

RES3DINVx64 ver. 3.19
Basic, Professional and Enterprise versions
with multicore and 64-bit support

for Windows 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, vector and non-conventional arrays)
On land, aquatic, cross-borehole
and time-lapse surveys

Geoelectrical Imaging 2-D & 3-D



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Table of Contents

	Topic	
Cover		i
1	Introduction.....	1
2	Computer system requirements	1
2.1	Differences between RES3DINVx64 Basic, Professional and Enterprise.....	2
3	Copy protection.....	2
4	Theory.....	4
5	Software installation	5
6	Using the program – a quick start.....	6
7	Data file formats	7
7.1	Survey grid types	7
7.1.1	Uniform rectangular survey grid.....	7
7.1.2	Non-uniform rectangular survey grid	11
7.1.3	Trapezoidal survey grid	12
7.1.4	Electrodes at arbitrary positions	14
7.1.5	Remote electrodes.....	16
7.1.6	Arbitrary positions versus trapezoidal and non-uniform grids	16
7.2	Topography information	17
7.2.1	Rectangular grids	17
7.2.2	Trapezoidal grids	17
7.2.3	Electrodes at arbitrary locations	17
7.2.4	Topography data in an unstructured list.....	17
7.3	I.P. data	18
7.4	Fixed regions.....	20
7.5	Incorporating a known boundary	21
7.6	Underwater surveys.....	23
7.7	Borehole, subsurface and long electrodes data format.....	25
7.7.1	Borehole electrodes format (deprecated).....	25
7.7.2	Arbitrary subsurface electrodes format.....	25
7.7.3	Long electrodes format	27
7.8	Tank boundaries.....	31
7.9	Time lapse survey data format (Professional).....	32
8	File menu options.....	33
8.1	Read data file	33
8.2	Data editing options	33
8.2.1	Automatically switch electrodes.....	33
8.3.1	Cut-off factor to filter data.....	34
8.3.2	Method to estimate topography	35
8.3.3	Estimate data errors	36
8.4	Data import	37
8.5	Data conversion options.....	39
8.5.1	Combine 3-D files into a single data set.....	39
8.5.2	Collate 3-D files for time lapse data	39
8.5.3	Discretize streamer data file (Enterprise)	40
8.5.4	Extend or refine model grid.....	40
8.5.5	Convert trapezoidal grid to arbitrary electrodes format.....	40
8.5.6	Display maximum model and data limits	40
8.5.7	Save sorted data file.....	41
8.5.8	Convert vector array file to normal format (Professional).....	41
8.6	Change buffer drive.....	41
8.7	Set number of CPU cores.....	41
8.8	Trace program execution.....	42
9	Change Settings	43
9.1	Change inversion parameters	43
9.2	Model Grid Settings	44
9.2.1	Settings for model layers depths and sides	44

9.2.2	Settings for data in arbitrary electrode format	46
9.2.3	Settings for data in trapezoidal grid format	50
9.3	Damping and filter settings	51
9.3.1	Vertical/Horizontal flatness filter ratio	51
9.3.2	Change of damping factor with depth.....	52
9.3.3	Use diagonal filter components	52
9.3.4	Use sensitivity values to damp variations near electrodes.....	53
9.3.5	Use L-curve method to select damping factor	54
9.4	Inversion settings	55
9.4.1	Automatically reset settings for pole-pole	55
9.4.2	Select robust inversion.....	55
9.4.3	Type of optimization method.....	56
9.4.4	Try to optimize model at each iteration.....	57
9.4.5	Use reference model in inversion	57
9.4.6	Use combined inversion method.....	57
9.4.7	Limit range of model resistivity.....	58
9.4.8	Choose logarithm of apparent resistivity	58
9.4.9	Jacobian calculation options	59
9.4.10	Time lapse inversion settings (RES3DINVx64 Professional)	60
9.4.11	Calculate model resolution.....	61
9.5	Forward Modeling Settings.....	62
9.5.1	Forward modeling routine settings	62
9.5.2	Point electrode calculation settings.....	63
9.5.3	Splice large survey grids (Enterprise).....	63
9.6	I.P. inversion settings	64
9.6.1	Type of I.P. calculation method.....	64
9.6.2	I.P. damping factor	65
9.6.3	Apparent I.P. cut-off value	65
9.6.4	Change range of model I.P. values	66
9.6.5	Select type of I.P. model transformation	66
9.6.6	Type of I.P. smoothness constraint.....	66
10	Inversion menu options.....	68
10.1	Carry out inversion.....	68
10.2	Display models with 3DViewer during inversion.....	68
10.3	Batch mode inversion.....	68
10.4	Save XYZ files in batch mode inversion	69
10.5	Calculate volume of investigation (VOI) index (Enterprise)	69
10.6	Save inversion parameters.....	69
10.7	Read inversion parameters	69
11	Displaying and exporting inversion model results.....	70
11.1	Display - File menu options	70
11.1.1	Read file with inversion results	70
11.1.2	Model Export.....	70
11.2	Display - Display menu options.....	71
11.2.1	Display inversion model.....	71
11.2.2	Display model with topography	71
11.2.3	Display model with 3DViewer	72
11.2.4	Display apparent resistivity or IP	72
11.2.5	Display resistivity or IP	72
11.2.6	Display model sensitivity values	72
11.2.7	Display data sensitivity values	72
11.2.9	Display depth slice	74
11.2.10	Display model change	75
11.2.11	Select type of model change to display	75
11.2.13	VOI display options.....	75
11.3	Display - Change display settings.....	76
11.3.1	Reverse colour scheme	76

11.3.2	Customise colour scheme	76
11.3.3	Read customised colour scheme.....	76
11.3.4	Colour/Black-White display	76
11.3.5	Use Voxler Rainbow colour scheme	76
11.3.6	Fade out model sections with low resolution	77
11.3.7	Vertical display scaling factor	77
11.3.8	Type of pole-dipole display.....	77
11.3.9	Flip horizontal slice display.....	77
11.3.10	Display horizontal sections with global coordinates	77
11.3.11	Display electrodes positions for data with trapezoidal grid format	77
11.3.12	Change model display settings	78
11.3.13	Choose font.....	79
11.3.15	Save contour values.....	79
11.4	Display - Edit data menu.....	80
11.4.1	Apparent resistivity statistics.....	80
11.4.2	RMS error statistics	80
11.5	Display - Print menu	83
11.5.1	Save screen as graphics file.....	83
11.5.2	Select type of bitmap graphics format.....	83
12	Help menu options	84
13	Some field examples.....	85
13.1	Landfill survey, Sweden.....	85
13.2	Base metal deposit, Australia	85
13.3	Floating electrodes survey, Panama	86
	Acknowledgements	87
	References	88
	Appendix A : Array types in RES3DINV	91
	Appendix B : Inversion of 2-D lines with off-line electrodes	92
	Appendix C : Using Paraview to display the model.....	94
	Appendix D : Using Voxler to display the model and data	96
	D.1 Displaying the model	96
	D.2 Displaying the data.....	101
	Appendix E : Using RES3DINVx64 on different PCs.....	104
	Appendix F : Computer hardware optimizations for large data sets and models	106
	Appendix G : Method to handle large data sets with unstable arrays.....	108
	Appendix H : Incorporating data noise estimates	109
	Appendix I : Combining data from different 3-D surveys	110
	Appendix J : Converting borehole electrodes data files to subsurface point electrodes format.	113
	Appendix K : Instructions for using the 3DViewer program.	115
	K.1 Viewing inversion results in the 3D viewer during inversion.....	115
	K.2 Viewing inversion results in the 3D viewer after inversion	116
	K.3 Display options in the 3DViewer.....	117
	Appendix L : Electrodes binning and segmentation of large survey grids (Enterprise).....	122
	Appendix M : Vector array survey data inversion (Enterprise).	126
	Appendix N : Volume of investigation (VOI) calculations (Enterprise).....	129
	N.1 Theory	129
	N.2 Calculating the VOI	129
	N.3 Displaying the VOI	130
	Disclaimer.....	133
	Support	133
	What's New	134

List of Figures

Figure 1. Some possible layouts for 3-D surveys.	1
Figure 2. A simple discretization model used in the inversion program with electrodes at the surface corners of each model cell in the top layer.	4
Figure 3. Uniform rectangular grid.	7
Figure 4. Non-uniform rectangular grid.	11
Figure 5. Example of a trapezoidal survey grid.	12
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.	14
Figure 7. Fixing the resistivity of a rectangular region in the inversion model.	21
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.	21
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.	24
Figure 10. Example display of a model grid with arbitrary point electrodes.	46
Figure 11. Example a model grid with inclined survey lines resulting in large empty spaces at the top-left and bottom-right two corners.	47
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.	48
Figure 13. Example trapezoidal grid display.	50
Figure 14. Type of model grid elements. (a) Rectangular element. (b) Convex trapezoidal element. (c) Almost degenerate trapezoidal element. (d) Degenerate concave trapezoidal element.	50
Figure 15. 3-D roughness filters with different components.	53
Figure 16. Methods for arbitrary electrodes.	63
Figure 17. Example of horizontal model sections displayed using (a) local coordinates, and (b) true global coordinates.	78
Figure 18. Example of data misfit histogram and correlation plots with (a) resistivity data only, and (b) both resistivity and I.P. data.	82
Figure 19. Inversion model for the Ekeboda landfill survey data set.	85
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).	86
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.	86
Figure 22. The inversion model for the Panama Canal floating electrodes survey. The first 4 layers correspond to the water column.	86
Figure 23. Arrangement of the electrodes for the Wenner alpha, beta and gamma arrays.	91
Figure 24. Normal, reverse and offset pole-dipole array arrangements.	92
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.	92
Figure 26. Example of a 2-D survey along a crooked line.	93
Figure 27. Example 3-D plot using the ParaView program for the Ekeboda landfill survey model.	95
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.	98
Figure 29. Volume rendered plot for the Ekeboda landfill model.	99
Figure 30. X-Z slice displayed using the Orthoimage plot for the Ekeboda landfill model.	99
Figure 31. Volume rendered plot for the Ekeboda landfill model with topography included.	100
Figure 32. A roll-along 3-D survey using 3 parallel lines of electrodes.	110
Figure 33. Underwater survey in Greece. The segments used in the segmentation inversion are shown by the colored lines.	122
Figure 34. Inverse models of Model_160x20-noise.dat survey data set with (a) standard monolithic inversion, (b) using 4 mesh segments.	124

Figure 35. Inverse models of Lambayanna field data set using (a) normal inversion method with a single mesh, (b) subdivision in 8 (2 by 4) segments.	125
Figure 36. (a) Example of vector I.P. survey layout. (b) Measured potential components at a receiver station.	127
Figure 37. Example of layout of a field survey with vector array.	127
Figure 38. 3-D resistivity and I.P. models from inverse model of vector array data set.	128
Figure 39. Volume of investigation (VOI) vertical sections for the BLK10PDP_ext.dat data set.	131
Figure 40. Model resolution index vertical sections for the BLK10PDP_ext.dat data set.	131

List of Tables

Table 1. Some example data files installed with the RES3DINV program.....	5
Table 2. Example data format for a regular rectangular survey grid.....	8
Table 3. Example of a pole-dipole array data set.	8
Table 4. Example of a dipole-dipole array data set.	9
Table 5. Example of a data set with mixed arrays.....	10
Table 6. Example of a non-uniform rectangular grid data format.	11
Table 7. Example data file with trapezoidal grid format.	13
Table 8. Data format with arbitrary point electrodes.....	15
Table 9. Example data file with remote electrodes specified.	16
Table 10. Example topography information for the rectangular grid format.	17
Table 11. Example topography information given as an unstructured list.	18
Table 12. Example I.P. data file.	19
Table 13. I.P. data given as percent frequency effect.....	19
Table 14. I.P. data given as phase angles.	19
Table 15. I.P. data given as metal factor.	20
Table 16. Example data file with a fixed region.....	20
Table 17. Data format for a known boundary.	22
Table 18. Floating electrodes survey with the water layer model as a known boundary.	23
Table 19. Example data file with underwater electrodes.....	24
Table 20. Example cross-borehole data file using the pole-pole array.....	27
Table 21. Example cross-borehole data file using the pole-dipole array.....	28
Table 22. Example data file with arbitrary subsurface point electrodes.....	28
Table 23. Example data file with long electrodes.....	30
Table 24. Example data file with tank boundaries.	31
Table 25. Example time-lapse data file.	32
Table 26. Example script file to combine 3-D data files into a single time-lapse file.....	39
Table 27. Example batch file format.	68
Table 28. Arrays types used in RES3DINV.	91
Table 29. Calculation times with different versions of RES3DINVx64.	104
Table 30. Calculation times on different computers.....	107
Table 31. Example data file with estimated noise values.	109
Table 32. Example script file to combine 3-D data files into a single data file with simple shifts.	110
Table 33. Example script file to combine 3-D data files into a single data file with general coordinate transform.....	111
Table 34. Part of the File_2_general.dat file with the global coordinates parameters.	112
Table 35. Part of the bor9pdp_ip_pts.dat file with data converted from boreholes to arbitrary subsurface point electrodes format.	113
Table 36. Part of the vector_ip.dat file with data format for the vector array.	126

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 (Loke et al. 2013a, 2014a). 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 different electrode arrays and arrangements for 3-D surveys are given in the free ‘Tutorial notes on electrical imaging’ (Loke 2019). 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 256GB RAM and support survey grids with up to 200,000 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).

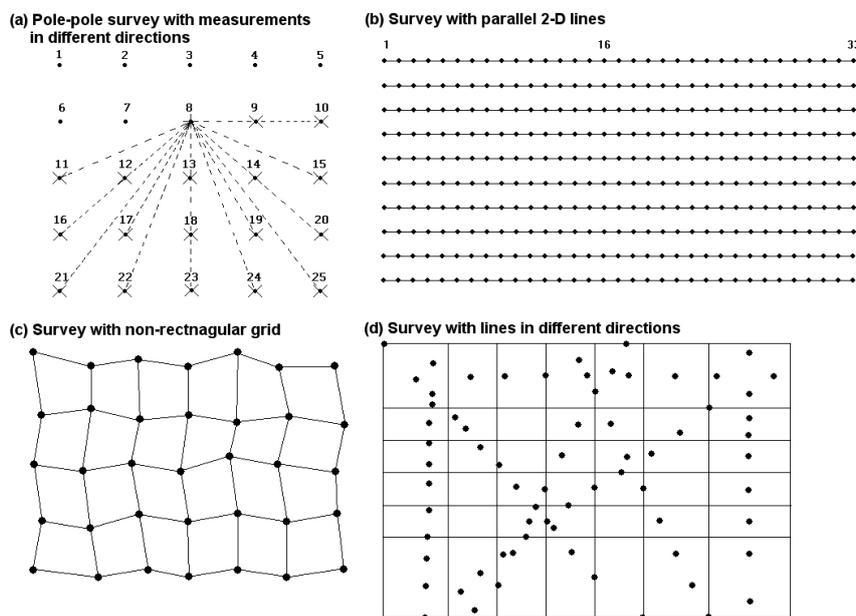


Figure 1. Some possible layouts for 3-D surveys.

2 Computer system requirements

RES3DINVx64 is a 64-bit program that will run under a 64-bit version of Windows 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 is optimized for this type of CPU.

RES3DINVx64 comes in three versions (Basic, Professional and Enterprise) depending on the license the license you have purchased. RES3DINVx64 Basic allows the use of up to 8 GB RAM while RES3DINVx64 Professional can access up to 256 GB RAM. The Enterprise version has additional features such as segmentation of large survey grids, inversion of data for vector arrays and VOI calculations. The following section has more details on the differences between the different 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 (not 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 Sate 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 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 be used with PCs having a dual operating system such as Windows and Linux.

2.1 Differences between RES3DINVx64 Basic, Professional and Enterprise

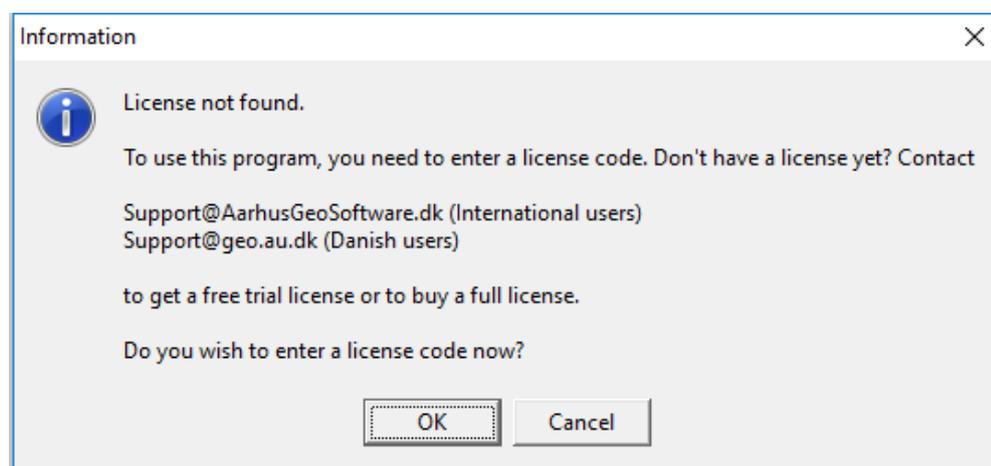
The version of RES3DINVx64 that the user is allowed to use depends on the license the software has. The main differences between the two versions are as follows.

- 1). Res3dinvx64 Basic is limited to 8 GB RAM memory space while Res3dinvx64 Professional can access up to 256GB 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 1.6 million nodes. In Res3dinvx64 the maximum mesh size depends on the computer RAM. With 256GB, it supports up to about 12 million nodes.

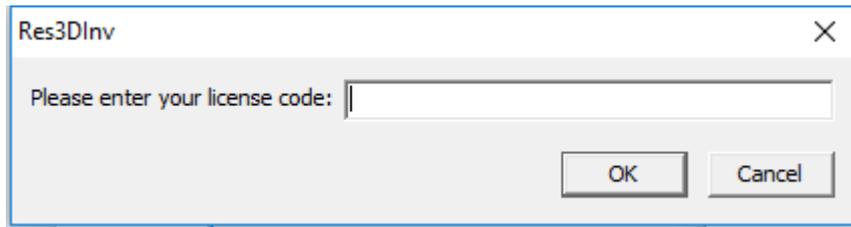
RES3DINVx64 Basic is probably sufficient for medium size surveys with up to several thousand electrodes positions. RES3DINVx64 Professional is recommended for more complex survey arrangements (particularly for mineral exploration) with very large surveys grids with tens of thousands of electrodes positions, data points and model cells, or for time-lapse surveys. RES3DINVx64 Enterprise version has all the features of the Professional version plus a few extra options, namely (i) mesh segmentation for inversion of very large surveys grids and data sets (with over 100,000 electrodes positions and data points), (ii) support for data sets with up to 600,000 electrodes positions and data points for workstations with 256GB RAM, (iii) vector array inversion and (iv) VOI (volume of investigation) calculation (Oldenburg and Li. 1999).

3 Copy protection

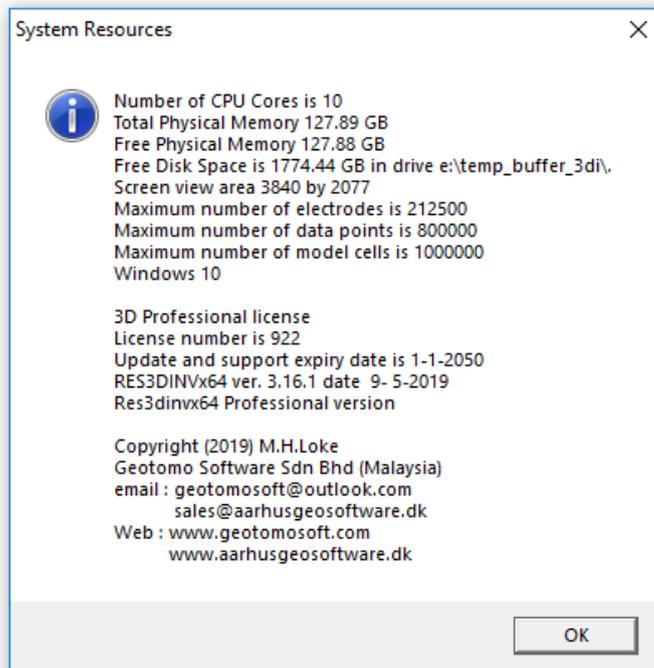
The program uses the Aarhus Geosoftware Internet based digital copy protections system for copy protection. Without the digital license, you can use the program to invert data sets with up to 200 electrodes (with a limit of 4 iterations in the inversion routine). If you had purchased the license for the 2-D resistivity/IP inversion program (RES2DINV) only, you can process data sets with up to 1000 electrodes (with a limit of 5 iterations) using the license provided with the Res3dinvx64 Starter version. With 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:

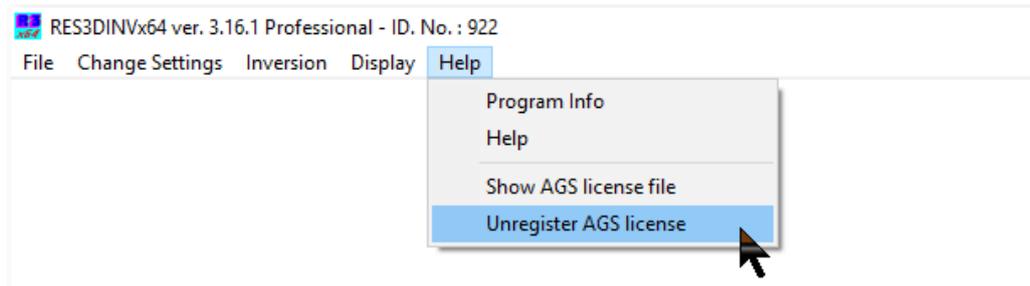


It is also possible to see the license information in ‘Help -> Show AGS license file’.

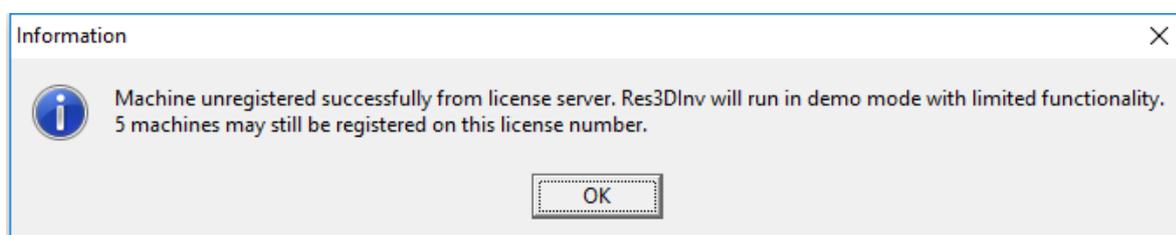
To unregister a license for use on another pc

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 -> Unregister 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 (Loke et al. 2003). The basic smoothness-constrained least-squares method is based on the following equation.

$$(\mathbf{J}^T \mathbf{J} + \lambda \mathbf{F}) \Delta \mathbf{q}_k = \mathbf{J}^T \mathbf{g} - \lambda \mathbf{F} \mathbf{q}_{k-1}, \quad (4.1)$$

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

$\alpha_x, \alpha_y, \alpha_z$ = weights for roughness filters

\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

k = iteration number

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. 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.

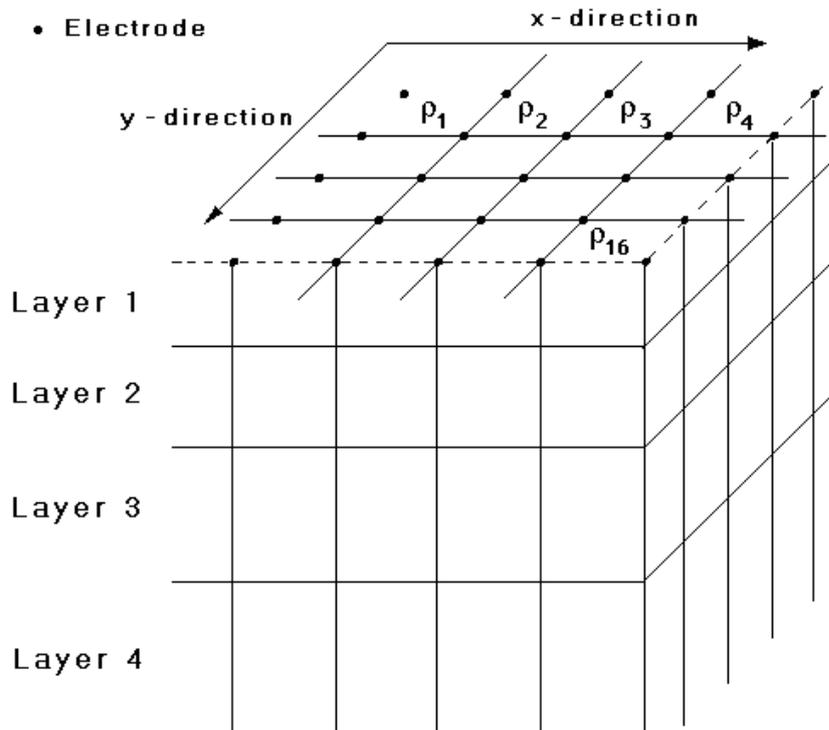


Figure 2. A simple discretization model used in the inversion program with electrodes at the surface corners of each model cell in the top layer.

5 Software installation

You can download the programs from the www.aarhusgeosoftware.dk website. 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\AGS\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.

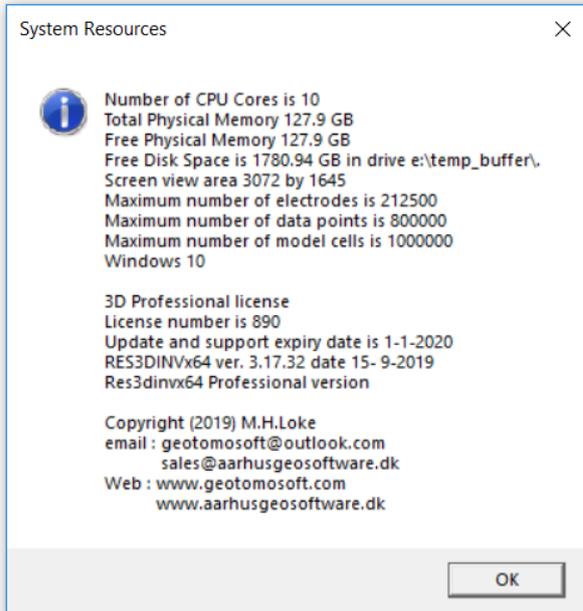
Depending on the type of field equipment you are using, the manufacturer of the equipment will probably also supply you with supplementary programs and example files to convert the raw data files obtained with the instrument into the format required by this program.

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

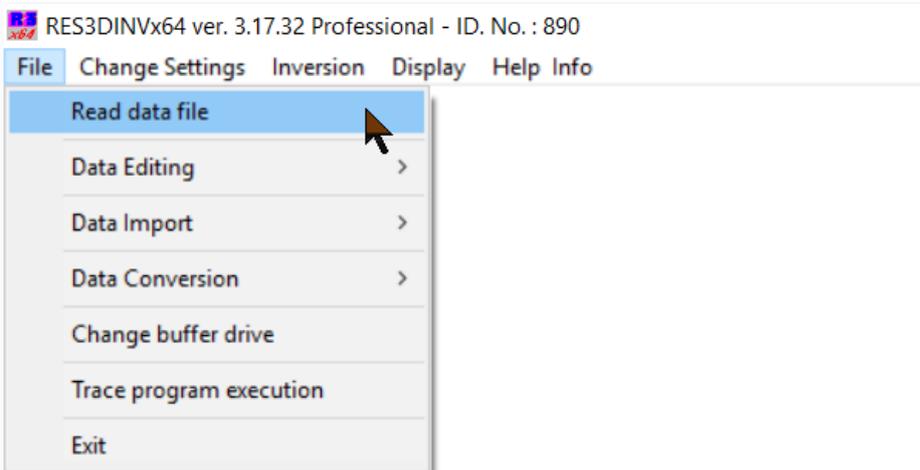
Res3dinvx64.exe	Main inversion program
Res3dinvx64_Intel_AVX2.exe	Version of program optimized for recent Intel CPUs supporting AVX2 instruction sets.
Res3dinvx64.PDF	Manual in PDF format
Res3dinv_Guide.pdf	Brief guide for getting started using RES3DINVx64
Res3dinv.chm	Windows Help file for this program
.dat-files	Input files containing data from DC (IP) surveys in a format that can be read by RES3DINVx64. In this manual, you can find numerous examples where different data files are used for inversions with different settings and configurations.
.inv-files	Output files containing inversion results.
.ivp-files	Files containing inversion parameter settings
.bth-files	.bth-files are used for batch inversions where multiple data sets can be scheduled for inversions. See examples below in this manual.
.txt-files	Used for forming a time lapse data set from individual data sets.
Combine-3D.ZIP	Example files used for demonstrating how multiple 3D data sets can be combined into a single data set.
RES3DINV.INI	Configuration file for the RES3DINVx64 program.
/misc_files	Subfolder containing numerous examples of input and outputs that can be used for testing different types of setups and/or inspiration for setting up inversions.

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. If necessary, navigate to the folder where the RES3DINVx64 program is installed to find the example data files. 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 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 formats

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 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 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. The rectangular (sections 7.1.1, 7.1.2) and trapezoidal (7.1.3) are intended for surveys with the electrodes arranged in a regular pattern. For more general arrangements, it is recommended that the arbitrary electrodes (7.1.4) format should be used.

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.

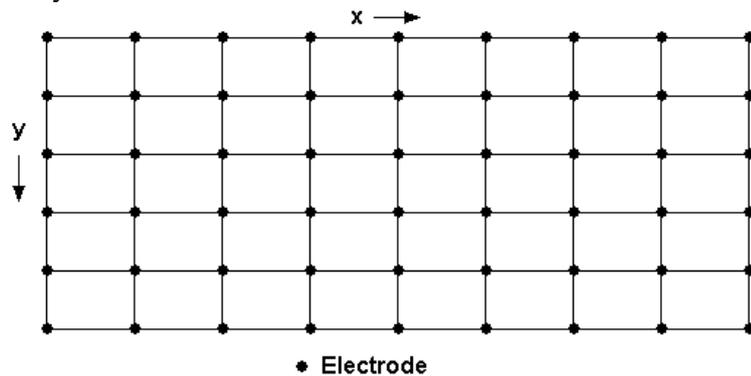


Figure 3. Uniform rectangular grid.

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>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. In the data file only 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>Followed by a few 0's: these are flags for other options, such as topography</i>
.	
.	
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.

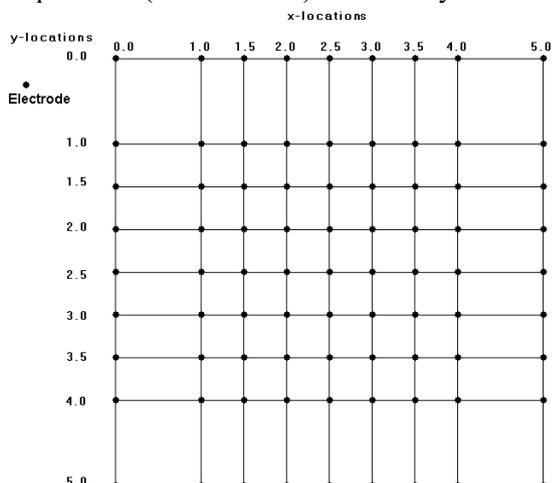


Figure 4. Non-uniform rectangular grid.

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 shows 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 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 would be better (see the following section).

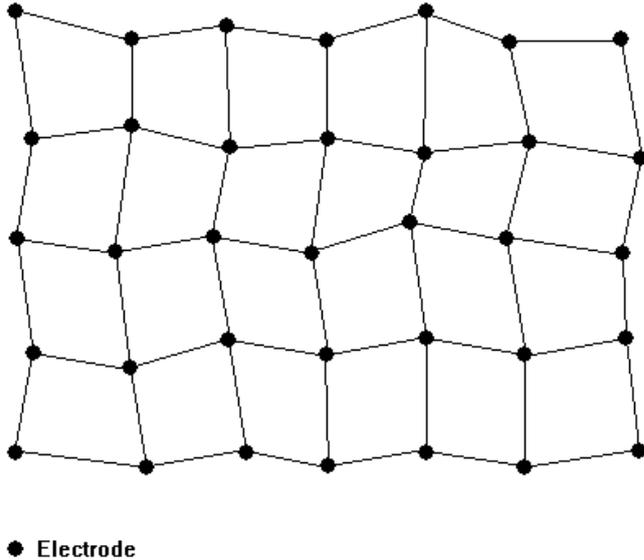


Figure 5. Example of a trapezoidal survey grid.

