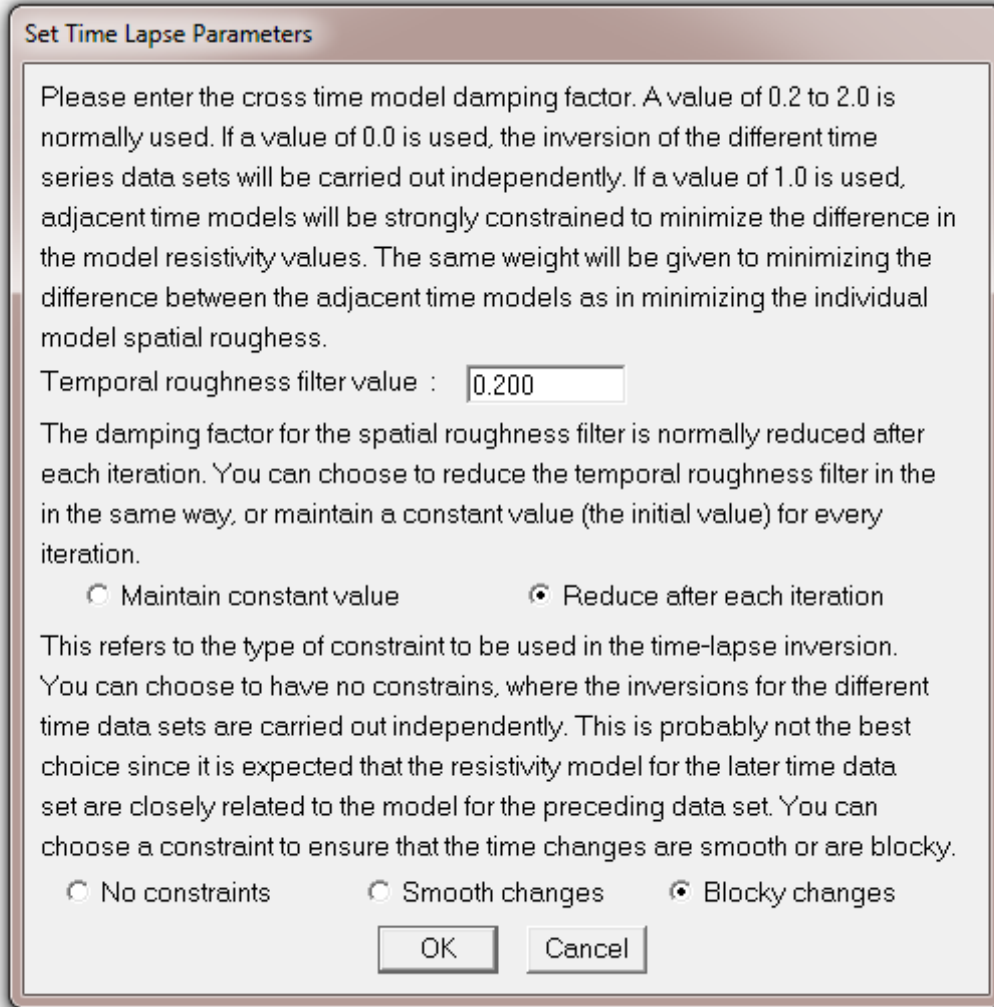
The first setting has an option that uses an optimized routine for calculating the Jacobian matrix values for data sets where the number of data points is much greater than the number of electrodes used in making the measurements. It uses an alternative algorithm to calculate the Jacobian matrix values that can be significantly faster than the standard routines. The expected reduction in the calculation time for the Jacobian matrix will be displayed in the dialog box. As a guide, this option should only be used when the expected reduction is more than 20%. Note for some very sparse data sets, this routine can be even slower than the standard method. This will be indicated by a negative value for the expected reduction in the calculation time.



The program uses the adjoint-equation method (Farquharson and Oldenburg 2004) to calculate the Jacobian matrix values from the potentials at the nodes of the finite-difference or finite-element mesh. The potential values are calculated and then stored in a disk file by the forward modeling routine. The program normally loads all the potentials into the computer memory in the Jacobian matrix calculation routine to reduce disk access time if the PC has sufficient RAM. However, it has been found that on some computers the process of loading a very large file (more than 64GB) into the computer memory can cause the system to crash as it prevents other programs from accessing the hard-disk. This option allows the user not to load the entire file into the computer memory at a single time but the program reads parts of the file it needs in calculation the Jacobian values for each data point. This will slower particularly if a conventional hard-disk is used as the buffer drive. However, if a SSD is used, the increase in computer time is probably small.

9.4.10 Time lapse inversion settings (RES3DINVx64 Professional)

This option sets several inversion parameters for the inversion of time-lapse data files. On selecting this option, the following dialog box is displayed.



Set Time Lapse Parameters

Please enter the cross time model damping factor. A value of 0.2 to 2.0 is normally used. If a value of 0.0 is used, the inversion of the different time series data sets will be carried out independently. If a value of 1.0 is used, adjacent time models will be strongly constrained to minimize the difference in the model resistivity values. The same weight will be given to minimizing the difference between the adjacent time models as in minimizing the individual model spatial roughness.

Temporal roughness filter value :

The damping factor for the spatial roughness filter is normally reduced after each iteration. You can choose to reduce the temporal roughness filter in the in the same way, or maintain a constant value (the initial value) for every iteration.

☐ Maintain constant value ☒ Reduce after each iteration

This refers to the type of constraint to be used in the time-lapse inversion. You can choose to have no constraints, where the inversions for the different time data sets are carried out independently. This is probably not the best choice since it is expected that the resistivity model for the later time data set are closely related to the model for the preceding data set. You can choose a constraint to ensure that the time changes are smooth or are blocky.

☐ No constraints ☐ Smooth changes ☒ Blocky changes

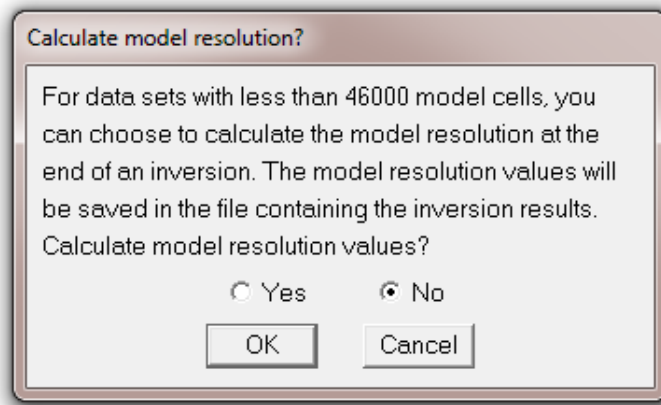
The smoothness-constrained least-squares optimization is modified to the following form for time-lapse data.

$$[J_i^T R_d J_i + (\lambda_i W^T R_m W + \alpha_i M^T R_t M)] \Delta r_i = J_i^T R_d g_i - (\lambda_i W^T R_m W + \alpha_i M^T R_t M) r_{i-1}$$

The ‘Temporal roughness filter’ sets the damping factor α in the above equation that attempts to minimize temporal changes in the resistivity across the different time models (Loke *et al.* 2014). The second option allows the use to use the same temporal damping factor for each iteration, or to reduce it in step with the spatial damping factor λ . The third set of options allows the user to use the L2 (smooth) or L1 (blocky) roughness constraint for the time-lapse models (Loke *et al.* 2014).

9.4.11 Calculate model resolution

This option is enabled using the following dialog box.



The model resolution matrix is given by

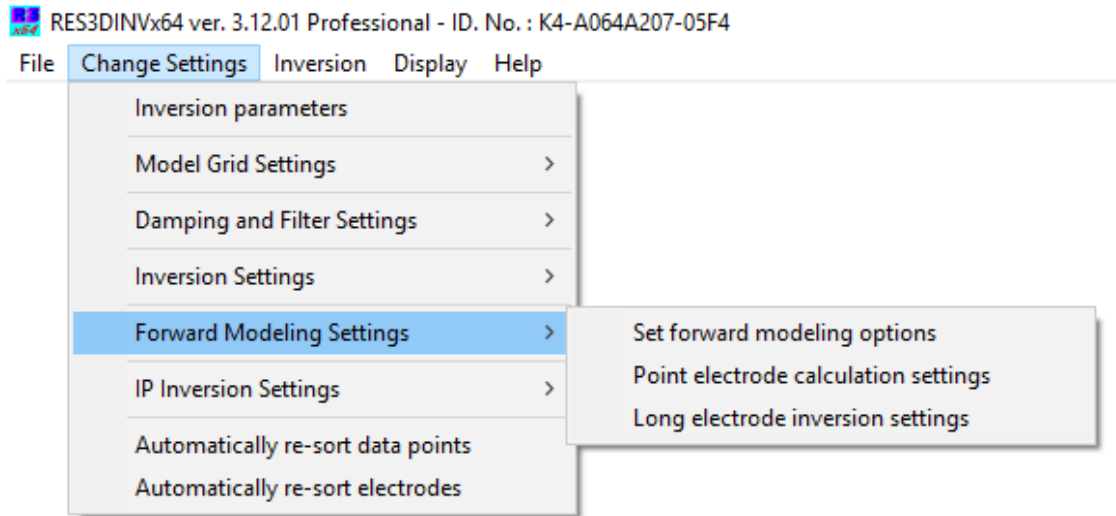
$$\mathbf{R} = (\mathbf{J}^T \mathbf{J} + \lambda \mathbf{F})^{-1} \mathbf{J}^T \mathbf{J}$$

The model resolution values of the model blocks are given by the diagonal elements of this matrix. The model resolution matrix \mathbf{R} may be viewed as a filter through which the inversion method attempts to resolve the subsurface resistivity (Day-Lewis *et al.* 2004). In the ideal case with perfect resolution, the elements of the main diagonal (R_{jj}) are 1 while the off-diagonal elements are 0. In practice, the model resolution values for most model blocks are much less than 1.0. The model resolution values give an indication of how well resolved are the different model cells by the data.

The time taken to calculate the model resolution matrix is proportional to the cube of the number of model blocks. The present maximum limit is about 46000 model blocks (for a computer with at least 24GB RAM) for the model resolution calculation option.

9.5 Forward Modeling Settings

This set of routines cover several aspects of the finite-difference and finite-element routines used to calculate the apparent resistivity and I.P. values. It has the following list of sub-options.



9.5.1 Forward modeling routine settings

These are several settings shown in the following dialog box.

Forward modeling routine settings

SELECT TYPE OF FORWARD MODELING METHOD
The finite-element is always used for models with topography. If there is no topography, both methods can be used. The finite-difference method is faster and requires less computer memory.

☒ Finite-difference method ☐ Finite-element method

SELECT HORIZONTAL MESH SIZE
You can select to use 2, 3 or 4 horizontal nodes in between adjacent electrodes in the finite-difference or finite-element mesh. Using more nodes can increase the accuracy of the results but the inversion will take longer to complete.

☐ 2 nodes ☐ 3 nodes ☒ 4 nodes

VERTICAL MESH SIZE
This option sets the vertical mesh size for surveys with surface electrodes. The default mesh is satisfactory for most situations. Where there are very large changes in the resistivity in the vertical direction, a finer mesh can give more accurate results. Use a finer mesh if there are subsurface electrodes.

☒ Default mesh ☐ Finer mesh ☐ Finest mesh

BOREHOLE VERTICAL MESH SIZE
This option sets the number of nodes vertically between adjacent borehole electrodes.

☒ 2 nodes ☐ 3 nodes ☐ 4 nodes

TYPE OF MESH BOUNDARY
This option sets the type of boundary mesh used at the sides and bottom of the mesh. The standard mesh is usually sufficient. However, for surveys that use very long current-potential distances, such as the offset pole-dipole or dipole-dipole arrays, it might be necessary to use the extended boundary mesh to get sufficiently accurate potentials.

☒ Standard boundary ☐ Medium extended ☐ Highly extended

OK Cancel

Type of forward modeling method - This program allows the user to select the finite-difference or finite-element method to calculate the apparent resistivity values. The program will normally use the finite-difference method, which is faster and requires less computer memory, if the data set does not contain topography. If the data set contains topography, the finite-element method is used.

Horizontal mesh size - By default, the program uses a finite-difference or finite-element grid with 2 nodes (in the x- and y-directions) between adjacent electrodes. This option allows you to use 3 or 4 nodes between adjacent electrodes for greater accuracy. Using more nodes will increase the accuracy of the forward modeling subroutine, but the computer time and memory required will also increase. For data sets with arbitrary point electrodes (section 7.1.4), the program will always use the 4 nodes option.

Vertical mesh size - This option sets the number of mesh lines in the z-direction. The default setting is to use a finer mesh for the near surface layers, and a coarser mesh for the deeper layers. However, the user can select a finer mesh for the deeper layers for cases when there is a large change in the resistivity in the vertical direction.

Borehole vertical mesh size – For data sets with borehole electrodes, this option sets the number of nodes between adjacent electrodes in the borehole.

Type of mesh boundary - The last option is to select the mesh used to model the boundaries at the sides and bottom of the finite-difference or finite-element mesh. By default, a standard boundary is used that uses fewer mesh lines to model the boundaries. This reduces the computer memory and calculation time required. For some arrays that have remote electrodes placed at a long distance from the other electrodes in the arrays used (such as the gradient array), it might be necessary to use a more highly extended boundary to obtain sufficient accuracy. This increases the total number of nodes used and thus the computer time and memory required. The ‘medium extended’ option can be used if there is insufficient memory.

9.5.2 Point electrode calculation settings

This option is used for data using the arbitrary point electrodes format. The program has two options to calculate the potentials at the electrode if it does not fall on a node in the finite-difference or finite-element mesh. The dialog box below will be shown when this option is selected.

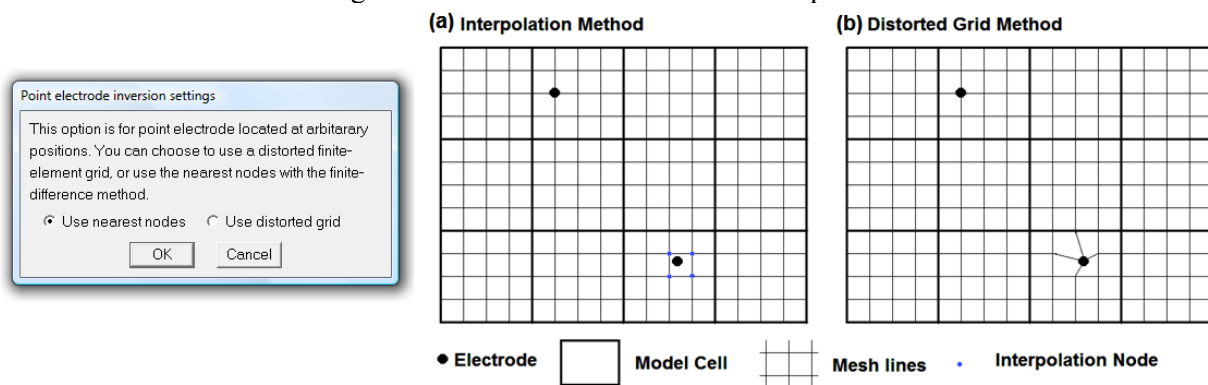
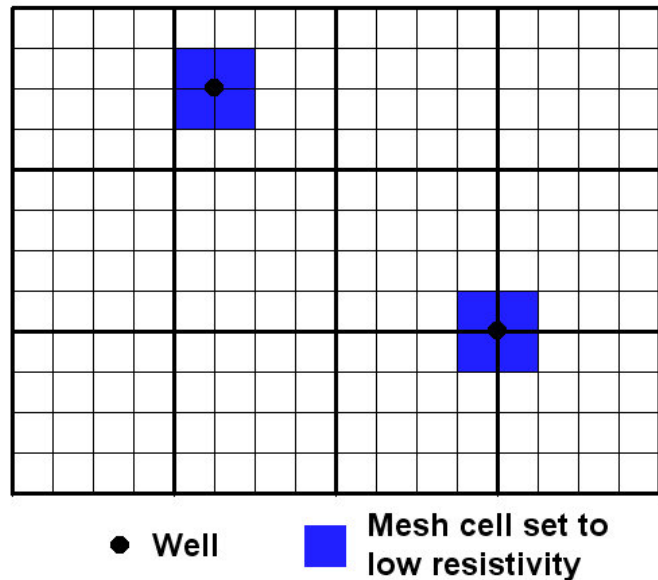
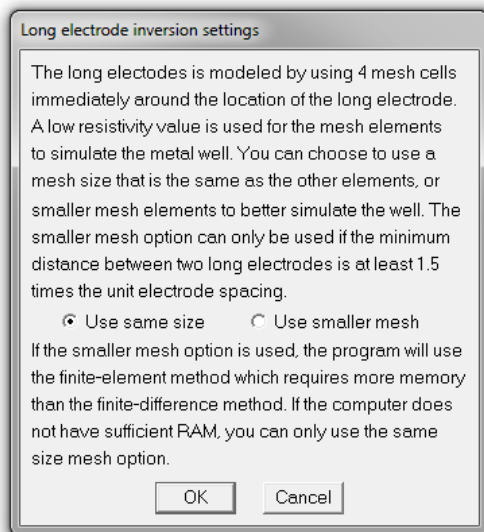


Figure 16. Methods for arbitrary electrodes.

In the ‘Use nearest nodes’ option (Figure 16), the program calculates the potential at the electrode by interpolating the potentials at the four nearest nodes in the mesh (and similarly replace a single current source node by four equivalent current sources). One advantage of this option for data sets without topography (with a rectangular model grid, i.e. not with the trapezoidal grid arrangement) is that the finite-difference method that requires less computer memory and time than the finite-element method can be used. The ‘Use distorted grid’ option moves the nearest node to the location of the electrode using a distorted finite-element mesh. The advantage of this option is that it gives more accurate results for arrays such as the dipole-dipole that measures small potential differences between electrodes that are close together. It requires the use of the finite-element method that requires more computer memory and longer calculation times compared to the finite-difference method.

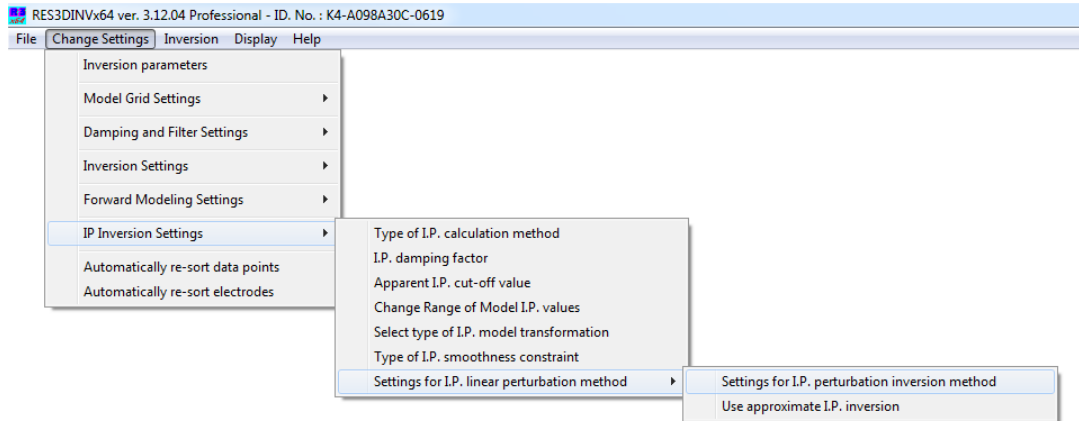
9.5.3 Long electrode inversion settings

The program uses mesh cells with a low resistivity to model the effect of long electrodes such as a metal well. This gives more realistic results when the electrode passes through a non-homogeneous medium. By default, the program uses mesh cells of equal size. You can also select to use smaller mesh cells around the position of the long electrode to better simulate the effect of the metal well. This uses a distorted finite element mesh around the position of the well.



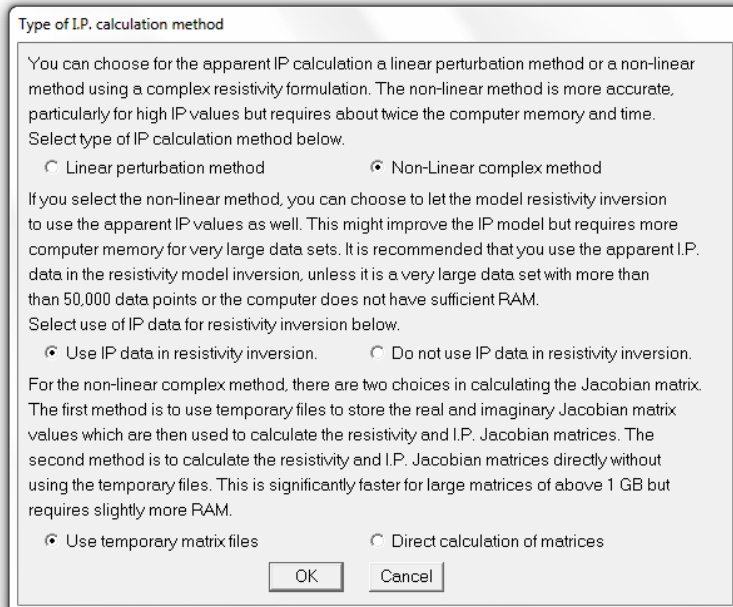
9.6 I.P. inversion settings

This covers a number of settings for the inversion of I.P. data as shown below in the following menu list.



9.6.1 Type of I.P. calculation method

Selecting this option will display the following dialog box. The first option is to select the type of method to calculate the apparent I.P. values.