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 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 I.P. 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</i>
0.00, 0.00 0.00, 6.00 102.4530	<i>Resistivity. The format for the rest is the same as before for rectangular grids.</i>
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.

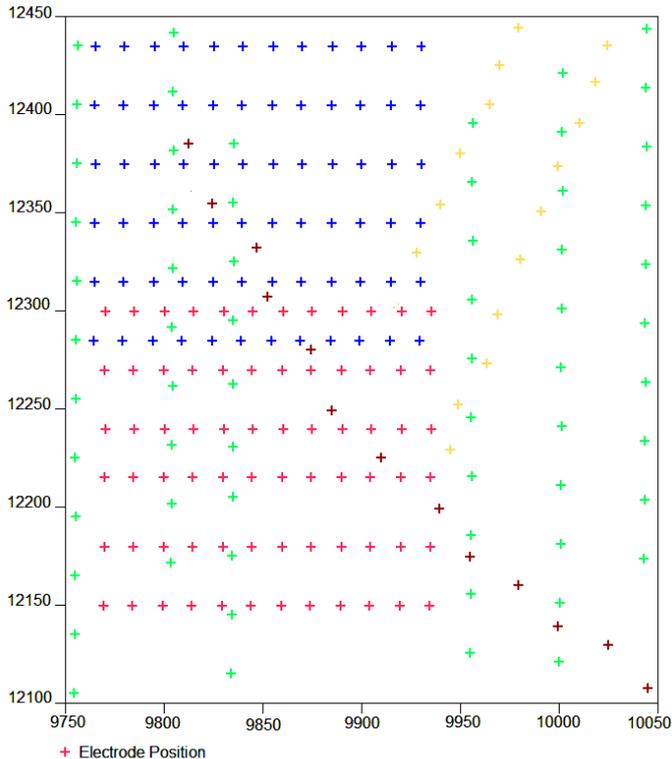


Figure 6. Survey with electrodes at arbitrary positions. Map showing positions of electrodes from different survey phases (marked by different colors). The different survey lines can have different electrode spacings and orientations.

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 2 to 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 if 4 mesh lines per model block is used. The survey area in Figure 6 is about 300 by 350 meters. If model blocks with 10 meters widths are used for the entire region, this would 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 many field data sets, all of the electrodes might be in the arbitrary point electrodes list. To avoid the two-line header for each point electrode, it is also possible to use a compressed format by specifying the header ‘Compressed format used for point electrodes coordinates’. As an example of this, see the file BLOCK12x11_points_compressed.dat.

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 allows 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).

The file Burra_1966_res.dat is an example field data set with electrodes in arbitrary positions together with topography.

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 actor.

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, such as in the Burra_1966_res.dat file. 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. This is useful to set the topography values in areas where there are no electrodes.

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 0.0	<i>1st topography data point</i>
2 1.0 0.0 0.0	<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 apparent resistivity measurements and apparent I.P. values. The file MODEL3IP.DAT is an example data file with both resistivity and I.P. 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 I.P. 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>
Percent frequency effect	<i>Type of IP data</i>
%	<i>IP unit</i>
1.0,10.0	<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.

If the data set contains I.P. values, known I.P. values can also be specified for fixed regions. The fixed I.P. value is specified after the fixed resistivity value, and in the same line. An example can be found in the file MODEL3IP_Fix.dat.

Rectangular regions

Data format

R

 x_1, y_1, z_1 x_2, y_2, z_2 ρ

2.0

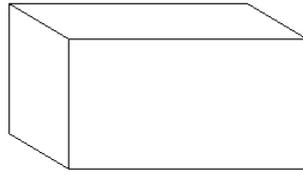
 (x_1, y_1, z_1)  (x_2, y_2, z_2)

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.

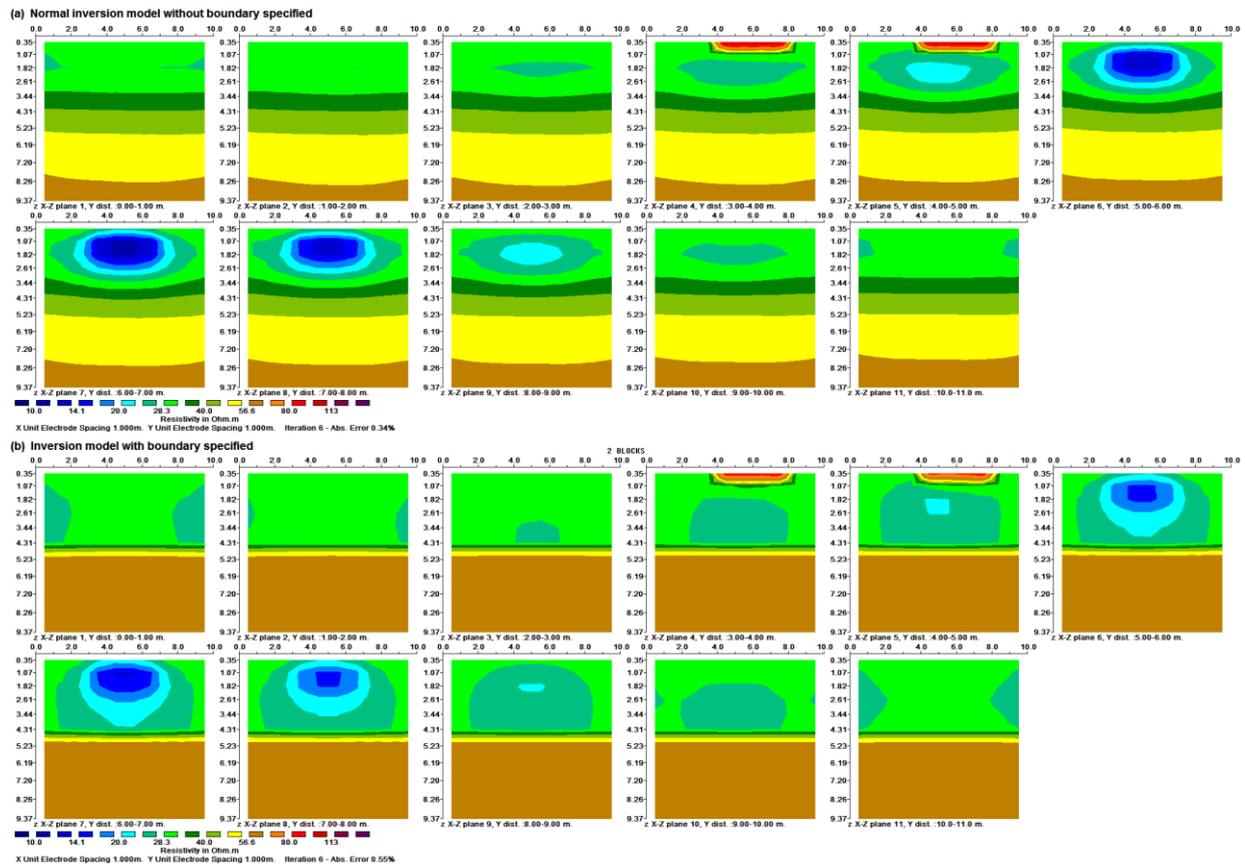


Figure 8. Inversion models for a surface survey, with and without a sharp boundary specified in the data file. The data was created from a synthetic model with a boundary at 4.8 meters between two layers with resistivities of 30 ohm.m and 60 ohm.m.

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.

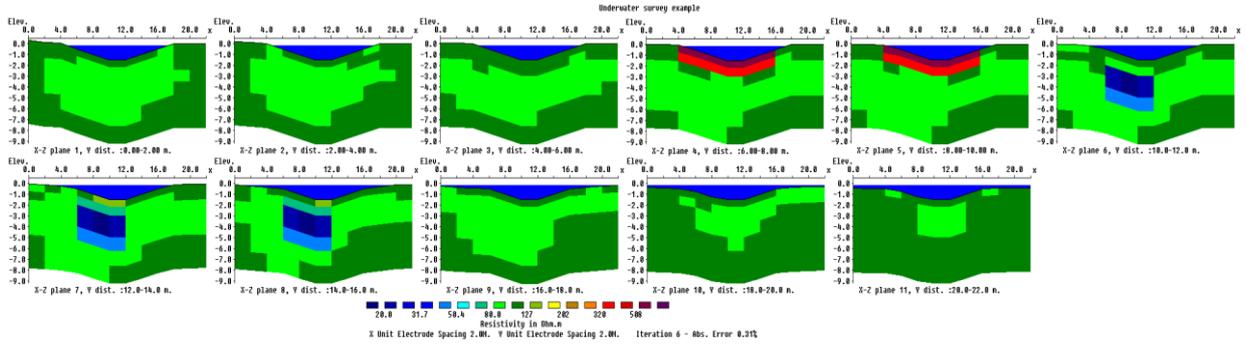


Figure 9. Example model from a survey with underwater electrodes. Plot of the model sections with topography from the WATER3D.INV file. The water layer is indicated by the blue zone at the top part of the sections. Note that some of the electrodes are above the water level, i.e. this data set has electrodes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

7.7.1 Borehole electrodes format (deprecated)

This format was used by previous versions of Res3dinvx64 up to ver. 3.16, but is not directly used in the present version. From ver. 3.17 onwards, a data file given in this format is automatically converted into the subsurface arbitrary electrodes format (section 7.7.2).

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. A similar data set where the grid is specified in a non-uniform format is given in the file BOR9ALL_NUGRID.dat. 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.

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. The borehole format has been superseded by the arbitrary subsurface electrodes format (described in the following section).

7.7.2 Arbitrary subsurface electrodes format

This is a modification of the arbitrary electrodes option that allows arbitrary subsurface electrodes including non-vertical boreholes. 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 necessarily coincide with the depths where the subsurface electrodes are located. Appendix J describes a modification of the data format where the depths to the layers are specified to ensure they coincide with the borehole electrodes.

The example data file `Subsurface_point_elects.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 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.

The file `BOR9ALL_sub_user_depths.dat` gives an example of how the data in the (deprecated) file `BOR9ALL.dat` is represented in the arbitrary subsurface electrodes format.

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

<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>

7.7.3 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.

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 (2019) 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	<i>The format for each data point is: electrodes used in measurement; x-, and y-locations and depth below surface of C1 electrode; x-, and y-locations and depth below</i>
2 0.000, 0.000, 0.000 2.000, 0.000, 0.000 99.922	
...	
2 3.000, 0.000, 0.000 0.500, 0.500, 0.350 99.484	

2	3.000, 0.000, 0.000	0.500, 0.500, 4.416	98.910	<i>surface of P1 electrode</i>
2	3.000, 0.000, 0.000	0.125, 0.500, 8.518	99.484	
...				

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 extend 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 (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.

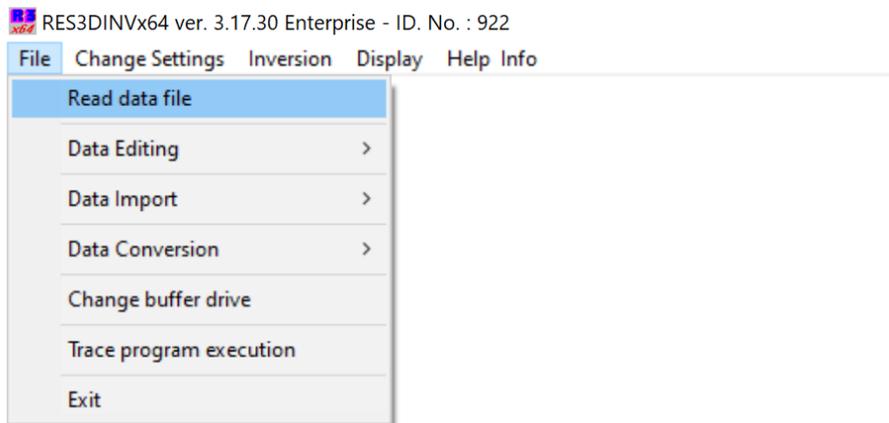
Table 25. Example time-lapse data file.

<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.

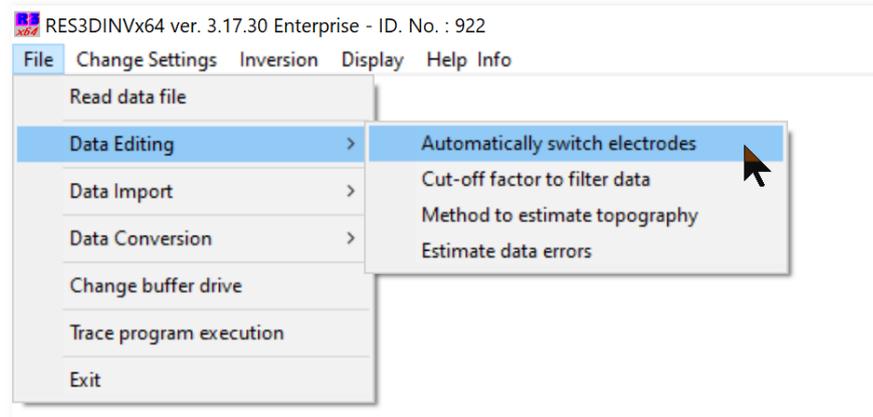


8.1 Read data file

This option reads in a data file in the RES3DINV 'dat' format, as described earlier in section 7.

8.2 Data editing options

This covers several options that change the input data file when it is read in.



8.2.1 Automatically switch electrodes

Clicking this option will bring up the following dialog box.

Switch electrodes

In some resistivity meters, electrode positions are stored in orders result in a negative geometric factor. E.g. dipole-dipole positions may be stored in the order C1-C2-P1-P2 rather than the correct order C2-C1-P1-P2.

Would you like the program to automatically switch electrodes for measurements where geometric factor is negative? Note that this setting does not work for dipole-dipole data and for cross borehole surveys.

- Do not switch electrodes
 Automatically switch electrodes

In some data sets, apparent resistivities are "erroneously" negative (e.g. for the C1-C2-P1-P2 dipole-dipole configuration with a negative geometric factor).

This option forces the apparent resistivity values to be positive. Note that there are cases where negative apparent resistivities might be real. In such cases, this setting should not be applied.

- No - do not force positive values
 Yes - force values to be positive

For data sets using the Wenner-Schlumberger configuration, the time for calculating the Jacobian during inversions may be reduced by swapping potential and current electrodes (e.g. assuming measurements were reciprocal).

Would you like the program to automatically swap potential and current electrode pairs when loading Wenner-Schlumberger data?

- No - do not swap electrodes
 Yes - swap electrodes

After reading in the data set, the program will sort the data points according to the electrode position, and in some cases convert the resistance to apparent resistivity values.

Do you want to save the sorted and converted data set in a different file?

- No - do not save the sorted data
 Yes - save the sorted data set

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. It should be noted that in some situations, the negative apparent resistivity values might be real. In this case, the sign of the apparent resistivity should not be automatically changed to positive. This is discussed in Appendix C of the lecture notes by Loke (2019). The third option swaps current electrode pairs when loading datasets using the Wenner-Schlumberger array configuration. This may reduce the computational work and time required to calculate the Jacobian during inversions (Loke et al. 2020). The fourth option allows the user to save the data, after it has been read and sorted by the program. The choice of the three above options will be reflected in the resulting, sorted data set.

8.3.1 Cut-off factor to filter data

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 non-colinear arrays, such as the offset type of array (where the current and potential electrodes are on different survey lines), the geometric factor relative error (Wilkinson et al. 2008, Loke et al. 2014b) can be used to filter out arrays that are likely to be unstable. Arrays with high geometric factor relative errors are very sensitive to errors in the positions of the electrodes.

8.3.2 Method to estimate topography

This option is only relevant for data with arbitrary point electrodes (section 7.1.4) that has topography as well and/or for data where topography is specified in an unstructured list (section 7.2.4). The program has three methods to estimate the topography for the model grid, as shown by the following dialog box. 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 very jagged contours. To avoid this, the second method that uses all the point electrodes to estimate the topography will give a more gradual variation in the topography. For large data sets, the two above methods tend to be very slow. A third, generalized method allows the user to specify the number of neighboring topography points for the interpolation of each grid point. This method is much faster than the abovementioned method. If the number of points with topography specified is very large, performance during data load can be improved substantially by not using all points during interpolation. The default setting is 50 which typically provides plausible topography interpolation and performs well. If the specified number of electrodes (or points with topography specified) exceeds the actual number of points, all neighbors will be included for interpolation.

Type of method to estimate topography

This option is only relevant for data with topography specified at point electrodes or in a separate list. Topography is interpolated to grid nodes by nonlinear weights based on inverse distances to the nearest points where topography is given. Two legacy methods use either the nearest 4 or all points with topography specified, respectively. For large data sets, these methods tend to be very slow. A third method uses a much more efficient and generalized algorithm to search for neighboring points. With this method, the minimum number of neighbors is specified. The method does not work for trapezoidal grids.

For some data sets, large areas of the model grid might be far away from the nearest topography points. In such areas, using only a few neighboring points, might lead to jagged topography. Increasing the number of neighbor points, will produce a topography interpolation.

- Use nearest 4 point electrodes
 Use all point electrodes
 Use nearest electrodes (fastest method)

8.3.3 Estimate data errors

This option estimates the likely data errors if they were not directly measured in the field survey using a voltage dependent model (Zhou and Dahlin 2003). It is assumed the likely data noise is proportional to the geometric factor of the array used and also the sensitivity of the geometric factor to errors in the positions of the electrodes. The user must enter the values for background noise, input current and accuracy of the electrode positions in the following dialog box.

Estimate data errors

You can estimate the data error if it was not directly measured by using the geometric factor of the arrays used. In general, the data error should increase with the geometric factor.

Calculate data error estimates :- No - do not estimate errors Yes - estimate errors

The estimated error use the assumed background noise in mV and the current used in mA. You can default values below to fit the survey conditions and the field instrument used.

Background noise in mV :- Current used in mA :-

Type of normalization used for data error vector. You can choose to normalize the data error vector so that the average weights is equals to 1.0, which is the same as the case without the data error estimate. This will give higher weights to the arrays with the lowest geometric factors in calculating the data misfit. Alternatively you can set the weights for the arrays with the smallest geometric factor to 1.0. The contribution to the data misfit calculated for the arrays with the smallest geometric factors will be the the same as without the data estimates, but the contribution for the arrays with very large geometric factors will be greatly reduced. The overall data misfit value reported will be lower.

Select type of normalization :- Use average weight of 1.0 Set maximum weight of 1.0

To ensure the calculated estimated errors are not too small, a minimum value is set for the estimated error as a percentage of the measured value as field surveys will always have some background noise. The percentage error can be changed to a value which you think is more appropriate for your survey.

Minimum percentage error :-

The error in the calculated apparent resistivity value due to errors in the positions of the electrodes can also be included if it is known. If a value of 0.0 is given, the contribution of the electrode position error will not be included.

Electrode position error :-

NOTE : This option must be selected before you read in the file with the data set where the error values are to be estimated.

8.4 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 RES2DINVx64 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.

Importing data from Geosoft GDB format

The program supports import of ERT/IP data from a Geosoft GDB file. The importer assumes that the relevant data is present in channels with specific predefined names. For a successful import, at least the position of one current electrode and one potential electrode must be present in the database. These two channels must be named T1X, T1Y, R1X and R1Y, respectively. T1X/T1Y are (true) horizontal coordinates of first current (transmitter) electrode, and R1X/R1Y describe the position of the first potential (receiver) electrode. If only four channels with electrode positions are specified, it will be assumed that all measurements are pole-pole. Similarly, 3 or 4 electrode configurations can be imported if channels named R2X/R2Y (second potential electrode position) and/or T2X/T2Y (second current electrode), respectively, are present.

Furthermore, it is required that apparent resistivities can be extracted directly or calculated from channels within the database. Apparent resistivities will be loaded directly from a channel named RHOA if present. Alternatively, if no RHOA channel is found, the program will look for two channels named VP and I, which will be assumed to contain measured potential and current (given in Volts and Ampere, respectively).

Topography can also be imported if channels named T1Z, R1Z, ... etc. (corresponding to the existing x-position channels) are available. It is assumed that topography and lateral (x,y) positions are given with respect to true horizontal coordinates (see above chapter on topographic data formats).

I.P. data can also be imported if a channel named CHG exists. Res3DInv assumes that such data is given in units of msec and is a result integrating the I.P. decay curve from 0.1 s to 1.0 s. If these settings need to be changed, they can easily be modified in the resulting .dat-file (see section 7.5).

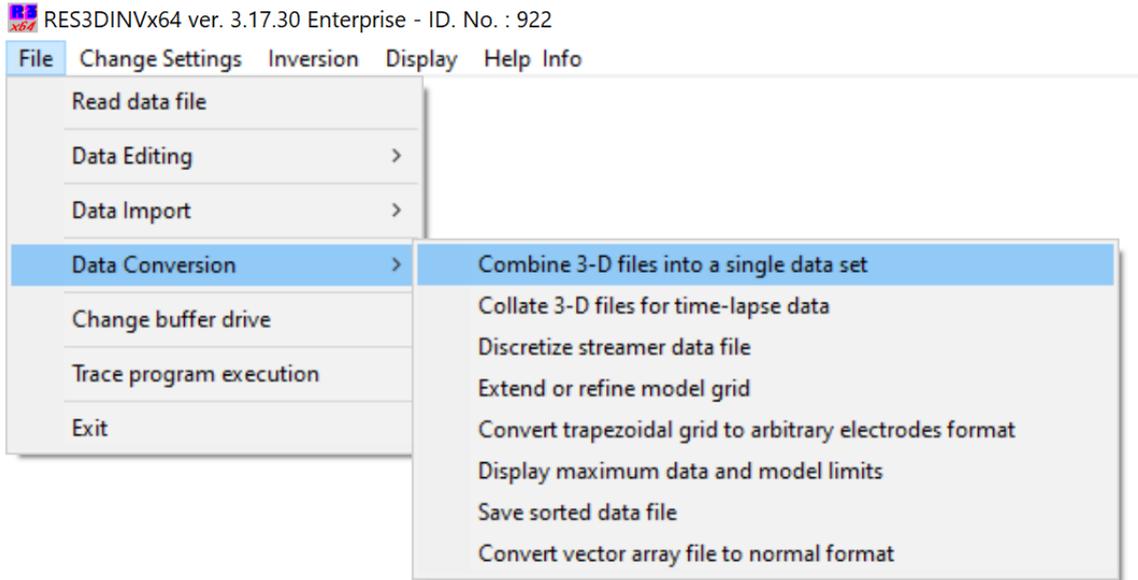
The import procedure for Res3DInv will use data from all lines of the imported GDB file and assemble this into a single .dat-file.

Note that the resulting file will list all electrodes as point electrodes, and a default 10 by 10 grid spanned by minimum/maximum coordinates of electrodes will be specified. To proceed with a setting up inversions, the user must therefore adapt the grid line positions and resolution to the specific set of measurements (see section 9.2.2).

Importing from GDB files requires installation of a set of files. The steps needed for this are described in Appendix O.

8.5 Data conversion options

This covers several options that convert the input data file.



8.5.1 Combine 3-D files into a single data set

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

8.5.2 Collate 3-D files for time lapse data

This option allows the user to combine separate 3-D data files using the same survey grid but measured at different times into a single time-lapse data file. On selecting this 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>
Exclude measurement if not defined at all times	<i>If measurements a made for some but not all times at a given electrode configuration, these measurements can either be included or ignored.</i>
1	<i>1 indicates that such measurements will be excluded. 0 will let them be included. 'Missing' measurements will then be assigned 0.0 resistivity which in turned will be ignored during the inversion process.</i>
Convert resistance data to apparent resistivity	<i>If measurements are given as resistance values, the collate function may either retain the use of resistance or convert to apparent resistivity.</i>
0	<i>0 Indicates that resistance values are retained.</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>

8.5.3 Discretize streamer data file (Enterprise)

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

8.5.4 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) :-

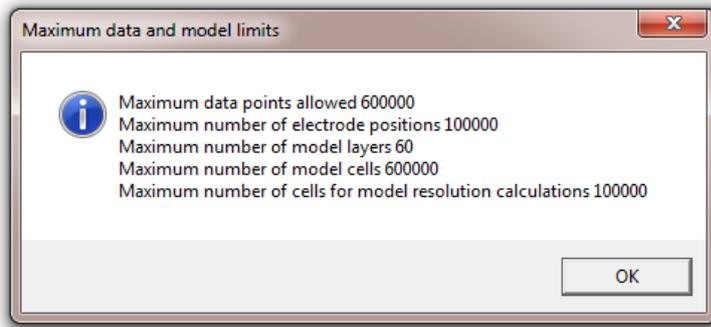
Refine model y-grid (0 or 1) :-

8.5.5 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 electrode 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.

8.5.6 Display maximum model and data limits

This option displays 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.

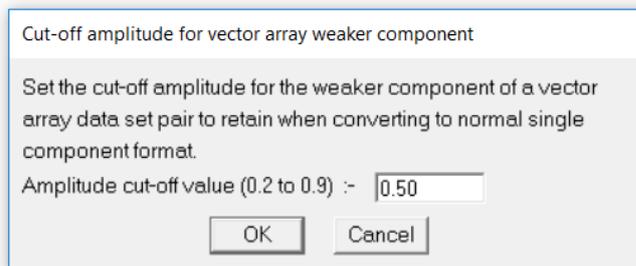


8.5.7 Save sorted data file

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.

8.5.8 Convert vector array file to normal format (Professional)

This option converts a data file in the vector array format to the normal single-component format. After reading in the data file, select the 'File – Convert vector array file to normal format' option as shown below. This will bring up the following dialog box.



The measurement with the larger amplitude, such as r_a in Figure 35b, is always saved to the data file. The weaker component r_b is included only if its amplitude is sufficiently large. The acceptable amplitude of the weaker component compared to the stronger component is set in the dialog box (for example $r_b > 0.5r_a$) for it to be retained in the data file. This avoids measurements with very low potentials and very high geometric factors where the calculated apparent resistivity value is very sensitive to noise. The user must have the Professional or Enterprise software license to use this option.

8.6 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.

8.7 Set number of CPU cores

Res3dinvx64 is parallelized and execution time for large inversions can be reduced by using several CPU cores. Generally, a high number of cores results in the fastest inversions, but using many cores also involves a computational overhead that increases execution time. In general, only large inversion problems benefit from using all available CPU cores. Note that some Intel CPUs use hyperthreading which (if activated) makes a computer appear to have twice the number of CPU cores (logical cores) than the actual number of physical cores. Hyperthreading does not work well for the calculations performed by Res3dinvx64, and the number of CPU cores used for inversions should not exceed the number of physical cores on your computer. The option to set the number of CPU cores also

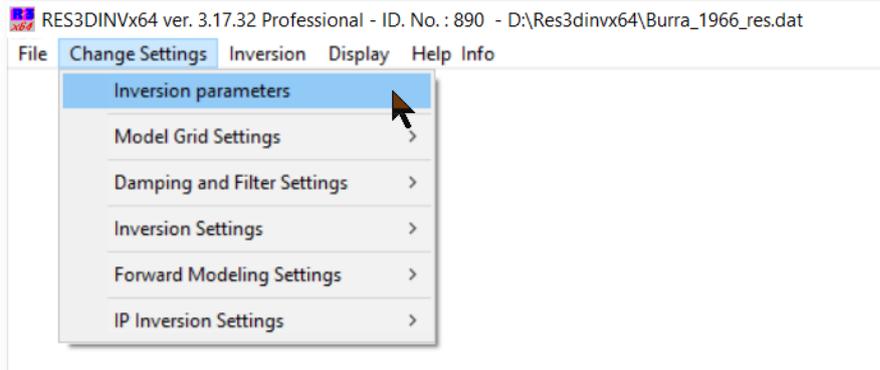
allows limiting hardware utilization if inversions are run on e.g. shared computational resources where several users have access.

8.8 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.

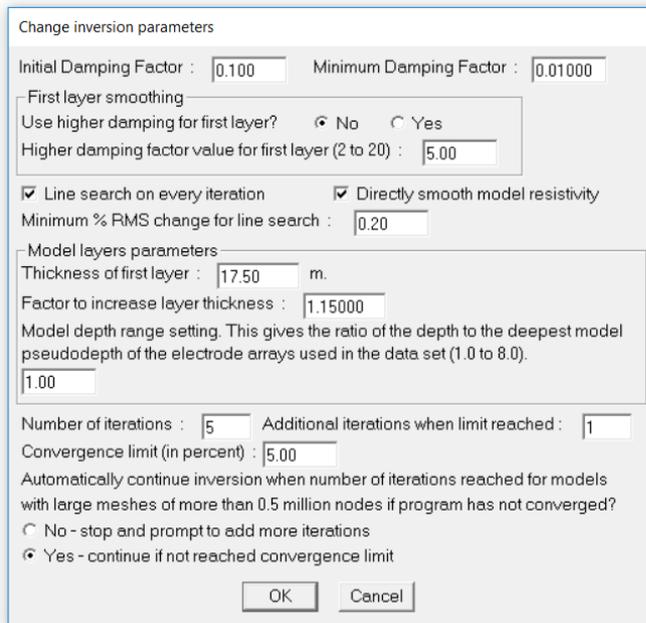
9 Change Settings

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 the layer thickness of the first layer in the inverse model.

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.

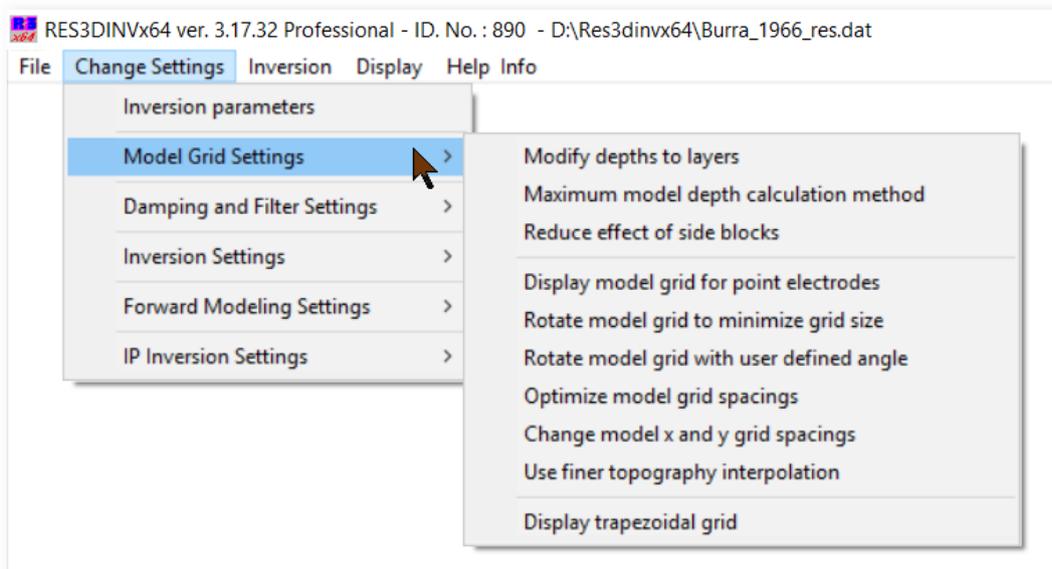
Additional iterations when limit reached - This sets the default additional number of iterations to be added when the maximum number of iterations is reached. If the value is greater than 0, the program will automatically proceed with the inversion without stopping if the convergence limit has not been reached for cases where the number of nodes in the finite-difference or finite-element mesh used exceeds 500,000 nodes. For large models, it can take several hours or days for the program to converge. This avoids stopping the program for several hours for a user input if the maximum number of iterations set is reached at odd hours when the program is not being manually monitored.

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.

Automatically continue inversion - For models with large finite-difference or finite-element meshes with millions of nodes, each iteration might take more than one hour. As the inversion to the number of iterations set could take several hours, the program might stop when it has reached the maximum number of iterations set at a time when it is not being monitored. This option allows the program to automatically continue if it has not reached the convergence limit even after it has reached the number of iterations set.

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

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 model blocks 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 8.9).

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 and non-uniform grid format

Display/edit grid and view point electrodes: This option displays the model grid together with the positions of point electrodes for a data file with the arbitrary electrodes (section 7.1.4) or non-uniform grid format (7.1.2). 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.