There are generally two approaches to calculate I.P. effects: the perturbation method and the complex resistivity method. The first approach considers the I.P. model as a small perturbation of the base resistivity model (Oldenburg and Li 1994). The effect of the chargeability m is to decrease the effective conductivity to $\sigma_{IP} = (1 - m) \sigma_{DC}$. The apparent IP is calculated by two forward models using the original (σ_{DC}) and perturbed (σ_{IP}) conductivities, and the apparent chargeability is calculated using the following equation.

$$m_a = [\phi(\sigma_{IP}) - \phi(\sigma_{DC})] / \phi(\sigma_{DC})$$

The apparent chargeability is calculated from the difference of two DC potentials. This tends to magnify numerical errors in the finite-difference or finite-element methods used to calculate the DC potentials. While this is not a serious problem in most traditional arrays, the increasing popularity of the offset pole-dipole and dipole-dipole arrays (White *et al.* 2001) can produce array configurations with extreme geometrical factors and consequently very low potentials. Errors in the calculated apparent I.P. values will consequently affect the I.P. inversion model obtained.

The second approach for I.P. model calculation is to treat the conductivity as a complex quantity with real and imaginary components (Kenma *et al.* 2000). The complex conductivity is given by

$$\sigma = \sigma_{DC} - i m \sigma_{DC}$$

The DC conductivity σ_{DC} forms real part, while $m \sigma_{DC}$ forms the imaginary part. A complex potential is then calculated for this complex model.

$$\phi = \phi_r + i \phi_i$$

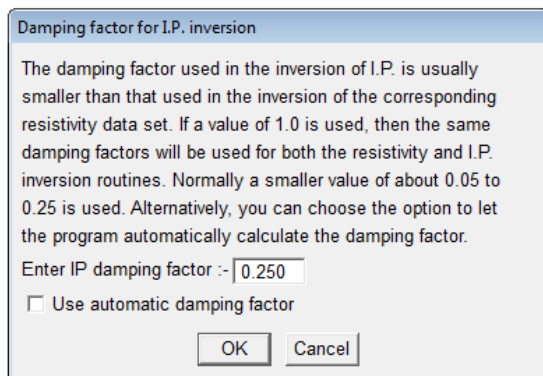
The complex potential has two components, ϕ_r and ϕ_i . As the real (resistivity) and complex (I.P.) potentials are calculated simultaneously, this resolves the roundoff problem in the perturbation method. The main disadvantage of the complex resistivity method is that it requires twice as much computer memory and time as perturbation method. The complex resistivity option is not available for data in the normal borehole format (Table 20 and Table 21), but it can be used if the subsurface electrodes are defined as arbitrary point electrodes (Table 22) below the surface.

If the complex resistivity option is selected, a two-step inversion process is used for each iteration. In the first step, the resistivity model is first calculated. The second option in the dialog box allows the user to select whether the I.P. data is used in creating the resistivity model. This ensures that the resistivity model is also optimal for the I.P. data. However, the computer memory required is larger. If there is insufficient memory, the option not to use the I.P. data in the resistivity inversion step can be selected that reduces the computer memory required.

The third option is concerning the calculation of the complex Jacobian matrix. By default, the Jacobian values for the complex potentials are stored in temporary disk files, and later converted to the apparent resistivity and I.P. Jacobian values. You can select the option to avoid the use of the temporary disk files. This reduces the computer time but at the expense of requiring more computer memory.

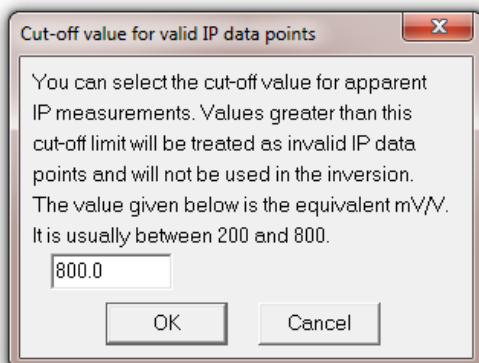
9.6.2 I.P. damping factor

The damping factor used in the I.P. inversion is usually smaller than that used in the inversion of the corresponding resistivity data set. If a value of 1.0 is used, then the same damping factors will be used for both the resistivity and I.P. inversion routines. Normally a smaller value of about 0.10 to 0.25 is used. Alternatively, you can choose the option to let the program automatically calculate the damping factor.



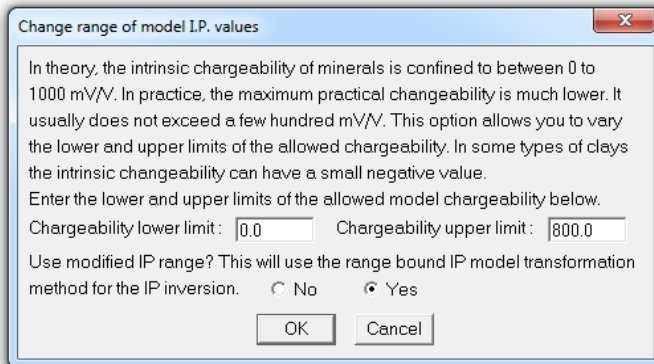
9.6.3 Apparent I.P. cut-off value

Many modern resistivity meter systems used in engineering and environmental surveys now have I.P. measurement capability as well. However, the I.P. data from most multi-electrode systems is probably of limited use for electrode spacings of more than a few meters. Most systems that use a battery power source that cannot deliver enough current (usually less than 1 ampere) for reliable I.P. signals, so the I.P. data is often extremely noisy. Although in theory the magnitude of measured apparent I.P. values can range up to 1000 mV/V, in practice natural I.P. effects produce much smaller values of usually less than 100 mV/V. This option sets an upper limit on acceptable apparent I.P. values above which the values are not used by the program to calculate the I.P. inversion model.



9.6.4 Change range of model I.P. values

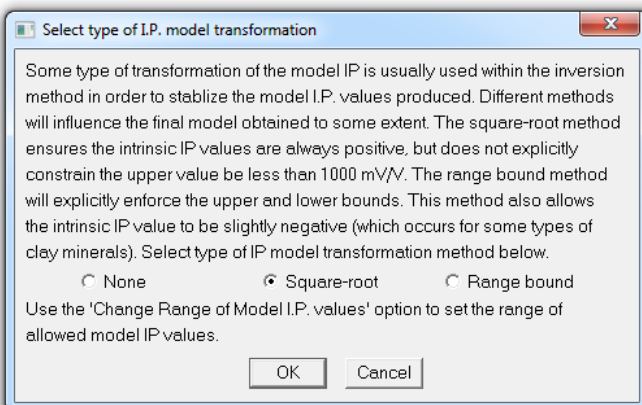
This sets the limits of the model I.P. values that the inversion routine can use. This can be used to limit the highest I.P. value in the inversion model, particularly if the I.P. data is noisy.



While negative apparent I.P. values are frequently observed (Nabighian and Elliot 1976), it is not commonly realized that the intrinsic I.P. can also have a negative value (Brandes and Acworth 2003). This program allows the model to have negative model I.P. values.

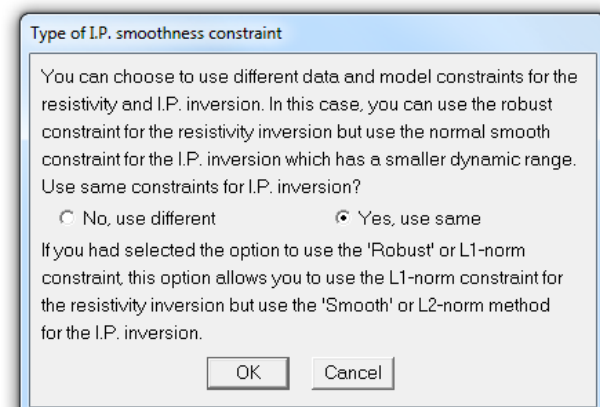
9.6.5 Select type of I.P. model transformation

This option will bring up the following dialog box. The 'Square-root' or 'Range bound' is normally used to ensure the model I.P. values produced by the inversion program do not exceed the allowed limits.



9.6.6 Type of I.P. smoothness constraint

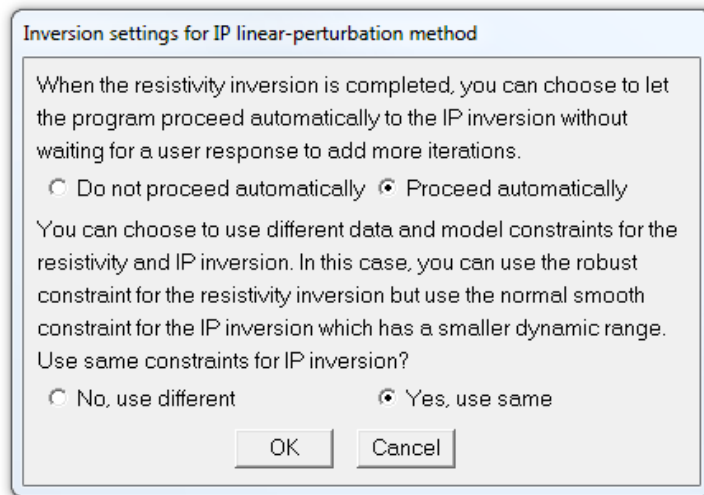
Normally the program uses the same smoothness constraint for the I.P. inversion as that used for the resistivity inversion. This option allows you to use a different smoothness constraint for the I.P. inversion. If the 'Robust' (L1-norm) method is used for the resistivity inversion, this option allows you to use the 'Smooth' (L2-norm) method for the I.P. inversion. Selecting the L2-norm constraint for the I.P. model might be useful for some cases as it has a much smaller range compared to the resistivity values. In theory, the I.P. model and (magnitude of the) data are limited to values of 0 to 1000 mV/V.



9.6.7 Settings for I.P. linear perturbation method

This covers two variations of the 'perturbation method'.

Type of I.P. inversion method: Selecting this menu option will display the following dialog box.

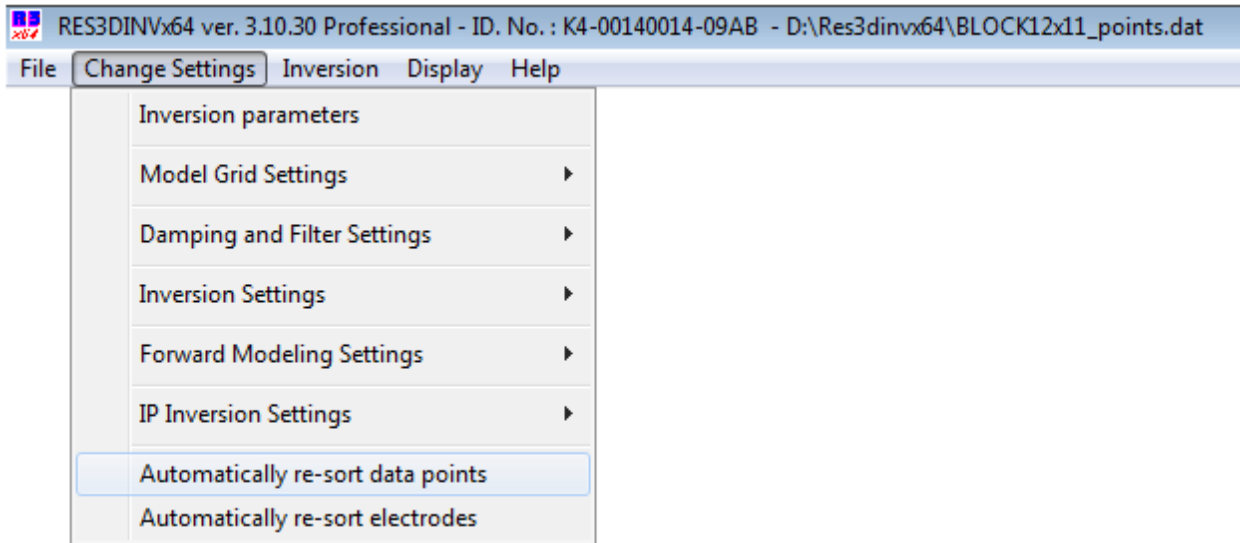


In the approach by Oldenburg and Li (1994), the resistivity model obtained at the last iteration of the inversion of the resistivity data set is used as the base resistivity model in the inversion of the I.P. data set. At the end of the resistivity inversion, the program will stop and show a dialog box to allow the user to add more iterations. You can avoid this by selecting the option for the program to proceed automatically. This is useful for the inversion of a large data set that might take several hours. The above dialog box also allows the user the use different constraints (L1 or L2 norm) for the resistivity and I.P. models).

Use approximate I.P. inversion: This option is only relevant if the 'perturbation method' is used for the I.P. model calculations. In some cases, particularly when negative apparent resistivities are encountered, the I.P. inversion routine in the perturbation method might not converge properly. This option is used to overcome such problems by using the Jacobian matrix for a homogenous resistivity model, instead of the model obtained from the resistivity inversion phase.

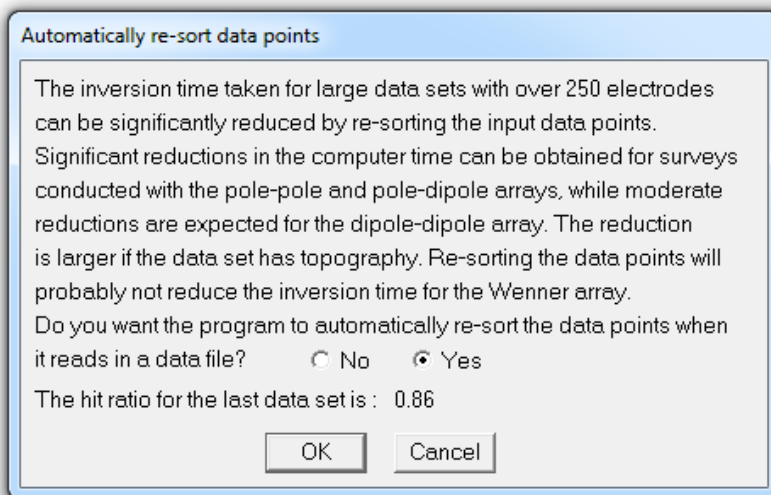
9.7 Miscellaneous options

This covers a few other options that do not affect the final inversion result, but can greatly reduce the computer time required by making optimum use of the computer resources and numerical algorithms.



9.7.1 Automatically re-sort data points

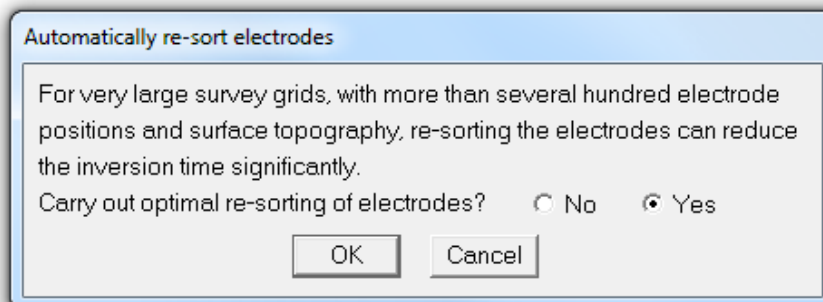
This option will bring up the following dialog box.



It basically rearranges the listing of the data points. It does not change the values, but can take advantage of parallelism in the numerical algorithms used to reduce the calculation time.

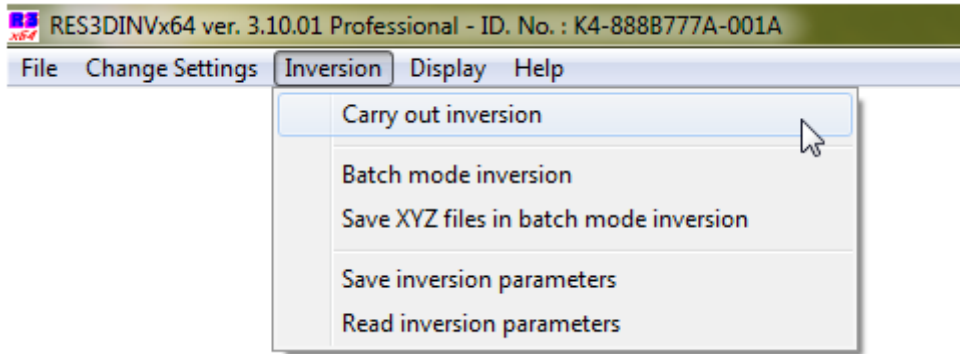
9.7.2 Automatically re-sort electrodes

This option will rearrange the list of electrodes used internally within the program so as to reduce the calculation time. It is completely transparent to the user.



10 Inversion menu options

The list of options under the 'Inversion' menu is shown below.



10.1 Carry out inversion

Select this option after you have read in the data file, and selected the proper inversion settings. The program will carry out the inversion of the data set on selecting this option.

10.2 Batch mode inversion

This option is intended for users to automatically invert a large number of data sets at one time. In the batch mode option, a script file, for example RESIS3D.BTH, is used to inform the program of the data files which need to be processed and the various inversion options used. On selecting the batch mode inversion option, you will be prompted for the batch mode script file. The batch mode script file makes use of the inversion parameters files (IVP) that are created by the RES3DINV program itself. The file RESIS3D.BTH is an example, with the following format.

Table 27. Example batch file format.

<i>RESIS3D.BTH file</i>	<i>Comments</i>
2	<i>Number of files to invert</i>
INVERSION PARAMETERS FILES USED	<i>Header to indicate batch mode</i>
DATA FILE 1	<i>Header for first file</i>
C:\Res3dinv\BLK10PDP.DAT	<i>Data file to invert</i>
C:\Res3dinv\BLK10PDP.INV	<i>Output file with inversion results</i>
C:\Res3dinv\RES3DINV_L1.IVP	<i>File containing the inversion settings</i>
DATA FILE 2	<i>Header for second file</i>
C:\Res3dinv\roots7.DAT	<i>Data file to invert</i>
C:\Res3dinv\roots7.INV	<i>Output file with inversion results</i>
C:\Res3dinv\RES3DINV_L2.IVP	<i>File with different inversion settings</i>
End file	<i>Indicates end of batch file</i>

Since the IVP files are created by the RES3DINV program, it is not necessary for the user to deal with the details about the file format. The creation of the IVP files is described in a following section.

10.3 Save XYZ files in batch mode inversion

When this option is enabled, the program automatically creates an XYZ file that contains the resistivity and location of the model blocks after the inversion of each data file.

10.4 Save inversion parameters

This option will save the current inversion settings used by the program into a text file with an IVP extension.

10.5 Read inversion parameters

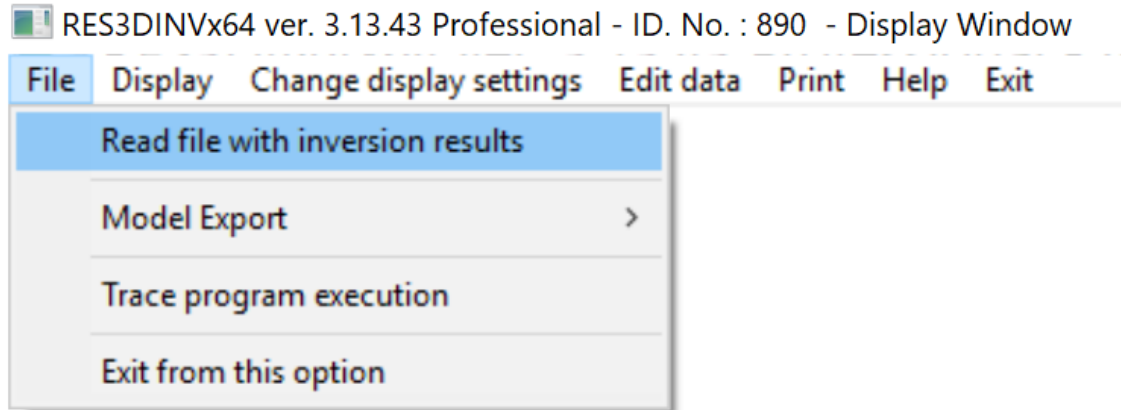
Using this option, the user can read an IVP file containing the inversion parameters which will then become the inversion settings the program will use for inverting a data file.

11 Displaying and exporting inversion model results

Selecting the 'Display' menu option will create a new window with a number of options to read the INV files produced from the inversion of the data sets, and to display and export the information to other programs.

11.1 Display - File menu options

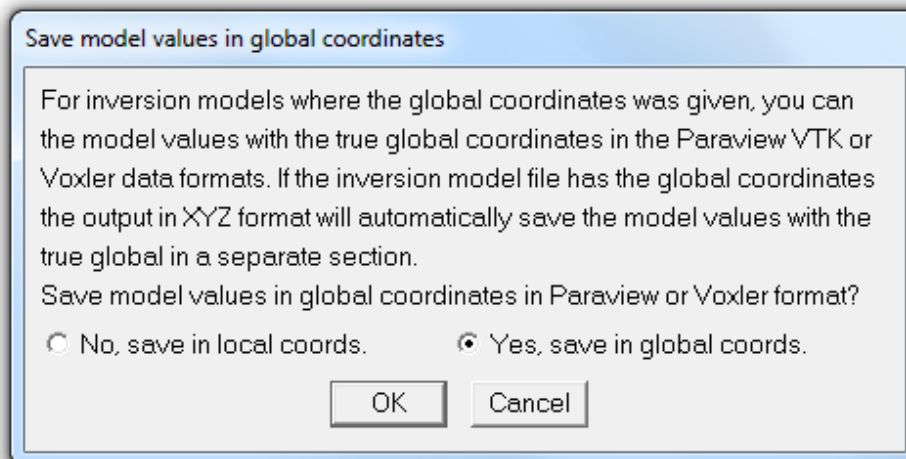
The list of operations available is shown below.



Read file with inversion results: You can read in the output data file produced by the inversion subroutine with an INV extension. This is normally the first operation to be conducted.