RES3DINVx64 ver. 3.19.1 Enterprise - ID. No. : 2075

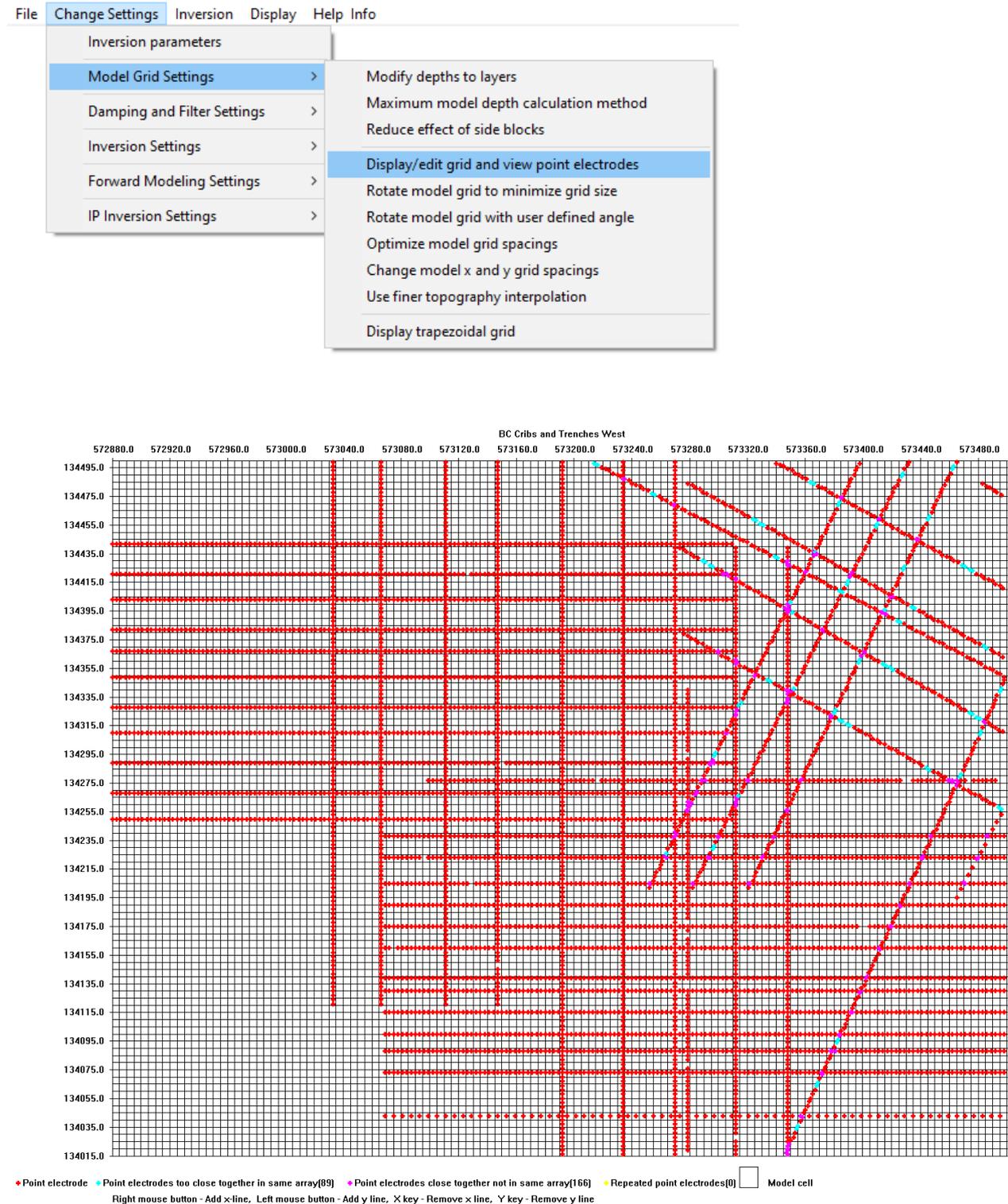
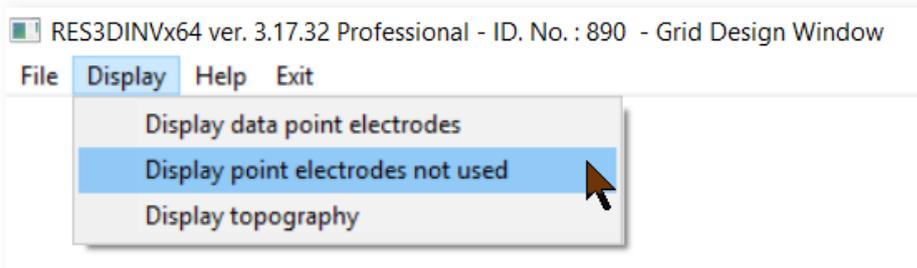


Figure 10. Example display of a model grid with arbitrary point electrodes.

The display or data can be modified is the 'Display' menu option within the sub-window showing the model grid and electrodes.



Display data point electrodes :- This option displays the electrodes used by a selected data point in green.

Point electrodes display options :- The user can select not to display the electrodes listed in the data file but are not used by the data points.

Display topography :- This option draws the topography contours.

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).

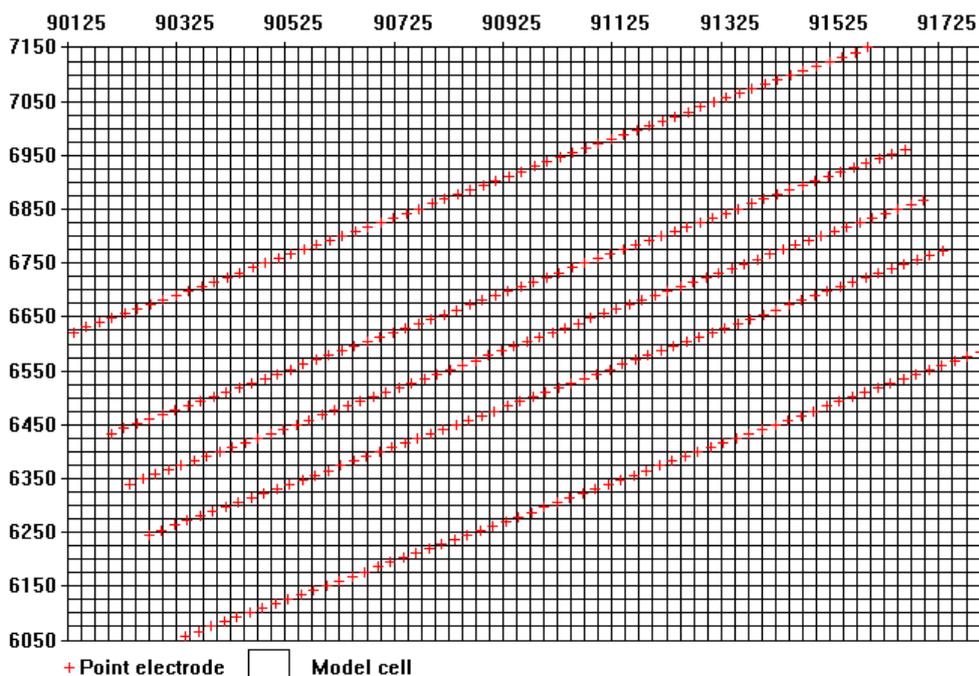


Figure 11. Example a model grid with inclined survey lines resulting in large empty spaces at the top-left and bottom-right two corners.

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.

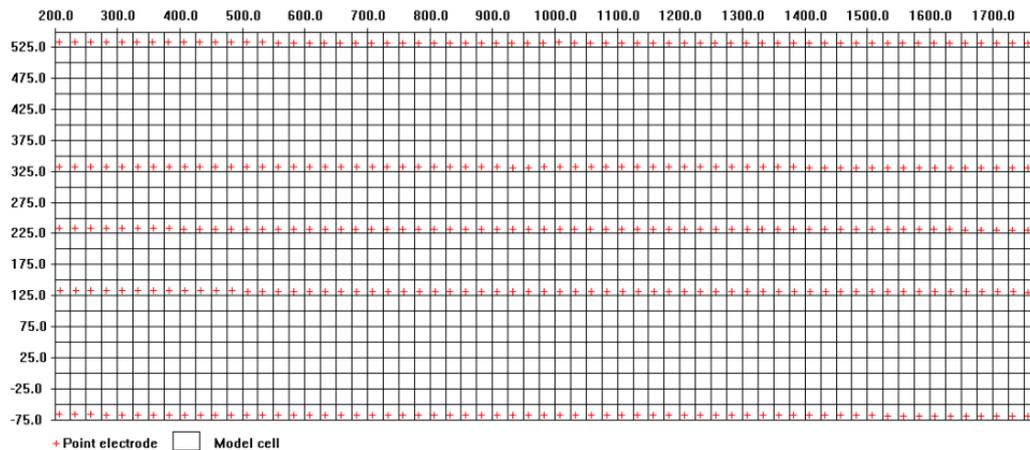


Figure 12. Model grid after a rotation of 20 degrees so that the model grid axis is aligned along the direction of the survey lines.

Change model x and y grid spacings : This option changes the x and y model grid spacings. In the example below, the survey was carried out using an electrode spacing of 100 m along lines in the x-direction with spacings of 200 to 400 m between the lines in the y direction. To reduce the model mesh size, a wider spacing is used in the y-direction.

Change x and y model grid spacings

Current X and Y model grid spacings are 100.00 and 200.00. Minimum electrode spacing is 90.00.

Replace present model grid with a new uniform grid? No, use present grid. Yes, use new uniform grid.

New X uniform model grid spacing :- New Y uniform model grid spacing :-

You can extend the model grid by changing the X and Y limits listed below.

New minimum X grid position :- New maximum X grid position :-

New minimum Y grid position :- New maximum Y grid position :-

Instead of changing the minimum and maximum positions of the model grid manually, you can select to add two model grid lines at the edges of the grid automatically. Add edge model grid lines automatically?

No, do not add edge grid lines. Yes, add extra edge grid lines.

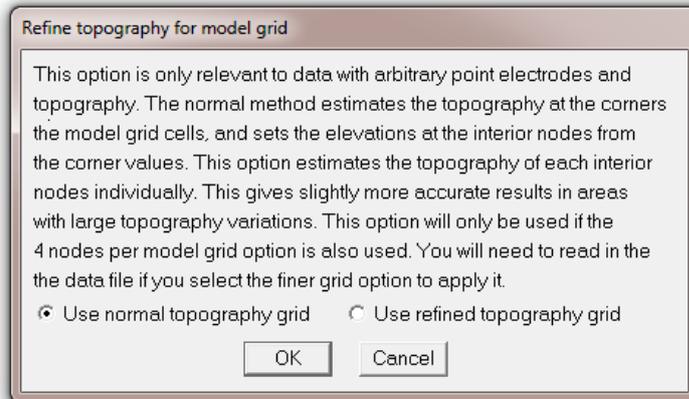
Do you want to use wider grid spacings in regions with few electrodes? This can significantly reduce the number of model grid lines if the distribution of electrodes is very irregular, or if there are remote electrodes used with the pole-dipole or gradient type of arrays.

No, do not adjust model grid spacings. Yes, automatically adjust model grid spacings.

The x and y edges of the model grid can also be changed directly by entering the coordinates, or automatically by choosing the option to add two extra grid lines at the sides. This reduces artifacts at the edges of the model due to structures outside the region covered by the electrodes used in the survey.

The user can also choose to optimize the grid spacings so that wider model grid spacings are used in regions where there are few electrodes, such as in the region between the main survey area and the remote electrodes used in gradient and pole-dipole type of surveys. This is the same as the “**Optimize model grid spacings**” option described previously.

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 block can be taken into account.



9.2.3 Settings for data in trapezoidal grid format

Display trapezoidal grid

This option displays 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.

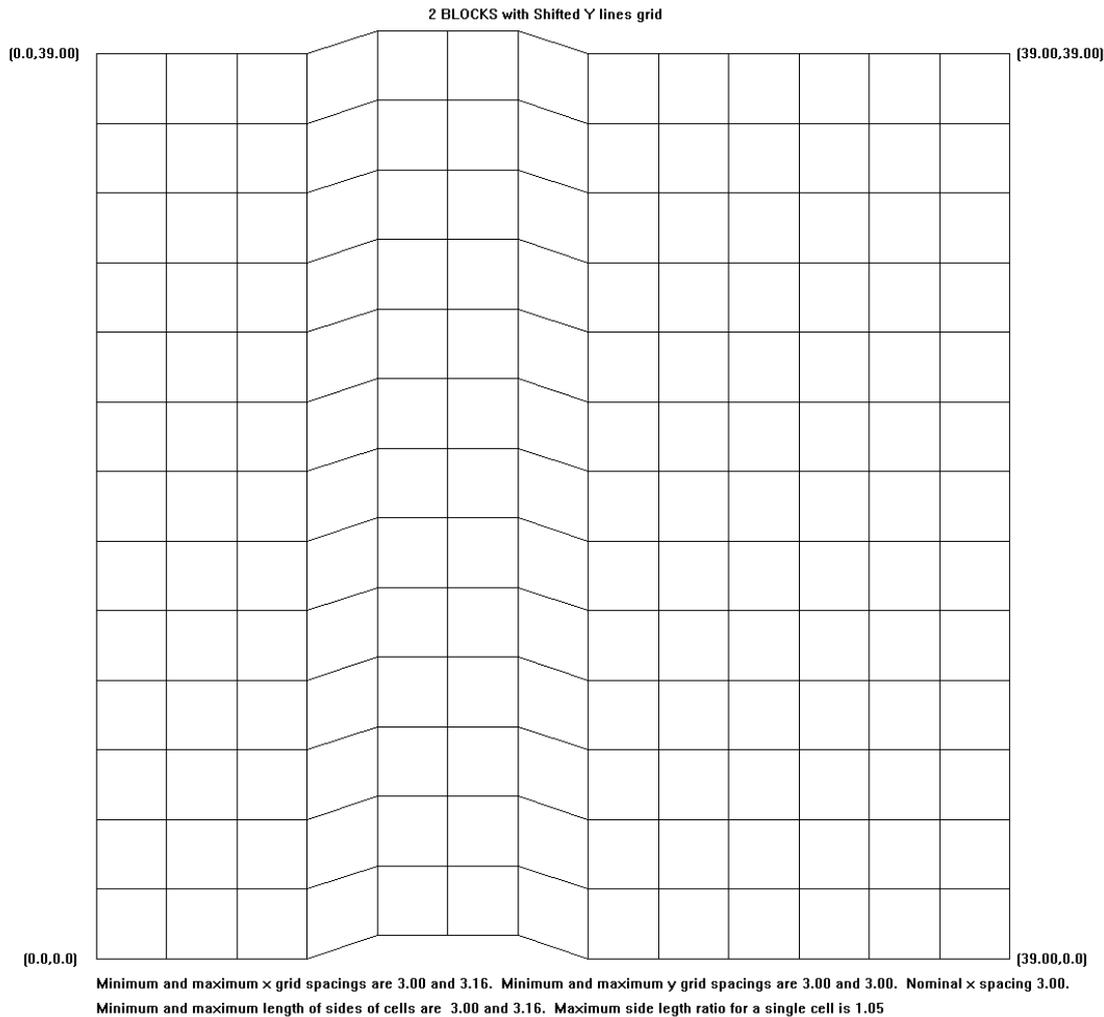


Figure 13. Example trapezoidal grid display.

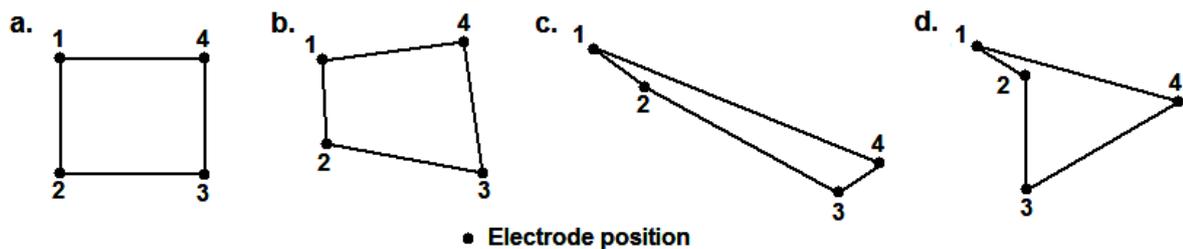
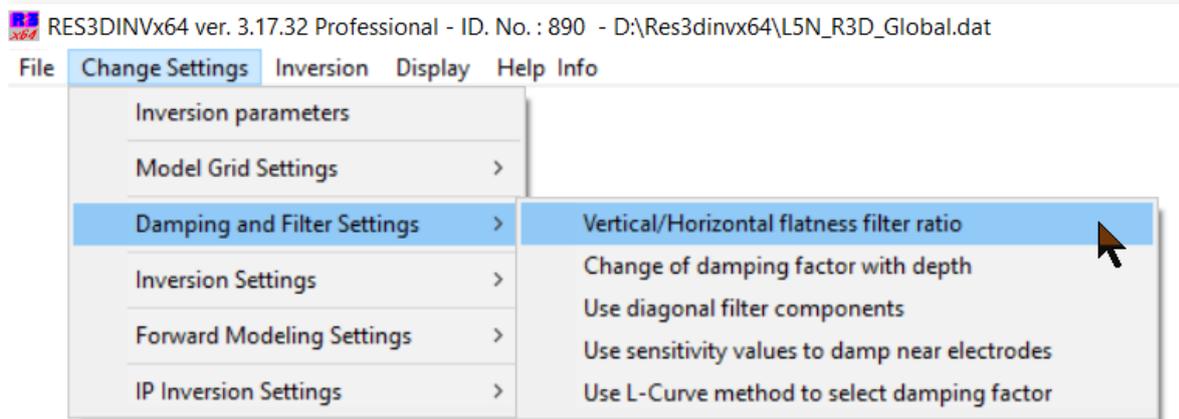


Figure 14. Type of model grid elements. (a) Rectangular element. (b) Convex trapezoidal element. (c) Almost degenerate trapezoidal element. (d) Degenerate concave trapezoidal element.

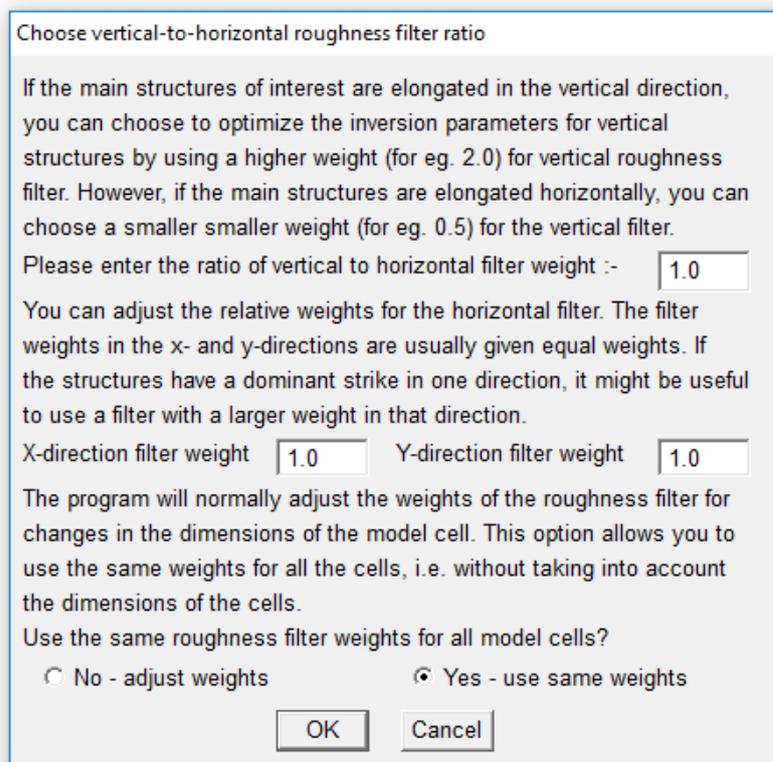
9.3 Damping and filter settings

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

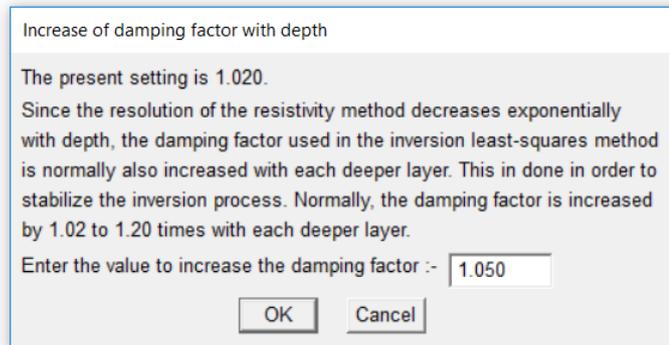
You can select the ratio of the relative weights given to the damping factor for the vertical flatness filter (C_z) and horizontal flatness filters (C_x and C_y). By default, the same damping factor is used for all of them. However, if the anomalies in the pseudosection are elongated vertically, you 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. In some cases, the data set might be from a single 2-D line which has bends which is generally aligned in the x-direction. You can essentially force the program to produce a 2-D model by putting the weight in the y-direction to be much higher than the x-direction, for example a weight of 1 in the x-direction and 10 in the y-direction.

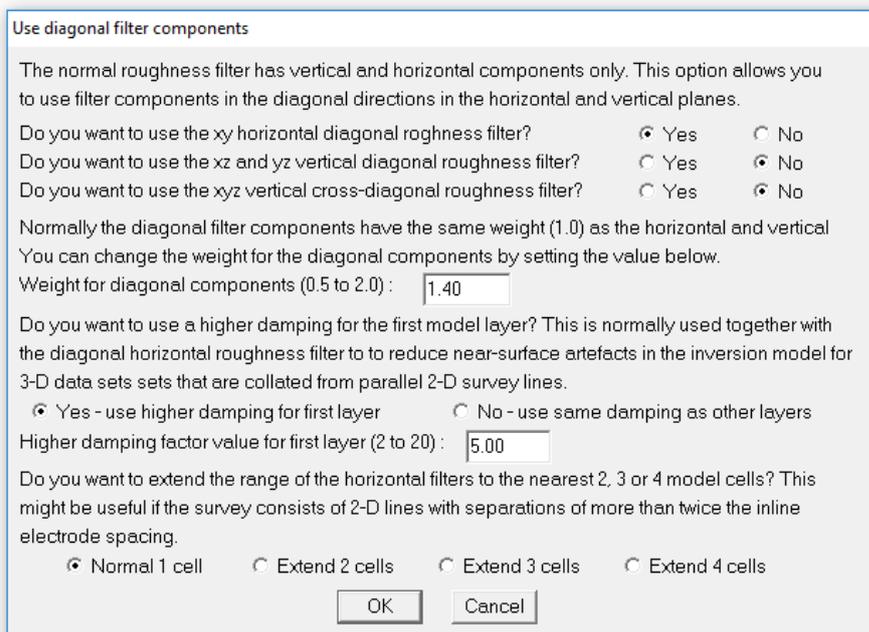
9.3.2 Change of damping factor with depth

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 the 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 (Figure 15). Selecting this option will display the following dialog box.



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 lower 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.

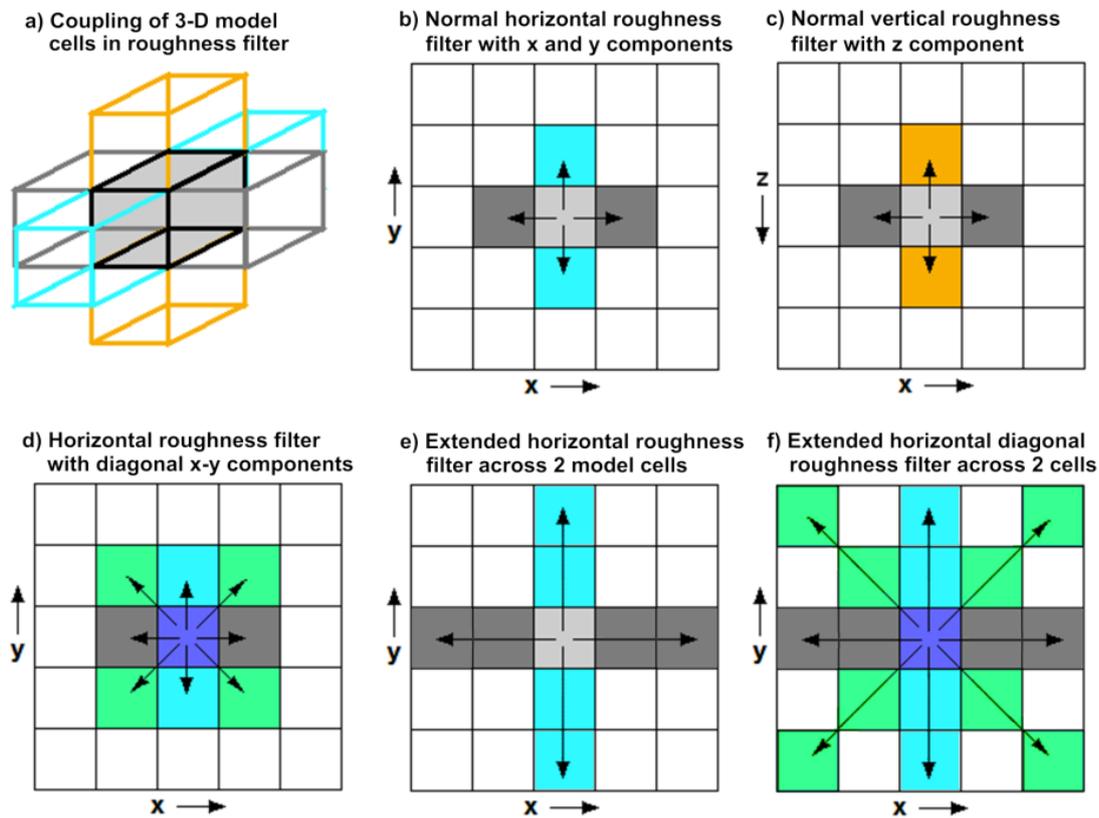


Figure 15. 3-D roughness filters with different components.

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 :-

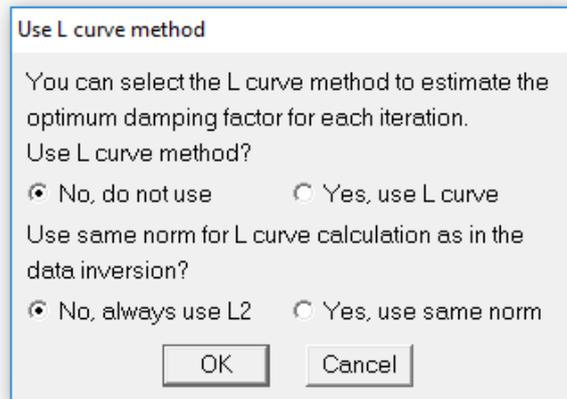
Only model cells above a set cutoff sensitivity value will be subject to a higher damping factor.

Cutoff sensitivity values to set higher damping factor :-

This amplitude of the extra damping to apply near the electrodes, the rate at which the extra damping decreases to the background value (1.0), and the cutoff sensitivity value for model cells where the extra damping is applied are set in the dialog box for this option.

9.3.5 Use L-curve method to select damping factor

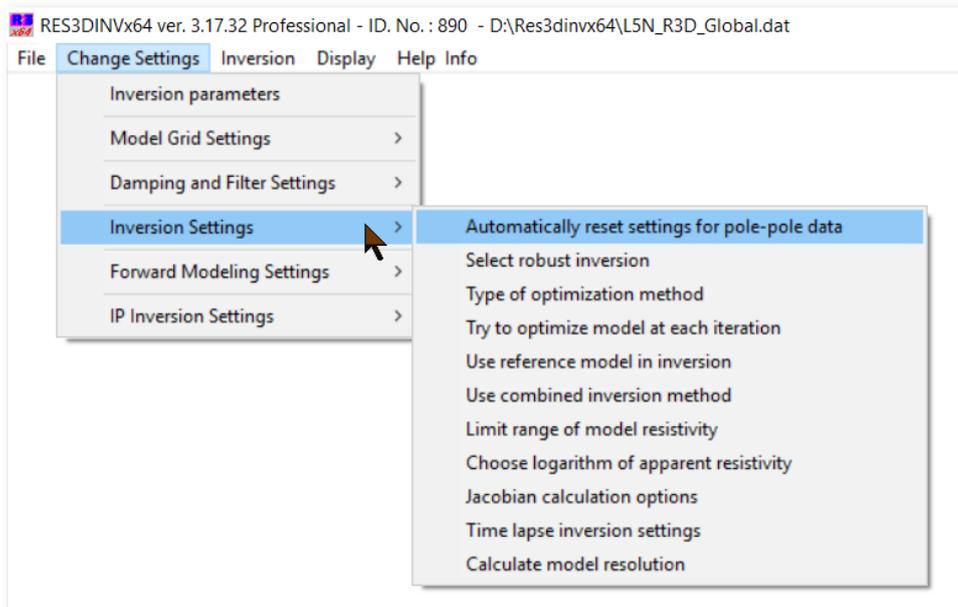
If you select this option, the program will attempt to find the optimum damping factor λ in equation (4.1) using the L-curve method (Farquharson and Oldenburg 2004; Loke et al. 2014a). For very large data sets with more than 10000 data points and/or model parameters, the time taken in each iteration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



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.

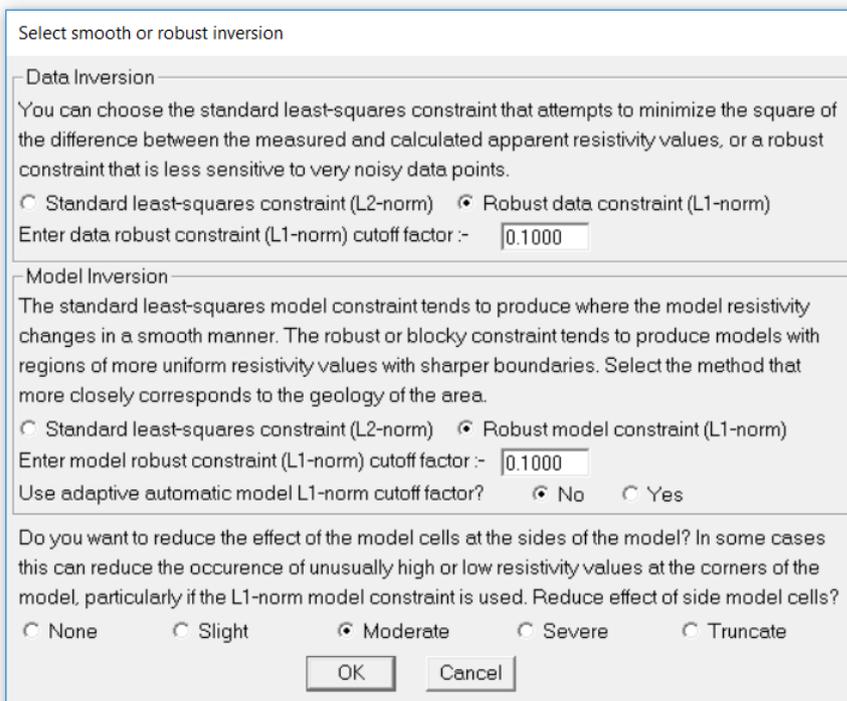


9.4.1 Automatically reset settings for pole-pole

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, POLEPOLE3D.IVP stored in the same folder as the RES3DINX64 program.

9.4.2 Select robust inversion

This option is used to select between the normal smoothness-constrained (L2 norm) and robust/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 (Farquharson and Oldenburg 1998). 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 option ‘Use adaptive automatic L1-norm factor’ allows the program to adjust the cutoff factor for each model block depending on the local model roughness at the block. 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 9.2.1).

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 50000), 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: For very large data sets and models (over 100000 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.

Jacobian matrix scaling: 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 where a local optimization using quadratic interpolation is used to find the optimal change in the model parameters.

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.

$$(\mathbf{J}^T\mathbf{J} + \lambda(\mathbf{F} + \mu\mathbf{I})) \Delta\mathbf{q}_k = \mathbf{J}^T\mathbf{g} - \lambda\mathbf{F}\mathbf{q}_{k-1} - \lambda\mu(\mathbf{q}_{k-1} - \mathbf{q}_m)$$

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.

The dialog box titled "Use reference model constraint" contains the following text and controls:

- Text: "In this option, you can constrain the model so that the deviation of the model resistivity from a homogenous reference model is limited."
- Text: "Use this reference model constraint?" with radio buttons for "Yes" (selected) and "No".
- Text: "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."
- Text: "Damping factor value (0.01 to 1.00):" with an input field containing "0.2".
- Text: "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."
- Text: "Value of user defined reference resistivity:" with an input field containing "29.342".
- Text: "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."
- Text: "Use adaptive reference damping factor?" with radio buttons for "Yes" and "No" (selected).
- Text: "For an I.P. data set, you can use the same reference damping factor for the I.P. model or a different damping factor."
- Text: "Use same damping factor for I.P. model?" with radio buttons for "Yes" (selected) and "No".
- Text: "If you choose to use a different I.P. reference damping factor, enter the value."
- Text: "I.P. damping factor value (0.01 to 1.00):" with an input field containing "0.1000".
- Text: "The average apparent I.P. value in mV/V is :- 0.37"
- Text: "You can select to use this reference I.P. model value or set it to zero."
- Text: "Use average apparent I.P. value" (radio button selected) and "Use zero reference I.P. value" (radio button).
- Buttons: "OK" and "Cancel".

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.

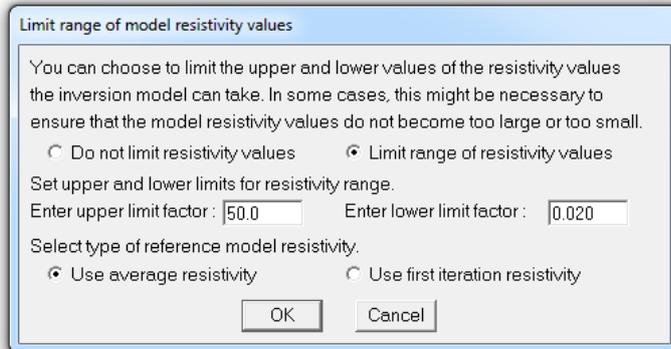
9.4.6 Use combined inversion method

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

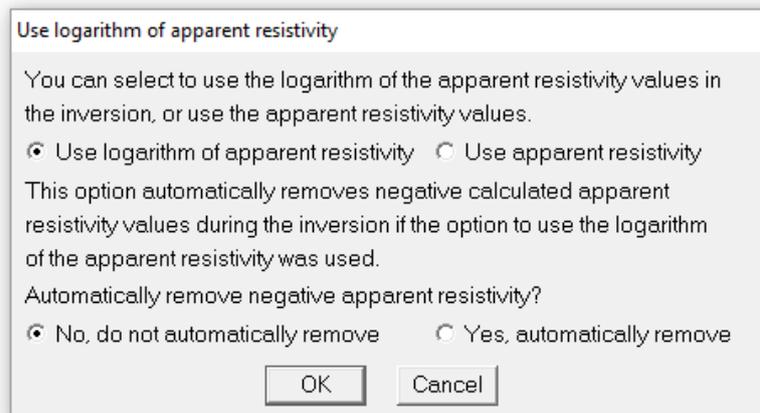
When you select this option, the following dialog box will be shown.



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

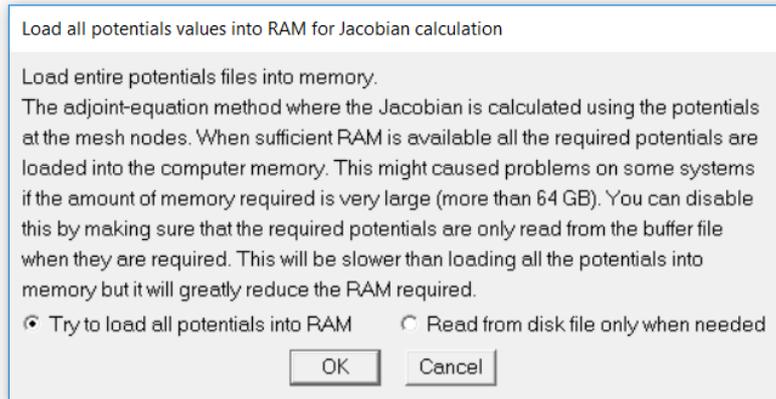
By default, the program will use the logarithm of the apparent resistivity values as the data parameter when carrying out the inversion. For most cases, this gives the best results. In some cases, for example with negative or zero apparent resistivity, this is not possible. This option enables the apparent resistivity value 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. The option to automatically remove data points with negative calculated apparent resistivity values is automatically disabled if the apparent resistivity (i.e. not its logarithm) or resistance is used as the data inversion parameters. This allows for cases where negative apparent resistivity values are real, see Appendix C of the notes by Loke (2019) for situations where this might occur.

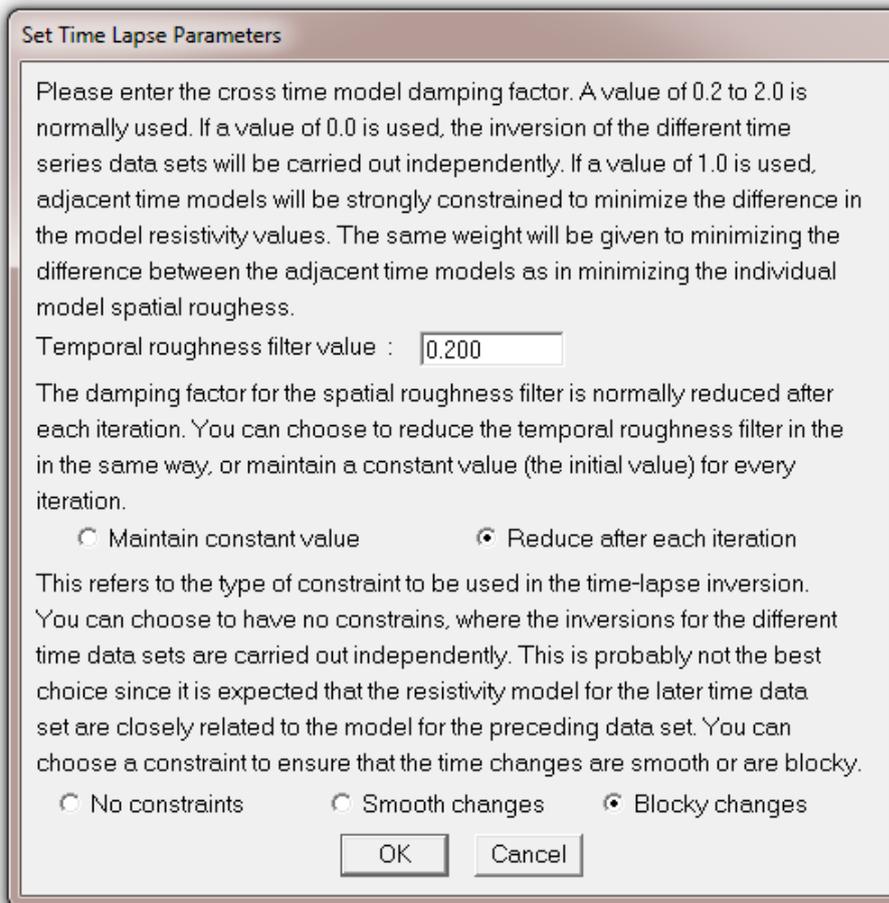
9.4.9 Jacobian calculation options

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 calculating the Jacobian values for each data point. This will slower if a conventional hard-disk is used as the buffer drive. However, if an 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.



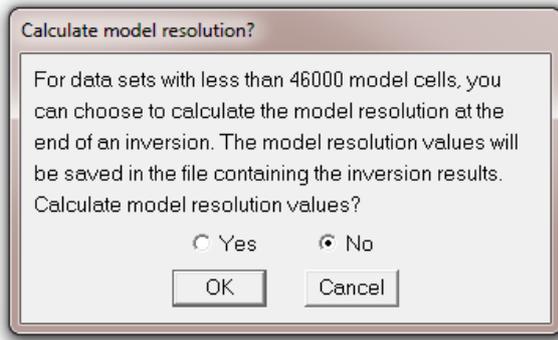
The smoothness-constrained least-squares optimization is modified to the following form for time-lapse data.

$$[\mathbf{J}^T \mathbf{J} + \lambda (\mathbf{F} + \alpha \mathbf{M}^T \mathbf{R}_t \mathbf{M})] \Delta \mathbf{q}_k = \mathbf{J}^T \mathbf{g}_k - \lambda (\mathbf{F} + \alpha \mathbf{M}^T \mathbf{R}_t \mathbf{M}) \mathbf{q}_{k-1}$$

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.



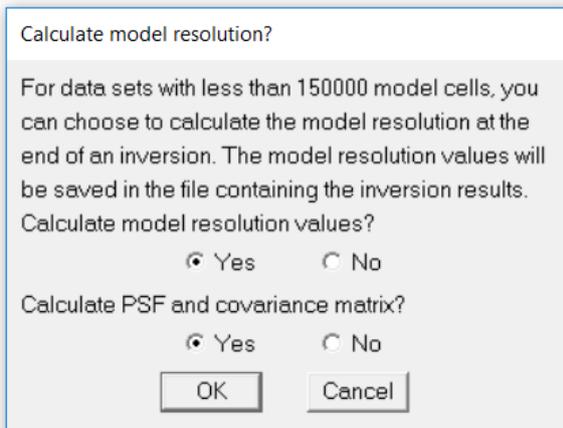
The model resolution matrix is given by

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

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 126000 model blocks (for a computer with at least 128 GB RAM) for the model resolution calculation option.

Users with the 'Enterprise' license will see the following dialog box.



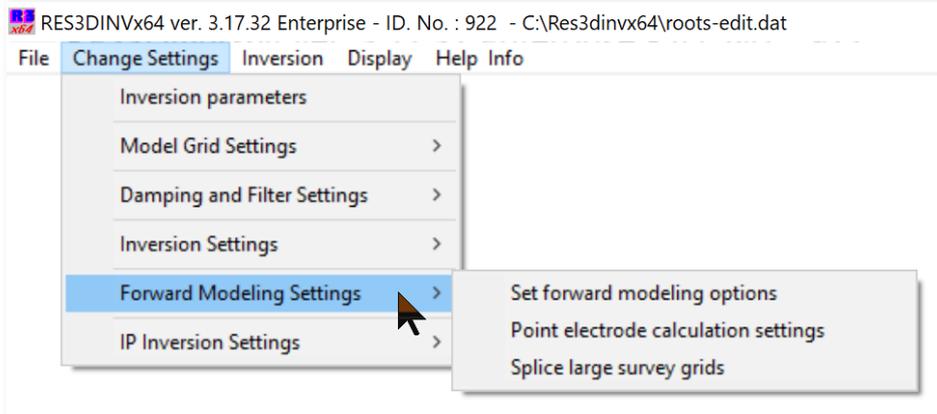
The point-spread function (Oldenborger and Routh 2009) gives a measure of how widely the information from a region of the subsurface is spread out to the surrounding model cells in the inverse model. The covariance matrix (Menke, 1989) shows how data errors are mapped into the model errors. It is given by the following equation.

$$[\text{cov } \mathbf{m}] = \sigma_d^2 (\mathbf{J}^T \mathbf{J} + \lambda \mathbf{F})^{-1}$$

σ_d is the data variance.

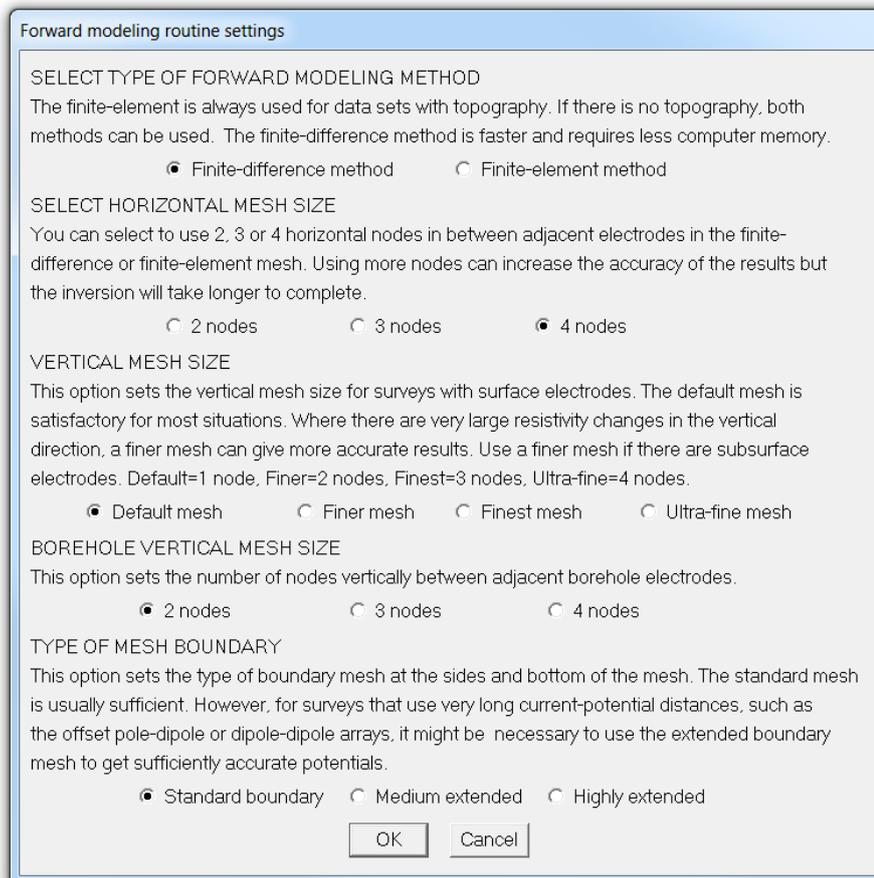
9.5 Forward Modeling Settings

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.



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), it is recommended that you use the 4 nodes option unless the model grid spacing is much less than the spacing between adjacent electrodes.

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. If the data set has subsurface electrodes, the finer mesh (with 2 nodes between vertical mesh lines) is automatically set if the default mesh (with 1 node between vertical mesh lines) is used.

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 has 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.

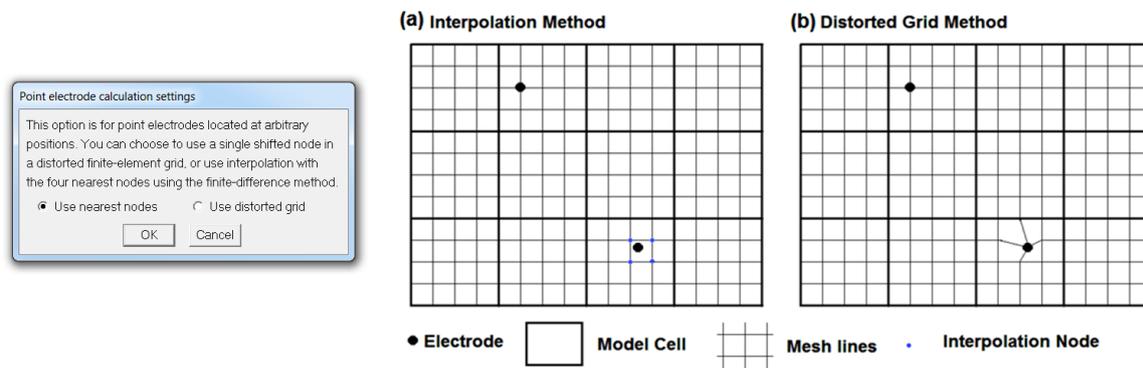


Figure 16. Methods for arbitrary electrodes.

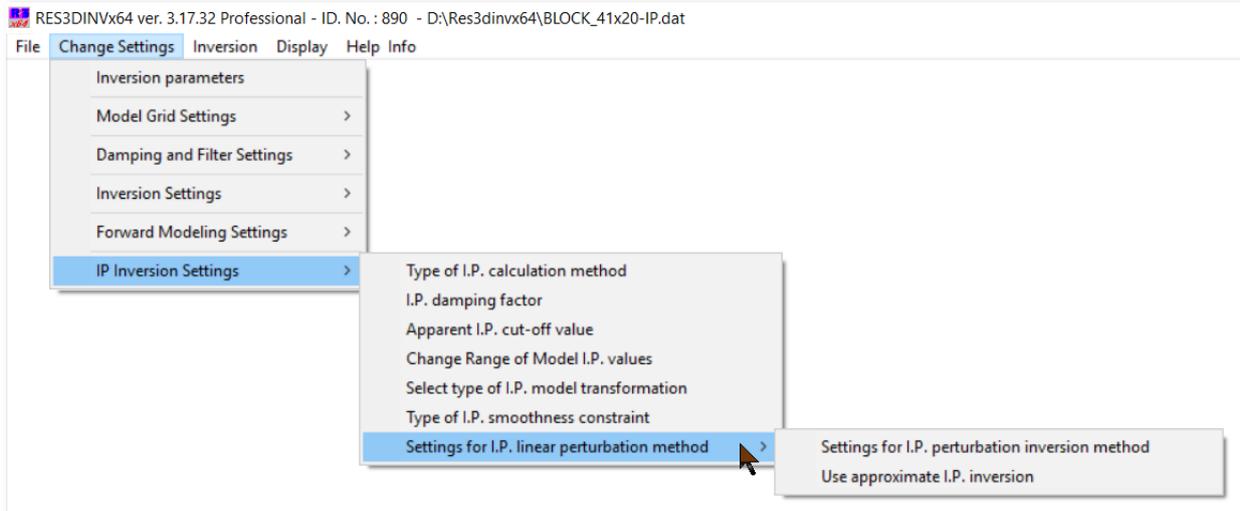
In the ‘Use nearest nodes’ option (Figure 16), the program calculates the potential at the electrode by interpolating the potentials at the four nearest nodes in the mesh (and similarly replace a single current source node by four equivalent current sources). One advantage of this option for data sets 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 Splice large survey grids (Enterprise)

This option is intended for very large survey grids with hundreds of thousands of electrodes positions. It subdivides the finite-element mesh into smaller sub-meshes in the forward modeling calculation which can greatly reduce the computer time required to invert a very large data set. It is only available for users with the ‘Enterprise’ license. Please refer to Appendix L for more details.

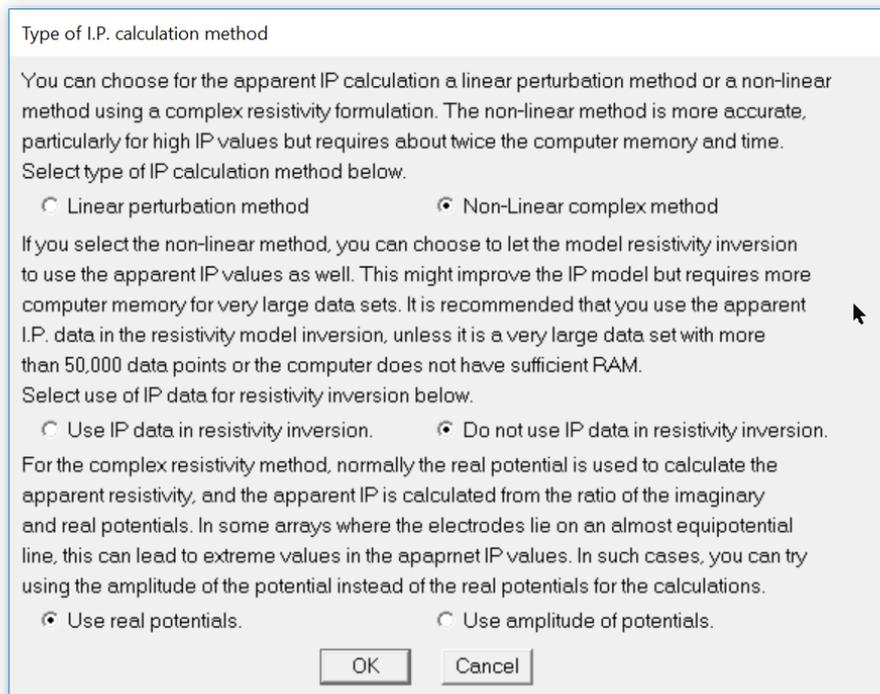
9.6 I.P. inversion settings

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 linear 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 for 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.

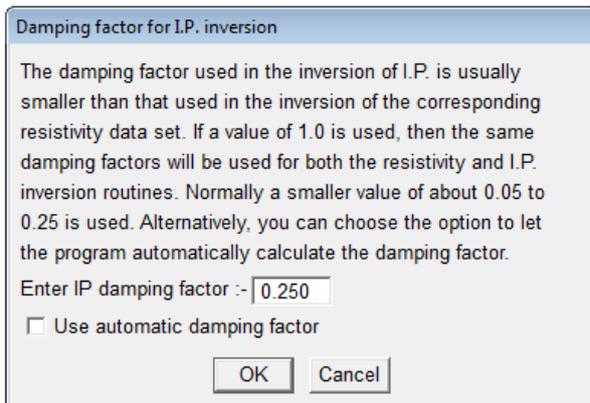
$$\phi = \phi_r + i \phi_i$$

The complex potential has two components, ϕ_r and ϕ_i . 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 the perturbation method.

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.

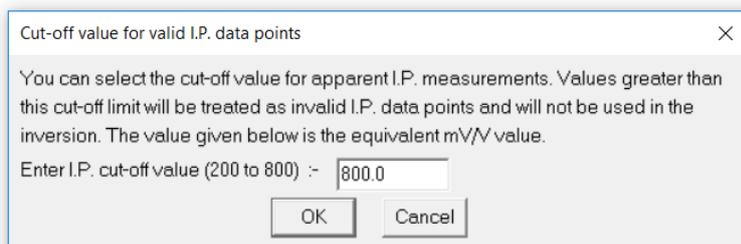
9.6.2 I.P. damping factor

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.



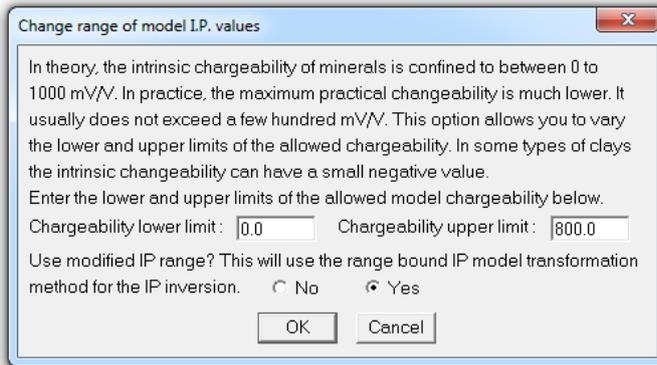
9.6.3 Apparent I.P. cut-off value

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.



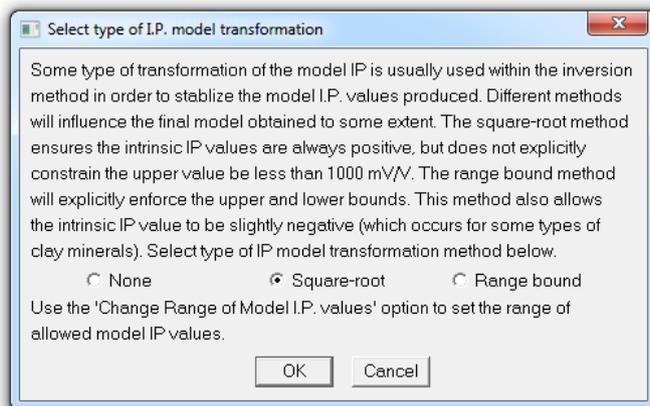
9.6.4 Change range of model I.P. values

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.



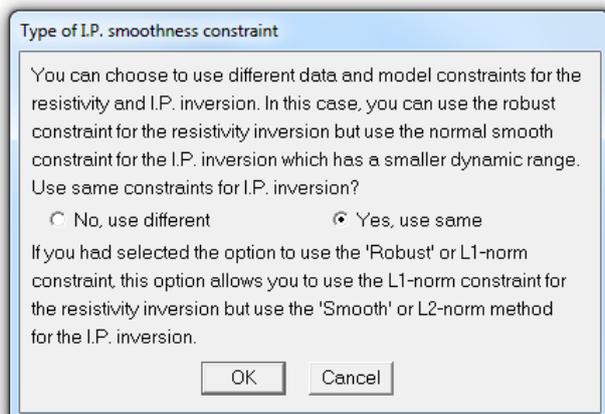
9.6.5 Select type of I.P. model transformation

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. The 'square-root' method ensures that the minimum model I.P. values is 0.0 but does not directly limit the maximum I.P. value (which is theory cannot exceed 1000 mV/V but in practice is much smaller, usually less than 100 mV/V). The 'range-bound' method directly limits the lower and upper range of the model I.P. values.



9.6.6 Type of I.P. smoothness constraint

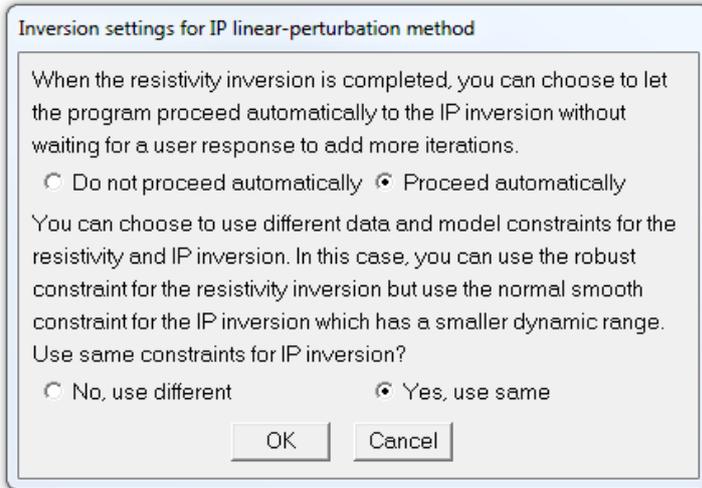
Normally the program uses the same smoothness constraint for the I.P. inversion as that used for the resistivity inversion. This option allows you to use a different smoothness constraint for the I.P. inversion. If the 'Robust' (L1-norm) method is used for the resistivity inversion, this option allows 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.



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.

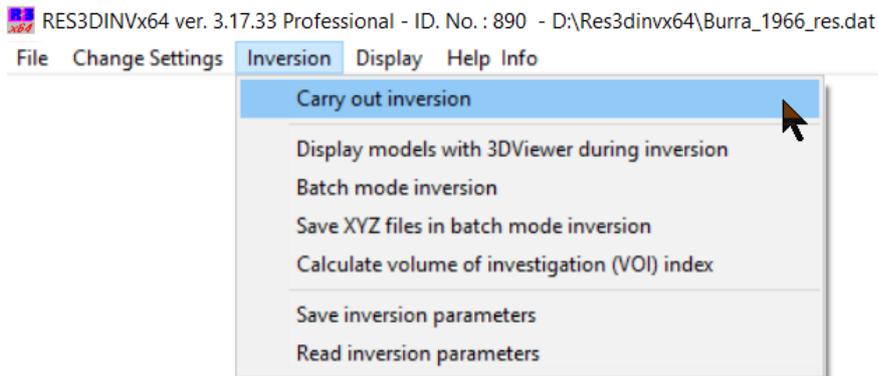


In the approach by Oldenburg and Li (1994), the resistivity model obtained at the last iteration of the inversion of the resistivity data set is used as the base resistivity model in the inversion of the I.P. data set. At the end of the resistivity inversion, the program will stop and show a dialog box 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 to 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.

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 Display models with 3DViewer during inversion

The inverse model obtained after each iteration is normally displayed as 2-D depth layers. This option enables the use of the AGS 3DViewer program to display the models in 3-D during the inversion. The program will automatically start the 3-D viewer after the first inverse model is obtained. If the time taken in each iteration is less than 3 seconds, the 3DViewer will not be used as the model will be displayed as 2-D slices. This option is only available with the Aarhus Geosoft digital license system, as well as the 3-D Basic, Professional or Enterprise software license. If you are still using the USB dongle, you will need to change to the digital license system.

10.3 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 (such as 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.

10.4 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.

10.5 Calculate volume of investigation (VOI) index (Enterprise)

This option is only available for users with the 'Enterprise' license. Please refer to Appendix N for more details.

10.6 Save inversion parameters

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

10.7 Read inversion parameters

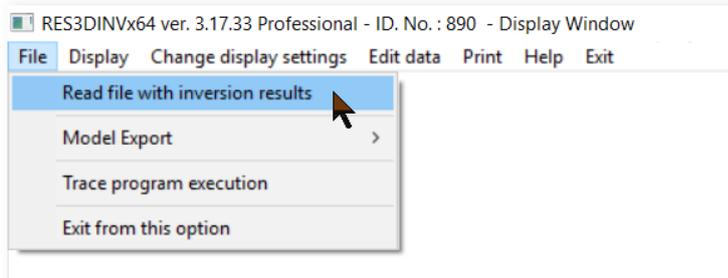
Using this option, the user can read an IVP file containing the inversion parameters which will then become the inversion settings the program uses for inverting a data file.

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.

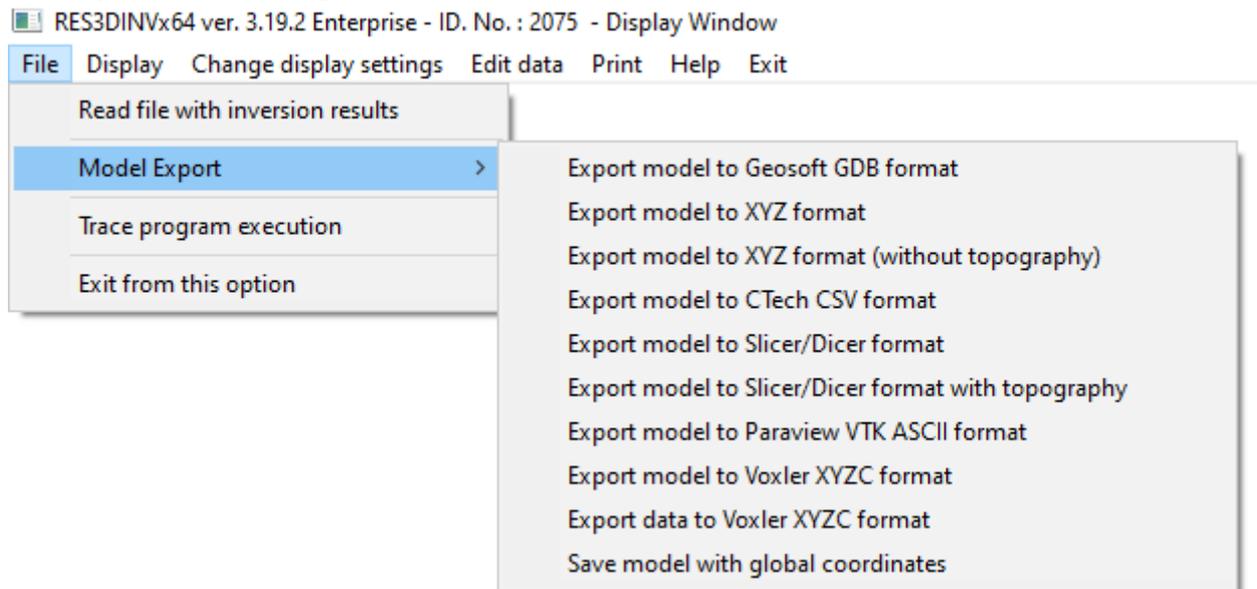


11.1.1 Read file with inversion results

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.

11.1.2 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.



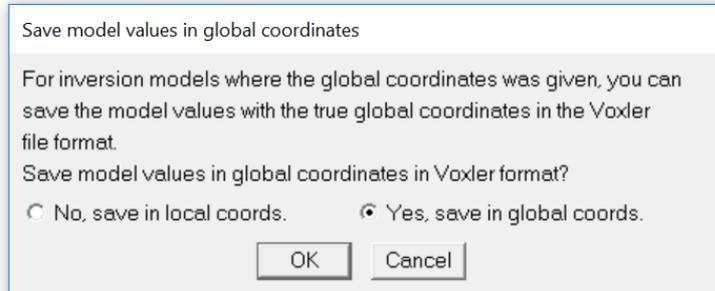
Geosoft GDB is binary format which can be used for e.g. Oasis montaj. XYZ is a generic ASCII text format used by the Geosoft Inc. software. Voxler is a 3-D contouring program (Appendix E) by Golden Software which is similar to the Surfer program by the same company that is widely used for 2-D displays. 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. 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.

Export model to Geosoft GDB format:

This option allows the user to export model results to a GDB data base file. The output contains a fixed number of channels (i.e. 'columns') with fixed names. Channels named x1,y1,z1,x2,y2,z2,...,x8,y8,z8 provide corner coordinates of each model block. Channels sens and sens_vol provide raw block sensitivities and sensitivities normalized by volume (see section 11.2.6). Channels reso, reso_v, reso_vr, reso_i and reso_vri provide resolution values for each block if resolution calculations were enabled (section 9.4.11). The abovementioned resolution channels refer to (in the same order as in the above)

total resolution, resolution per unit volume, resolution/volume ratio, total resolution index and resolution/volume index (see section 11.2.8). Channels res0 and ip0 refer to block resistivity and i.p. values. If the model contains multiple timesteps, additional channels named e.g. res1, res2 will be created.