Model Export : This is a list of sub-options where the model values stored in the INV file can be exported to a variety of 3-D display and contouring software. XYZ is a generic text based format used by the Geosoft Inc. software. Voxler is a 3-D contouring program (Appendix E) by Golden Software which is similar to the Surfer program by the same company that is widely used for 2-D displays. VTK is a format that can read by the free 3-D graphics display program Paraview (Appendix D) widely used in academic circles and government agencies.

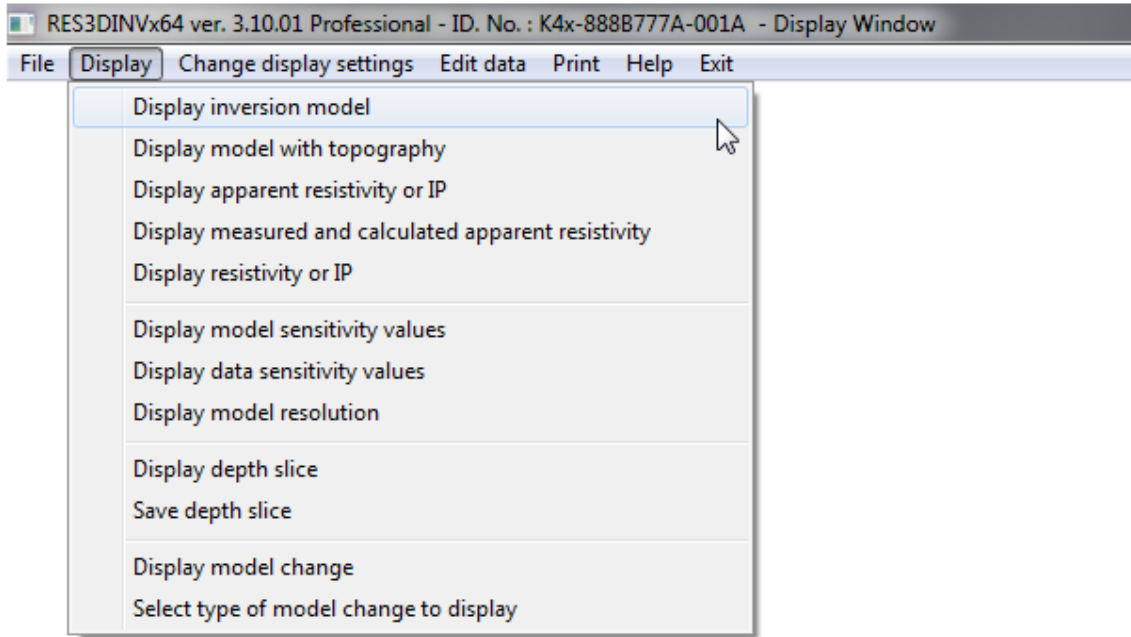
Save model with global coordinates (Model Export) : This option is only relevant for inversion models for data with arbitrary point electrodes where the model grid was rotated to reduce the grid size (section 9.2). The true global coordinates are also saved in such file. On selecting this option, the following dialog box is shown.



For output models data in the XYZ format, the coordinates of the model values in the true coordinates are automatically saved. Selecting 'Yes' to this option will save the model values with the true global coordinates if the Paraview VTK or Voxler XYZC output option are selected. Paraview (Appendix D) uses the coordinates of the hexahedral blocks that make up the model, so it shows the model outline more accurately. Voxler (Appendix E) uses a rectangular grid system, so it will extrapolate the corners of the grid if the model axis is not in the North-South or East-West direction.

11.2 Display - Display menu options

This is a set of options related to the display of models as sections on the screen.



Display inversion model: Select this option to plot the model. You can plot the model in the form of horizontal or vertical slices through the earth.

Display model with topography: If the data file contains topographical information, this option will display the model in the form of vertical slices with the topography.

Display apparent resistivity or IP: This option allows you to display the apparent resistivity (or I.P.) pseudosections for measurements made in the x- or y-directions. The pseudosections can only be displayed if the survey was conducted using a conventional array such as the pole-pole, dipole-dipole, Wenner or Wenner-Schlumberger.

Display resistivity or IP: This allows the user to choose between displaying the resistivity or I.P. model.

Display model sensitivity values: The INV file containing the inversion model also contains a listing of the integrated sensitivity value which is defined by

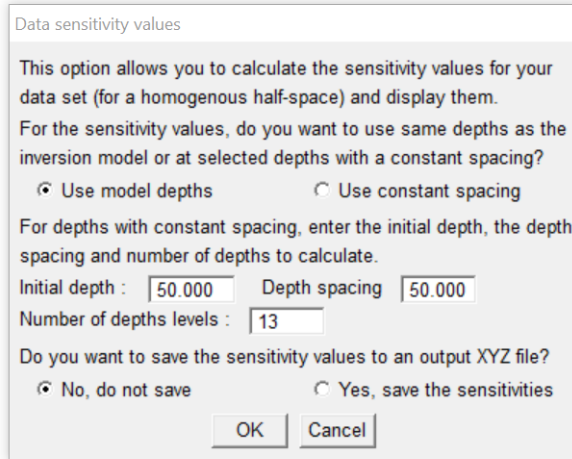
$$s_j = \sum_{i=1}^{i=m} |J_{ij}|$$

s_j is the integrated sensitivity value for the j th model cell for a data set with m data points, and J_{ij} is the Jacobian matrix value for the i th data point associated with the j th model cell. Since the size of the model blocks at the sides and bottom are larger than those in the interior, the sensitivity values for these edge blocks can be much larger unless the option to reduce the effect of the side blocks was selected (section 9.2). The RES3DINVx64 program also calculates the sensitivity per unit volume value S_j where the integrated sensitivity value (s_j) is divided by the volume of the model block (V_j).

$$S_j = \frac{1}{V_j} \sum_{i=1}^{i=m} |J_{ij}|$$

This removes the effect of the model block size. The sensitivity value is a crude measure of the information content for a model block as it does not take into account redundancy in the data. A better measure of the information content is the model resolution value (Loke 2016).

Display data sensitivity values: The previous option uses the sensitivity values integrated over the model block. This option basically uses the point sensitivity values for a homogeneous half space. The user has an option to calculate the sensitivity values at depths different from that used in the inversion model. The dialog box for this option is shown below.



Data sensitivity values

This option allows you to calculate the sensitivity values for your data set (for a homogenous half-space) and display them.

For the sensitivity values, do you want to use same depths as the inversion model or at selected depths with a constant spacing?

☒ Use model depths ☐ Use constant spacing

For depths with constant spacing, enter the initial depth, the depth spacing and number of depths to calculate.

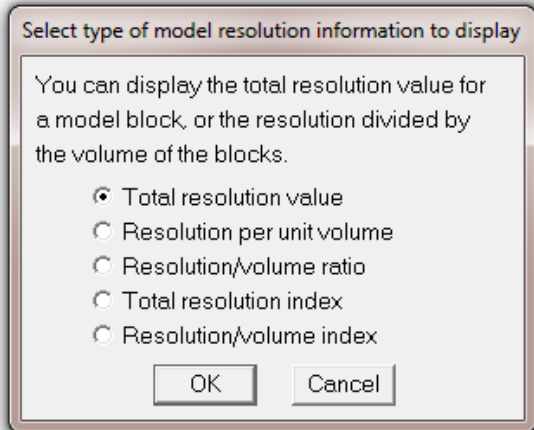
Initial depth : Depth spacing

Number of depths levels :

Do you want to save the sensitivity values to an output XYZ file?

☒ No, do not save ☐ Yes, save the sensitivities

Display model resolution : If the option to calculate the model resolution values was selected before the inversion of a data set (section 9.4), the resolution values will be saved in the inversion file. This option displays the saved model resolution values in the form of model sections. You can either display the model resolution values, or the model resolution normalized by the volume of the model block.



Select type of model resolution information to display

You can display the total resolution value for a model block, or the resolution divided by the volume of the blocks.

☒ Total resolution value

☐ Resolution per unit volume

☐ Resolution/volume ratio

☐ Total resolution index

☐ Resolution/volume index

The resolution matrix is calculated using the equation

$$\mathbf{R} = (\mathbf{J}^T \mathbf{J} + \lambda \mathbf{F})^{-1} \mathbf{J}^T \mathbf{J}$$

\mathbf{R} is the resolution matrix, λ is the damping factor and \mathbf{F} contains the roughness filter matrix terms. \mathbf{J} is the Jacobian (sensitivity) matrix. The model resolution output $r(i)$ (resolution value of i th model block) is taken from the diagonal values $R(i,i)$ of the resolution matrix \mathbf{R} . The sensitivity value depends on the size of the model cells, so in turn this affects the resolution values. Other things being equal, a model block with a larger volume will have a larger resolution value by virtue of its size. The thickness of the model layers increase with depth, and the blocks at the sides extend laterally to the edges of the finite-element/finite-difference mesh. Thus, the blocks at the sides have a much larger volume than neighboring blocks in the interior of the model. To reduce variations in the resolution values due to the size of the blocks, first the volume $v(i)$ of each block is calculated. The normalized resolution values, $r_n(i)$, is calculated using the following equation.

$$r_n(i) = r(i) \cdot \frac{v_{\min}}{v(i)}$$

Note the minimum block volume v_{\min} is used in the equation, so for blocks with the smallest size located in the topmost layer the value of $r_n(i)$ should be the same as $r(i)$. The 'Resolution/volume ratio' option displays the values calculated using the following equation.

$$r_r(i) = r_n(i) \cdot \frac{r_{\max}}{r_{n_max}}$$

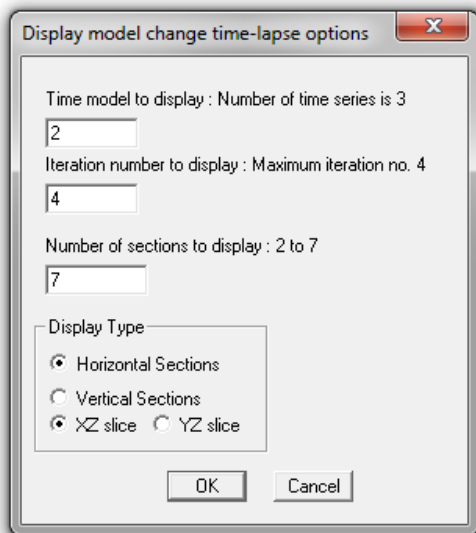
r_{\max} is the maximum value of $r(i)$, while r_{n_max} is the maximum value of $r_n(i)$. Some authors recommend using a value of 0.05 (i.e. 5%) as the cutoff value to judge whether a region has significant resolution. Using a value of 0.05 as the cutoff point for the model resolution values might be arbitrary as it does not take into account the model discretization used. If a finer model discretization (with more model cells) is used, we would expect on the average the model resolution for a cell at the same location will be reduced since the cell size is smaller. Theoretically the sum of the elements in a column of the model resolution matrix is equals to 1.0. The average value of the array elements in the column would then be equals to $1.0/m$, where m is the number of model cells. A more useful measure to judge whether a model cell is resolved is the ratio the cell resolution value (i.e. the diagonal element of the resolution matrix) to this average value. The ‘Total resolution index’ and ‘Resolution/volume index’ values are basically the respective resolution values divided by this average value. It is basically

$$r_n(i) \rightarrow r_n(i) \cdot m$$

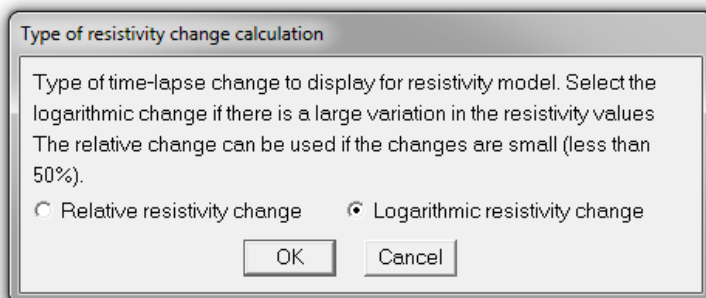
A value of 10 to 20 for the resolution index is probably a reasonable cutoff value.

Display depth slice: This displays the model resistivity (and I.P. if present) for a selected depth. If there is no topography, it is basically the same as that for one of the model layers. If there is topography, this displays the model values at a constant depth which might cut through several model layers. The model values can also be saved into a XYZ text file.

Display model change: This option is only used if the file with the inversion results contains time-lapse data. The user can select the change in resistivity between a later time series model and the first time series model using the following dialog box.

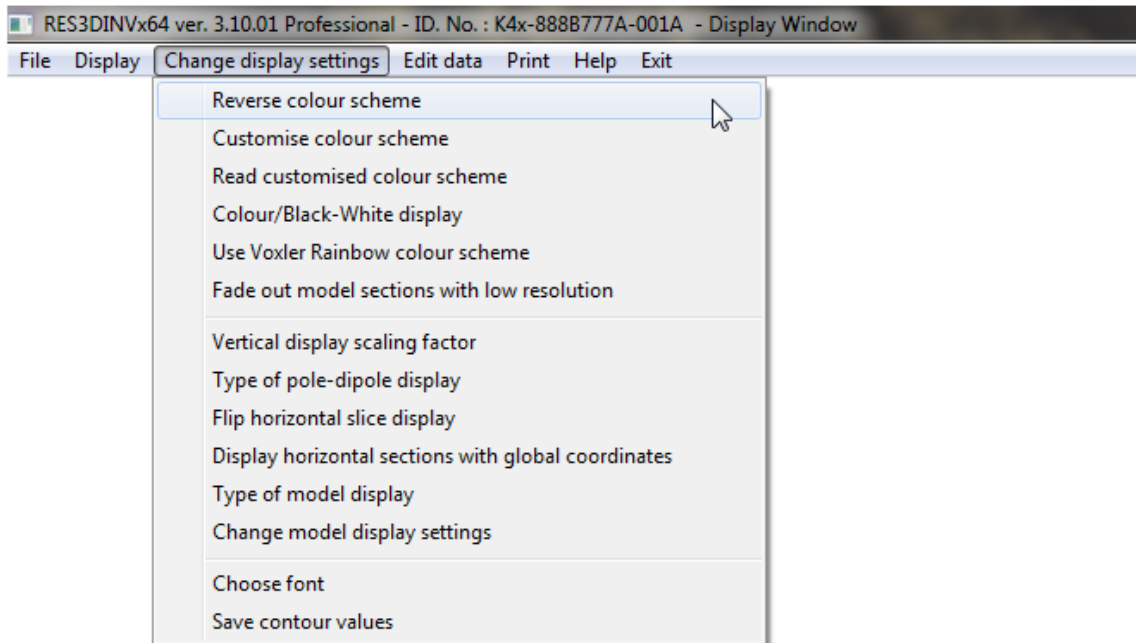


Select type of model change to display: This option selects the formula used to calculate the percentage change in the model resistivity between two time series models. Normally the change in the logarithms of model resistivity is used. However, the user can select the relative change (the change in the resistivity divided by the resistivity of the first time series model).



11.3 Display - Change display settings

This is a group of options to modify the settings for the model slices as displayed by the previous options.

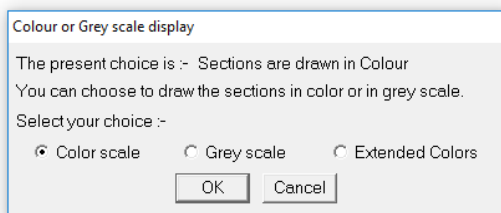


Reverse colour scheme: Normally the program uses a colour scheme where blue is used for the low resistivity and red for the high resistivity values. This option allows the user to reverse the colour scheme so that blue is used for the high resistivity values and red for the low resistivity values.

Customise colour scheme: This enables the user to change the colours used for the sections.

Read customised colour scheme: You can change the colour scheme to a set of customised colours that was earlier saved in a disk file. In some cases when running this program in the background, the colour scheme might change to the palette used by the foreground program. You can use this option to restore the colour scheme used by this program.

Colour/Black-White display: By default, the program will display the pseudosections and model sections in color. This option allows you to display the sections in black and white (a gray scale) where different shades of gray ranging from pure white to pure black are used.



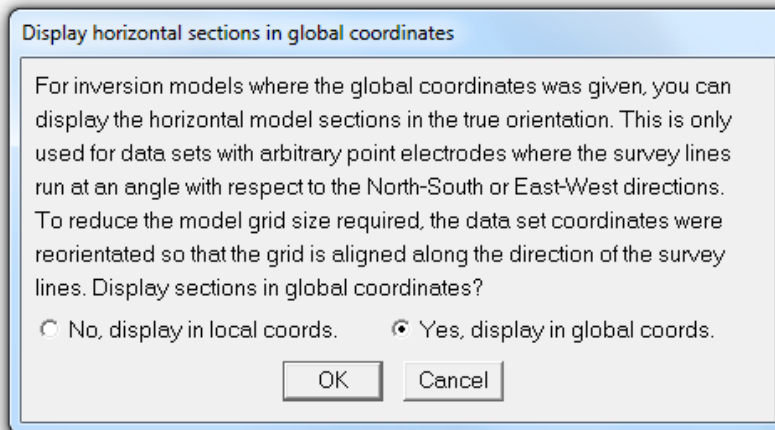
The 'Color scale' and 'Grey scale' options use 17 different colors, such as in Figure 17. The 'Extended Colors' option uses twice as many colors to display finer variations.

Vertical display scaling factor: This option allows you to specify the ratio of the vertical scale to the horizontal scale, i.e. the vertical exaggeration factor, in the display. Convenient values to use are 2.0, 1.5 and 1.0.

Type of pole-dipole display: This option is only relevant for pole-dipole data sets with measurements with the "forward" and "reverse" pole-dipole arrays (see Appendix A). Here you can choose to display the apparent resistivity values measured with the array in the "forward" or "reverse" configuration.

Flip horizontal slice display: This option allows the user to locate the minimum (x,y) location at the bottom-left or top-left corner of the display for model plotted as horizontal slices.

Display sections with global coordinates : This option is only relevant for inversion models for data with arbitrary point electrodes where the model grid was rotated to reduce the grid size (section 9.2). On selecting this option, the following dialog box will be shown.



Normally the horizontal model sections will be displayed using the local coordinates (Figure 17a). If 'Yes' is selected, the sections will be shown with the true global coordinates (Figure 17b). In this example, the model grid is inclined about 10 degrees from the East-West direction.

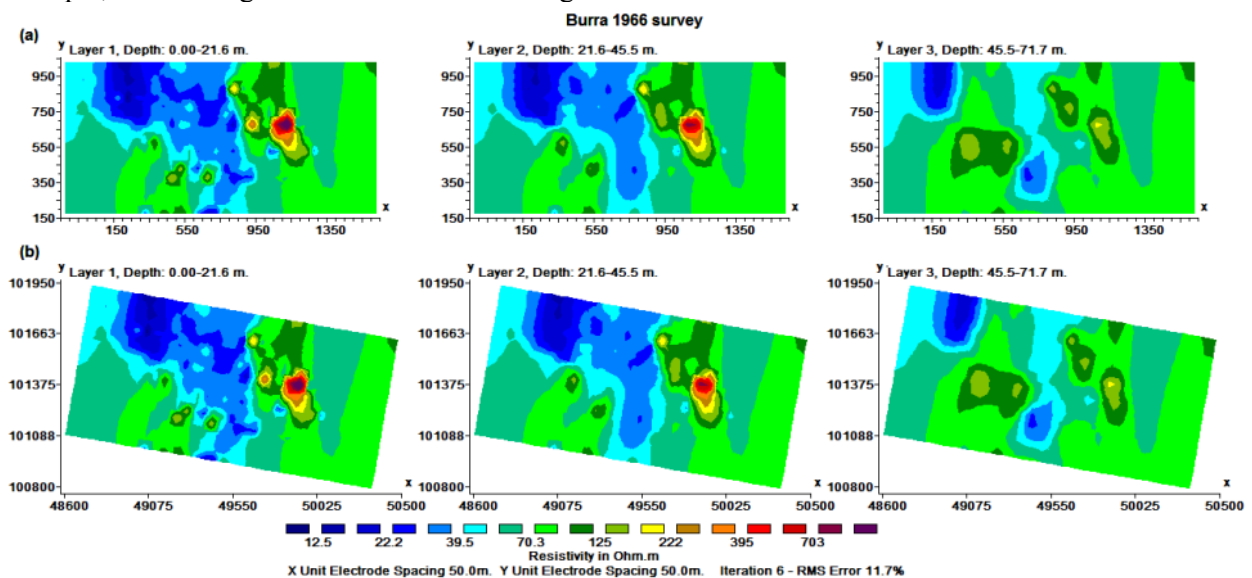
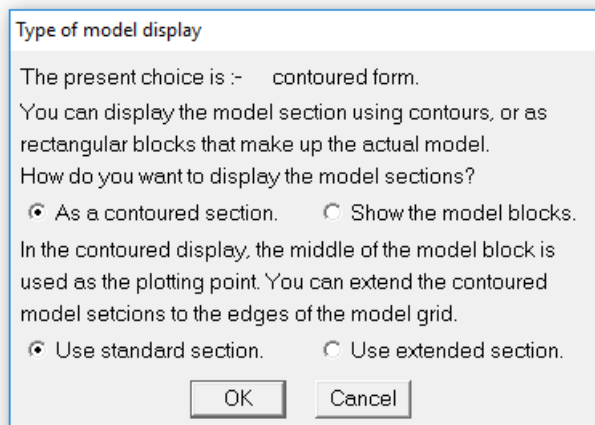
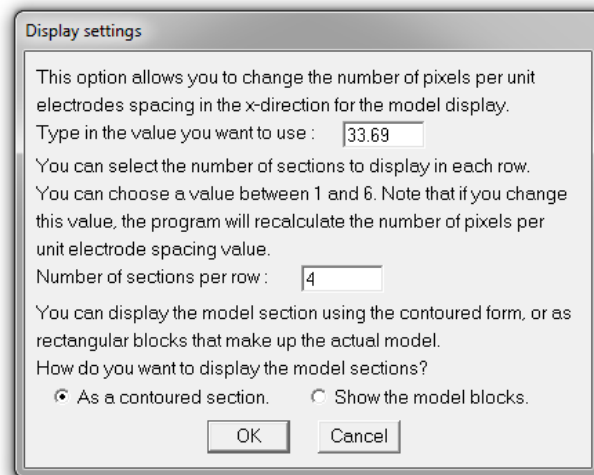


Figure 17. Example of horizontal model sections displayed using (a) local coordinates, and (b) true global coordinates.

Type of model display: This is used to plot the model sections in contour form or in block form. When the model is shown in contoured form, the center of the model cells as used as the plotting points. This gives a slight gap at the top of the model. The 'Use extended section' fill up the gap by extending the contoured section.



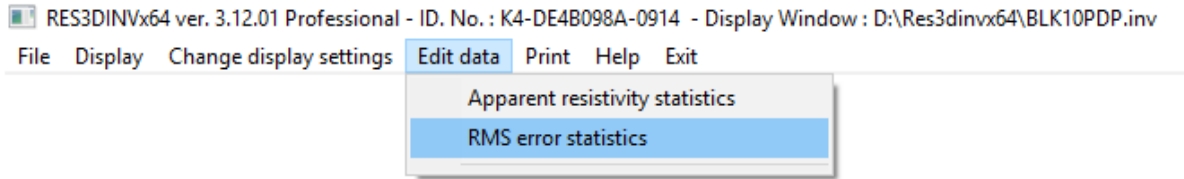
Change model display settings: This is used to set the number of sections displayed across the screen in a horizontal row, as well as to adjust the scale used. On selecting this option, the following dialog box will be shown.



The top option adjusts the scale used in plotting the sections on the screen. The second option sets the number of sections displayed along each row. The maximum number allowed is 6.

11.4 Display - Edit data menu

This has a few options to remove very noisy data points. The following list of options is available under this menu item.



Large 3D surveys can involve many thousands of data points. In the most general case, the array for a particular measurement can be orientated in any direction. To obtain a good inversion model, the “bad” data points must be removed from the data set. One possible way of removing the “bad” data points from the data set is by statistical techniques. In the program, two methods are used.

Apparent resistivity statistics: This sub-option just displays the distribution of the apparent resistivity values as a bar chart. It is meant to be first used to detect data points that obviously have wrong values. This could be caused by hardware problems, such as very poor ground contact at the electrodes or a break in one of the wires. This data points will probably have apparent resistivity values that are several orders of magnitude larger or smaller than the other data points. These “bad” data points can be removed by moving the left blue or right green cursor lines.

RMS error statistics: This sub-option just displays the distribution of the percentage difference between the logarithms of the observed and calculated apparent resistivity values. It can only be used after carrying out a trial inversion of the data set. If I.P. data is present, the user can choose to use the resistivity or I.P. data for the histogram plot. On selecting this sub-option, the distribution of the RMS errors will be displayed in the form of a bar chart (Figure 18). It is expected the “bad” data points will have relatively large “errors”, for eg. above 100 percent. To remove the points with large errors, just move the green cursor line to set the cut-off error limit to remove the “bad” data points. An example of the plot is shown below that uses a cut-off value of 50%. The points removed are marked in red in the correlation plot on the right.

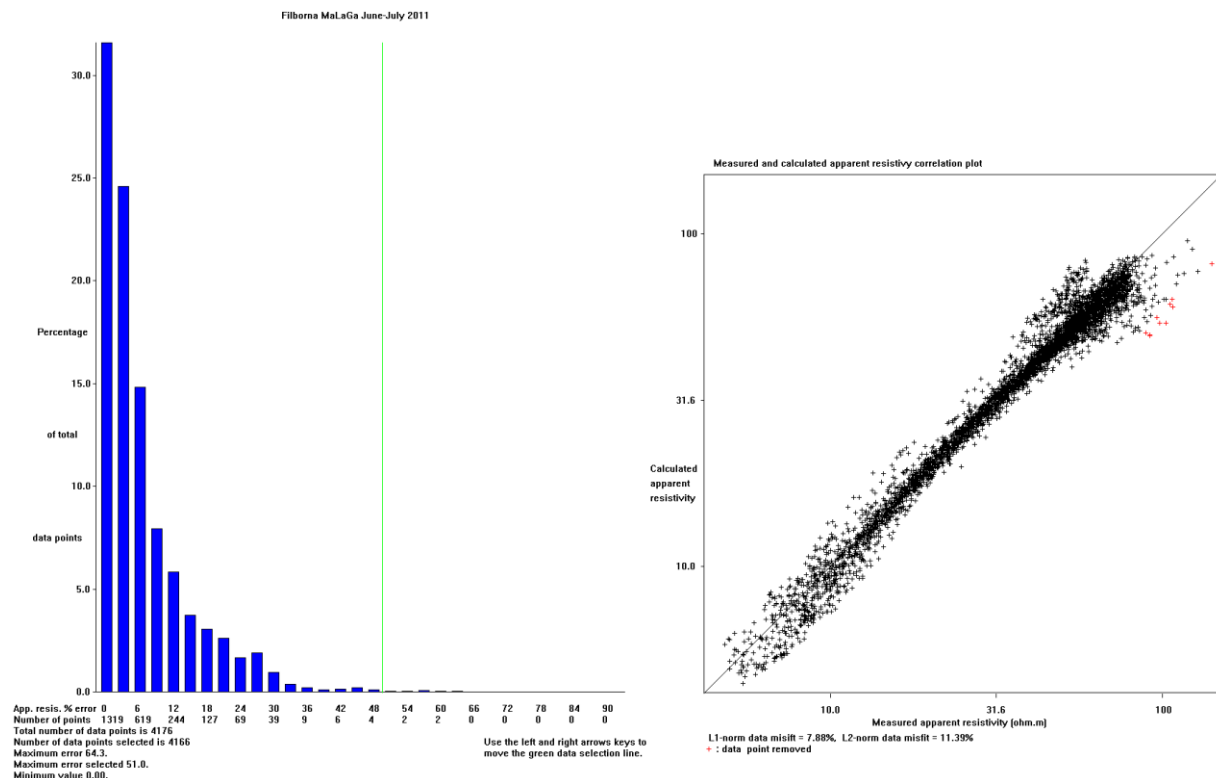


Figure 18. Example of data misfit plot.

If the input data has the estimated error values for each data point (Appendix H), such as from reciprocal measurements, the program will also calculate a normalized data misfit. For the L1-norm data misfit, the normalized data misfit (L_{1N}) is given by

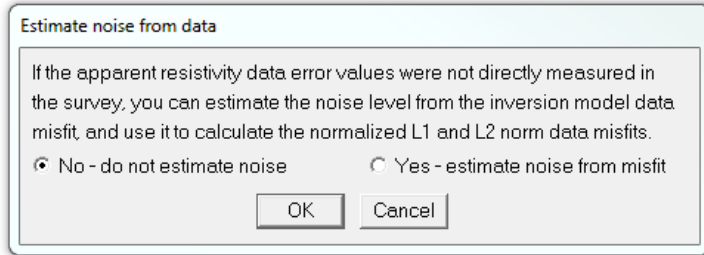
$$L_{1N} = \frac{1}{m} \sum_{j=1}^m \left| \frac{\rho_{cj} - \rho_{mj}}{\Delta\rho_{mj} + \varepsilon} \right|$$

where ρ_c and ρ_m are the calculated and measured apparent resistivity values and $\Delta\rho_m$ is the estimated error. In some cases, the estimated error might be zero if the normal and reciprocal measurements give the same apparent resistivity value due to the limited accuracy of the measuring instrument. To avoid an infinite value for the normalized misfit, we add a small positive value ε to the denominator. The L2-norm data misfit is calculated in a similar way using the following equation.

$$L_{2N} = \sqrt{\frac{1}{m} \sum_{j=1}^m \left(\frac{\rho_{cj} - \rho_{mj}}{\Delta\rho_{mj} + \varepsilon} \right)^2}$$

Ideally the normalized misfits should be about 1.0 if the calculated values fit the data to within the noise level. The example file *21x12_blocks_noise.inv* is an example inversion file with estimated error values.

In most surveys, the data noise values are not measured. If the inversion file does not have the estimated error values, the following dialog box will be displayed.

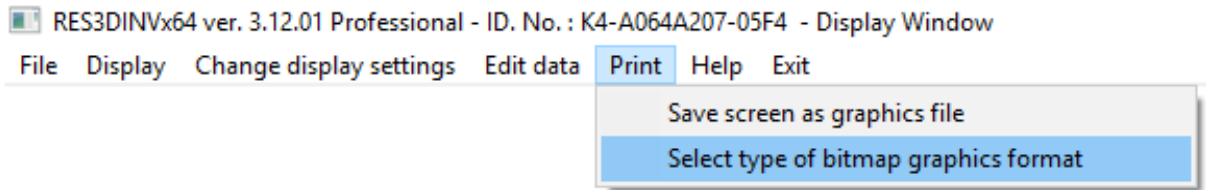


If the 'Yes' option is selected, the program attempts to estimate the noise level for each data point using a 'voltage-dependent' noise model (Zhou and Dahlin, 2003). Note the normalized values are reasonable only if the assumptions of the 'voltage-dependent' and Gaussian noise models are correct.

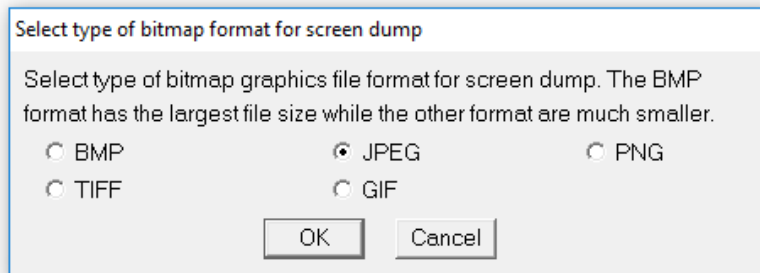
When the user selects the 'Exit' option, the data will be saved in a new data file with data points having a higher data misfit than the cutoff value removed from the data set.

11.5 Display - Print menu

Print - Save screen as graphics file : This option located under the 'Print' menu makes a screen dump of the sections drawn on the screen.



Print – Select type of bitmap graphics format : This option selects the type of bitmap graphics format to use for the screen dump. The options are shown below.



12 Some field examples

Some of the early 3-D surveys were conducted using the pole-pole array with measurements between different pairs of electrodes arranged in a rectangular grid, such as the ESCAN method (Li and Oldenburg 1992) or the cross-diagonal method (Loke and Barker 1996). However, most recent commercial 3-D surveys consists of a number of parallel 2-D lines with possibly a few cross-lines (Chambers *et al.* 2006). 3-D surveys are now widely used for mapping very complex areas for mining (Legault *et al.* 2008), engineering and environmental (Dahlin *et al.* 2002, Rucker *et al.* 2010) studies. In this section, the results from three very different field surveys are shown to illustrate the different type of data sets processed by the program. Many other examples can be found in Loke (2015).

12.1 Landfill survey, Sweden

This survey was conducted over the Ekeboda landfill site in Sweden. The field survey (Johansson *et al.* 2007) data set consists of 10 parallel lines with 61 electrode positions along each line. The unit electrode spacing along each line is 5 meters, while the spacing between the lines is 10 meters. This is a common arrangement in field surveys where the spacing between the lines can be two (or more) times the in-line electrode spacing. However, an inversion model with model cells of 5 meters in both directions is used to reduce banding effects. Furthermore, a higher damping factor for the top layers together with a horizontal roughness filter with diagonal components is used (Loke and Dahlin 2010). The final inversion model (Figure 19) shows a prominent low resistivity region that corresponds to the landfill material with a base at about 22 meters.

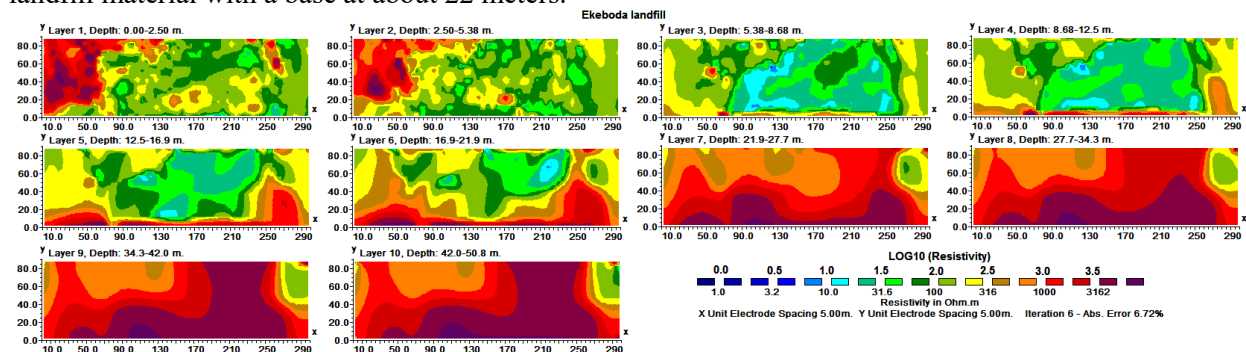


Figure 19. Inversion model for the Ekeboda landfill survey data set.

12.2 Base metal deposit, Australia

This is an interesting example of a 3-D resistivity and IP survey provided by Arctan Services Pty. and Golden Cross Resources, Australia. Copper Hill is the oldest copper mine in NSW, Australia. An earlier survey was conducted in 1966 using mapping, rock chip sampling, an I.P. survey and 7 drill-holes (White *et al.* 2001). Copper porphyry with minor gold and palladium mineralization were found to occur in structurally controlled fractures and quartz veins. However, due to the very complex geology, large differences in ore grades were found in drill-holes that were less than 200 meters apart. To map the ore deposit more accurately, a new 3-D resistivity and I.P. survey using the pole-dipole array was used. The survey covered a large (1.6x1.1 km) area using a series of 1.6 km lines with a spacing of 25 m between adjacent electrodes. Figure 20a shows the arrangement of the transmitter and receiver lines. Currents of up to 7 Amps were used. The entire survey took 10 days giving a total of over 7000 measurements. Further details about the survey layout and procedures used to improve the data quality as well as to reduce the survey time are described in the paper by White *et al.* (2001). The data was inverted with the RES3DINV program that produced a 3-D resistivity and I.P. model for the area. The 3-D I.P. model that shows the location of the mineralized zones more clearly is shown in Figure 20b. The inversion model output from the RES3DINV program was rearranged into a VRML format that could be read by a 3-D visualization program (please contact Arctan Services at www.arctan.com.au for the details) that enables the user to display the model from any direction. The 3D I.P. model shows two en-echelon north-south trends and two approximately east-west trends forming an annular zone of high chargeability. The results from existing drill-holes that had targeted the shallower part of the western zone agree well with the resistivity and I.P. model. A drill-hole, CHRC58, intersected a 217 m zone with 1.7 g/t gold and 0.72% copper coincided well an IP zone of greater than 35mV/V. The lower boundary of the western zone with high chargeability coincides well with assay results from existing drill-holes. The eastern zone with high chargeability and resistivity values do not outcrop on the surface and very little drilling has penetrated it.

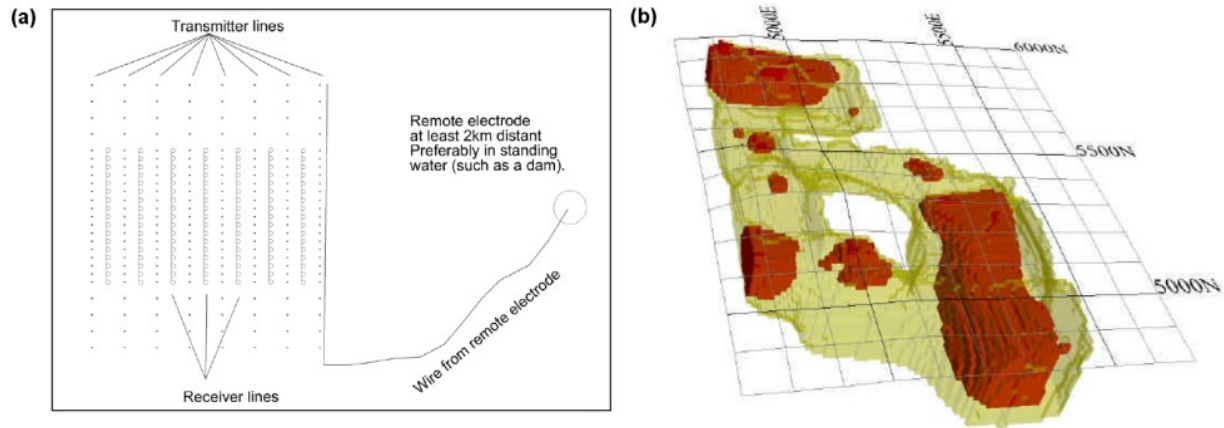


Figure 20. Example of a 3-D survey using the offset pole-dipole array. (a) Electrodes layout used for the 3-D survey of the Copper Hill area. (b) The IP model obtained from the inversion of the Copper Hill survey data set. Yellow areas have chargeability values of greater than 35 mV/V, while red areas have chargeability values of greater than 45 mV/V (White *et al.* 2001).

12.3 Floating electrodes survey, Panama

While the previous two example field surveys were conducted on land, this is an unusual example from an aquatic survey. This survey was conducted along the Panama Canal using a streamer cable pulled behind a boat (Noonan and Rucker 2011). The dipole-dipole array with an electrode spacing of 15 meters and a total cable length of 170 meters was used. This arrangement gave a depth of investigation of up to about 25 meters. The water depth was about 15 to 17 meters. The survey was conducted along several lines running along the axis of the canal. Auxiliary data such as GPS, water bathymetry and resistivity were also measured during the survey. Unlike land surveys, it is not possible to keep the lines straight in a mobile aquatic survey, as shown in Figure 21. Thus conventional 2-D inversion of each individual line did not give sufficiently accurate results. The data from the different 2-D lines were collated into a 3-D data file using the arbitrary electrodes data format. Furthermore, a sharp boundary corresponding to the water bottom at a depth of about 15 to 17 meters was added and the resistivity of the first layer (corresponding to the water column) was set at 67 ohm.m. The inversion model shows significant variations in the sub-bottom materials (the last 3 sections in Figure 22). The lowest resistivity material generally corresponds to moderately soft tuff, intermediate resistivity to moderately hard agglomerate and high resistivity to hard andesite (Noonan and Rucker 2011). The inversion of this data set with 13655 data points and 6006 model cells took about 13 minutes on a PC with an Intel i7 970 hex-core CPU and 24GB RAM.

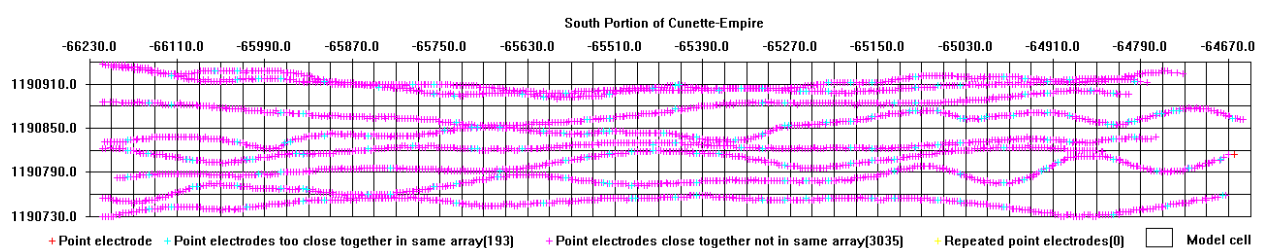


Figure 21. The model grid used for the Panama Canal floating electrodes survey with 20 by 20 meters cells. The location of the electrodes along the surveys lines are shown as colored points.

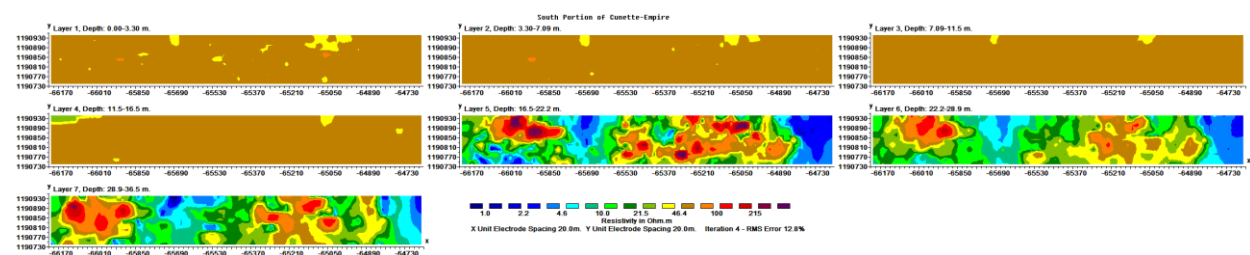


Figure 22. The inversion model for the Panama Canal floating electrodes survey. The first 4 layers correspond to the water column.

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Dr. Torleif Dahlin of Lund University in Sweden kindly provided the Ekeboda and Filborna field examples. A special acknowledgement to Ron Barker of the School of Earth Sciences, University of Birmingham for the 3-D Birmingham field test data set. Rockworks, Slicer/Dicer and Voxler are registered trademarks of Rockware Earth Science Software, Visualogic Inc. and Golden Software. Permission from Arctan Services Pty. and Golden Cross Resources to use the Copper Hill 3-D example is gratefully acknowledged. Dale Rucker of hydroGeophysics, Inc., Tucson, AZ kindly provided the Panama Canal survey example. Dr. Paolo Costantini provided the example with the inclined electrodes layout that provided a good example application for the option to minimize the model grid size. Kim Frankcombe and Phoenix Copper provided the interesting and historic Burra data set.