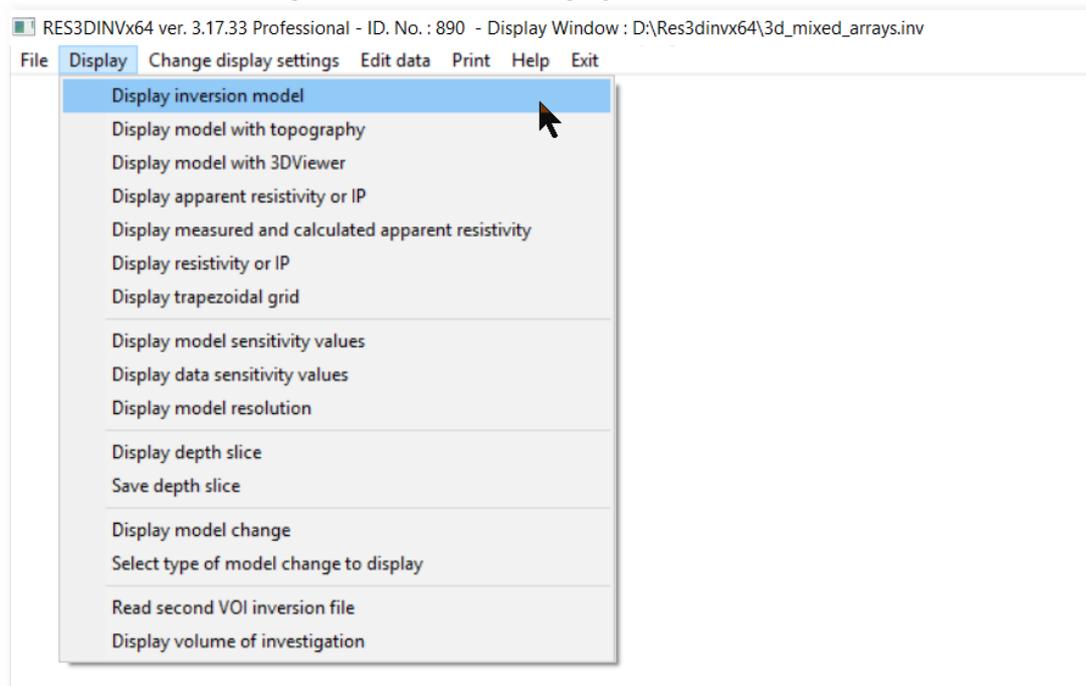
Save model with global coordinates (Model Export) : This option is only relevant for inversion models for data with arbitrary point electrodes where the model grid was rotated to reduce the grid size (section 9.2). The true global coordinates are also saved in such file. On selecting this option, the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



Selecting 'Yes' to this option will save the model values with the true global coordinates if the Voxler XYZC output option are selected. For output model output in the XYZ format, the coordinates of the model values in the true coordinates are automatically saved in the same file. For the VTK format, the program will automatically save the model values with the coordinates of the model blocks in the global coordinates in a separate file if the input file has the global coordinates.

11.2 Display - Display menu options

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



11.2.1 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.

11.2.2 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.

11.2.3 Display model with 3DViewer

This will use the AGS 3DViewer program to display the model. The model values will first be saved to a VTK file which is then read by the 3DViewer program. This option is only available with the the 3-D Basic, Professional or Enterprise software license. A detailed description of the use of the 3DViewer display option is given in Appendix K.

11.2.4 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. For other data sets, use the 'File-Model Export-Export data to Voxler XYZC format' to save the data points to a Voxler input data file, and then use Voxler to display the data points as a 3-D scatter plot (Appendix D.2).

11.2.5 Display resistivity or IP

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

11.2.6 Display model sensitivity values

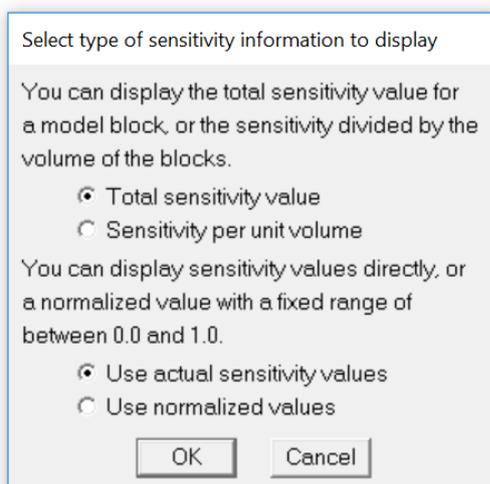
The INV file containing the inversion model also contains a listing of the integrated sensitivity value which is defined by

$$S_i = \frac{1}{m} \sum_{j=1}^m |J_{ij}|$$

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_i) is divided by the volume of the model block (V_j).

$$S_j = S_i \cdot V_m / V_j$$

V_m is the volume of the smallest block. 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 2018). The following dialog box is shown when this option is selected.



The sensitivity values depend on many factors such as the arrays used and resistivity of the model values. The second set of options normalize the sensitivity values so that they have a fixed range of between 0.0 and 1.0.

11.2.7 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

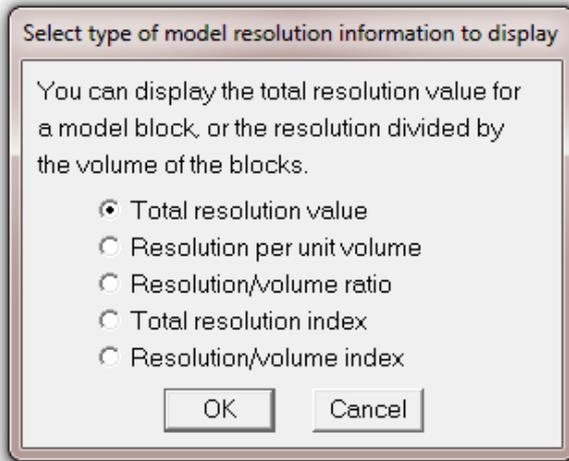
Number of depths levels :

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

No, do not save Yes, save the sensitivities

11.2.8 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.



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 thicknesses 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.

$$r_n(i) = r(i) \cdot V_{min} / V(i)$$

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.

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

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

$$r_{ni}(i) = r_n(i) \cdot m$$

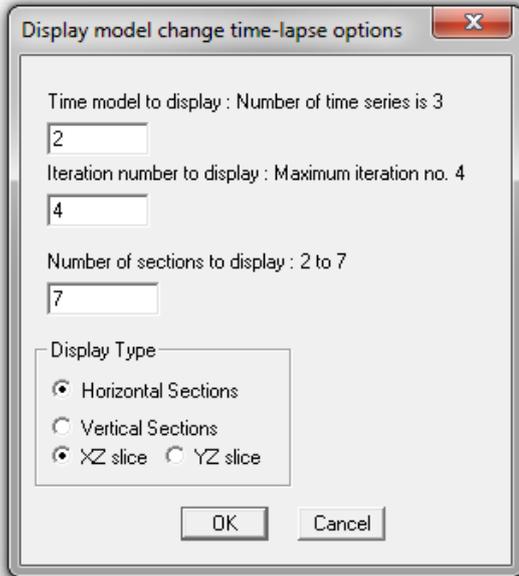
A value of 10 to 20 for the resolution index is probably a reasonable cutoff value.

11.2.9 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 that might cut through several model layers. The model values can also be saved into a XYZ text file.

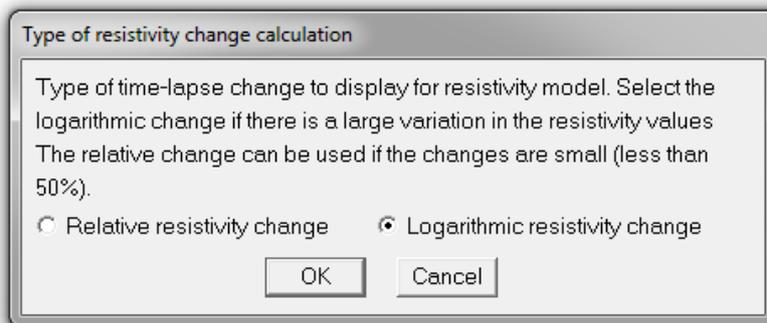
11.2.10 Display model change

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.



11.2.11 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).

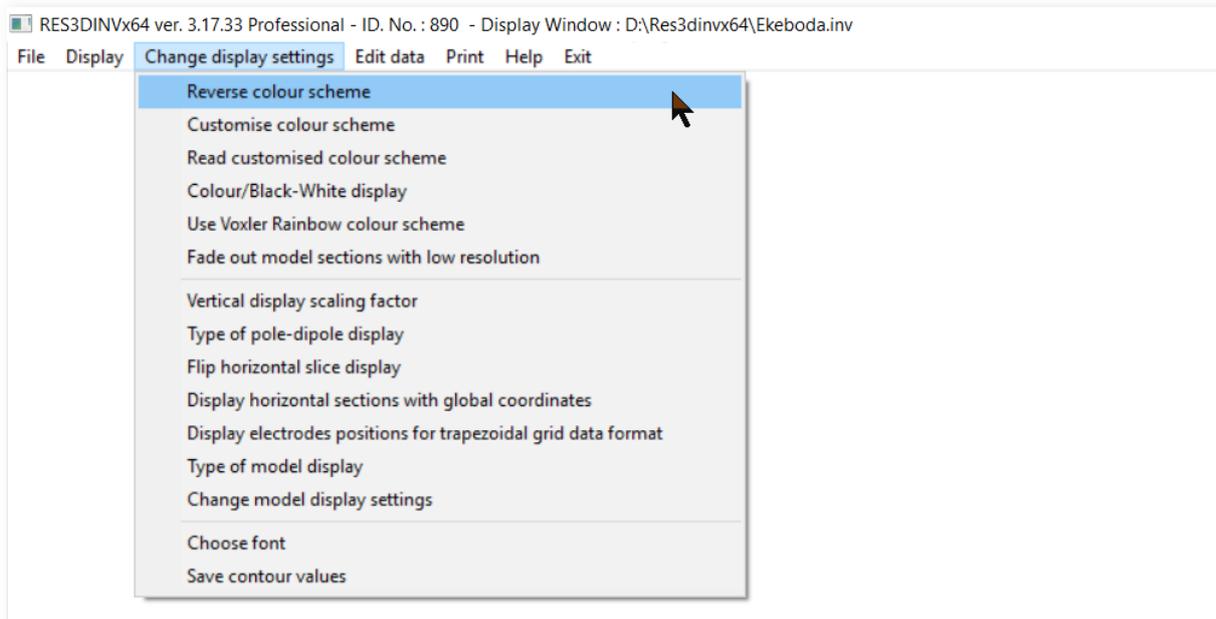


11.2.13 VOI display options

This option is only available with the 'Enterprise' software license. Please refer to Appendix N for more details.

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.



11.3.1 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.

11.3.2 Customise colour scheme

This enables the user to change the colours used for the sections.

11.3.3 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.

11.3.4 Colour/Black-White display

By default, the program will display the pseudosections and model sections in colour. 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.



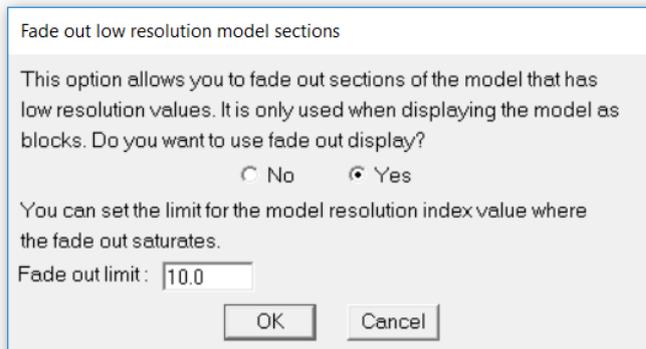
The 'Color scale' and 'Grey scale' options uses 17 different colors, such as in Figure 17. The 'Extended Colors' options uses twice as many colors to display finer variations.

11.3.5 Use Voxler Rainbow colour scheme

This changes the colours used in the model display to the scheme used in the Voxler Rainbow colour scheme.

11.3.6 Fade out model sections with low resolution

This option is only used if the model resolution values were calculated in the inversion of the data set. The following dialog box is shown when this option is selected.



The resolution value used is the ‘Total resolution index’ (section 11.2.8).

11.3.7 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.

11.3.8 Type of pole-dipole display

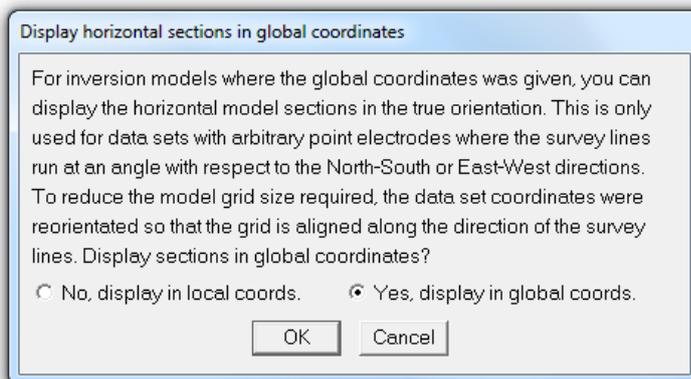
This option is only relevant for pole-dipole data sets with measurements with the “forward” and “reverse” pole-dipole arrays (see Appendix A). Here you can choose to display the apparent resistivity values measured with the array in the “forward” or “reverse” configuration.

11.3.9 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.

11.3.10 Display horizontal 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.

11.3.11 Display electrodes positions for data with trapezoidal grid format

This option is only relevant for data sets using the trapezoidal grid data format. It allows the user to display the positions of the electrodes and the model grid lines on top of the topmost model layer when the model is displayed as horizontal sections.

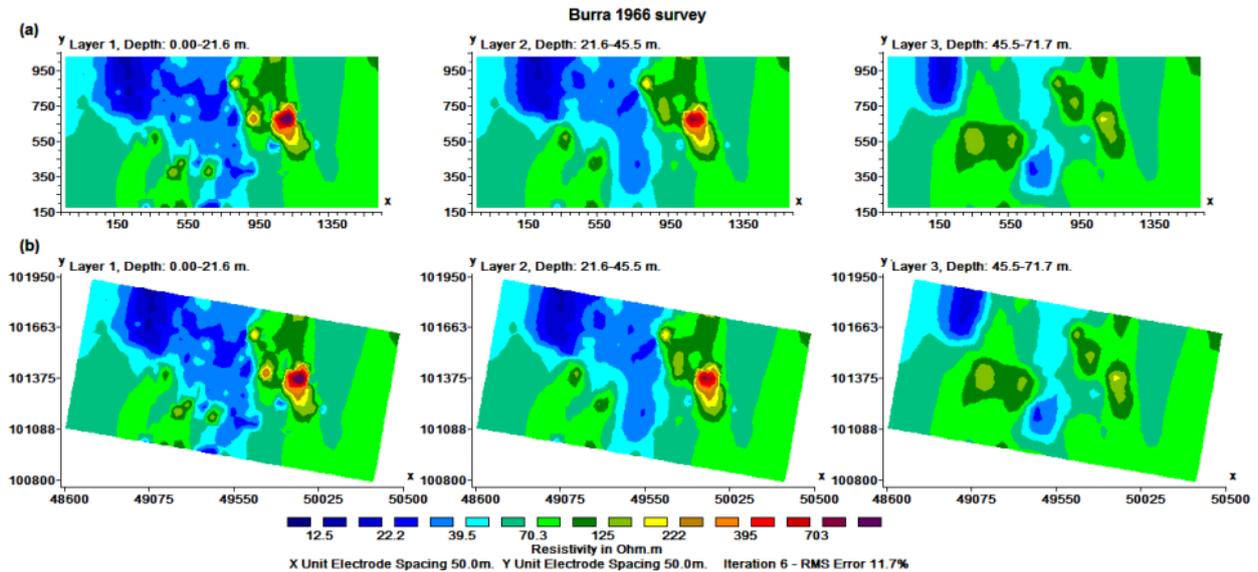


Figure 17. Example of horizontal model sections displayed using (a) local coordinates, and (b) true global coordinates.

11.3.12 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.

Change display settings

This option allows you to change the number of pixels per unit electrodes spacing in the x-direction for the model display.

Type in the value you want to use :-

You can select the number of sections to display in each row. You can select a value between 1 and 6. If you change this value, the program will recalculate the number of pixels per unit electrode spacing value.

Number of sections per row :-

You can display the model section using the contoured form, or as rectangular blocks that make up the actual model. Select type of model display below.

As a contoured section. Show the model blocks.

In the standard contoured display, the middle of the model block is used as the plotting point. You can extend the model sections to the edges of the model grid.

Use standard section. Use extended section.

The top option adjusts the scale used in plotting the sections on the screen.

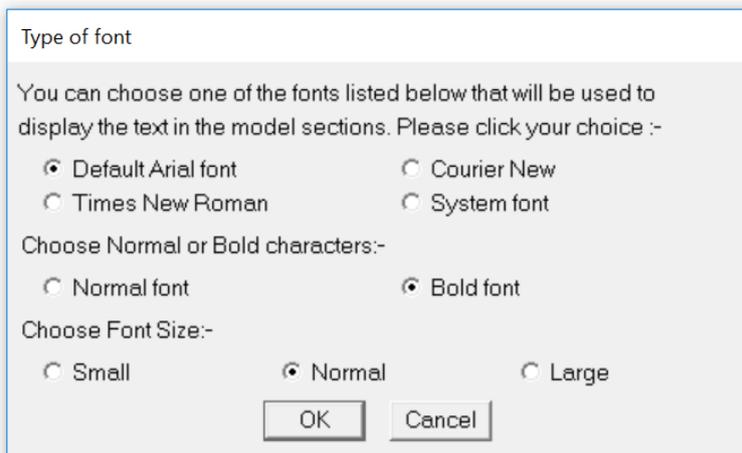
The second option sets the number of sections displayed along each row. The number allowed is between 1 and 6.

The third option selects the type of model displayed as contoured sections or as model blocks. If there are a large number of model cells, drawing as contoured sections can be slow.

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.

11.3.13 Choose font

This option allows the user to change the font used in displaying the model sections using the dialog box shown below.

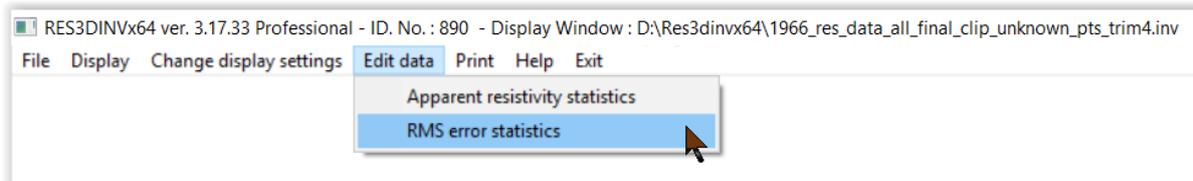


11.3.15 Save contour values

This saves the contour values used in the most recent display of the model sections into a text file.

11.4 Display - Edit data menu

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



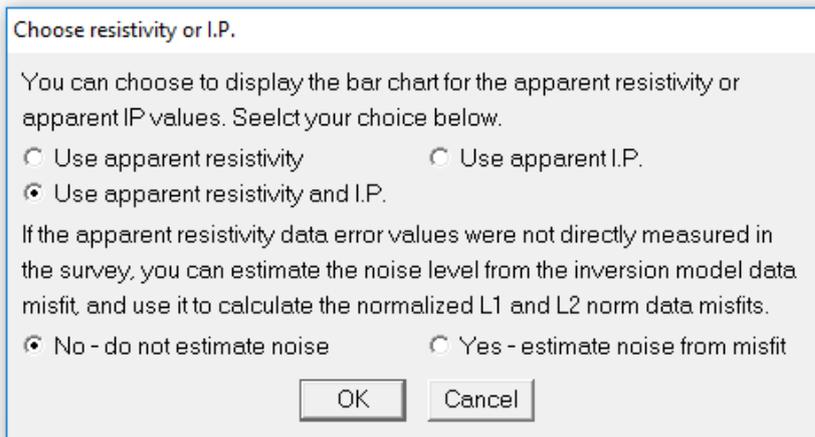
Large 3D surveys can involve many thousands of data points. In the most general case, the array for a particular measurement can be orientated in any direction. This makes manual editing of the data set very difficult. To obtain a good inversion model, the “bad” data points must be removed from the data 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.

11.4.1 Apparent resistivity statistics

This sub-option just displays the distribution of the apparent resistivity values as a bar chart. It is meant to be used initially 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. These 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.

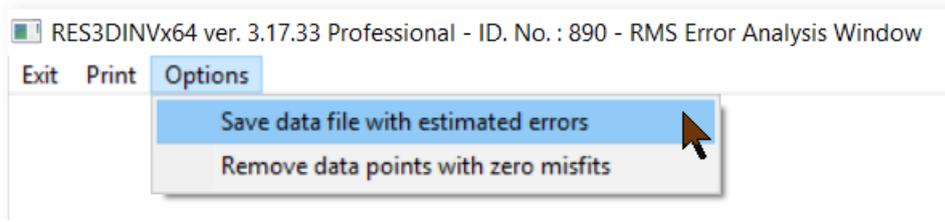
11.4.2 RMS error statistics

This sub-option displays the distribution of the percentage difference between the logarithms of the observed and calculated apparent resistivity values as histogram and correlation scatter plots (Figure 18). It can only be used after carrying out a trial inversion of the data set. Figure 18a shows an example of the histogram and scatter plot for a resistivity data set. On selecting this option, the program will first display a dialog box for the user to select the iteration to use for displaying the data misfits. If I.P. data is present, the following dialog box is next shown.



The user can choose to use the resistivity or I.P. data for the histogram plot, or display both the resistivity and I.P. histogram plots at the same time (Figure 18b). Displaying both histogram plots is useful to filter out data points with high apparent resistivity and I.P. data misfits. A data point with a high resistivity data misfit does not always have a high I.P. misfit, and vice-versa. Both the resistivity and I.P. data will be displayed as scatter plots on the right half of the screen. It is expected the “bad” data points will have relatively large “errors”, for example above 100 percent. To remove the points with large errors, just move the green cursor line (using the left and right arrow keys) to set the cut-off error limit to remove the “bad” data points. An example of the plot is shown in Figure 18a that uses a cut-off value of 50%. The points removed are marked in red in the correlation plot on the right. For the I.P. bar chart plot, a blue cursor line is used. To move the blue cursor line, use the ‘Home’ and ‘PgUp’ keys.

The following main menu bar is shown in this window.



When the user selects the 'Exit' option in the main menu bar, 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.

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.

The 'Options' menu has the following options.

Save data points with estimated errors – This will save the estimated errors (if this was chosen in the dialog box shown when the 'RMS error statistics' option was selected) into a file when the user exits this window.

Remove data points with zero misfits – This option is only used when the inversion was carried out used the logarithm of the apparent resistivity, and the option to automatically remove data points where the calculated apparent resistivity was negative (section 9.4.8). These data points that were automatically removed will have zero data misfits in the 'inv' file that stores the inversion results. This option will remove these data points when the user exits this window.

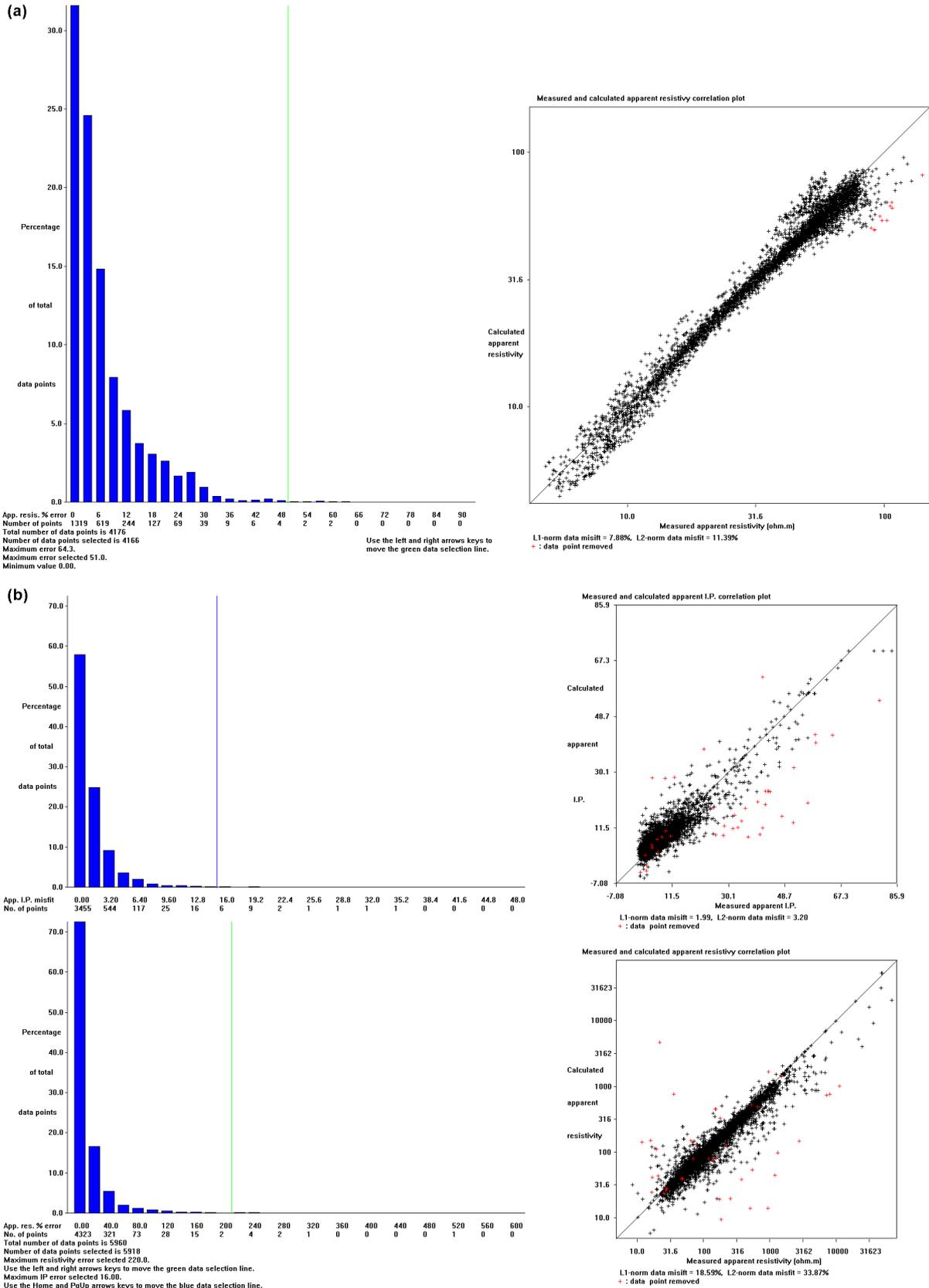
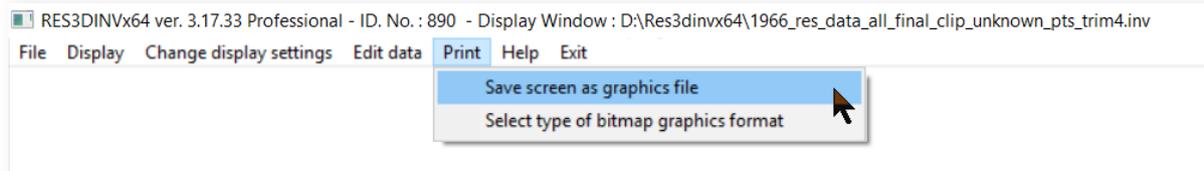


Figure 18. Example of data misfit histogram and correlation plots with (a) resistivity data only, and (b) both resistivity and I.P. data.

11.5 Display - Print menu

This menu has two options as shown below.

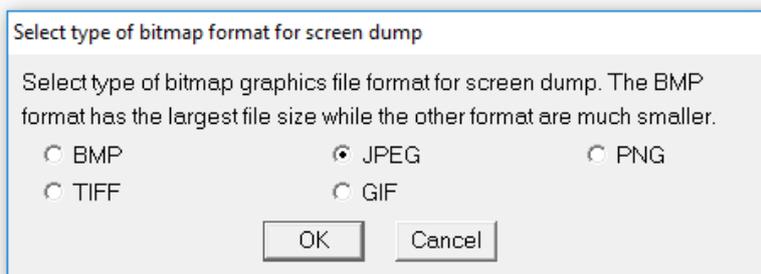


11.5.1 Save screen as graphics file

This option located under the 'Print' menu makes a screen dump of the sections drawn on the screen.

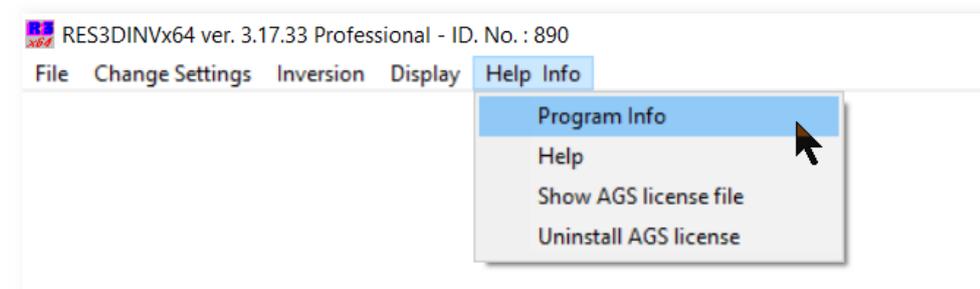
11.5.2 Select type of bitmap graphics format

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



12 Help menu options

The last main menu Help option displays the following sub-menu options.



12.1 Program info

This display the software copyright information.

12.2 Help

This option loads up the Res3dinv.chm help file if it is located in the same folder as the Res3dinvx64.exe file.

12.3 Show AGS license file

This displays the contents of the file containing the software license.

12.4 Unregister AGS license

This removes the digital license from the PC so that it can be transferred to another PC.

13 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 consist 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 (Rucker et al. 2010; Loke et al. 2013a) 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 (2019).

13.1 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.

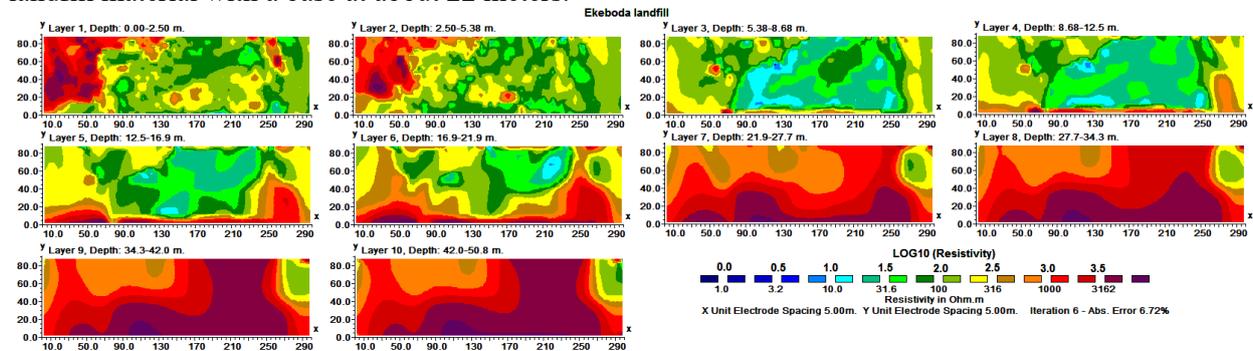


Figure 19. Inversion model for the Ekeboda landfill survey data set.

13.2 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 that enables the user to display the model from any direction. The 3-D 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.

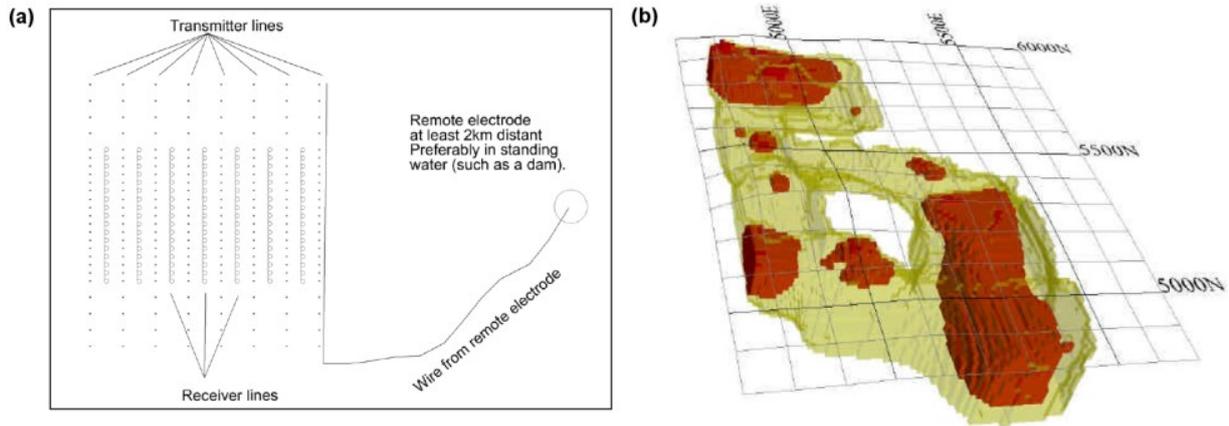


Figure 20. Example of a 3-D survey using the offset pole-dipole array. (a) Electrodes layout used for the 3-D survey of the Copper Hill area. (b) The IP model obtained from the inversion of the Copper Hill survey data set. Yellow areas have chargeability values of greater than 35 mV/V, while red areas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

13.3 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.