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Appendix A : Array types in RES3DINV

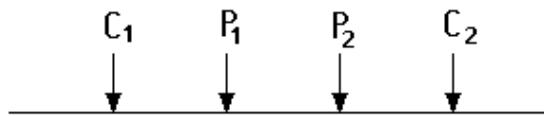
A list of the arrays supported by the RES3DINV program together with their number codes are given below.

Table 28. Arrays types used in RES3DINV.

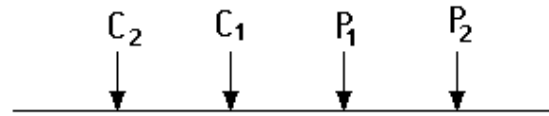
Array name	Number code	Number of electrodes
Wenner (Alpha)	1	4
Pole-Pole	2	2
Inline Dipole-Dipole	3	4
Wenner (Beta)	4	4
Wenner (Gamma)	5	4
Pole-Dipole	6	3
Wenner-Schlumberger	7	4
Equatorial dipole-dipole	8	4
Offset pole-dipole (only used as sub-array number with data in the general array format)	10	3
Non-conventional or general array	11	2 to 4
Cross-borehole survey (apparent resistivity values)	12	2 to 4
Cross-borehole survey (resistance values)	13	2 to 4
Gradient array (only used as sub-array number with data in the general array format)	15	4

A description of the different arrays types is given in the free tutorial notes on electrical imaging (Loke 2016). In general for an array with four electrodes, there are three possible arrangements for the electrodes. The Wenner array has three different variations (Figure 23). The “normal” Wenner array is actually the Wenner alpha array.

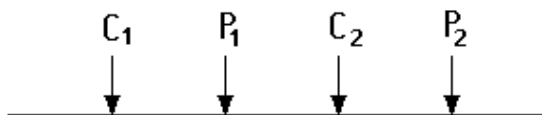
a) . Alpha



b) . Beta



c) . Gamma



**Three possible arrangements
for a four-electrode array**

Figure 23. Arrangement of the electrodes for the Wenner alpha, beta and gamma arrays.

The different variations of the pole-dipole array are shown in Figure 24. If an offset dipole-dipole array is used, the general array data format should be used with a sub-array type of 0. The number of electrodes is normally set at 3 for this array. In this case, it is assumed that the remote C2 electrode is sufficiently far away so that its effect can be neglected, and the geometric factor is calculated using the positions of the C1, P1 and P2 electrodes only (see section 7.1.5).

For data sets where more than one position is used for the remote electrode, and if the remote electrode is close to the survey grid, the best option will be to treat the ‘pole-dipole’ type of array as a conventional array with 4 electrodes. In this case, the position of the C2 electrode should be included in the calculation of the geometric factor. The model grid should be extended using the non-uniform rectangular grid format (section 7.1.2) so that it incorporates the remote electrode. If necessary, the electrodes at arbitrary locations (section 7.1.4) data format can be used if the remote electrode does not fall on a convenient model grid point.

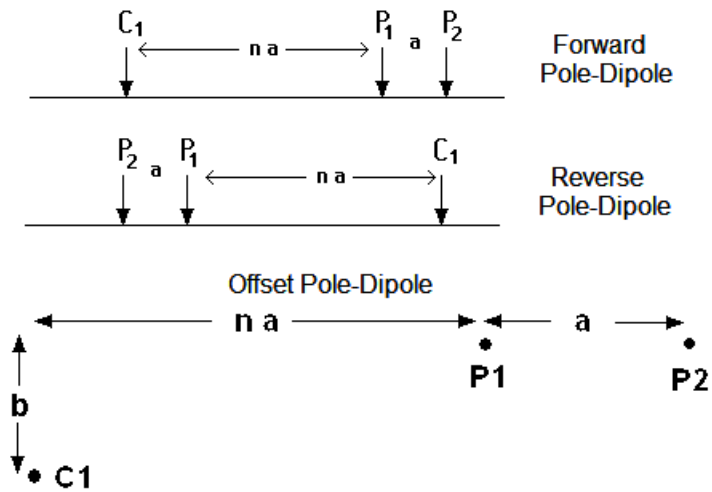


Figure 24. Normal, reverse and offset pole-dipole array arrangements.

The general array with number code 11 is always given with a secondary sub-array number code. If the arrays are actually one of the conventional arrays, the number code for the conventional array is used as the sub-array number (for example if it is a dipole-dipole array the sub-array number is then 3). If it is not one of the conventional arrays, or if it is a mixture of different arrays (such as the dipole-dipole and gradient), the sub-array number is given as 0. An example was shown in Table 5 in section 7.1.1. Another example is in file L5N_Resistivity_Global.dat included in the set of files installed with the Res3dinvx64 program. This data set uses the arbitrary electrodes data format.

Appendix B : Inversion of 2-D lines with off-line electrodes

In a 2-D survey, it is normally assumed all the electrodes lie in a single straight line. The RES2DINV program allows two exceptions to this rule, the equatorial dipole-dipole and the offset pole-dipole arrays with some limitations. For the equatorial dipole-dipole array, the spacing between the C1 and C2 electrodes is the same for all measurements and must be the same as the spacing between the P1 and P2 dipole. It does not handle a case with different spacings between the C1 and C2 (or P1 and P2) dipoles (Figure 25a). For the offset pole-dipole array, the RES2DINV program does not allow the C1 electrode to be at the same x-location as the P1 electrode (Figure 25b).

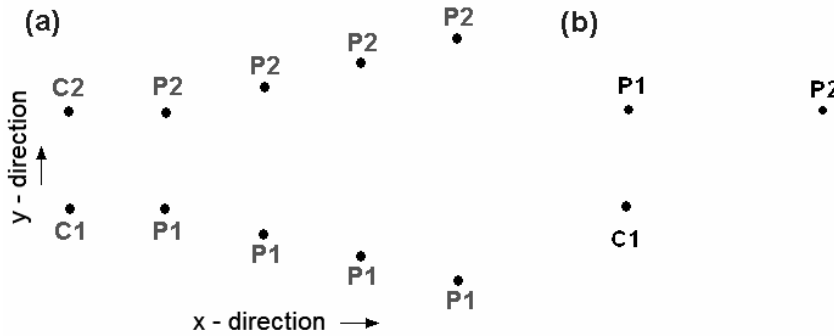
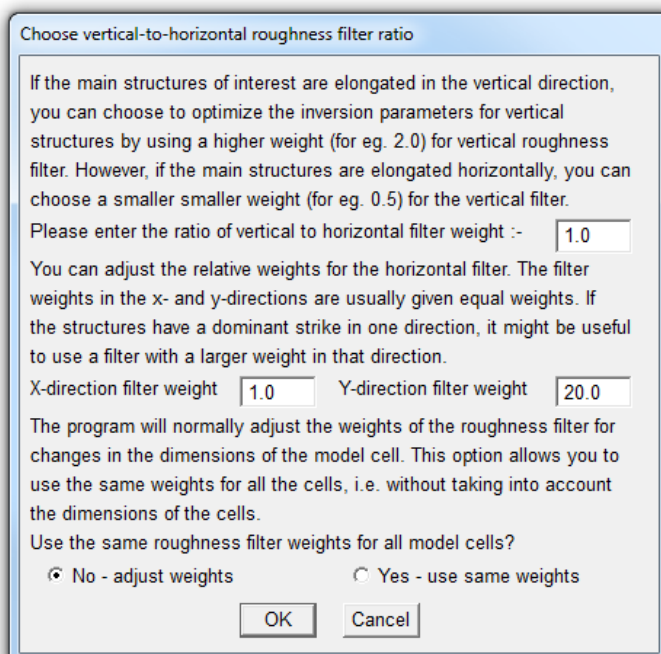


Figure 25. (a) Equatorial dipole-dipole array with different potential dipole lengths, (b) offset pole-dipole array with the C1 electrode at the same x-location as the P1 electrode.

If a 2-D survey is carried out with such arrays, there is only one survey line (in the x-direction). However, as the electrode positions are not collinear, it is necessary to use a 3-D modeling routine to calculate the potentials. To accommodate the different offsets in the y-direction, the non-uniform rectangular grid format (section 7.1.2) to setup the model discretization grid. For the example in Figure 23a, the number of grid lines in the y-direction must be at least 8. For the offset pole-dipole (Figure 25b), although there are only two y positions used, it is recommended that four y grid lines to be used. Two of the y grid lines are dummy lines, with one above the P1-P2 electrodes and another below the C1 electrode positions. If the spacing between consecutive measurements in the x-direction is highly variable (such as from a mobile survey instrument), it might be necessary to use the data format with electrodes at arbitrary positions (section 7.1.4).

As there is essentially only information along the x-direction, the weight of the roughness filter in the y-direction should be set to a high value of more than 10.0 (eg. 20.0), as shown below, using the 'Change Settings – Damping and Filter Settings – Vertical/horizontal flatness filter ratio' option. The option to set this is described in section 9.3.



Another situation that might arise is a 2-D survey along a crooked line, as shown in Figure 26. You will need to use the arbitrary electrodes data format (section 7.1.4) with a model grid that covers all the electrodes. The left and right x -limits are set by the first and last electrodes. The bottom and top y -limits must be set so that it covers the maximum deviations from the straight line. The average electrode spacing can be used as a guide to set the x model grid spacing, and you can work out approximate the number of grid lines needed in the x -direction from the distance between the first and last electrodes. For the y model grid, you should have at least 4 (or more) grid lines depending on the curvature of the line. This will result in an odd number of model cells in the y direction, so you can pick out the middle y row to use in place of the 2-D model. The y grid spacing should not be less than half and not more than twice the x grid spacing. The above example has a 21 by 4 model grid for a line with 22 electrodes. The inversion of such a data set should not take more than a few minutes on a modern multi-core PC. Again, you should set a higher damping factor for the y -direction to minimize variations in that direction.

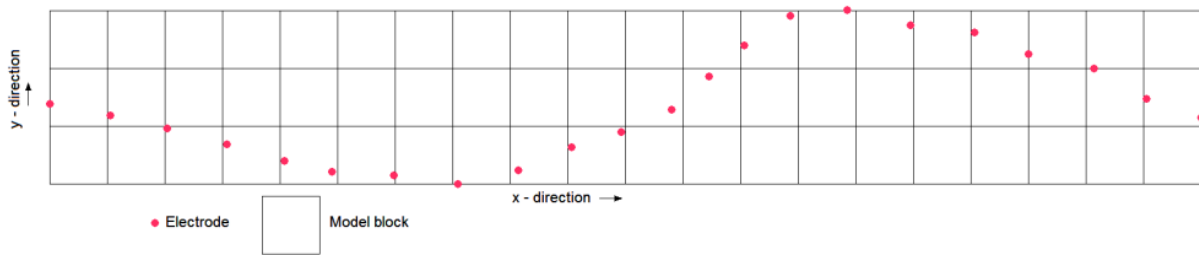
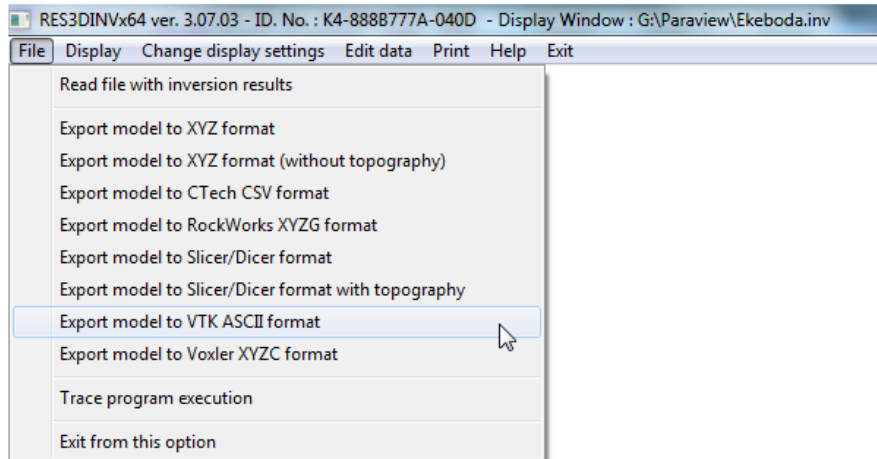


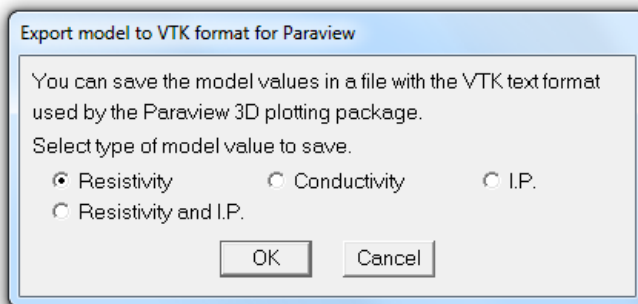
Figure 26. Example of a 2-D survey along a crooked line.

Appendix C : Using Paraview to display the model

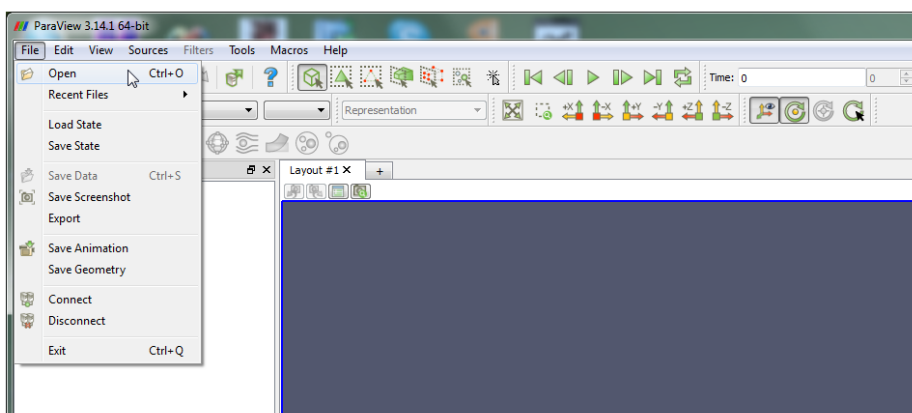
Paraview is an open-source free 3-D graphics package that is particularly popular with academic institutions and government agencies. The Paraview program can be downloaded from the www.paraview.org website which also contains a number of guides and tutorial manuals in pdf format. RES3DINVx64 has an option to save the model values in the VTK format that can be read by the Paraview program. The first step is to export the inversion model values stored in an 'inv' file by RES3DINV into the VTK format. To do that, first read in the 'inv' file in the program 'Display' window. Next use the menu shown option.



After selecting this option, the following dialog box to select the type of information to export will be shown.



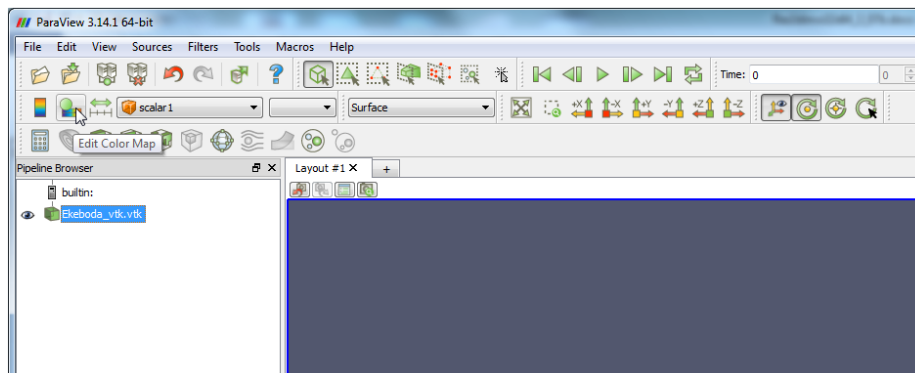
This will be followed by a dialog box to select the iteration number for the model values. The model values will then be saved in a file with the 'vtk' extension. Now, start up the Paraview software and use the 'File-Open' option to read in the vtk file, as shown below.



After reading in the vtk file, you will see a green cube with the name of the data file. To make use of the data, click the 'Apply' button in the 'Properties' window in the lower left section of the screen. The model section will be drawn in the 'Layout' window on the lower right side of the screen using the default settings. Below only a few common operations will be described. The Paraview program has

many features but a relatively steep learning curve. Please refer to the manuals and tutorials for the details.

One common operation is to customize the color scale, using the ‘Edit Color Map’ option as shown below.



The following section was displayed after enabling the ‘Use Logarithmic Scale’ and ‘Automatic Rescale to Fit Data Range’ options.

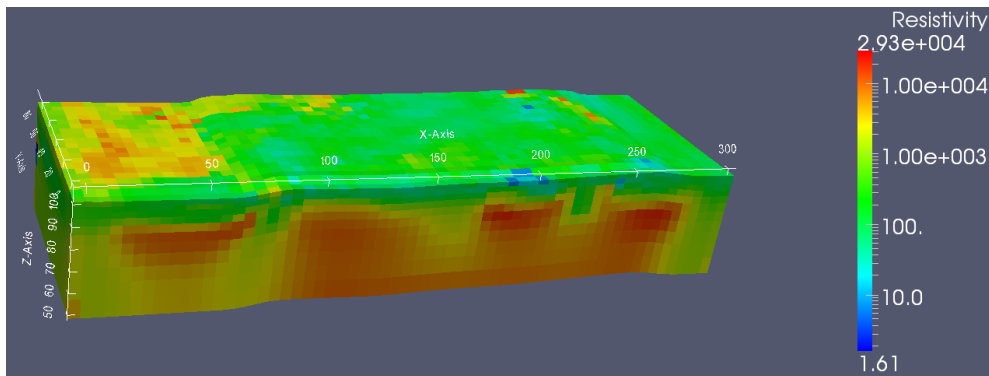
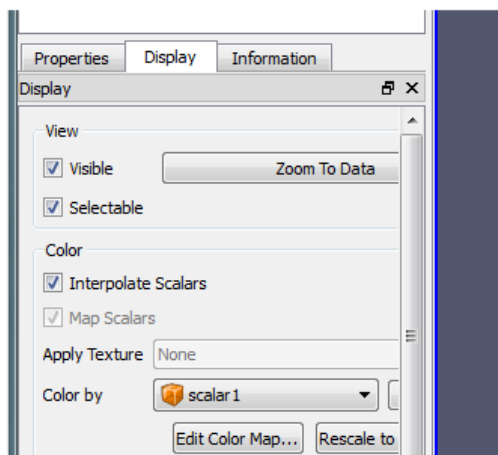


Figure 27. Example 3-D plot using the ParaView program for the Ekeboda landfill survey model.

Figure 27 was displayed by after selecting the ‘Surface’ option in the ‘Representation’ tab (see the figures of the Paraview top menu bars shown earlier). The axes are displayed by selecting the options in the ‘Display’ tab in the located next to the ‘Properties’ tab as shown below.

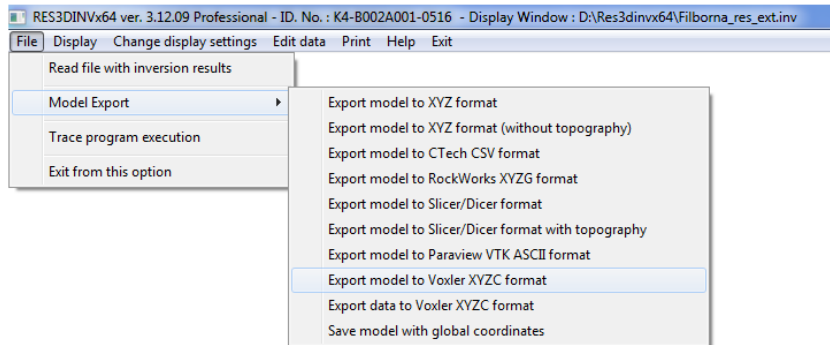


This section gives a very brief introduction to the ParaView program. It is recommended the user follow the exercises in the free ‘The ParaView Tutorial’ (Moreland, 2011) that covers many of the software features. The program has options to display the image as a rendered volume, slices, isosurfaces, contours and many other forms.

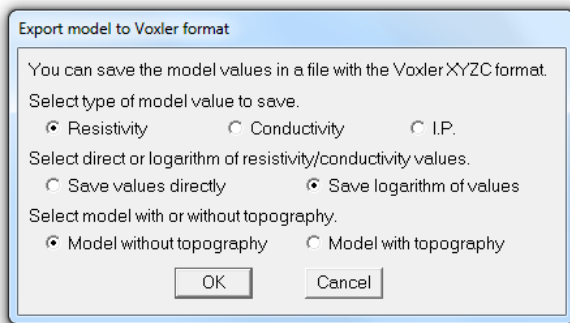
Appendix D : Using Voxler to display the model and data

D.1 Displaying the model

Voxler is a popular commercial 3-D graphics package by Golden Software (www.goldensoftware.com) that can be used to display the inversion model in different forms. The first step is to export the inversion model values stored in an ‘inv’ file by RES3DINV into the format used by Voxler. To do that, first read in the ‘inv’ file in the program ‘Display’ window. Next use the ‘File-Model Export-Export model to Voxler XYZC format’ menu option shown below.

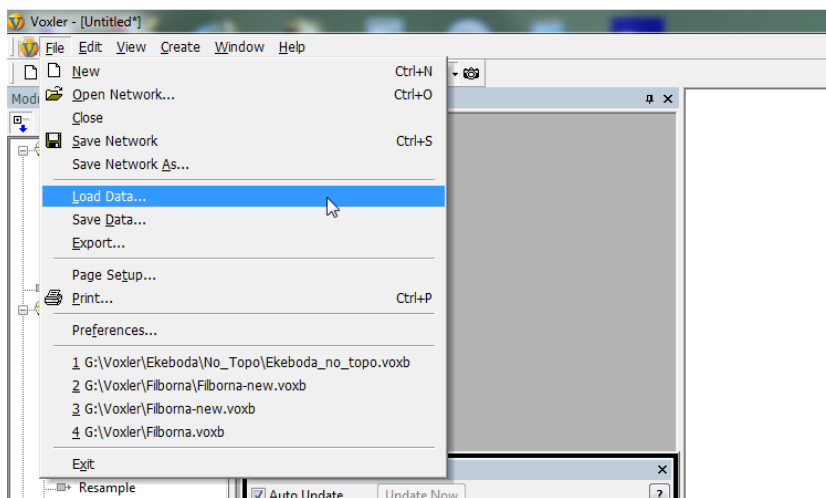


On selecting this option, the following dialog box will be shown.

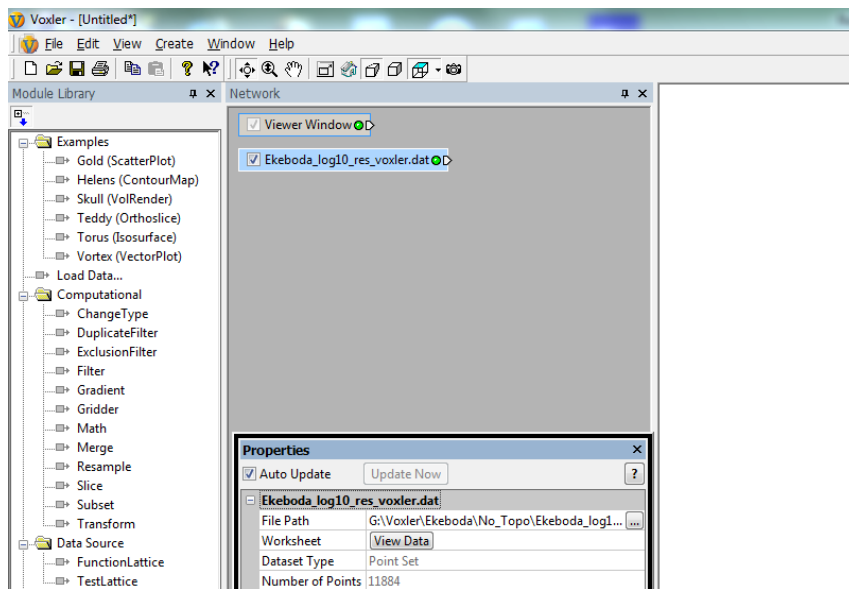


For models with I.P., you can select to export the resistivity/conductivity or I.P. values. For many data sets, the resistivity has a very large range of more than two orders of magnitude. Selecting to save the logarithm (to base 10) of the value will reduce it to a linear range.

As an example, we will use an inversion model from a landfill survey in Sweden (Loke and Dahlin 2010) described earlier section 12.1. We will first look at the plotting of the model without topography that was exported to Voxler format as described above (saving as logarithm of resistivity), in a file Ekeboda_log10_res_voxler.dat. To start plotting the model, and use the option ‘Load Data’ in Voxler (or ‘Import’ in Voxler 3) to read in a data file as shown below.

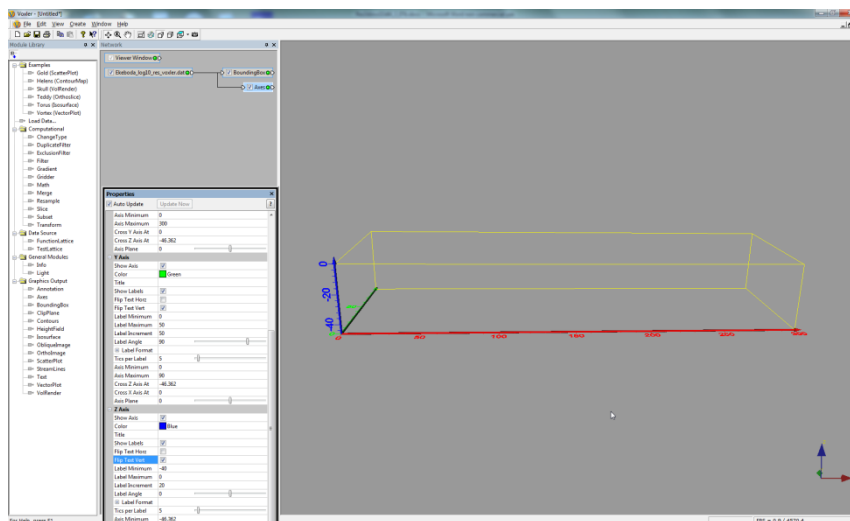


After you read in the file, you should see the name appearing in the Network window in Voxler, as shown below.

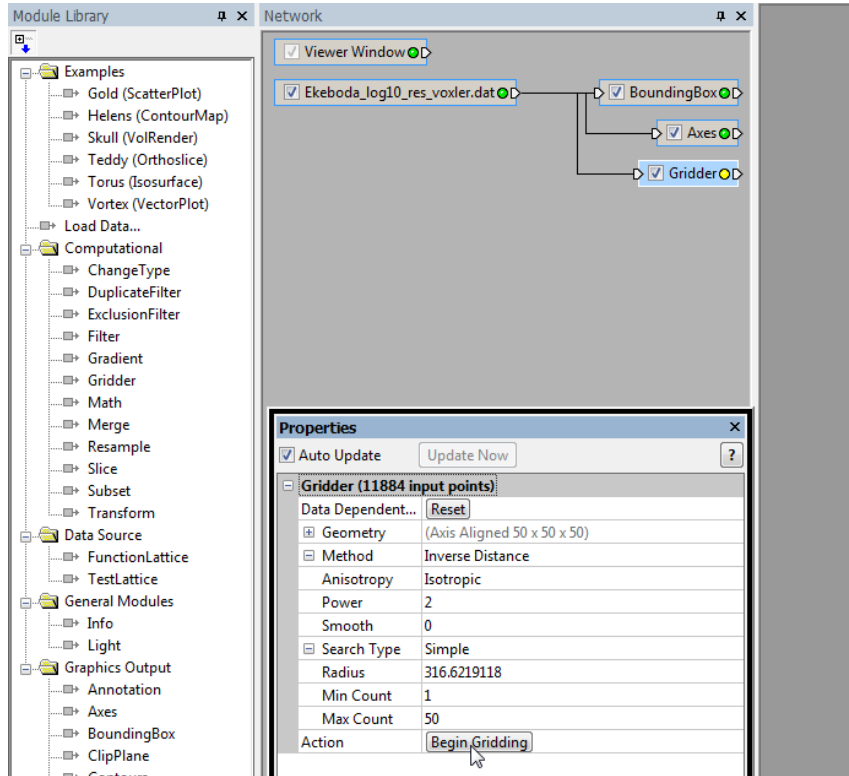


Next, we will carry out three operations that are usually first implemented for all data sets.

- (1). First set up a bounding box that shows the spatial limits of the data set, by selecting the 'Graphics Output – Bounding Box' option in the 'Module Library' window. Make sure the data set is highlighted in light blue in the 'Network' window (as show in the previous diagram) when you select this option.
- (2). The next step is to display the x, y and z axis by selecting the 'Graphics Output – Axes' option in the 'Module Library' window. Make sure the data set is highlighted in light blue in the 'Network' window as well when you select this. You should then see the axes drawn as Red (x), Green (y) and Blue (z). At this point, rotate the box in the 'Viewer' window so that the z axis is pointing upwards. You might want to change the settings in the 'Properties' window for the 'Axes' module, for example making the arrows thinner by setting the 'Axis Thickness' value to about 0.4 from the default value of 1.0. In the display below, the option 'Flip Text Vert' was also selected.



- (3) The third common operation is to grid the data. To do that, first click the data file name in the 'Network' window so that it is highlighted in light blue again. Next double click the 'Computational – Gridder' option in the 'Module Library' window. This should then display the 'Properties' window for the 'Gridder' module. Voxler has two gridding options, 'Inverse distance' and 'Local polynomial'. You might need to try both to determine which method gives the best results for your particular model. Click the 'Begin Gridding' option at the bottom of the 'Properties' window to start the gridding calculation which normally takes a few seconds. Once the gridding is complete, you can now display the data in various forms.



Next we will look at a few common ways to display the data.

Isosurface

This plots the surface contour for the value selected. In Figure 17, it appears that the boundary of the low resistivity material in the landfill is marked by the 56 ohm.m contour (or about 1.75 on the log scale). To plot the isosurface corresponding to this value, first make sure the 'Gridder' module is selected (highlighted in light blue), then double click the 'Graphics Output – Isosurface' option. This will show an isosurface (corresponding to the middle resistivity value) in the 'Viewer' window and the 'Properties' box for it. In the 'Properties' box, you can adjust the parameters for the isosurface display. The following changes were made to get the display in **Figure 28**. Isovalue = 1.75, Color Map = change to Rainbow, and Data range (click button) to 0.75 (Min) and 3.75 (Max). This displays the low resistivity material in the landfill as a green isosurface in **Figure 28**.

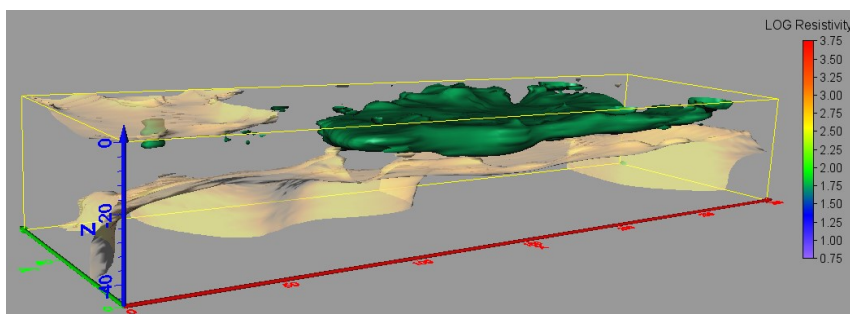


Figure 28. Isurface plot for the Ekeboda landfill model. The green surface has a value of 1.75 (log scale) or about 56 ohm.m. The light brown surface has a value of 3.0 or 1000 ohm.m.

Note it is possible to display more than one isosurface, by selecting the 'Gridder' module followed by the 'Graphics Output – Isosurface' option, as shown in **Figure 28** for the high resistivity material below the landfill and to one corner near the surface. To add the color scale, click the + symbol next to the Legend label at the bottom-right of the 'Properties' box.

Volume rendering

This displays the model as a 3-D image. To use it, first select the 'Gridder' module by clicking it so that it is highlighted, then select the 'Graphics Output – VolRender' option. Adjust the settings in 'Properties' until you get the color image you want. It has an 'Opacity' setting. If it is set to 1.0, only the

model values at the sides and surface are displayed. Reducing it allows the interior parts to be displayed. For example, **Figure 29** used a setting of 0.5.

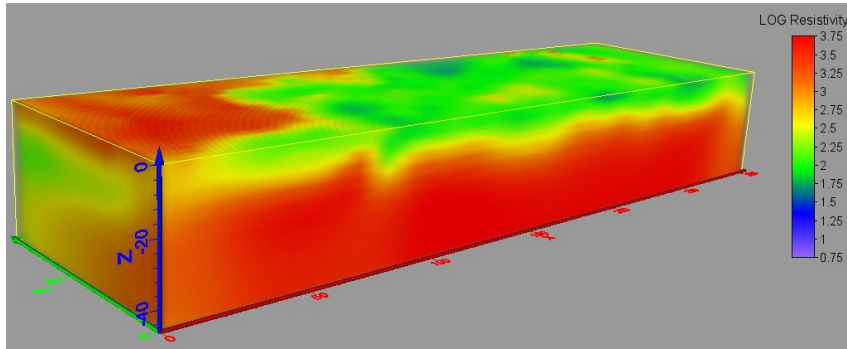


Figure 29. Volume rendered plot for the Ekeboda landfill model.

Displaying slices – Orthoimage

This displays a selected slice through the model. First select the ‘Gridder’ module by clicking it, then select the ‘Graphics Output – Orthoimage’ option. **Figure 30** shows an example of an X-Z vertical slice. You can display several slices by selecting the ‘Orthoimage’ option again, for example to display an X-Y horizontal slice in the same display.

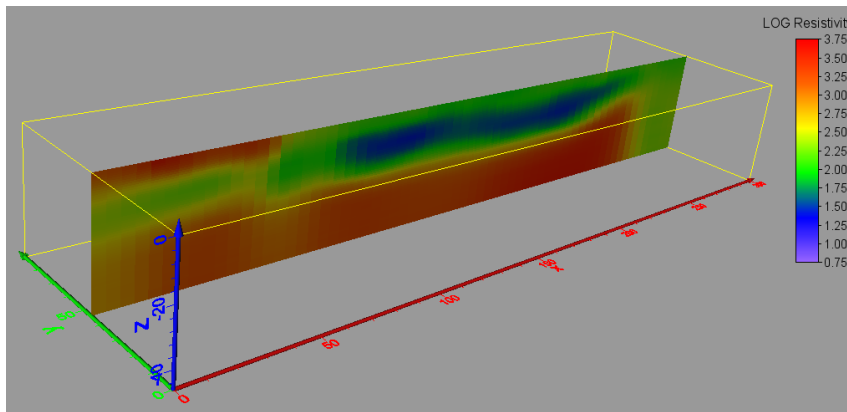
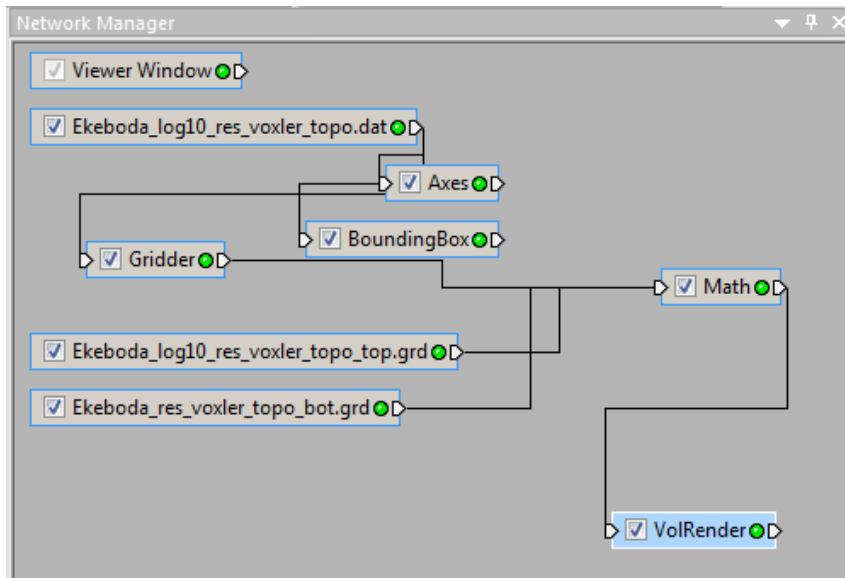


Figure 30. X-Z slice displayed using the Orthoimage plot for the Ekeboda landfill model.

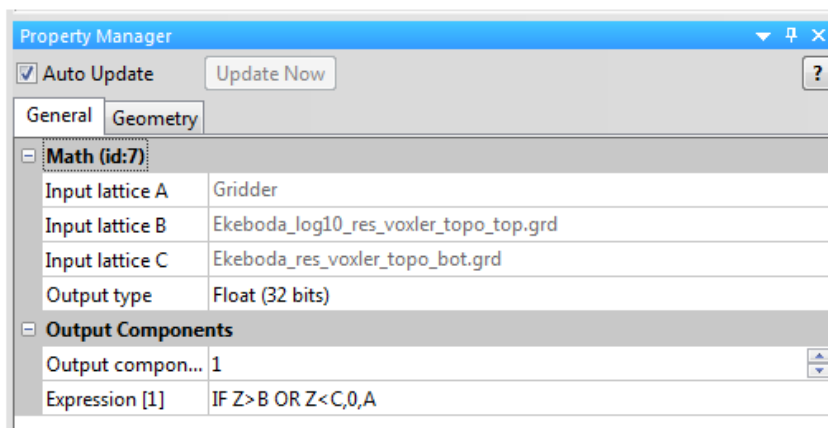
Displaying a model with topography

If the model has topography, and the option to export the model with topography was chosen, the RES3DINVx64 program will generate two more files in addition to the Voxler ‘dat’ file. The additional files have a ‘grd’ extension (in the SURFER GRD format) that contains the coordinates of points on the ground surface (with a ‘_top.grd’ in the file name) and the bottom (with a ‘_bot.grd’ in the file name). These files are used by Voxler to blank out the regions above the ground surface and below the lower limit of the model.

To display the model with topography, first read in the ‘dat’ file and set up the ‘Bounding Box’ and ‘Axes’ as was done previously. The main additional step is to include a ‘Math’ module before using a final module to display the model. After setting up the ‘Gridder’ module, select the ‘Math’ module (under the ‘Computational’ list in the ‘Module Manager’ on the left side of the window). Now you need to read in the grd files using the ‘File-Import’ menu option. The next step is to join the grd files to the ‘Math’ module in the ‘Network Manager’ window. First click the right end of the rectangular box with the name of the ‘..top.grd’ file, hold down the left mouse button, and move the cursor to the left end of the ‘Math’ module. When they are connected, you will see a small dialog box. Select the ‘Connect Input Lattice B’ option in the dialog box. Connect the ‘..bot.grd’ file to the ‘Math’ module in the same way, and choose the ‘Connect Input Lattice C’ option in the dialog box. The ‘Network Manager’ window should look something like in the following figure.



Next click the 'Math' module to show the 'Property Manager' for this module. In the 'Expression [1]' row, type in 'IF Z>B OR Z<C,0,A' as shown below.



After that, click the 'VolRender' option in the 'Module Manager' window (or 'Isosurface' if you wish to display an isosurface). **Figure 31** shows Ekeboda landfill model after adding the topography.

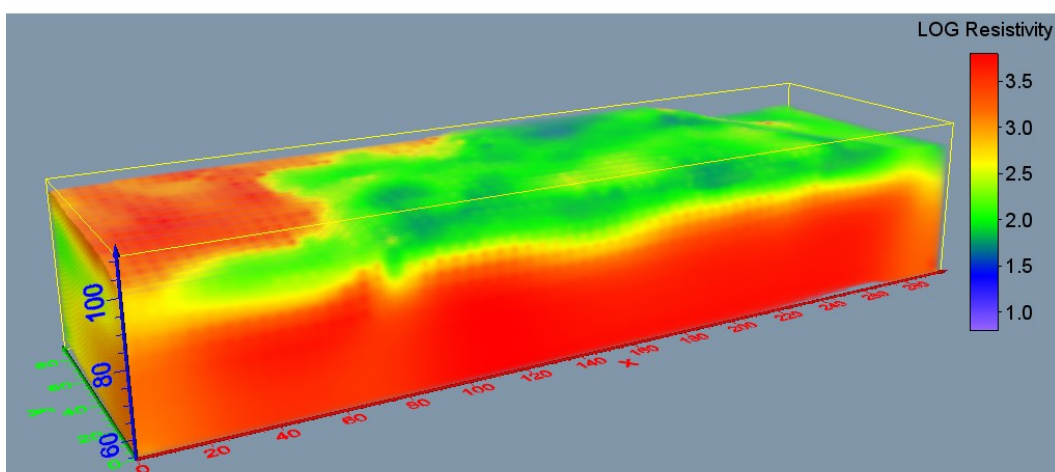


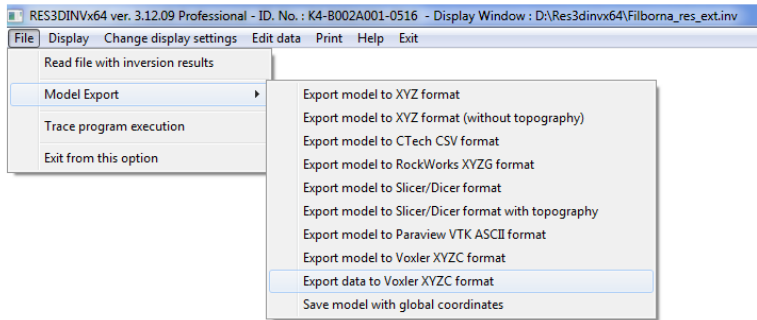
Figure 31. Volume rendered plot for the Ekeboda landfill model with topography included.

You might see small steps on the top surface of the model displayed. This is because Voxler interpolates the model values into a rectangular grid system. This is in contrast to the Paraview program (**Figure 27**) that directly displays the hexahedral blocks in the model with topography.

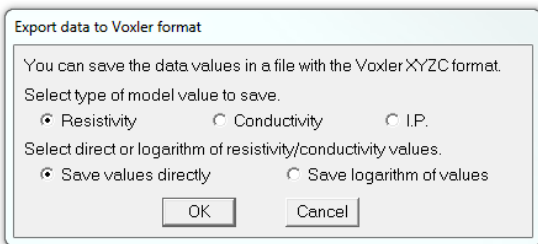
If you use Voxler regularly, it is recommended that you purchase the 'Voxler 3 Full User's Guide' as well from Golden Software that has more details on the different functions in the software.

D.2 Displaying the data

For 2-D surveys, the data is frequently displayed in the form of pseudosections. For 3-D surveys, a single data set might consist of measurements made in different directions, so a contoured display is probably not practical as it is possible two data points might fall in the same location in the plot. One alternative is to use a scatterplot type of display. This section describes using Voxler to display the scatterplot. As an example, we will use the `Filborna_res.inv` example file provided in the list of files installed with the program. This was from a Landfill survey to investigate migration of methane gas (Loke et al. 2014). After reading in the `Filborna_res.inv` file, select the 'File-Model Export-Export data to Voxler XYZC format' as shown below.