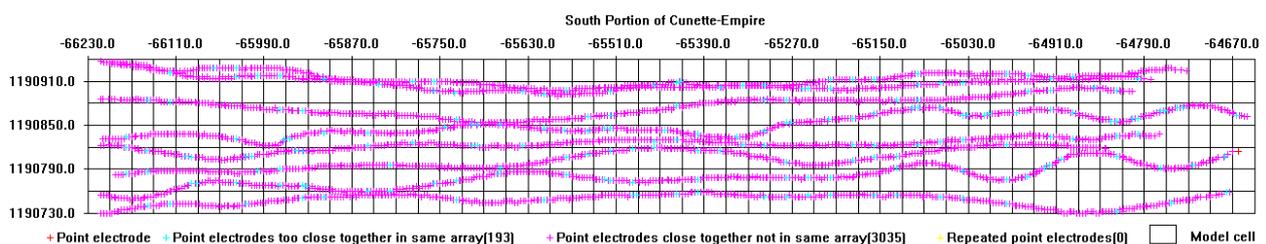


Figure 21. The model grid used for the Panama Canal floating electrodes survey with 20 by 20 meters cells. The location of the electrodes along the surveys lines are shown as colored points.

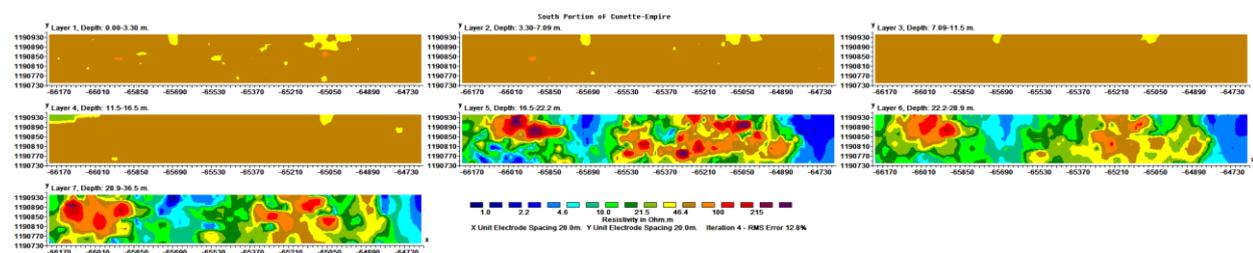


Figure 22. The inversion model for the Panama Canal floating electrodes survey. The first 4 layers correspond to the water column.

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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. Nikos Papadopoulos of the Institute of Mediterranean Studies (Greece) provided the challenging Lambayanna data set. Iris Instruments provided the vector array field 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
Vector array (only used as sub-array number with data in the general array format)	16	3 or 4

A description of the different arrays types is given in the free tutorial notes on electrical imaging (Loke 2019). For an array with four electrodes there are three possible arrangements for the electrodes (Carpenter and Habberjam 1956). The Wenner array has three different variations (Figure 23). The “normal” Wenner array is actually the Wenner alpha array.

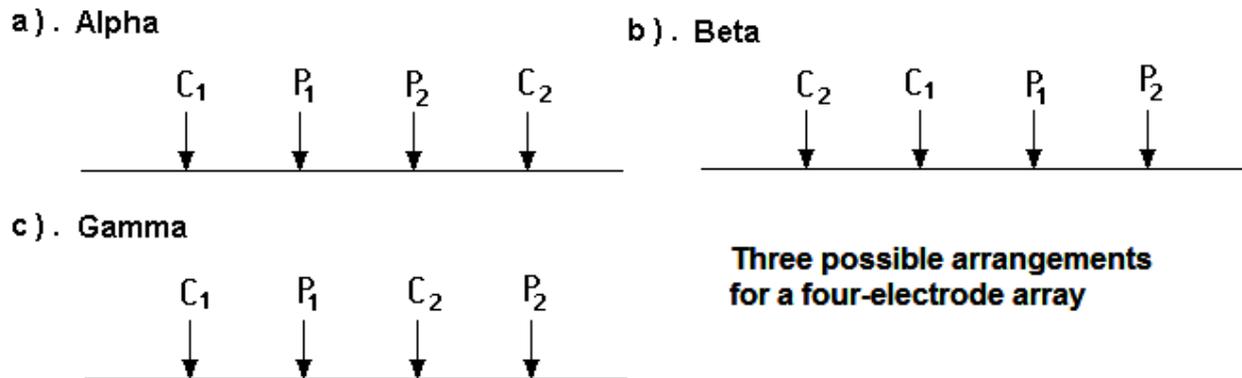


Figure 23. Arrangement of the electrodes for the Wenner alpha, beta and gamma arrays.

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.

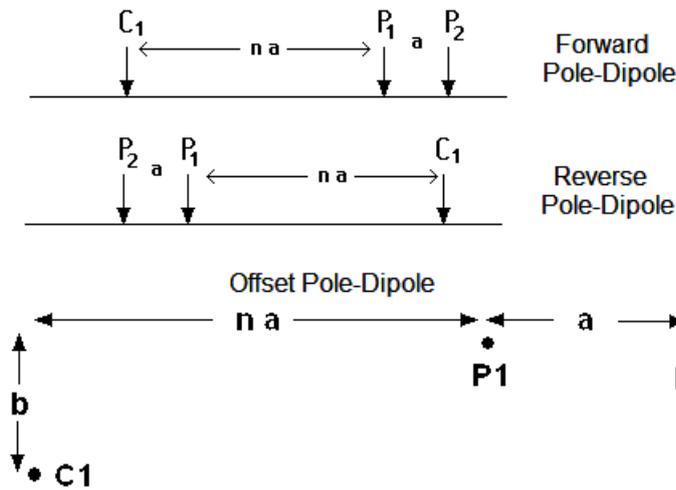


Figure 24. Normal, reverse and offset pole-dipole array arrangements.

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).

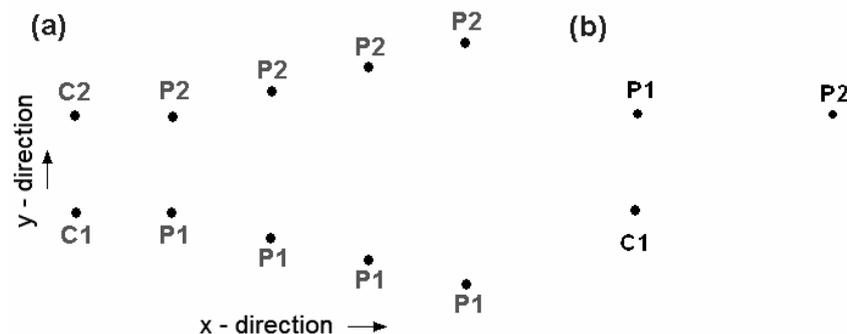
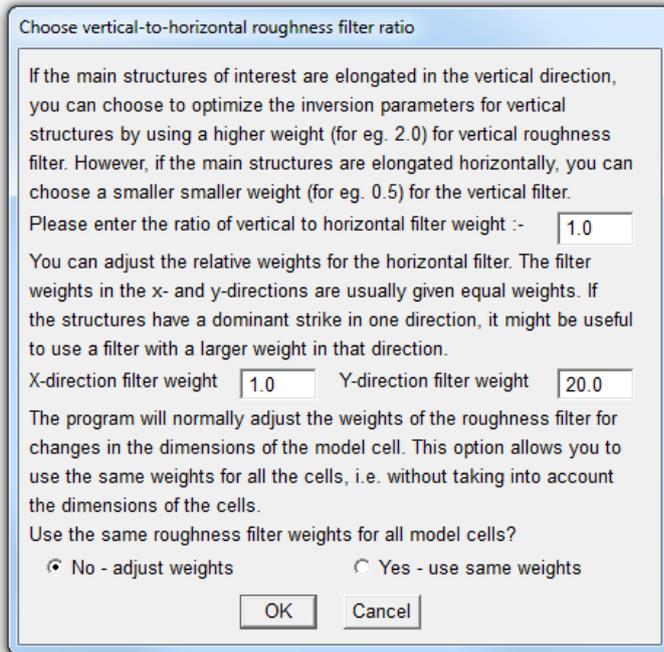


Figure 25. (a) Equatorial dipole-dipole array with different potential dipole lengths, (b) offset pole-dipole array with the C1 electrode at the same x-location as the P1 electrode.

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. This could be due to a winding path in a land survey, or due to drifting of a floating streamer in an aquatic survey. 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.

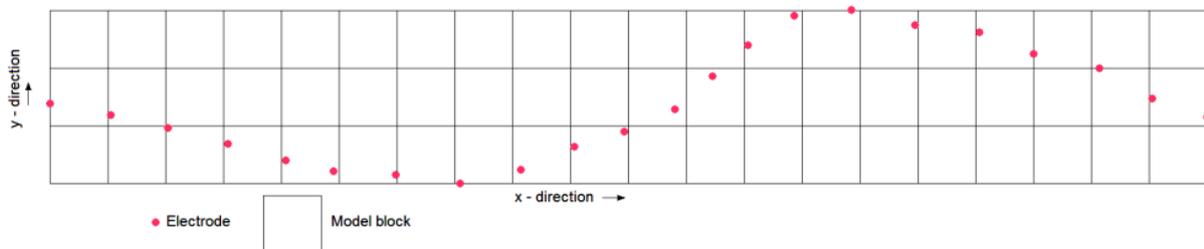
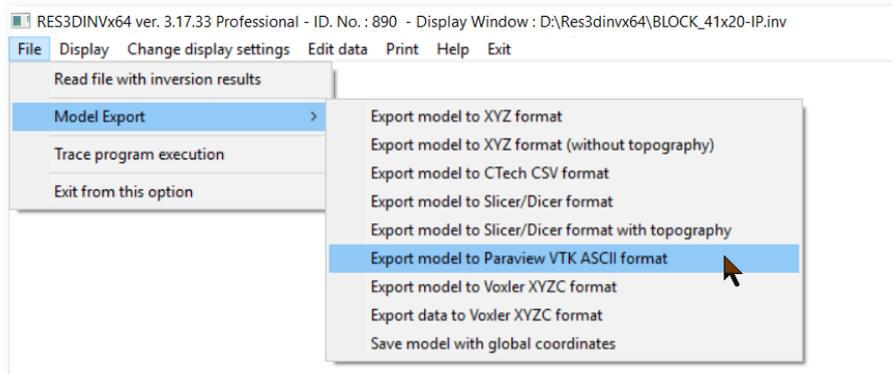


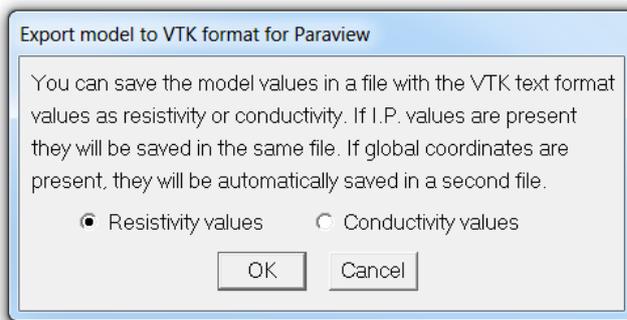
Figure 26. Example of a 2-D survey along a crooked line.

Appendix C : Using Paraview to display the model

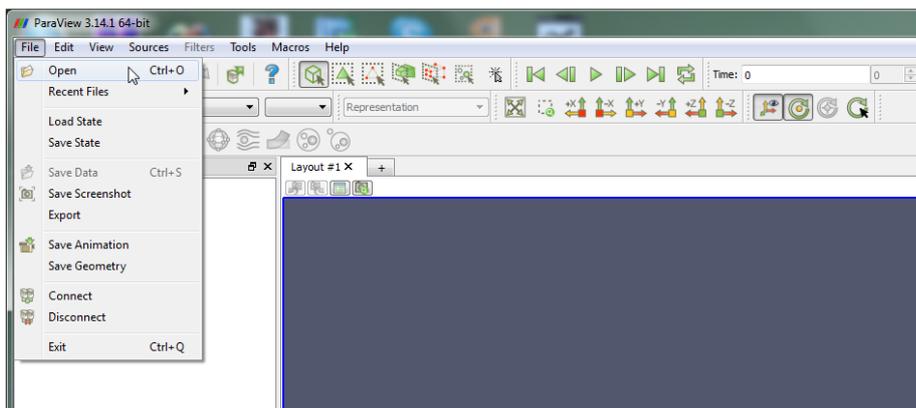
Paraview is an open-source free 3-D graphics package that is popular with academic institutions and government agencies. The Paraview program can be downloaded from the www.paraview.org website which also contains a number of guides and tutorial manuals in pdf format. RES3DINVx64 has an option to save 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 RES3DINVx64 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. If I.P. is present, the I.P. model will be saved to the same file.

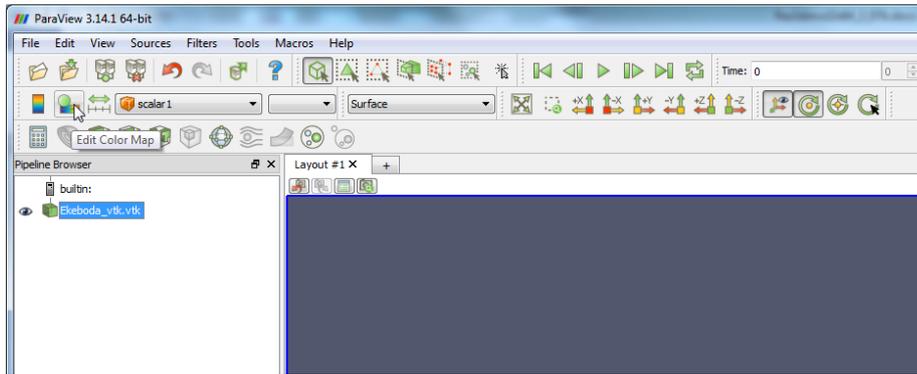


This will be followed by a dialog box to select the iteration number for the model values. The model values will then be saved in a file with the ‘vtk’ extension. Now, start up the Paraview software and use the ‘File-Open’ option to read in the vtk file, as shown below.



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.

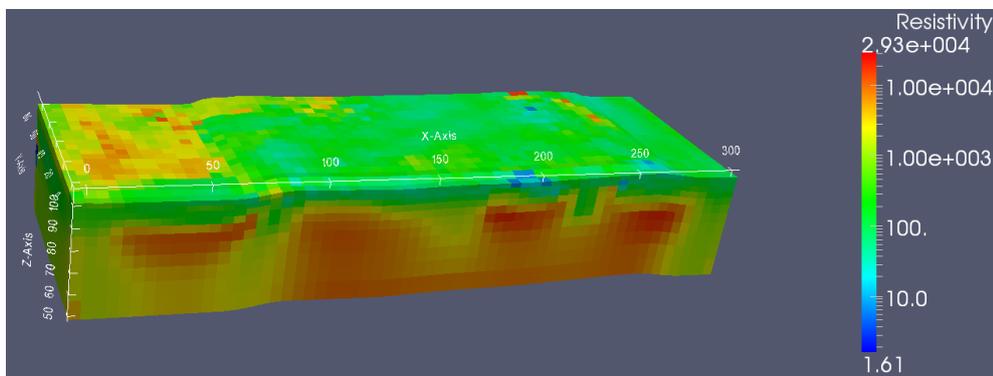
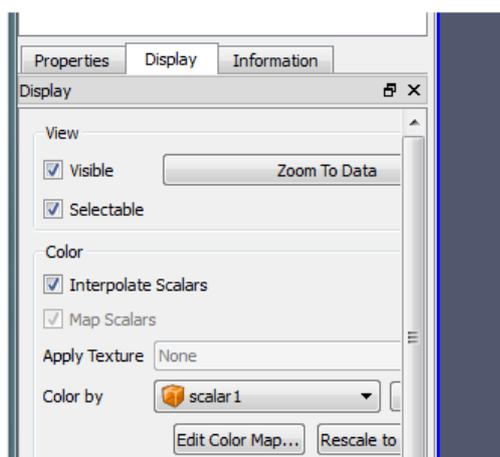


Figure 27. Example 3-D plot using the ParaView program for the Ekeboda landfill survey model.

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.

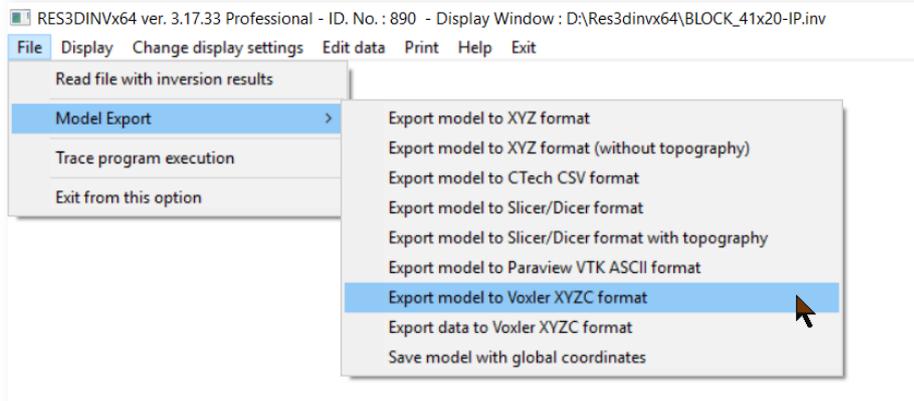


This section gives a very brief introduction to the ParaView program. It is recommended the user follow the exercises in the free ‘The ParaView Tutorial’ (Moreland 2011) that covers many of the software features. The program has options to display the image as a rendered volume, slices, isosurfaces,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

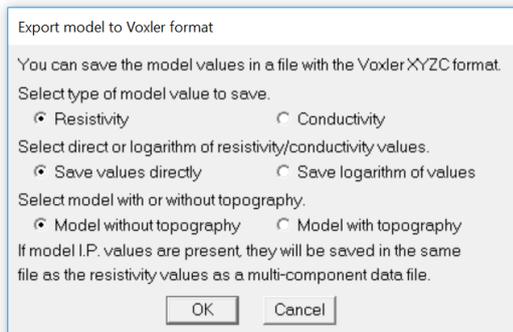
Appendix D : Using Voxler to display the model and data

D.1 Displaying the model

Voxler is a popular 3-D graphics package by Golden Software (www.goldensoftware.com) that can be used to display the inversion model in different forms. It is generally easier to use than Paraview. 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.

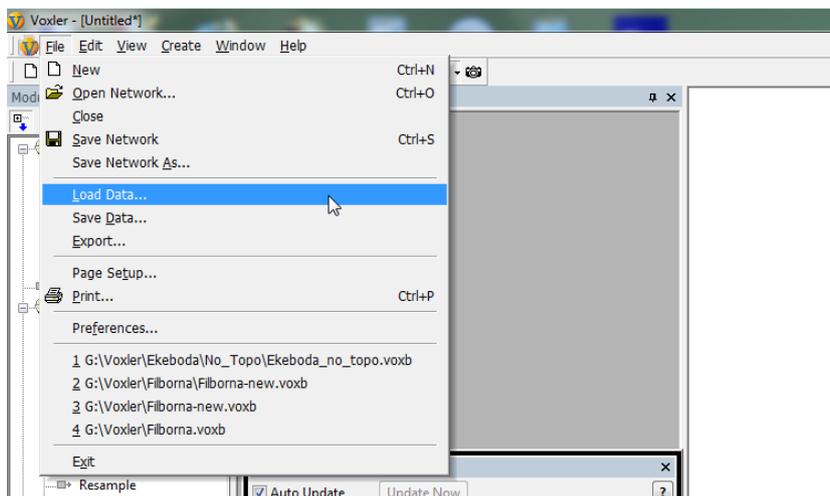


On selecting this option, the following dialog box will be shown.

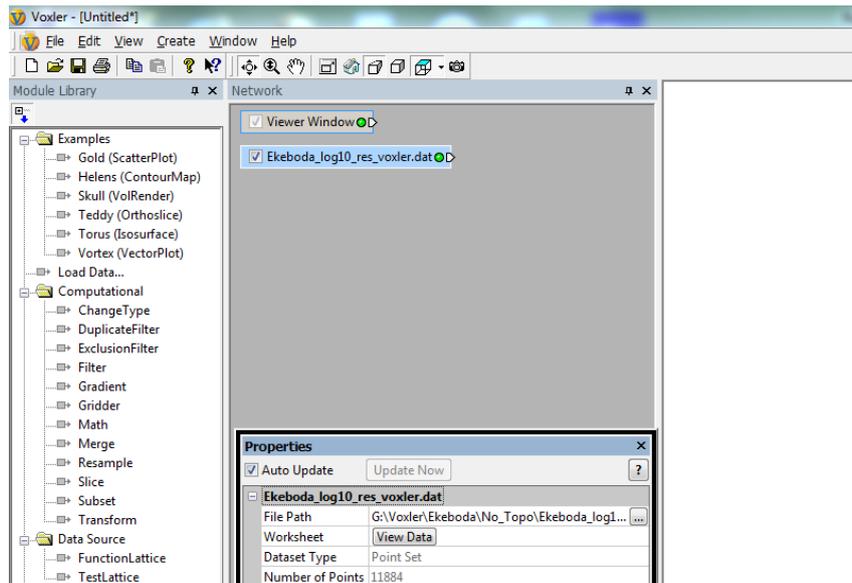


If I.P. values are present, they are saved together with the resistivity values as a multiple component file. Similarly, the sensitivity and model resolution values (if present) are saved to the same file. The sensitivity values are normalized so that the values range between 0.0 and 1.0. For many data 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 13.1. 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, first use the option ‘Load Data’ in Voxler (or ‘Import’ in Voxler 3) to read in a data file as shown below.

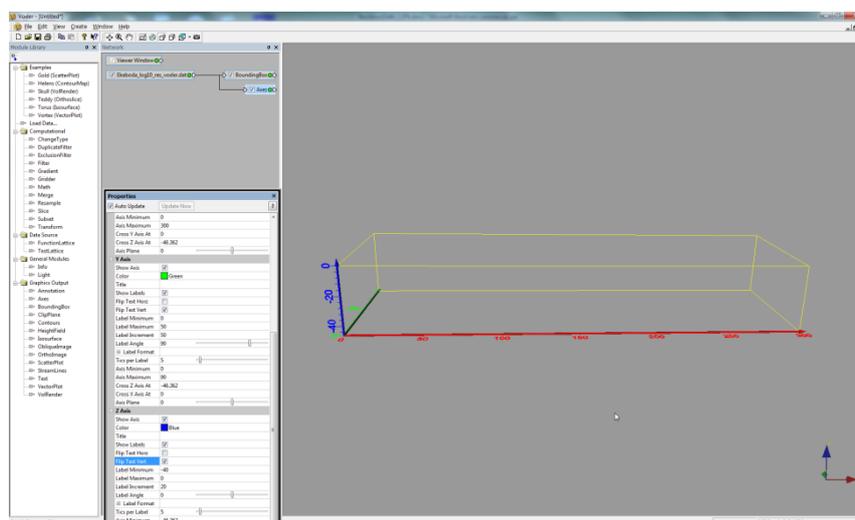


After you read in the file, you should see the name appearing in the Network window in Voxler, as shown below.

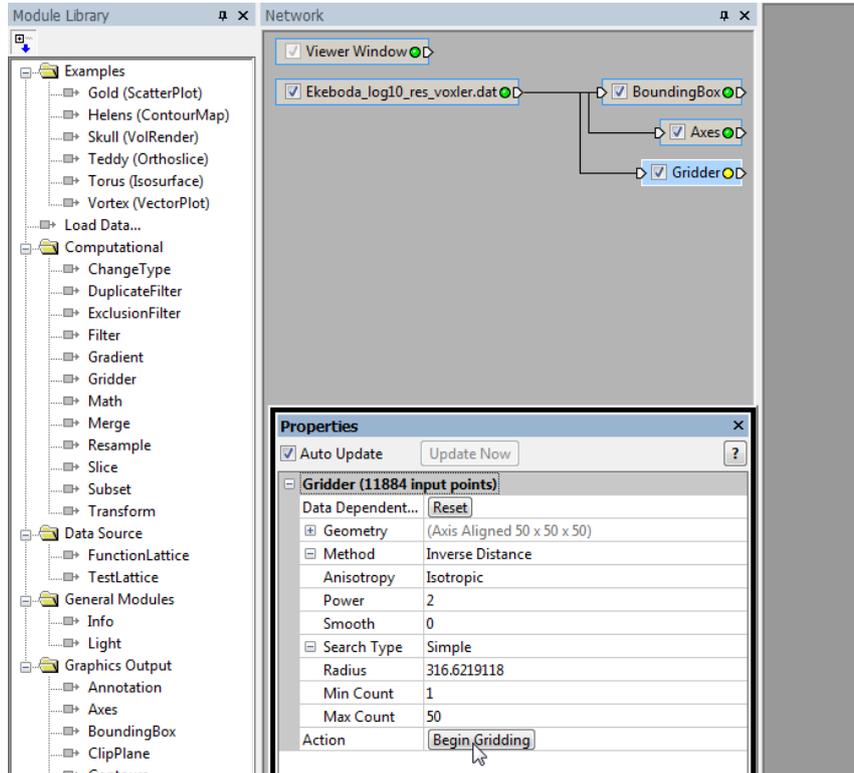


Next, we will carry out three operations that are usually first implemented for all data sets.

- (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 shown in the previous diagram) when you select this option.
- (2). The next step is to display the x, y and z axes 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 0.3 from the default value of 1.0. In the display below, the option 'Flip Text Vert' was also selected for the z axis.



- (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.

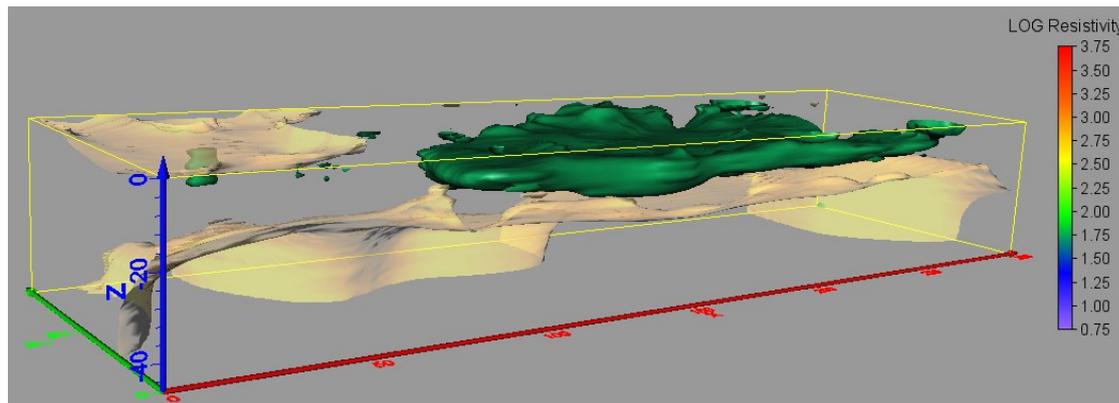


Figure 28. Isurface plot for the Ekeboda landfill model. The green surface has a value of 1.75 (log scale) or about 56 ohm.m. The light brown surface has a value of 3.0 or 1000 ohm.m.

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. You can use both the isosurface and the volume rendered plots in the same display.

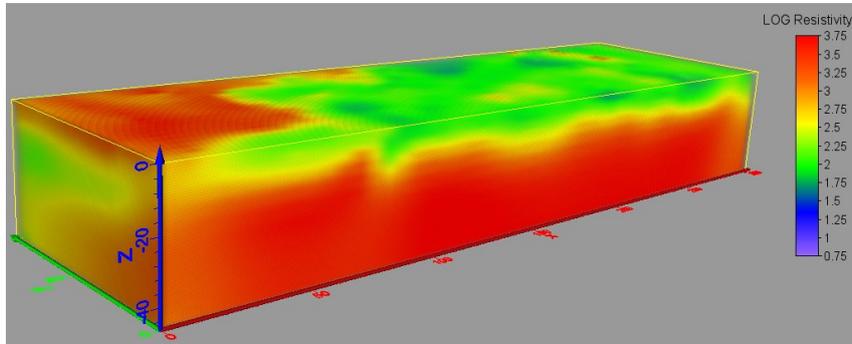


Figure 29. Volume rendered plot for the Ekeboda landfill model.

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.

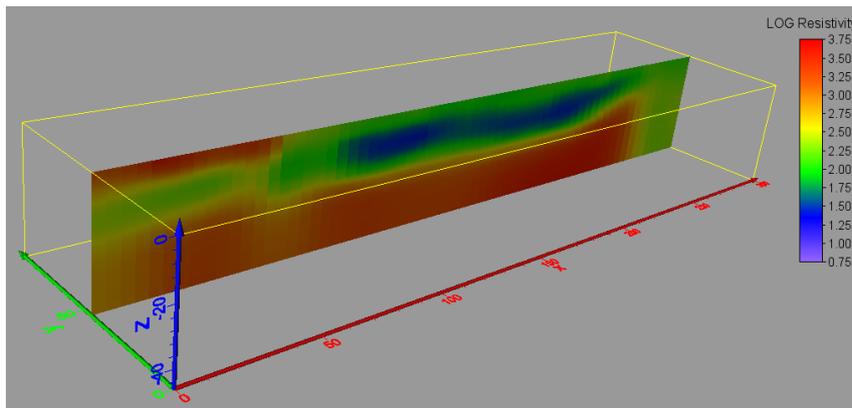
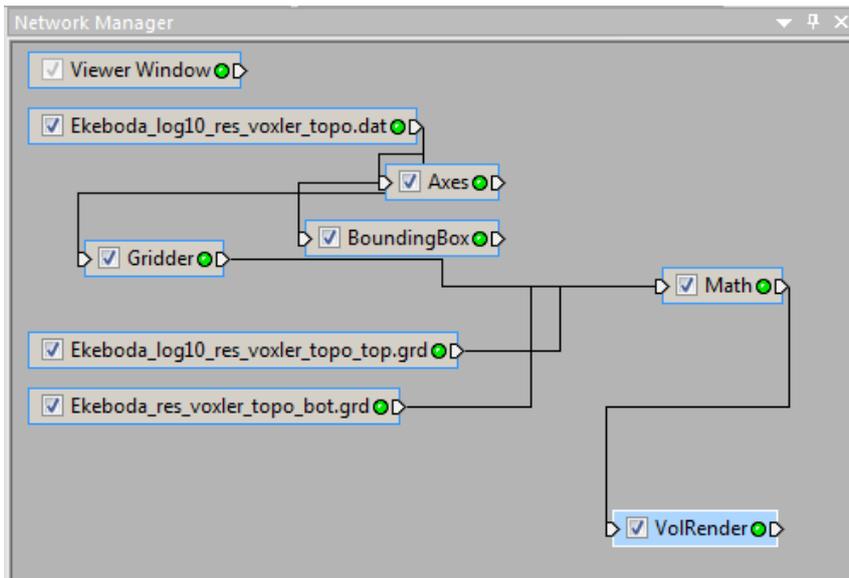


Figure 30. X-Z slice displayed using the Orthoimage plot for the Ekeboda landfill model.

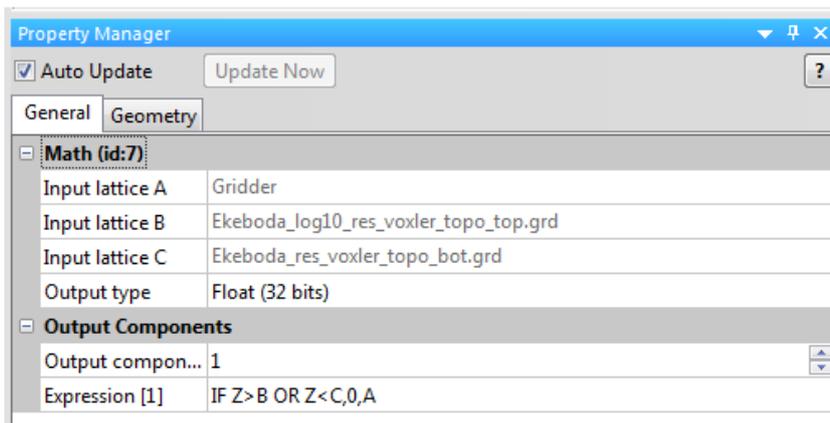
Displaying a model with topography

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.

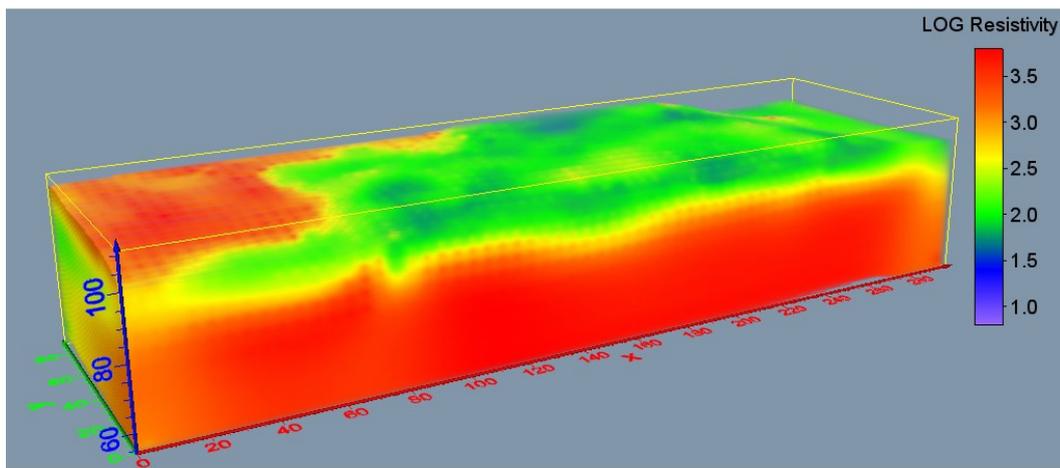


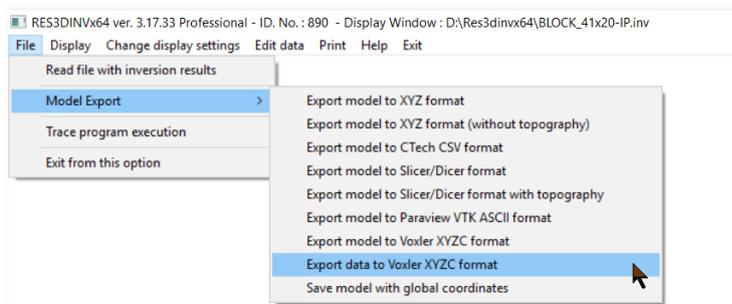
Figure 31. Volume rendered plot for the Ekeboda landfill model with topography included.

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.

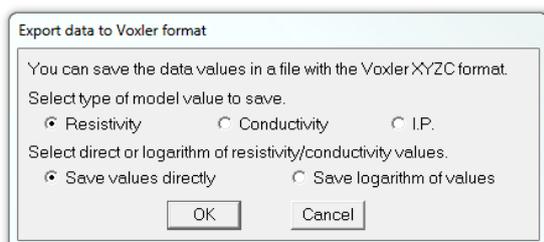
If you use Voxler regularly, it is recommended that you purchase the 'Voxler Full User's Guide' as well from Golden Software that has more details on the different functions in the software.

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 scatter-plot 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.

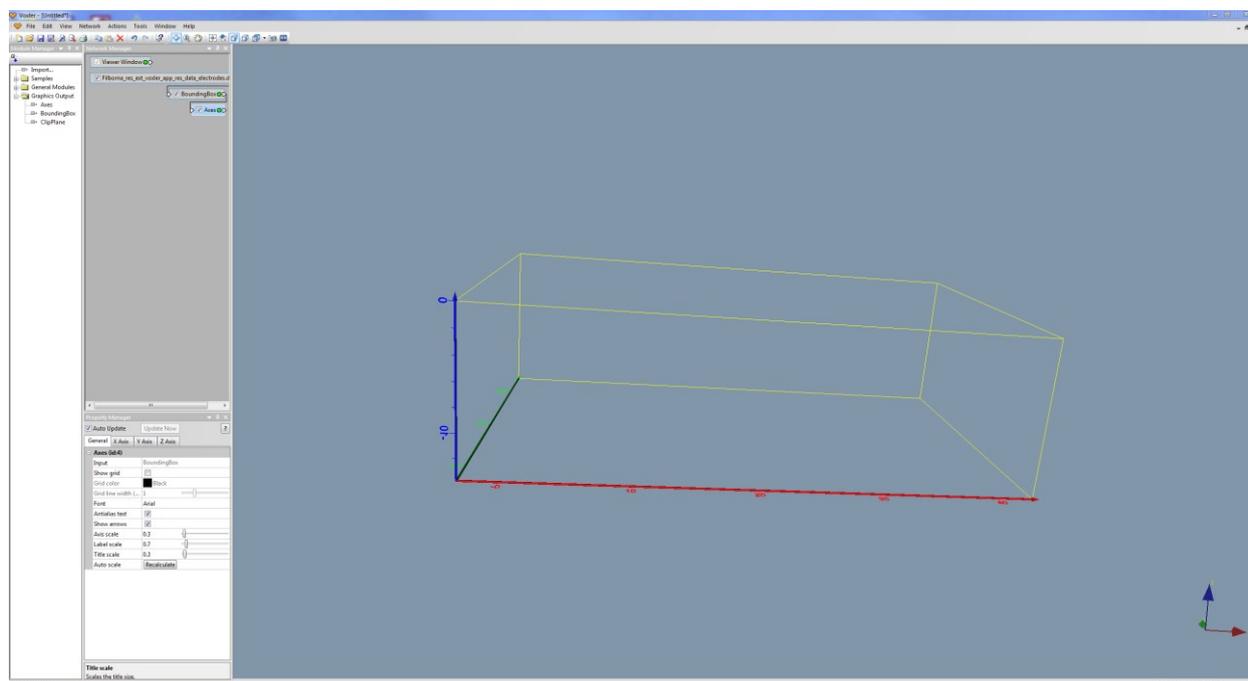


You will then see the dialog box below. If the resistivity values have a small to moderate range, you can save the values directly. If it has a very large range, use the option to save the logarithm (to base 10) of the values.

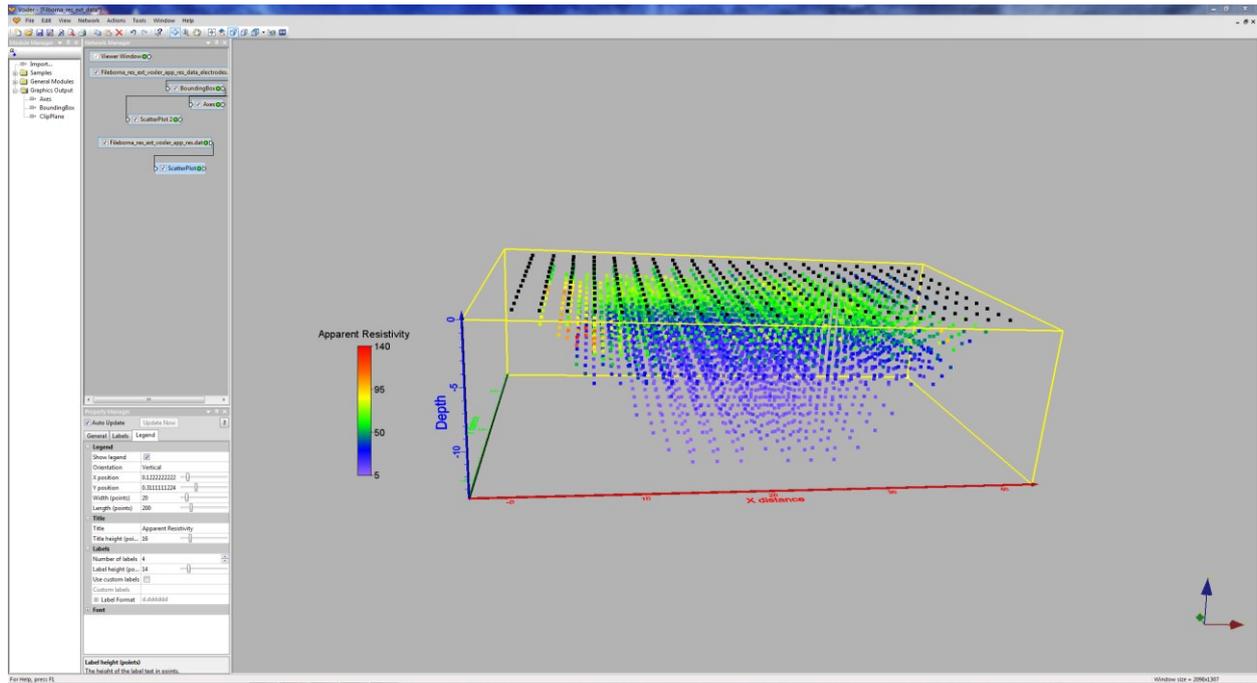


This will create two output files, ‘Filborna_res_voxler_app_res_data_electrodes.dat’ and ‘Filborna_res_ext_voxler_app_res.dat’. There are two main steps in creating the scatterplot in Voxler.

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.



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.

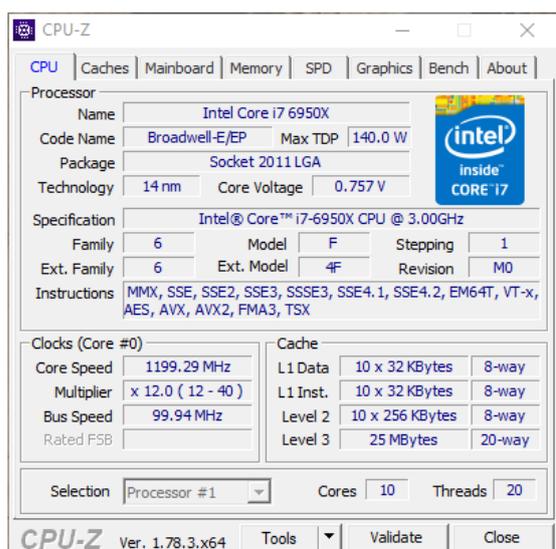
Note the 3-D scatter-plot, like the pseudosection plot in 2-D, is just a convenient means to display the data. It does not imply the region actually ‘sensed’ by the array is at the position of the point in the plot. In fact, for some arrays such as the dipole-dipole, there is very little sensitivity 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 scatter-plot 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 that has 18 to 28 cores that is used on workstation PCs. Some workstations have more than one CPU (usually two to four) in order to increase the processing power. They also frequently support 256 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. Different generations of Intel CPUs support different instructions sets that improve the performance of computationally intensive programs such as RES3DINVx64. Since version 3.18, RES3DINVx64 is compiled such that it utilizes Advanced Vector Extensions (AVX) if this is supported by the CPU present. For CPUs with no AVX support, the program still works. Note that versions earlier than 3.18 were distributed with a separate executable named Res3dinvx64_Intel.exe which supported AVX. Note that this now deprecated file may still be present in your RES3DINVx64 directory after you update to 3.18 and beyond.

The instruction sets, AVX2 and AVX-512 have been implemented in recent and high-end CPUs. The file Res3dinvx64_Intel_AVX2.exe is compiled specifically for CPUs supporting AVX2. An executable that is compiled for AVX-512 instructions is available upon request (ags.support@seequent.com).

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 13.1 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 electrode 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 present 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.

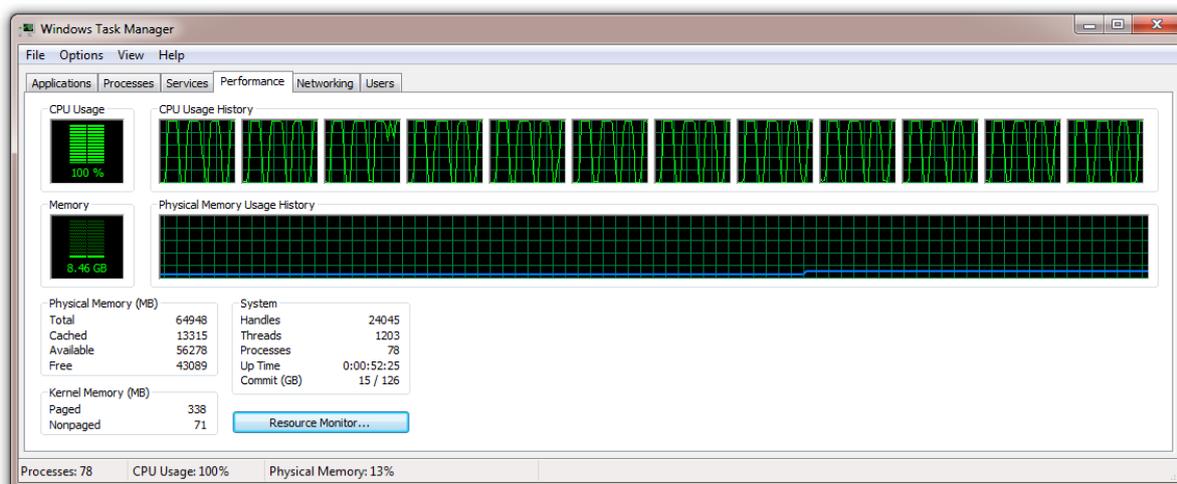
RAM size : This puts a limit on the maximum grid size for the model and finite-element mesh. For some operations, if there is sufficient RAM the program can load the data required into the computer memory instead of accessing the hard-disk repeatedly. This can greatly reduce the calculation time. It 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 64GB with 16 GB modules. The higher end consumer level motherboards have 8 RAM slots that supports a maximum of 128GB 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 512 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 higher end Intel CPUs have a maximum of 28. Beyond that, a workstation level PC is required. The workstations use the Xeon CPUs that can have 8 to 28 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 and Jacobian matrix 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 and 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. However, the use of the special registers usually reduces the CPU clock speed, so there is some tradeoff.

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 enough 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. The SATA based SSDs are several times faster than conventional HDDs, while the NVMe SSDs are 5 or more times faster than the SATA SSDs.

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.

Table 30 shows the calculation time for a moderately large I.P. data set with 4277 data points and 667 electrodes positions using the arbitrary electrodes data format on different PC systems. The data set has topography so the finite-element method is used. The model grid has 55680 model blocks with a finite-element mesh with 1875167 nodes. Most of the computer time is spent in the forward modeling and Jacobian matrix calculation routines. The computers used as follows.

Laptop :- Dell Mobile Precision 5520 laptop with quad-core CPU.

Desktop 1 :- Generic desktop with hex-core Sandy Bridge E CPU.

Desktop 2 :- Generic desktop with 10-core Broadwell E CPU.

Workstation 1 :- Dell Precision Tower workstation with dual 8-core Xeon E5 CPUs.

Workstation 2 :- Dell Precision Tower workstation with single 18-core Xeon W CPU.

The maximum memory required during the inversion was about 17 GB, and all the systems have SSDs. The CPU-Z program was used to identify the CPUs, and the single and multiple thread benchmarks from this program are also listed. All the calculation times listed are those obtained with the hyper-threading function of the CPUs disabled. It was found that with hyper-threading the program was generally about 3% to 4% slower! In the slower systems (Laptop, Desktop 1 and Workstation 1) the computer time is dominated by the CPU. The reduction in the calculation time between Workstation 2 and Desktop 2 is relatively small despite the large increase in the number of cores (and cost!). This is partly because the Xeon 18-core CPU runs at a lower clock speed, and single-thread operations such as hard-disk access (which is not affected by the number of CPU cores) becomes increasingly important as the time taken by the CPU intensive multi-thread operations is reduced. However, the workstation systems are more stable and can be used to process large data sets and models (with tens to hundreds of thousands of data points and electrode positions, over 5 million nodes) for calculations that can take several days.

Table 30. Calculation times on different computers.

Computer	Laptop	Desktop 1	Desktop 2	Workstation 1	Workstation 2
Time (s)	17666	19972	9968	15070	8008
No. Cores	4	6	10	2x8	18
Model	i7-7820HQ	i7-3930K	i7-6950X	E5-2650 v2	W-2195
Clock (GHz)	2.9	3.2	3.0(3.5)	2.6(3.0)	2.3(2.9)
CPU-Z	426/2087	374/2018	508/5297	321/4497	485/8711
RAM(GB)	32	64	128	128	256

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 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.

It should be noted that in some surveys using unconventional arrays, such as the Iris Instruments Full-Waver distributed systems (Truffert et al. 2018), negative apparent resistivity values can occur and are real and not due to noise. This is caused by a combination of the non-collinear geometry of the electrode layout and large resistivity contrasts. In such cases, the resistivity itself (and not the logarithm of the apparent resistivity), should be used as the inversion data parameters so that negative values can be accommodated. Appendix C of the notes by Loke (2019) has a more complete discussion of this issue. Appendix M describes an alternative method to invert data from the Full-Waver distributed system where a vector array layout is used.

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 31 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 are 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.

Table 31. 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.

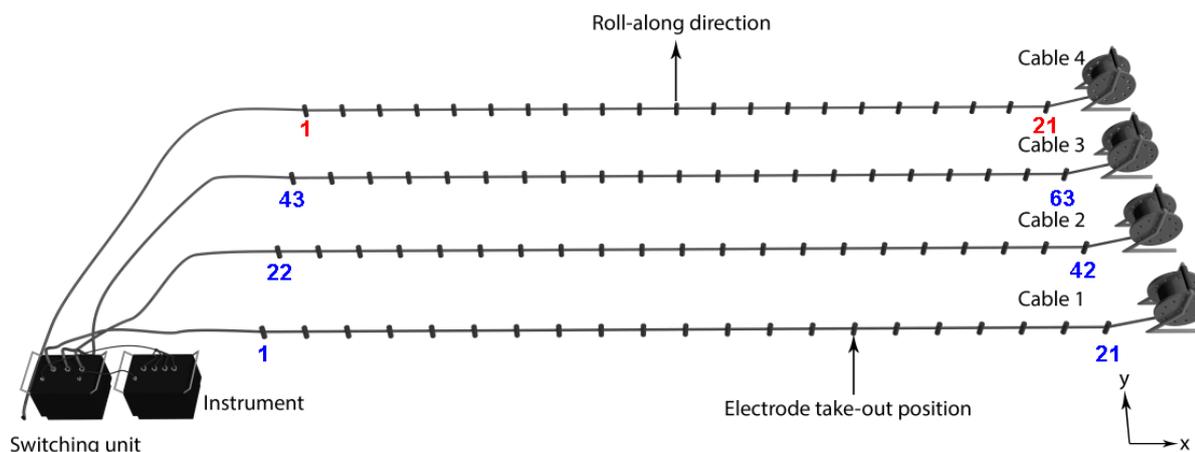


Figure 32. A roll-along 3-D survey using 3 parallel lines of electrodes.

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 is usually saved 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 32. 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 32 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 elevation reference point.

Table 33 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 33. 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 34 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 be at the vertices of a right-angle triangle that covers half the survey area.

The files described in this section are in the Combine-3D.zip which should be copied to the same folder where the Res3dinvx64 program was installed.

Table 34. 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	<i>Main data section</i>
14.0, 6.0 2.0, 6.0 26.0, 6.0 38.0, 6.0 29.334	<i>Last 2 data points with the positions of the</i>
16.0, 6.0 4.0, 6.0 28.0, 6.0 40.0, 6.0 31.759	<i>electrodes in local coordinates</i>
Topography	<i>Header to indicate topography section present</i>
1	<i>Flag to indicate true x-y horizontal positions</i>
Topography in unstructured list	<i>Header indicate topography points in a list</i>
Number of topography data points	<i>Header for number of topography points</i>
63	<i>Number of topography points</i>
Topography data points (index,x,y,z)	<i>Header to indicate format used</i>
1 0.0 0.0 0.00	<i>Coordinates of 1st point</i>
2 2.0 0.0 0.00	<i>Coordinate of 2nd point</i>
.....	<i>Other topography data points</i>
.....	<i>listed</i>
63 40.0 6.0 0.00	<i>Last topography point</i>
	<i>Indicates end of batch file</i>
Global coordinates information present	<i>Header to indicate global coordinates present</i>
Type of global coordinates information (0=point-to-point)	<i>Header for flag to indicate type of global coordinate information</i>
0	<i>Only this option is used at present</i>
Number of points	<i>Header for number of points used in coordinate transformation</i>
3	<i>Recommend use 3 points in a right-angle triangle</i>
Local x-y Global x-y	<i>Header for section with coordinates of points</i>
0.0000, 0.0000 0.0000, 9.0000	<i>First pair of points with x-y coordinates</i>
0.0000, 6.0000 0.0000, 15.0000	<i>Second pair of points with x-y coordinates</i>
40.0000, 6.0000 40.0000, 15.0000	<i>Third pair of points with x-y coordinates</i>
0	
0	
0	

Appendix J : Converting borehole electrodes data files to subsurface point electrodes format.

The conventional data format (used in ver. 3.16 and earlier) for borehole electrodes only supports vertical boreholes, while the arbitrary subsurface point electrodes format supports a more general arrangement. Res3dinvx64 ver. 3.17 now automatically converts a data set in the old borehole format into an arbitrary electrodes data format with subsurface electrodes. Table 35 shows an example of the bor9pdp_ip.dat files converted into the new format.

Table 35. Part of the bor9pdp_ip_pts.dat file with data converted from boreholes to arbitrary subsurface point electrodes format.

<i>bor9pdp ip_pts.dat</i>	<i>Comments</i>
Block Model with IP	<i>Name of survey</i>
9,9	<i>Model grid is 9 x 9 in x and y directions</i>
Nonuniform Grid	<i>Type of model grid</i>
X-location of grid lines	<i>Header for x grid lines</i>
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0	<i>X grid values</i>
Y-location of grid lines	<i>Header for y grid lines</i>
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0	<i>Y grid values</i>
11	<i>General array data format</i>
0	<i>No sub-array</i>
Type of data (0=Apparent Resistivity, 1=Resistance)	<i>Header for data type</i>
0	<i>Coordinate of 2nd point</i>
Point Electrodes outside grid present	<i>Header to indicate arbitrary point electrodes</i>
Number of point electrodes	<i>Header for number of point electrodes</i>
Subsurface point electrodes present	<i>Header to indicate subsurface electrodes</i>
Borehole format converted to subsurface point electrodes	<i>Special header to indicates this was a borehole data set</i>
Compressed format used for point electrodes coordinates	<i>Header to indicate compressed format used</i>
1 2.000, 2.000, 0.000, 1.000	<i>First point electrode</i>
2 2.000, 2.000, 0.000, 2.000	<i>Index, x, y, elevation, depth below surface</i>
...	<i>Same for other point electrodes</i>
32 2.000, 6.000, 0.000, 8.000	<i>Last point electrode</i>
User defined depths to layers present	<i>Header to indicate model depths given in file</i>
Number of layers	<i>Header for number of layers</i>
8	<i>Eight layers</i>
Depth of layers	<i>Header for list with depths</i>
1 1.0000	<i>Index, first layer depth</i>
2 2.0000	<i>Index, second layer depth</i>
.....	<i>Same for other layers</i>
8 8.0000	<i>Last layer</i>
3880	<i>Number of data points</i>
IP present	<i>Flag to indicate I.P. data present</i>
Chargeability	<i>Type of I.P. data</i>
mV/V	<i>Unit for I.P. data</i>
0.1000, 1.0000	<i>Parameters for I.P. data</i>
3 0.0 0.0 0.0 1.0 0.0 0.0 2.0 0.0 0.0 100.2730 1.968	<i>First data point</i>
3 0.0 0.0 0.0 2.0 0.0 0.0 3.0 0.0 0.0 100.2550 1.963	<i>Second data point</i>
..	
..	
3 2.0 6.0 8.0 6.0 6.0 7.0 6.0 6.0 6.0 103.6360 1.345	<i>Last data point</i>
0,0,0,0	<i>End with a few 0s</i>

In the converted file, the depths to the model layers are specified in the file so that the inverse model will have layer boundaries at the same depths as the borehole electrodes. This is indicated by the header 'User defined depths to layers present' placed after the section with the subsurface point

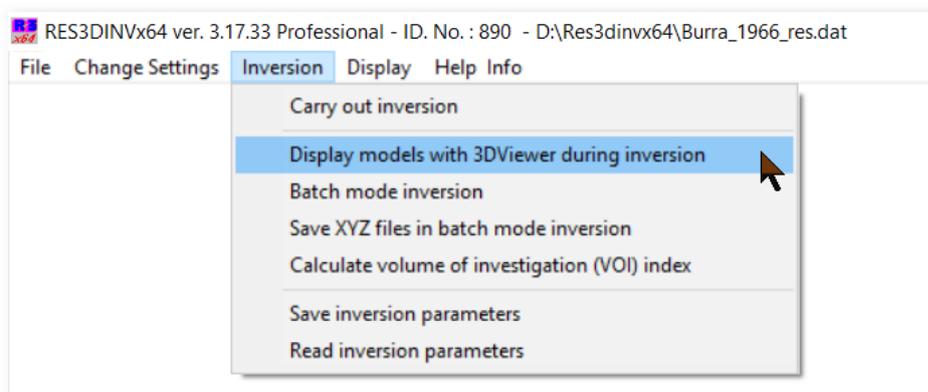
electrodes list in Table 35. The number of layers and the depths to the layers are listed in this new section.

Appendix K : Instructions for using the 3DViewer program.

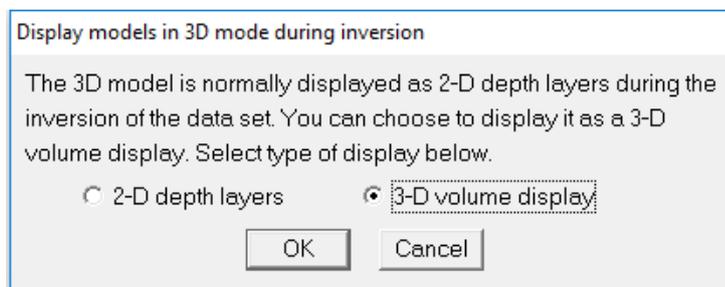
The 3DViewer module included with RES3DINV Basic, Professional and Enterprise enables the inversion results to be viewed in 3D during and after inversion. The 3DViewer is a limited version of the 3D viewer included with Aarhus Workbench by Aarhus GeoSoftware.

K.1 Viewing inversion results in the 3D viewer during inversion

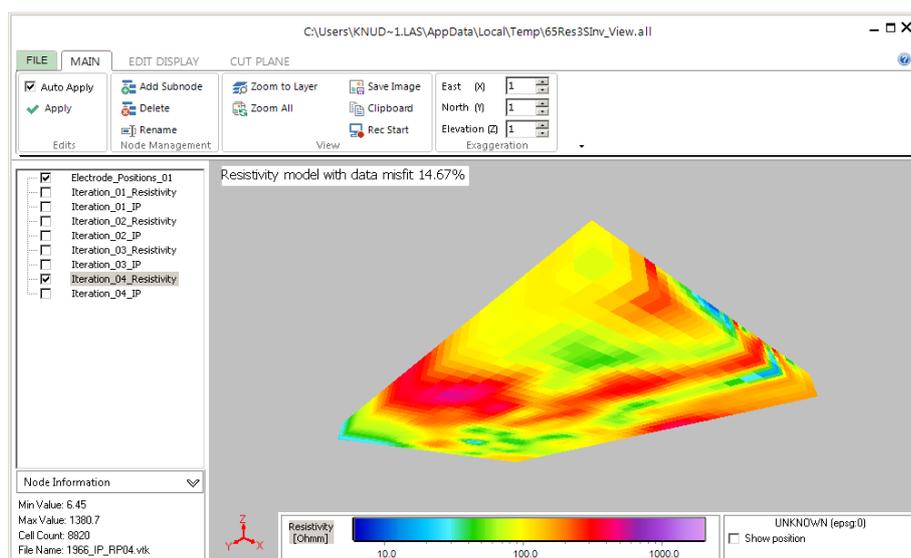
To view the result of each iteration during the inversion select 'File-Display models with 3DViewer during inversion during inversion', as shown below.



And select the '3-D volume display' option.



The 3DViewer will now automatically open in a new window after the first iteration is done, and each new iteration will be added in the menu to the left as they are done:

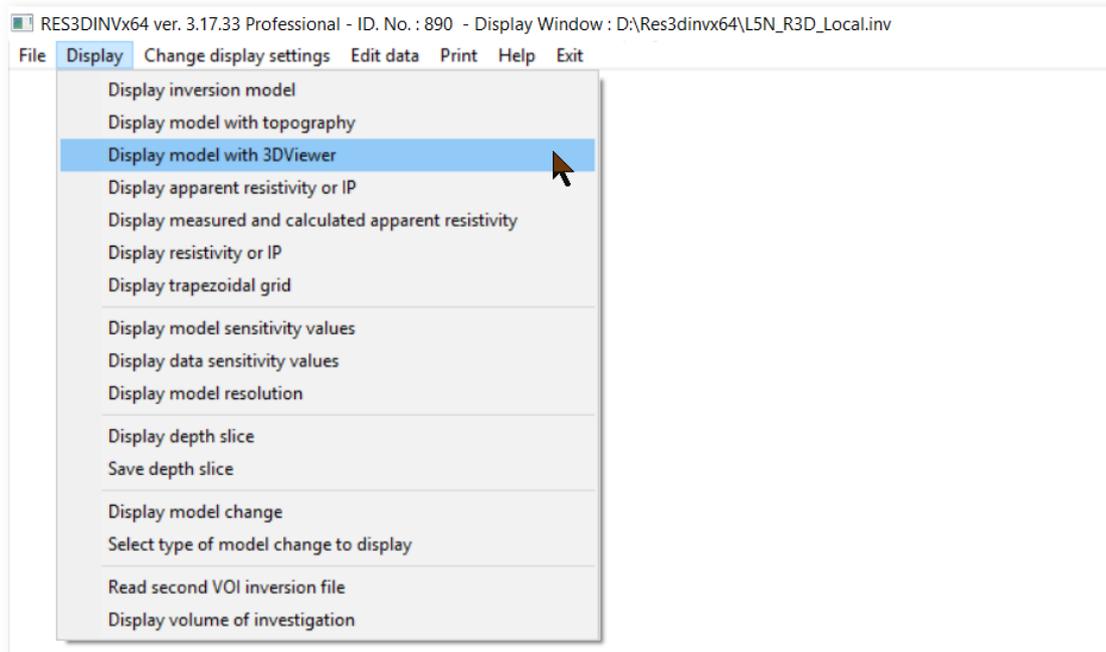


Each iteration can be toggled on and off by ticking the box next to the iteration in the menu to the left. Note: Remember to still keep an eye on the RES3DINV window as any popup messages during the inversion will still be shown in this window.

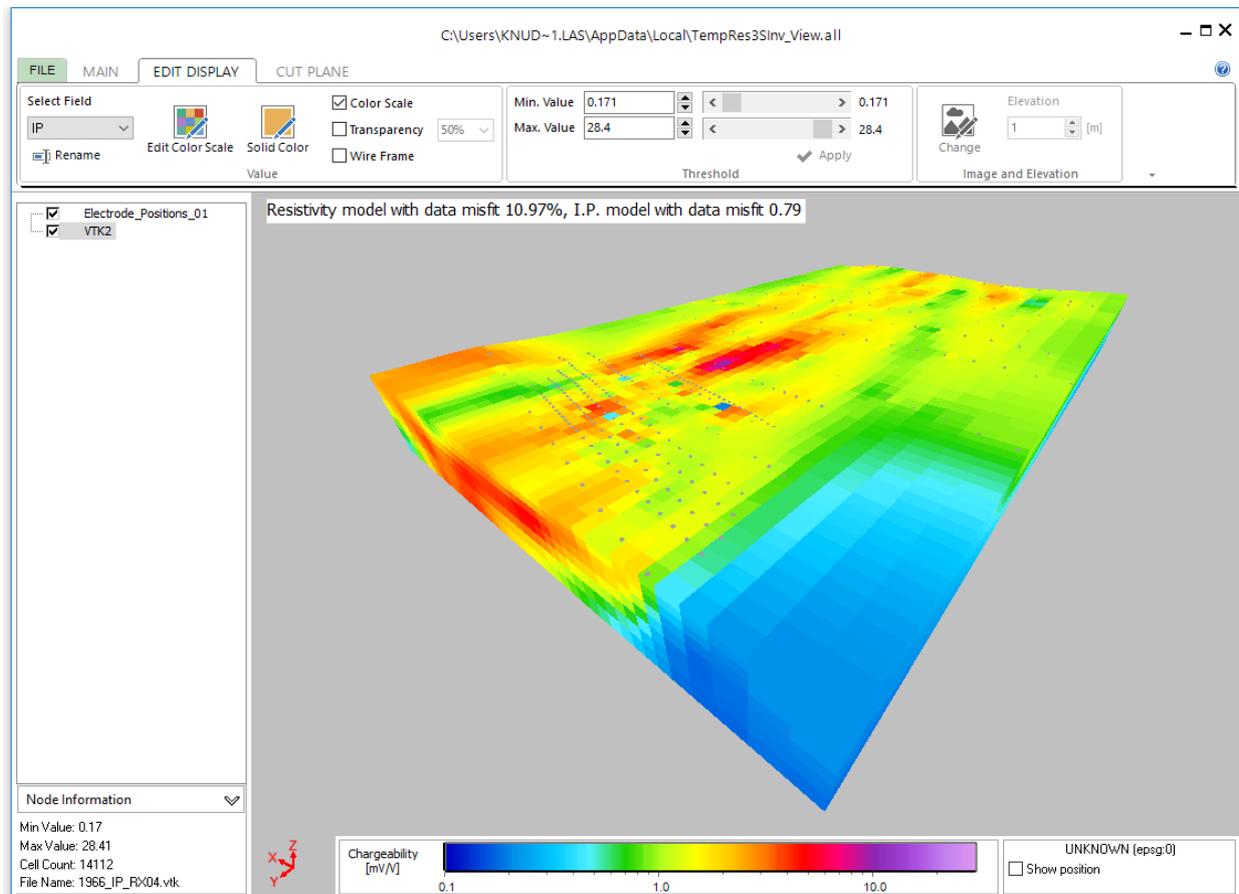
Note: If the iteration time is less than 0.1 seconds the results will be shown in RES3DINV in the normal way, and the option to display the inversion result after inversion should be used instead to show the result in the 3D viewer.