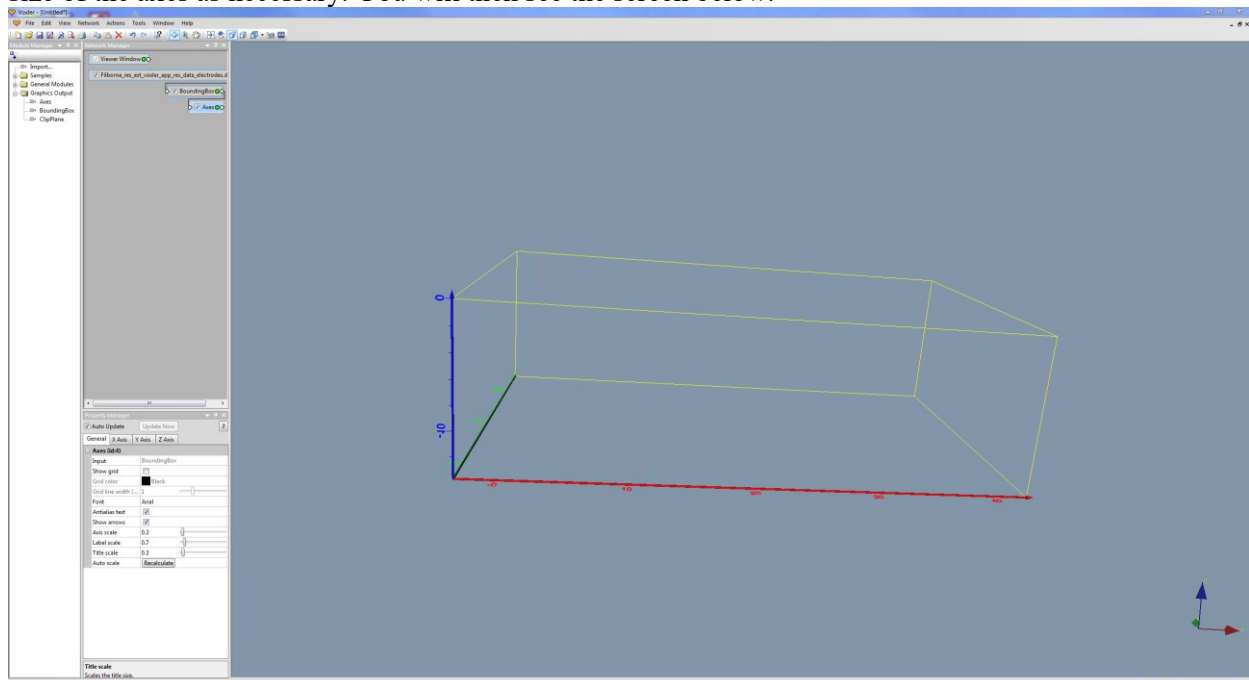


You will then see the dialog box below. If the resistivity values have a small to moderate range, you can save the values directly. If it has a very large range, use the option to save the logarithm (to base 10) of the values.

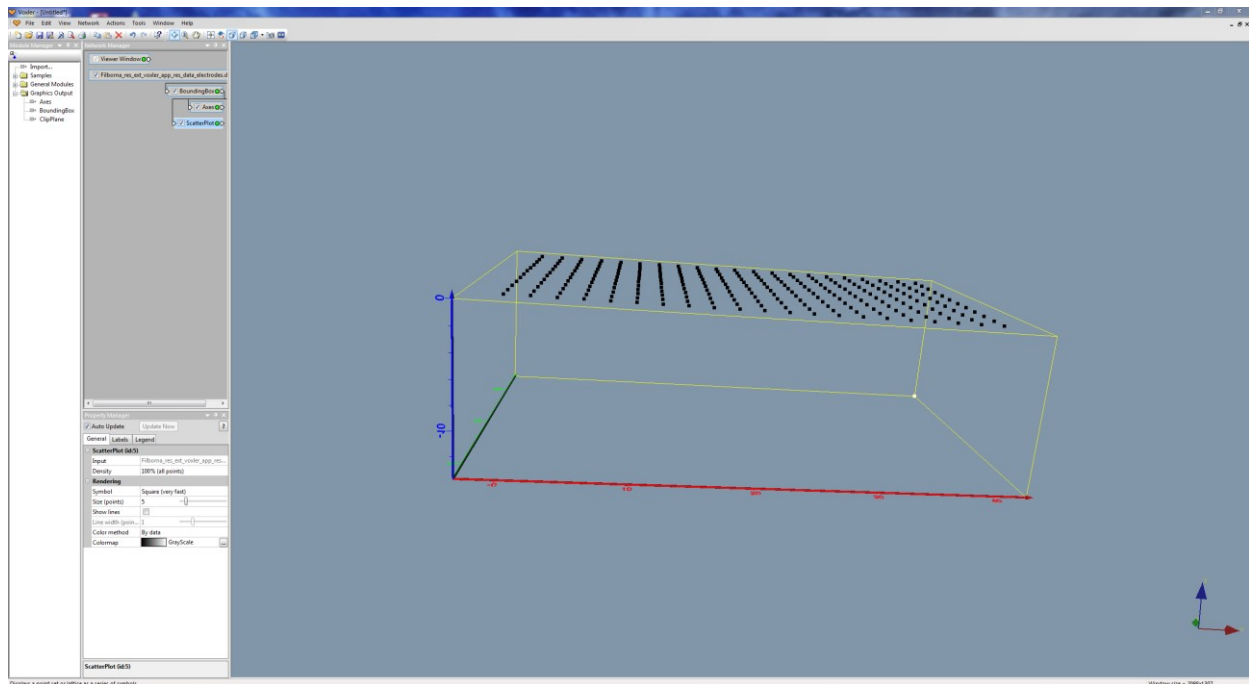


This will create two output file, 'Filborna_res_voxler_app_res_data_electrodes.dat' and 'Filborna_res_ext_voxler_app_res.dat'. There are two main steps in creating the scatterplot in Voxler.

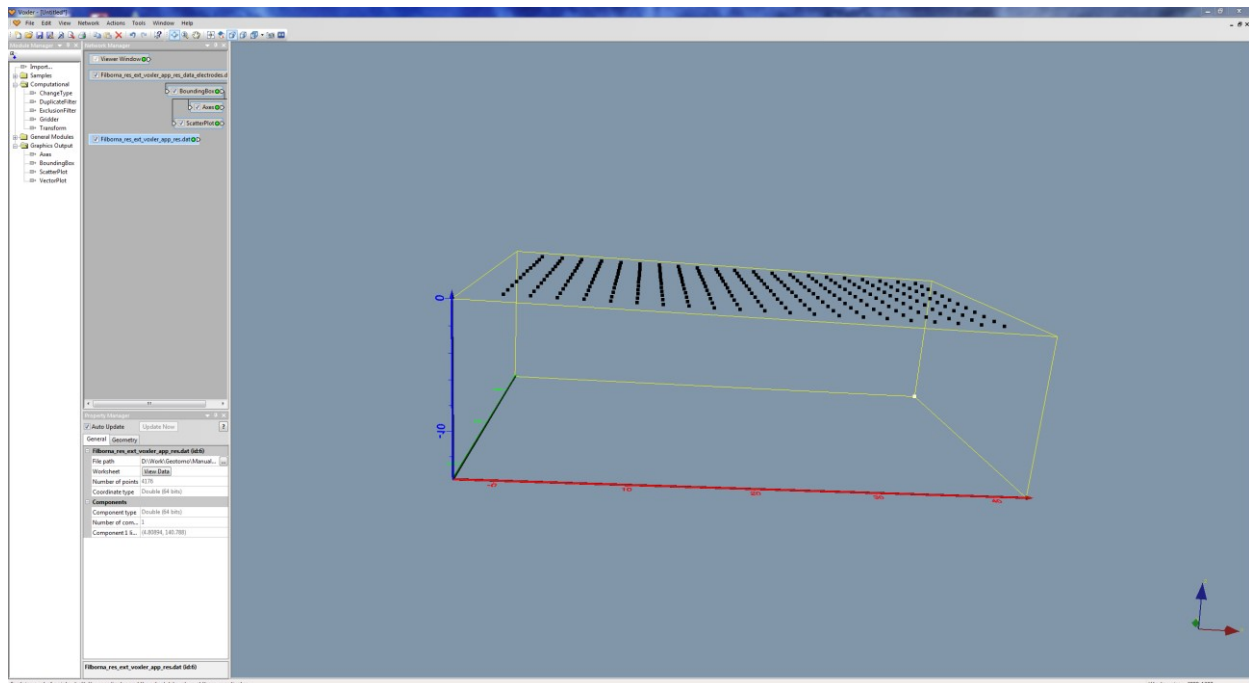
1). First use the 'Load Data' in Voxler (or 'Import' in Voxler 3) to read in the 'Filborna_res_voxler_app_res_data_electrodes.dat'. This file has the positions of the electrodes on the ground surface and provides a box that encloses the apparent resistivity data points. After you read in the file, select the 'Bounding Box' and 'Axes' options as done previously in displaying the model. Adjust the size of the axes as necessary. You will then see the screen below.



Next, to plot the electrodes position, click the 'Filborna_res_voxler_app_res_data_electrodes.dat' tab in the 'Network Manager' window to select it. Now click the 'Graphics Output – ScatterPlot' option in the 'Module Manager' window. Leave the 'Colormap' option in the 'Property Manager' as 'GrayScale' so that the electrodes on the surface will be displayed as black rectangles, as shown below.

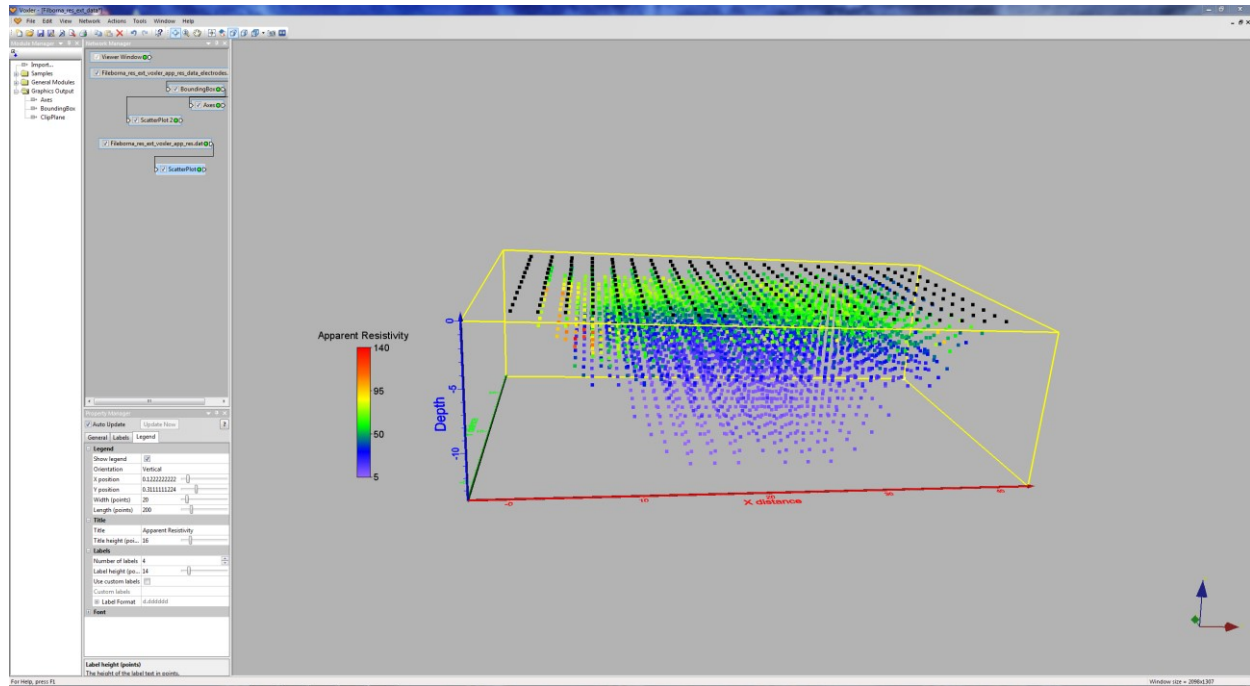


2). The next step is to include the apparent resistivity values into the display. Read the 'Filborna_res_ext_voxler_app_res.dat' file into Voxler. It will appear as a separate tab in the 'Network Manager' window as shown below.



With the 'Filborna_res_ext_voxler_app_res.dat' tab highlighted, click the 'ScatterPlot' option in the 'Module Manager' window. Change the 'Colormap' option from 'Grayscale' to 'Rainbow' or another color scheme to differentiate the data points from the electrodes on the surface. Adjust the settings in the 'ColorMap' option to change the range of values displayed, add a legend, adjust the fonts and other settings to make the display clearer.

The final output might look something like the display below.

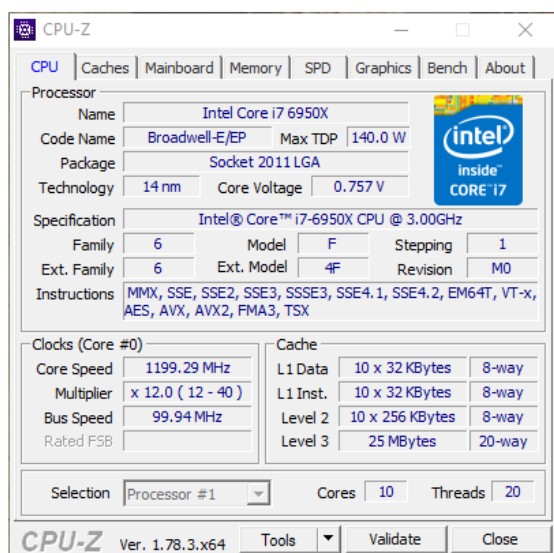


This 3-D survey used a series of parallel cables each with 21 electrodes. The system was designed so that the electrodes on only 3 adjacent cables can be accessed simultaneously (Loke et al. 2014b). Thus, most of the measurements use inline arrays (the pole-dipole array in this case), with a limited number of cross-line measurements. In the scatterplot, the inline data points fall directly below the lines of electrodes on the surface, while the cross-line data points fall between the lines.

Note the 3-D scatterplot, like the pseudosection plot in 2-D, is just a convenient means to display the data. It does not imply the region actually ‘sensed’ by the array is at the position of the point in the plot. In fact, for some arrays such as the dipole-dipole, there is very little sensitivity at the position of the pseudosection data point. A more reliable method to gauge the information content in the data set is the model resolution values (section 9.4.11). Also, a scatterplot display is only meaningful for a survey with all the electrodes on the surface, while a resolution plot can be used for any type of survey.

Appendix E : Using RES3DINVx64 on different PCs

The RES3DINVx64 program is optimized for low cost consumer level personal computers with a single CPU. The code has been highly optimized for speed such that even a laptop computer is sufficiently fast for most data sets. However, for some very large surveys with over 50000 data points and 100000 model parameters, a more powerful computer would help to reduce the inversion time to less than a day. At present, the Intel CPU with the maximum number of cores is the Xeon processor series (such as the Haswell EP series) that has 14 to 18 cores that is used on workstation PCs. The high-end consumer level Intel CPUs has a maximum of 10 physical cores (such as the Broadwell-E 6950X CPU). Some workstations have more than one CPU (usually two to four) in order to increase the processing power. They also frequently support 128 GB (or more) RAM on the motherboard. As an example, a workstation PC with four 8-core hyper-threading CPUs will have 64 logical parallel threads. A separate version of Res3dinvx64 that is optimized Intel CPUs is provided as the Res2dinvx64_Intel.exe file. It is located in the Win_Updates\Res3dinvx64\ Res3dinvx64_Intel folder in the CD provided. Updates can be downloaded from the ‘Download’ page of the www.geotomosoft.com website in the update file for the Res3dinvx64 program. This version should only be used for PCs with the Intel Sandy Bridge, Ivy Bridge, Haswell, Broadwell, Skylake or Kabylake CPUs. Copy the Res2dinvx64_Intel.exe file to the same folder as the Res3dinvx64.exe program. Then manually create a shortcut to the Res3dinv_Intel.exe file on the Windows desktop. The Res3dinvx64_Intel_AVX2.exe program is optimized for the Intel Haswell, Broadwell, Skylake or Kabylake that supports the AVX2/FMA instructions. Do not use the Res3dinvx64_Intel.exe or Res3dinvx64_Intel_AVX2.exe program on a PC with the AMD CPU, or older Intel CPUs. You can use the free CPU-Z program to determine the type of CPU in the PC. An example is shown below for the Intel Broadwell-E i7 6950X CPU that supports the AVX2 instructions.



Version 3.11 onwards use a new compiler that generates highly optimized code for Res3dinvx64 that is about 20% to 40% faster for some data sets. Below are the calculation times for a few data sets. The computer system has an Intel hex-core Sandy Bridge CPU with 64 GB RAM and a 1TB SSD. The number of nodes in the finite-element mesh used is also shown in the table below.

Table 29. Calculation times with different versions of RES3DINVx64.

Software Version	Number of nodes	Version 3.10	Version 3.11	Speedup (%)
Ekeboda data set	571554	1706	1019	40
Burra I.P. data set	1131013	2882	1804	37
Injection well data set	616504 x 12	5304	4152	22

The Ekeboda data set is described in section 12.1 of this manual. A description of the Burra I.P. data set and inversion model can be found in Loke *et al.* (2013). The injection well data set is from a time-lapse survey with 12 snapshots at the Cripple Creek and Victor Gold Mine (Colorado, USA) described in Loke *et al.* (2014a). The main benefit of the new optimized numerical libraries is in the inversion of data sets with topography (that requires the finite-element method) where a large mesh with more than half-a-million nodes is required but has a relatively small number of electrodes positions.

Appendix F : Computer hardware optimizations for large data sets and models

Very large 3-D surveys that involve tens of thousands of data points and electrode positions are becoming more common with advances in field survey equipment and measurements techniques. The grid model used to interpret the data can have over 5 million nodes. This is particularly common in mineral explorations surveys where the electrode positions do not fall in a simple grid, and the arbitrary electrodes format is used. Such data sets presents a challenge to invert the data within a reasonable time with desktop or workstation PCs that costs a fraction of the mainframe computers or networked PCs that are usually required. The following hardware options can be tweaked so as to minimize the computer time required assuming RES3DINVx64 Professional is used.

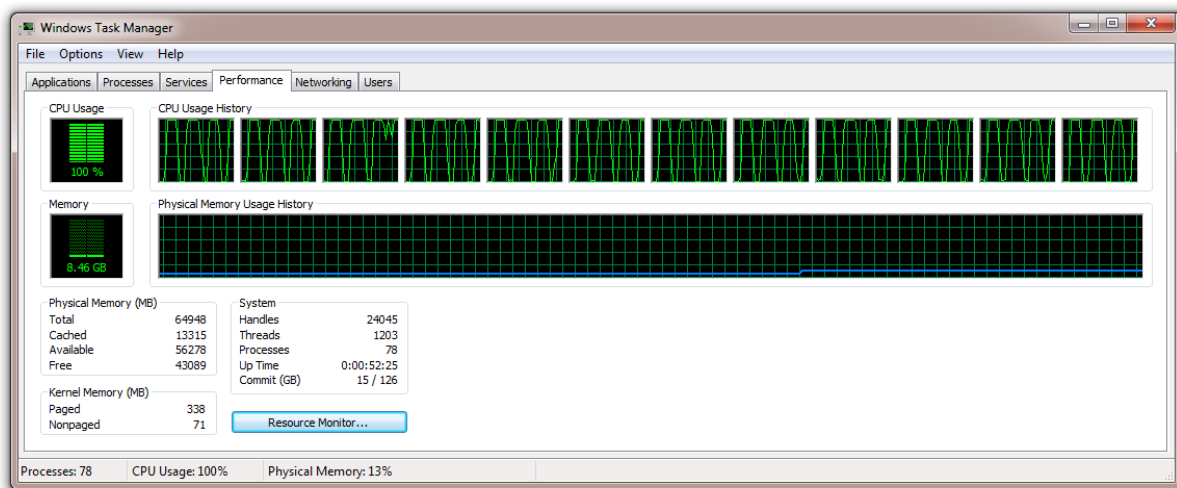
RAM size : This puts a limit on the maximum grid size for the model and finite-element mesh. For some operations, if there is sufficient RAM the program can load the data required into the computer memory instead of accessing the hard-disk repeatedly. This can greatly reduce the calculation time. It is strongly recommended that virtual memory (where hard-disk space is used as memory space) is not used as the program has to continuously save and retrieve data from the hard-disk. This makes the calculations extremely slow. The maximum amount of RAM possible should be installed in the PC. Conventional PC motherboards usually have 4 RAM slots that put a limit of 32GB RAM using 8 GB modules, or 64GB with the newer 16 GB modules. The E CPU series (usually with at least 6 cores) and associated motherboards have 6 to 8 RAM slots that usually gives a maximum of 64GB RAM. The newer motherboards for the Haswell-E CPU now support up to 128 GB RAM. This is probably the maximum limit for off-the-shelf consumer level systems. To further increase the RAM size, workstation level PCs using the Intel Xeon series CPUs with non-conventional motherboards that have more RAM slots or support higher capacity RAM modules are needed. They frequently have more than one CPU and cost several times more than conventional PCs. The RAM limit is commonly between 128 and 256 GB.

CPU type : The RAM size determines the maximum size of the data set and model that can be processed, while the CPU determines the time taken to run the inversion in calculation intensive parts of the program. Conventional CPUs have a maximum of 4 cores, while the E series have a maximum of 6 cores for the Sandy Bridge and Ivy Bridge (8 for the Haswell) CPU series. The E series gives the maximum speed that can be obtained with conventional PCs. Beyond that, a workstation level PC with more than one CPU is required. The workstations use the Xeon CPUs that can have 8 or more cores. They also support two or more CPUs. For example, a workstation with four quad-core CPUs will have a total of 32 physical computational cores (or 64 virtual cores with hyper-threading). Most of the calculation intensive parts of the program, such as the finite-difference or finite-element calculations, can be parallelized to take advantage of all the computational cores. A finer level of parallel calculations is by using the special registers in the CPU. The Intel CPUs have SSE registers that can carry out more than one calculation simultaneously. All of the 64-bit CPUs have SSE registers that can carry out 4 single-precision calculations in parallel. The Sandy Bridge later CPUs have the AVX registers to carry out 8 calculations simultaneously. The Haswell and later CPUs also support FMA (fused-multiply-add) operations that carry out a multiplication and addition in a single operation.

The Graphics Processor Unit (GPU) or special coprocessors such as the Intel Xeon Phi have a much larger number of computational cores. However GPUs are much more difficult to program except for simple matrix multiplications. They are both limited to about 6 to 8 GB local RAM, so this puts a practical limitation on the size of the problems where they can be used, unless special techniques to split up the calculations into blocks (which involves some overhead in memory transfer) are used. For resistivity inversion problems that require only 8 GB RAM, using the conventional CPU is usually fast and the computer time is sometimes limited by the speed of the hard-disk.

Hard-disk : Increasing the RAM space and number of CPU cores will reduce the time taken by the computationally intensive parts of the program. The speed of the hard-disk then becomes the remaining bottleneck on fast workstations. The program stores some temporary data into buffer files that are usually placed in the drive with the largest free disk space. Hard-disks are either the conventional magnetic HDD (usually 7200 rpm) or Solid-State-Drives (SSD). The faster SSDs can significantly reduce the calculation time for models with large grid that might involve buffer files of more than 100 GB size. The buffer disk capacity should be at least 4 to 8 times the RAM size. The price of SSDs can be about an order of magnitude higher than conventional magnetic hard-disks with the same capacity.

You can use Windows Task Manager (press Ctrl-Alt-Del) to check the parts of the program that take the most time. Click the 'Performance' tab in the Task Manager to show the CPU and memory usage, as shown below.



This example is for PC with a six-core CPU and 64 GB RAM. Note 12 CPU cores are shown due to hyper-threading. Most of the time the CPU usage is close to 100% indicating that all the cores are fully used. The 'CPU Usage' drops close to 0% when the program is accessing the hard-disk. You can check the part of the computer that is the bottleneck by monitoring the CPU and memory usage while running the inversion of a large data set. Note that some of the routines that do not use the hyper-threading function will show a 50% usage for the i7 type of CPUs as they only use the physical cores.

Appendix G : Method to handle large data sets with unstable arrays

The development of new surveys system with hundreds of electrodes that can be controlled using a single central system has made possible new electrodes layouts to cover wider arrays more efficiently, particularly in mineral exploration. The ‘offset’ type of array where the 4 electrodes used in a measurements are not collinear is common in such surveys. This can lead to ‘unstable’ arrays where the apparent resistivity value as calculated by the finite-difference or finite-element method is negative (Wilkinson et al. 2008, Loke et al. 2014b). The negative apparent resistivity values can occur in areas where with large resistivity contrasts or significant topography, even though the geometric factor (for homogeneous half space with a flat surface) is positive. The logarithm of the apparent resistivity is normally used in the resistivity inversion routine as the resistivity value in an area with large contrasts can have a huge range. Using the logarithm is usually preferred as it helps to stabilize the inversion process. However, this method cannot be used if the measured or calculated apparent resistivity value is negative. The following schedule to handle large data sets that might have potentially unstable arrays is proposed.

- 1). First filter out the arrays that have large geometric factors or geometric factor relative errors (section 8.3).
- 2). Run the inversion using the logarithm of the apparent resistivity as the inversion data parameter. However enable the option for the program to automatically remove arrays that have negative calculated apparent resistivity values during the inversion (section 9.4.8). At the end of the inversion, save the arrays after trimming out the ‘unstable’ arrays into a new data file.
- 3). If necessary, carry out another inversion of the trimmed data set.

To avoid stopping the inversion process when a negative calculated apparent resistivity value occurs, select the option to remove these data points automatically (see section 9.4.8). You can remove the data points where this problem occurs at the end of the inversion process.

Appendix H : Incorporating data noise estimates

Some types of resistivity surveying instruments record an estimate of the random noise for each measurement. This is usually made by repeating the same measurement several times. The data error estimate is then calculated from the standard deviation in the readings. This actually give a measure of the repeatability in the readings, i.e. the random noise. Note that this data error estimate does not include sources of systematic errors such as coupling between the cables. A better method to estimate the data error is by using reciprocal measurements (Van et al. 1991, Zhou and Dahlin 2003).

To include the data error estimate in a data file, the error values are entered after the apparent resistivity value. The file 21x12_blocks_noise.dat is an example of a data file from a surface survey with the error values. Part of the file is shown in Table 30. with an explanation of the changes needed. Note there are two new additions to the data format. Firstly, just before the section of the file with the measured apparent resistivity data points, there are 3 extra lines. The first line 'Error estimate for data present' is a header to indicate that the data file contains the data error estimates. The second new line is a header to explain the use of the next line. The third line contains a flag to indicate to the program the units used in the error estimate. At present, use a value of '0' to indicate that the error value has the same units as the data value. For example, if the measurements are given as ohm.m, then the error values must also be in ohm.m. Measurements in most instruments are given as resistance values (i.e. ohm), or voltage plus current values which can be converted to resistance values. To calculate the apparent resistivity value, the resistance value is multiplied by the geometric factor. The error value recorded by the instrument is probably in the form of a resistance (ohm) value. Thus, the error estimate recorded by the instrument must also be multiplied by the same geometric factor before it is entered into the DAT file format used by this program. The use of the flag for the unit used by the error value makes it possible for future versions of the program to allow the use of other units for the error value, for example the data in ohm.m while the error in ohm. Another possibility is the error given as a percentage value.

Table 30. Example data file with estimated noise values.

<i>21x12_blocks_noise.dat file</i>	<i>Comments</i>
Model with 2 blocks	<i>Title</i>
21,12	<i>Number of electrodes in x- and y-directions</i>
1.0	<i>x unit electrode spacing</i>
1.0	<i>y unit electrode spacing</i>
11	<i>Array type, 11 for general</i>
7	<i>Wenner-Schlumberger subarray</i>
Type of measurements (Resistivity=0,Resistance=1)	<i>Header for type of measurement</i>
0	<i>Apparent resistivity</i>
2170	<i>Number of data points</i>
Error estimate for data present	<i>Header to indicate error estimates present</i>
Type of error estimate (0=same unit as data)	<i>Header for type of error value</i>
0	<i>Indicates same as data</i>
4 0.0,0.0 3.0,0.0 1.0,0.0 2.0,0.0 102.970 0.050	<i>For each data point, enter number of electrodes, x- and y-locations of the C1-C2-P1-P2 electrodes, apparent resistivity and estimated error</i>
4 0.0,0.0 5.0,0.0 2.0,0.0 3.0,0.0 101.129 0.361	
4 0.0,0.0 7.0,0.0 3.0,0.0 4.0,0.0 101.500 0.770	
4 0.0,0.0 9.0,0.0 4.0,0.0 5.0,0.0 100.413 0.217	
.	<i>Repeat for all data points</i>
.	
.	
0	<i>Followed by a few 0's: these are flags for other options, such as topography</i>
0	
0	
0	

Appendix I : Combining data from different 3-D surveys

This option allows the user to combine data from different 3-D spreads over the same area. Many resistivity-meter systems have a limited number of electrodes that can be used at the same time. A roll-along system is then used to cover the entire survey area.

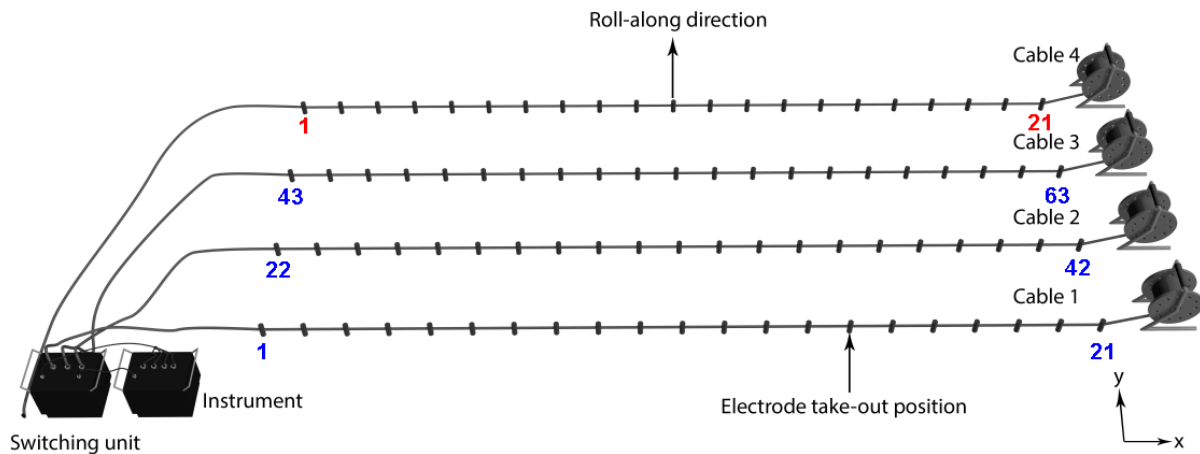


Figure 32. A roll-along 3-D survey using 3 parallel lines of electrodes.

Figure 32 shows an example where the system can address 3 cables with 21 electrodes each at a single time giving a total of 63 electrodes (Loke et al. 2014b). Frequently the spacing between the lines is larger than the electrode spacing along the lines. Each data set usually saves the data using a local coordinate system when converted to the Res3dinv 'dat' format. As an example, consider the case where the inline electrode spacing is 2 meters and the interline spacing is 3 meters. Electrode 1 in the first data set (in blue) will be located at (0,0) while electrode 63 is at (40,6). To reduce the survey costs, frequently a new set of readings is taken offset from the first set of lines without any overlap. Electrode 1 (in red, Figure 31) for the new set of readings will have an actual coordinate of (0,9) but the data file for that survey places the coordinate for this electrode at (0,0). To combine the data from several sets of measurements, the coordinates for the second and subsequent data sets have to be shifted to the correct positions.

Table 31. Example script file to combine 3-D data files into a single data file with simple shifts.

<i>Combine-3-files-shift.txt</i>	<i>Comments</i>
Combine 3-D data files	<i>Title of this set of files</i>
Number of files	<i>Header</i>
3	<i>Indicates three files in this example</i>
Type of coordinate shift (0=simple translation,0=general)	<i>Header for type of coordinate shift</i>
0	<i>0 to indicate simple translation</i>
Name of first file	<i>Header for first file</i>
c:\temp\File 1.dat	<i>Data file name including drive and folder</i>
X and Y and Z shifts	<i>Header for shifts</i>
0.0,0.0,0.0	<i>Shifts in X, Y and Z directions. None for first file.</i>
Name of second file	<i>Header for start of second file</i>
c:\temp\File 2.dat	<i>Name of second file</i>
X and Y and Z shifts	<i>Header for shifts</i>
0.0,15.0,0.0	<i>Shifts in X, Y and Z directions</i>
Name of third file	<i>Header for third file</i>
c:\temp\File 3.dat	<i>Name of third file</i>
X and Y and Z shifts	<i>Header for shifts</i>
0.0,30.0,0.0	<i>Shifts in X, Y and Z directions</i>
Name of output time-series data file	<i>Header for output combined file</i>
c:\temp\File 123.dat	<i>Name of combined data file</i>
End file	<i>Indicates end of script file</i>

Table 31. Example script file to combine 3-D data files into a single data file with simple shifts. shows an example script file to combine 3 data files into a single file. In this example, the coordinates of the electrodes in the second and third files undergo a simple translation without and rotation, i.e. the surveys

lines are parallel as in Figure 31. There are no shifts in the x direction, so the x shifts are 0.0 for the second and third files. However, in a more complex case, the shift in the x direction can be non-zero. In most cases, there are no shifts in the vertical (z) direction as the topography for the different lines will likely be measured using a common datum point.

Table 32. Example script file to combine 3-D data files into a single data file with general coordinate transform. shows the script file for a more general case that can handle a situation with survey lines in different directions. For the local coordinates to be changed into the common coordinate system used for the combined data file, the file should contain a section with the global coordinates that gives the relationship between the local coordinates and the true coordinates. If the file does not contain the section with the global coordinates, the program will assume that the coordinates given in the data file are the true coordinates. A common situation where this might occur is when the arbitrary electrodes data format is used and the positions of the electrodes are given in the true longitude and latitude coordinates in meters.

Table 32. Example script file to combine 3-D data files into a single data file with general coordinate transform.

<i>Combine-3-files-general.txt</i>	<i>Comments</i>
Combine 3-D data files	<i>Title of this set of files</i>
Number of files	<i>Header</i>
3	<i>Indicates three files in this example</i>
Type of coordinate shift (0=simple translation,0=general)	<i>Header for type of coordinate shift</i>
1	<i>1 to indicate general coordinate shifts</i>
Name of first file	<i>Header for first file</i>
c:\temp\File_1_general.dat	<i>Data file name including drive and folder</i>
Name of second file	<i>Header for start of second file</i>
c:\temp\File_2_general.dat	<i>Name of second file</i>
Name of third file	<i>Header for third file</i>
c:\temp\File_3_general.dat	<i>Name of third file</i>
Name of output time-series data file	<i>Header for output combined file</i>
c:\temp\File_123_general.dat	<i>Name of combined data file</i>
End file	<i>Indicates end of script file</i>

In the above example script file, File_1_general.dat does not have the section with the global coordinates parameters, so the program uses the electrode coordinates given without changing them. Table 33 shows the last part of File_2_general.dat that has the global coordinates section. The section with the global coordinates parameters is given after the main data section with the measured apparent resistivity data points. If other information such as topography or fixed regions are present, they should be given before the section with the global coordinates information. The program uses 3 matching pairs of points with the coordinates given in the local coordinates and the corresponding global coordinates. It then calculates the translation and rotation needed to change the coordinates of the electrodes from the local coordinates to the common global coordinates for the combined data set. The 3 points must not be in a straight line. Ideally they should at the vertices of a right angle triangle that covers half the survey area.

Table 33. Part of the File 2 general.dat file with the global coordinates parameters.

<i>File 2 general.dat</i>	<i>Comments</i>
12.0, 6.0 0.0, 6.0 24.0, 6.0 36.0, 6.0 27.378	Main data section
14.0, 6.0 2.0, 6.0 26.0, 6.0 38.0, 6.0 29.334	Last 2 data points with the positions of the
16.0, 6.0 4.0, 6.0 28.0, 6.0 40.0, 6.0 31.759	electrodes in local coordinates
Topography	Header to indicate topography section present
1	Flag to indicate true x-y horizontal positions
Topography in unstructured list	Header indicate topography points in a list
Number of topography data points	Header for number of topography points
63	Number of topography points
Topography data points (index,x,y,z)	Header to indicate format used
1 0.0 0.0 0.00	Coordinates of 1 st point
2 2.0 0.0 0.00	Coordinate of 2 nd point
.....	Other topography data points
.....	listed
63 40.0 6.0 0.00	Last topography point
	Indicates end of batch file
Global coordinates information present	Header to indicate global coordinates present
Type of global coordinates information (0=point-to-point)	Header for flag to indicate type of global coordinate information
0	Only this option is used at present
Number of points	Header for number of points used in coordinate transformation
3	Recommend use 3 points in a right-angle triangle
Local x-y Global x-y	Header for section with coordinates of points
0.0000, 0.0000 0.0000, 9.0000	First pair of points with x-y coordinates
0.0000, 6.0000 0.0000, 15.0000	Second pair of points with x-y coordinates
40.0000, 6.0000 40.0000, 15.0000	Third pair of points with x-y coordinates
0	
0	
0	

Disclaimer

This software is provided “as is” without any express or implied warranties including its suitability for a particular purpose. Neither the author nor the subagent will assume responsibility for any damage or loss caused by the use of this program. In the event of program bugs, every effort will be made to correct the bugs and a replacement program will be provided over the Internet. After the first year, there is an annual fee for software updates and technical support. However, the software version in the CD provided and downloaded updates released up to one year after the software purchase can still be used indefinitely if the user chooses not to upgrade. Please refer to the ‘Ordering & Enquires’ page of the www.geotomosoft.com website (or email to sales@aarhusgeossoftware.dk with your license number) for the annual fee that is applicable to your license.

Support

Please contact your distributor if you have any questions concerning this program. A frequent source of queries is when the results obtained are not what you expect, or the program refuses to accept your data file. In such a case, support will only be provided if a copy of the data file is sent together as an attachment with your email, preferably compressed into a ZIP file. The most common causes of problems are (a) the data in the DAT file is not given in the correct RES3DINV format, (b) excessive noise in the data set (particularly for dipole-dipole surveys and/or I.P. data sets), and (c) instrument malfunction or field survey errors. It is only possible to trace the source of the problem if a copy of the data file is provided. Please note that support is only available for registered users of the full version of the program. Technical support is not provided for users of the demo version of this software. For technical support, you can contact the software provider at the following email addresses.

geotomosoft@outlook.com, geotomosoft@gmail.com, geotomo_software@yahoo.com

The following information will be required for technical support.

1. Your license number. This license number is displayed near the middle of the initial information box when the RES3DINVx64 program starts up.
2. The name of your company or institution.
3. Approximate date (month/year) your company or institution purchased the software.

If you purchased the software more than one year ago, please refer to the ‘Ordering & Enquires’ page of the www.geotomosoft.com website on renewing the support.

What's New

Version 2.00 - Upgrade to Windows 3.1 and 95.

Version 2.01 - Code optimizations for Windows 95/NT systems. Maximum grid size increased to 43-by-43 (1849) electrodes for systems with 128 MB RAM.

Version 2.03 - Support for non-uniform survey grids

Version 2.04 - Support for robust inversion.

Version 2.05 – Support for equatorial dipole-dipole (rectangular) array. Options to save the model resistivity and I.P. values in the Rockworks and Slicer/Dicer programs added.

Version 2.06 - Option to use 4 nodes between adjacent electrodes added. This gives greater accuracy, but at a huge increase in the computer time, for cases with large resistivity contrasts near the surface. The user can now stop the inversion process at the end of the current iteration by pressing the 'N' key. After displaying the model sections, the user can view the results from the later or earlier iterations by pressing the 'PgUp' or 'PgDn' key.

Version 2.07 – Options to carry out the inversion of IP data sequentially and to determine the I.P. damping factor automatically were added.

Version 2.10 – Incomplete Gauss-Newton inversion option added.

Version 2.11 – Data compression option for the incomplete Gauss-Newton method added. Maximum number of electrodes increased to 5041, and maximum number of data points to 67500, for systems with 1 GB RAM. The computer must have Win NT/2000/XP and a hard-disk using the NTFS file system format.

Version 2.12 – Option to use 3 nodes between adjacent electrodes added. Option to save model values in a binary format for the Slicer-Dicer program also added.

Version 2.13 – Support for 3-D underwater surveys added. Optimization made to inversion code for data from surveys with multi-channel instruments. For such surveys, the inversion subroutine is about 20-50% faster than version 2.11.

Version 2.14 – Support for borehole surveys and trapezoidal survey grids added.

Version 2.15 – Parallel computations on Pentium 3 and Pentium 4 computers. Optimizations made for surveys for surveys with the Wenner-Schlumberger array to further reduce the inversion time.

Version 2.16 – Batch mode inversion option added.

Version 2.20 – Multi-core CPU support added.

Version 2.21 – Cache optimization support added.

Version 3.00 – 64-bit version with support for up to 8 GB RAM.

Version 3.01 – Memory support increased to 16 GB RAM for RES3DINVx64.

Version 3.02 - Support for electrodes at arbitrary positions added and memory support increased to 128 GB for RES3DINVx64.

Version 2.22/3.03 - Support for diagonal roughness filters. Support for up to 12 CPU cores with RES3DINVx32, and 64 cores with RES3DINVx64.

Version 3.04 - Complex resistivity inversion option for IP data in RES3DINVx64. Option to include known boundary, and to set water layer resistivity for survey with floating electrodes in RES3DINVx64.

Version 2.23/3.05 - Support for topography data given as unstructured list added.

Version 3.05 - Options to reduce the calculation time for surveys with sparse electrodes arrangement, and for PCs with Intel CPUs in RES3DINVx64.

Ver. 3.06 – Support for long electrodes, and to reduce the Jacobian matrix calculation time for dense data sets in RES3DINVx64.

Ver. 3.07 – Option to calculate model resolution for models with up to 46,000 model cells in RES3DINVx64.

Ver. 3.08 – Option to rotate data set x and y axes to reduce model grid size required to model data with electrodes at arbitrary positions in RES3DINVx64. Option to convert data in trapezoidal grid format to arbitrary electrodes format added.

Version 3.09 – Support for tank boundaries, option to display trapezoidal grid and detection of degenerate trapeziums in RES3DINVx64.

Version 3.10 – Support for time-lapse data.

Version 3.11 – Support for AVX and FMA instructions. Finite-element mesh size limit for Res3dinvx64 Basic increased to 1.2 million nodes. New compiler used that generates faster code. Support for underwater surveys using the arbitrary electrodes layout.

Version 3.12 – Support for L-curve method added. Forward modeling routines consolidated into a single set. Option to use sensitivity values to reduce artifacts near subsurface electrodes added. Finite-element mesh size limit for Res3dinvx64 Basic increased to 1.4 million nodes.

Version 3.13 – Option to combine 3-D data sets into a single file. Scatter plots for calculated versus measured apparent resistivity and I.P. data. Screen dump to BMP, JPEG, PNG, TIFF and GIF formats. Finite-element mesh size limit for Res3dinvx64 Basic increased to 1.5 million nodes.