K.2 Viewing inversion results in the 3D viewer after inversion

Once the inversion is done the inversion results can be viewed in the 3DViewer by selecting ‘Display’ and loading in the relevant .INV file. Once this is done select ‘Display model with 3DViewer’, as shown below.



After choosing resistivity or conductivity display and selecting which iteration to display the 3DViewer will open in a separate window.



Two layers will be present in the 3DViewer, ‘Electrode_Positions_01’ holding the electrode positions and ‘VTK2’ holding the inversion result. If both resistivity and IP results are present it is possible to toggle between the two by highlighting the ‘VTK2’ layer and selecting between the two in the ‘Select Field’ dropdown under the ‘EDIT DISPLAY’ tab.

K.3 Display options in the 3DViewer

A number of basic and advanced visualization options are available in the 3DViewer, some of them will be presented in the following. The most self-explanatory options will not be presented.

Navigation and rotation

To rotate the view, press and hold the left mouse button and move the mouse to rotate the view. To change the center of rotation, press and hold the right mouse button and drag the content in the 3DViewer relative to the center of rotation. To zoom in and out use the scroll wheel on the mouse or select the options 'Zoom to layer' and 'Zoom all' in the 'MAIN' tab.

Vertical and horizontal exaggeration

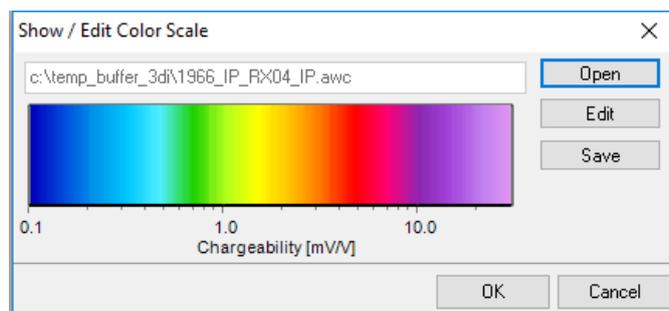
Vertical and horizontal exaggeration can be added in the 'Exaggeration' panel in the 'MAIN' tab.

Changing the size and color of the electrode positions

The size of the electrode position points can be changed by highlighting the 'Electrode_Positions_01' layer in the menu to the left, changing the 'Point Size' property in the 'Edit Display' tab and selecting 'Apply'. The color can be changed by selecting 'Solid Color' in the same tab. The electrode position display can be disabled entirely by unchecking the layer in the menu to the left.

Change and edit the color scale

The color scale of a layer can be changed by selecting the layer in the menu to the left and then selecting 'Edit Color Scale' in the 'EDIT DISPLAY' ribbon. This will open the window seen below.

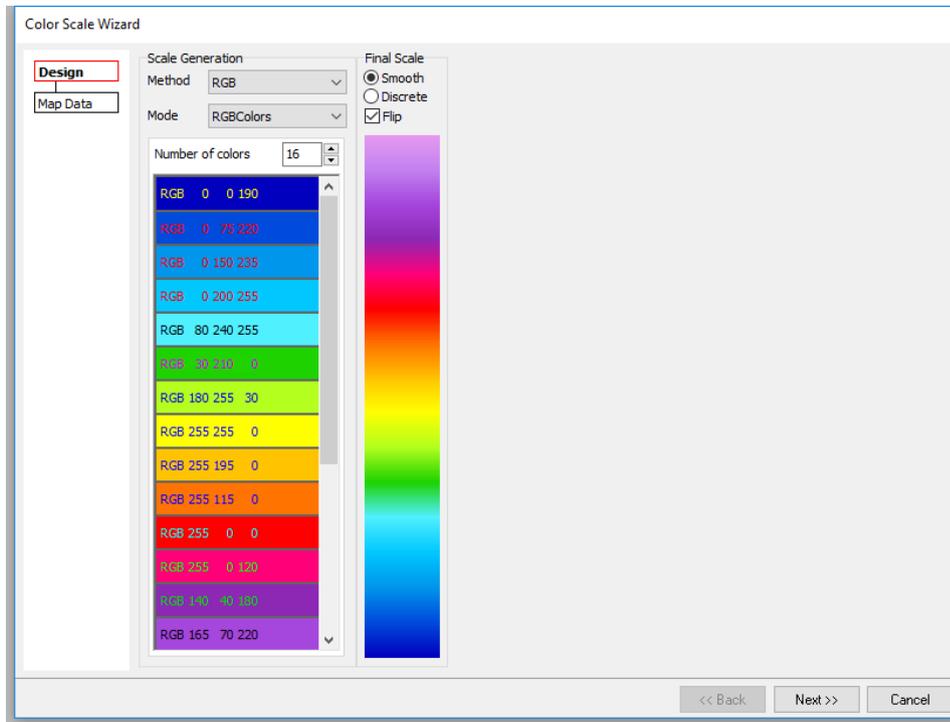


In this window it is possible to choose between 3 options: Open, Edit and Save.

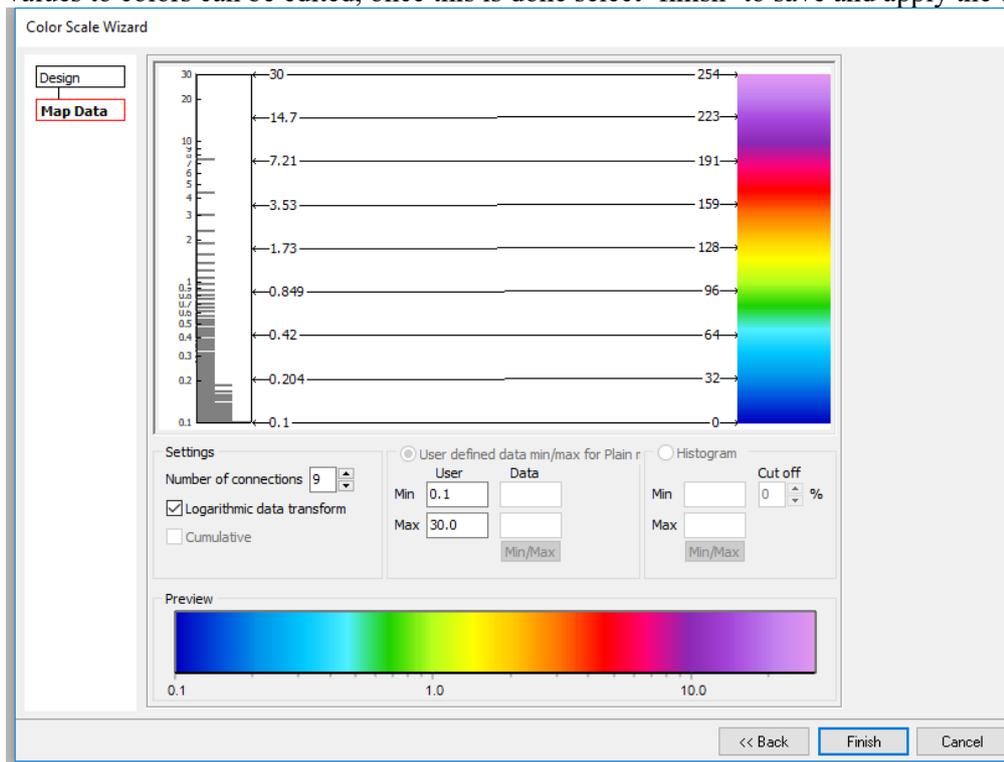
If you select 'Save' you can save the color scale for future use.

If you select 'Open' you can choose between a number of predefined color scales by selecting 'Standard', or you can select a previously saved color scale by selecting 'Open folder' and navigate to the folder where the color scale is saved.

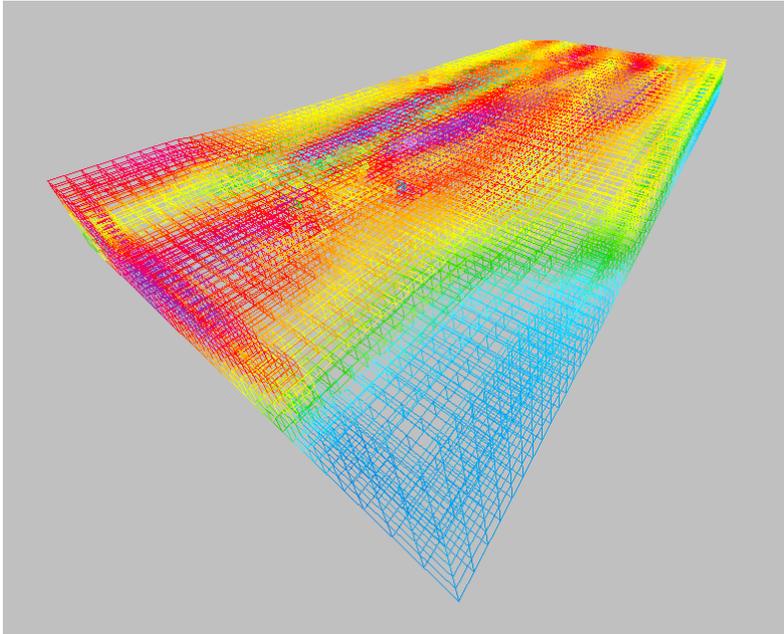
If you select 'Edit' you can create a custom color scale. First you must choose the color range and type of color scale in the window displayed below.



By selecting next you are taken to the window seen below. In this window the range and mapping of values to colors can be edited, once this is done select 'finish' to save and apply the color scale.

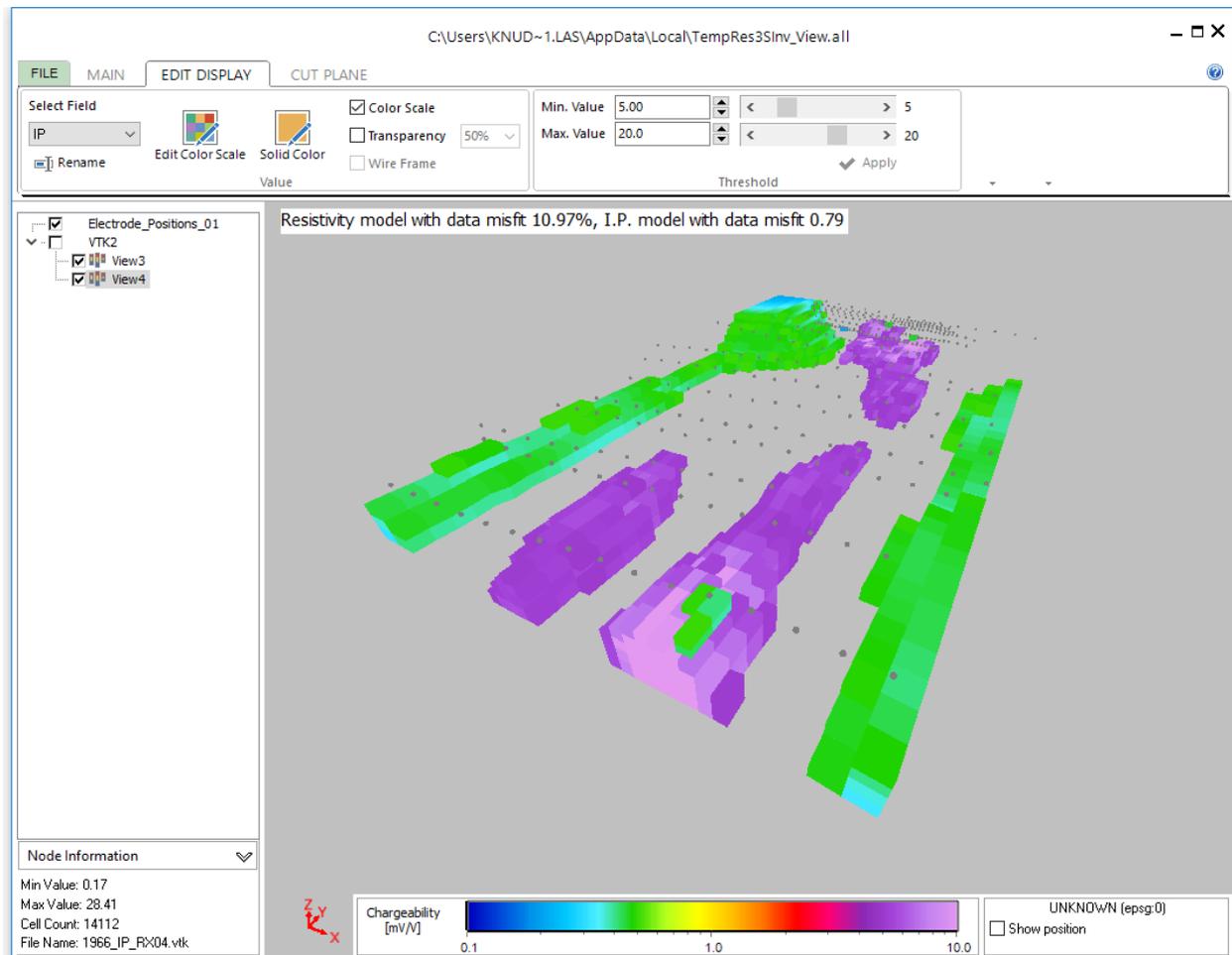


It is possible to see the result as a wire frame instead of as a solid block by selecting 'Wire Frame' next to the color scale option:



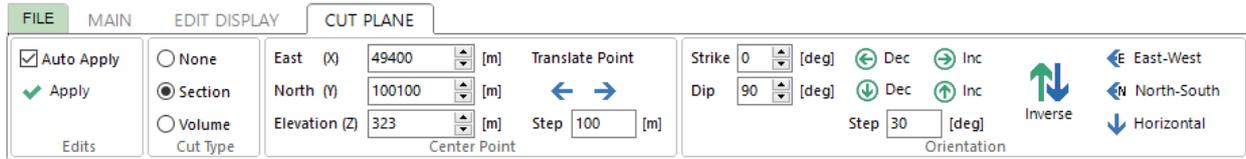
Showing a selected range of resistivity or chargeability values only

It is possible to only show the results within a certain range by using the 'Threshold' option found in the 'Edit Display' tab, define the minimum and maximum value and select apply. It is possible to show several ranges by creating subnodes to a layer, this is done by selecting 'Add Subnode' in the 'MAIN' tab while having the layer highlighted in the menu to the left. Each subnode can be thresholded individually. An example of IP data where the chargeability ranges from 0.0 to 0.5 and from 5.0 to 20.0 is selected is displayed below.



Cut planes and fence diagrams

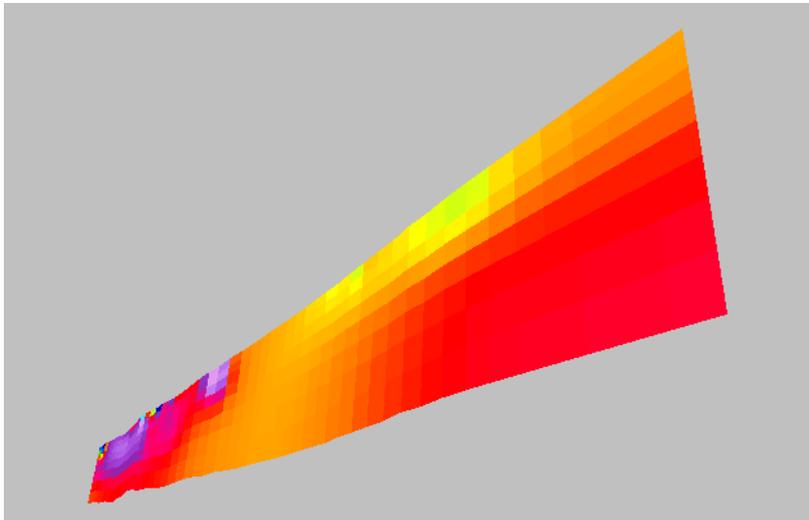
Another way of showing “the inside” of inversion results is through cut planes. Most options relating to cut planes are found under the ‘CUT PLANE’ tab as shown below.



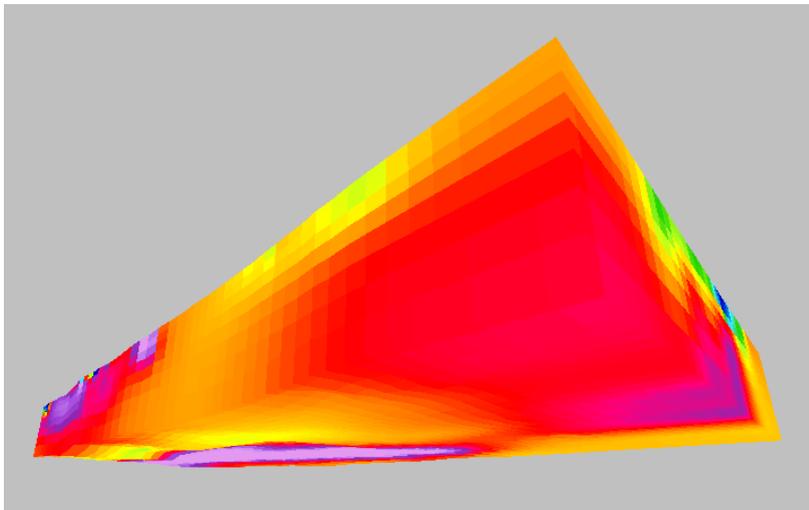
To edit the cut plane properties of a layer in the 3D viewer highlight the layer in the menu to the left, there are 3 options:

‘None’, this is the standard setting, and means that cut planes are turned off.

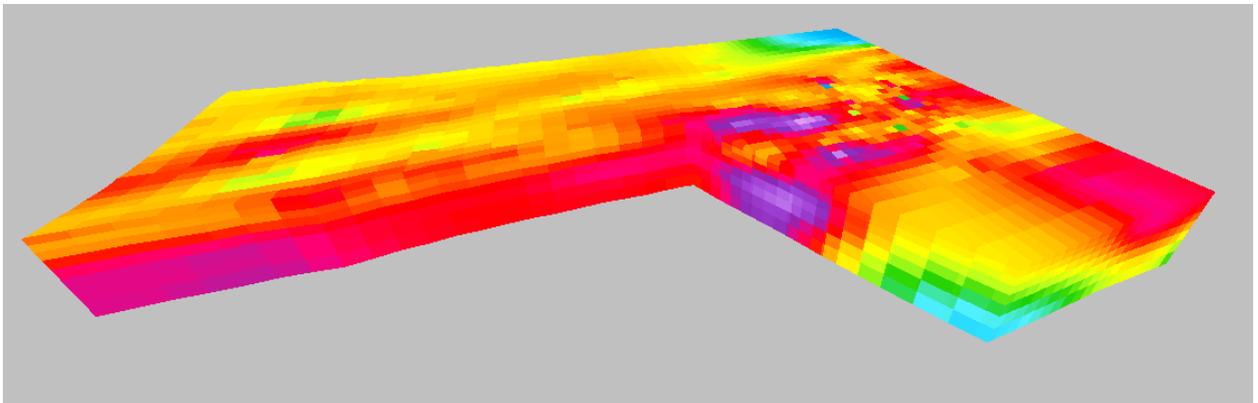
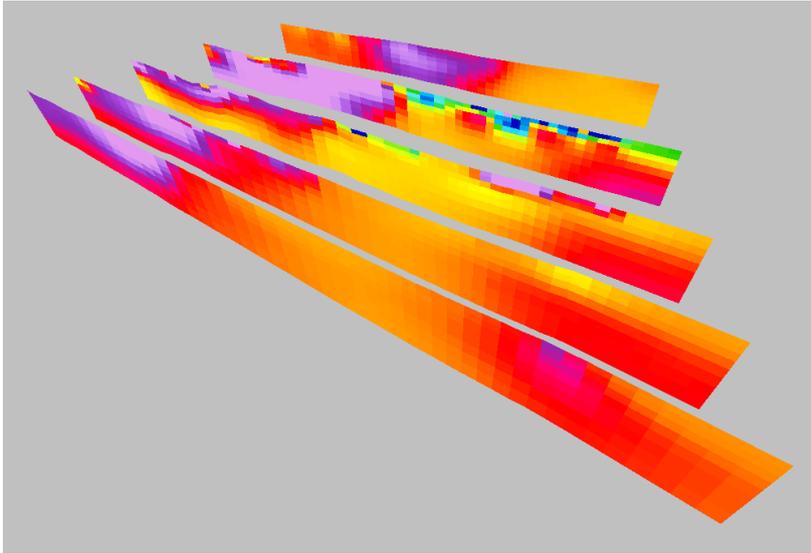
‘Section’, this setting shows a slice of the inversion result as shown below. The slice can be horizontal, vertical or even in oblique angles, this is controlled through the ‘Strike’ and ‘Dip’ settings in the ‘Orientation’ panel. The cut plane is moved by defining its position in the ‘Center Point’ panel, or by using the ‘Translate Point’ arrows to move the plane in the direction perpendicular to the plane, the translation distance is set under the arrows. The location of the cut plane can be viewed by selecting ‘Cut Plane’ in the ‘MAIN’ tab.



‘Volume’, this option is very similar to the ‘Section’ option, but instead of only showing a slice of the result, everything on one side of the cut plane is seen, as shown below. Which side of the plane to show can be toggled by selecting the ‘Inverse’ option.



Note that it is possible to create more advanced views such as fence diagrams or cubes with cutouts by creating several subviews with different cut planes as show below. It is also possible to combine cut planes and thresholding.



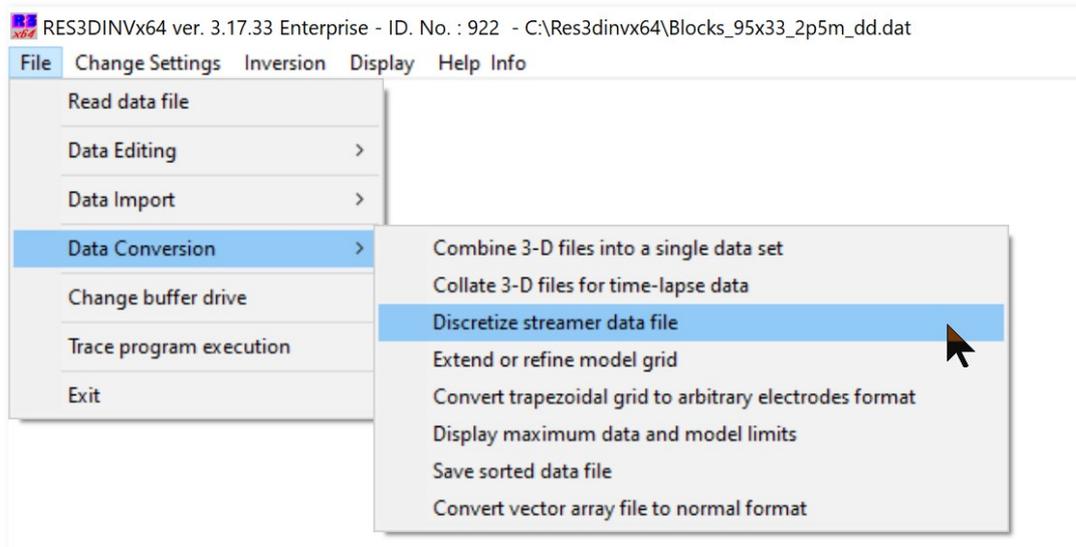
Appendix L : Electrodes binning and segmentation of large survey grids (Enterprise).

This option is intended for very large surveys with several hundred thousand electrode positions and data points, and usually with more than 100 model grid lines in both the x and y directions. The survey is commonly carried out using a mobile measuring system, such as a capacitively coupled resistivity meter (Hildes et al. 2005; Kuras et al. 2006) or a streamer pulled behind a boat or floating platform in a shallow marine site (Oikonomou et al. 2019) in the Lambayanna submerged archaeological area, Greece. Figure 33 shows the electrode positions and the inverse model grid for the data from this survey. Data from such surveys normally use the arbitrary electrodes data format as the electrode positions do not fall in a simple rectangular pattern. This data set has 215873 electrode positions and 164414 data points. The inverse model has 10 layers and 422500 model cells. The inversion of this data set using standard monolithic inversion approach took 19.1 days on a PC with an 18-core CPU and 256 GB RAM. To handle such large data sets in a reasonable time, two new options have been added. These options are only available in the ‘Enterprise’ version of the program.

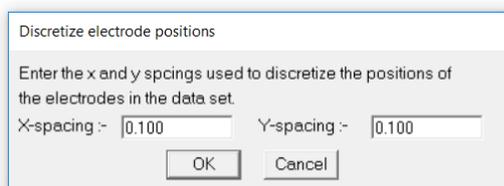


Figure 33. Underwater survey in Greece. The segments used in the segmentation inversion are shown by the colored lines.

Electrode discretization (binning) :- After reading in the data set, this option is selected via the ‘File - Data Conversion - Discretize streamer data file’ option.

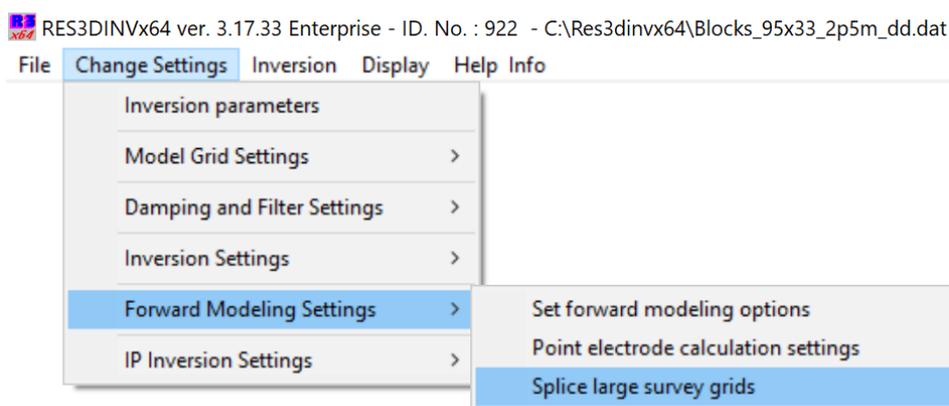


On selecting this option, the following dialog box will be shown.

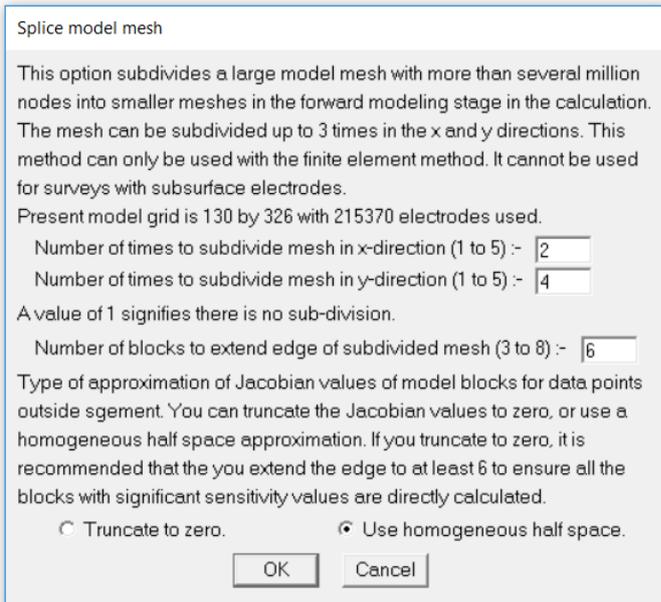


In this case, the positions of the electrodes in the data set will be rounded up to the nearest 0.1 m (the binning interval). The discretization spacing should not be more than half the electrode spacing. The larger the binning interval, the greater the reduction in the number of electrode positions. However, this will cause larger distortions in the inverse model as the electrodes are no longer exactly at the positions they were used to make the apparent resistivity measurements. The reduction in the number of electrodes position versus the degree of model distortion is data dependent. As an example, for the survey shown in Figure 33, using a binning interval of one-tenth the dipole length will only reduce the number of electrode positions by 8%.

Mesh segmentation :- Mobile surveys with a streamer usually use arrays with a relatively limited length (i.e. the length of the streamer) compared to a normal static system. Due to the limited footprint of the arrays, the apparent resistivity values are affected by a fairly limited region of the subsurface. The finite-element mesh used to model the data in Figure 33 has more than 9 million nodes. The calculation time, computer memory and disk space reduce increases non-linearly with the number of nodes. The segmentation option subdivides the model grid into smaller grids that takes advantage of the limited footprint of the arrays. After reading in the data file, select the ‘Change Settings – Forward Modelling Settings – Slice large survey grids’ option as shown below.



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



As the model grid is longer in the y-direction, it is subdivided by 4 times in the y-direction and 2 times in the x-direction. This divides the model mesh into 8 segments (Figure 33). The model cells outside the area covered by the electrodes in an array have a limited effect on the calculated potential values. The effect of the cells decreases approximately by the square of the distance. To include the effects of these external cells, the model grid is extended to a limited extent beyond the region covered by the electrodes in a segment. It is recommended the edges of the segments are extended by 2 to 6 model grid lines. The segments are shown in Figure 33 have some overlap due to the extended edges.

The Jacobian matrix values are calculated using the adjoint equation method by the finite-element method when a single mesh is used. However, when the mesh is subdivided into segments, it is not possible to directly calculate the sensitivity values for the model blocks outside the segment. The program provides an option to use the sensitivity values for a homogeneous half-space for these blocks as an approximation. The second option truncates the sensitivity values for the blocks to zero. This is intended for situations where the homogeneous half-space approximation sensitivity values are very different from the true sensitivity values, such as an underwater survey where the water layer has a resistivity that is much lower than the subsurface. If the sensitivity values are truncated to zero, or if is an underwater survey data set, it is recommended that the edges of the segments are extended to at least 6 model grid lines beyond the electrodes used by the data points in each segment. This ensures that the sensitivity values for the model blocks that have significant values are directly calculated.

Figure 34 shows the inverse models obtained for the *Model_160x20-noise.dat* data set using standard single finite-element mesh, and with a 4 by 1 segmented mesh. This is a synthetic data set with voltage dependent random noise added. The standard inversion took 4240 seconds on an 18-core PC (using inversion settings in *Model_160x20-noise-standard.ivp* file), while the segmented mesh inversion took 2188 seconds (using inversion settings in *Model_160x20-noise-segments.ivp* file). There are no significant differences in the inverse models.

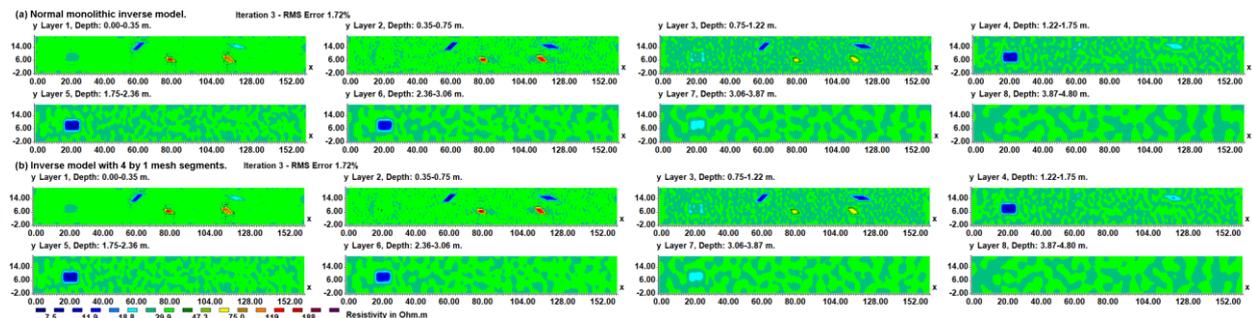


Figure 34. Inverse models of *Model_160x20-noise.dat* survey data set with (a) standard monolithic inversion, (b) using 4 mesh segments.

Figure 35a shows the first 5 layers of the model from the Lambayanna survey using standard monolithic inversion with a single mesh with 9675548 nodes which took 19.1 days to invert. Figure 35b shows the results with the mesh subdivided into 8 segments which took 1.5 days that gives an almost identical model.

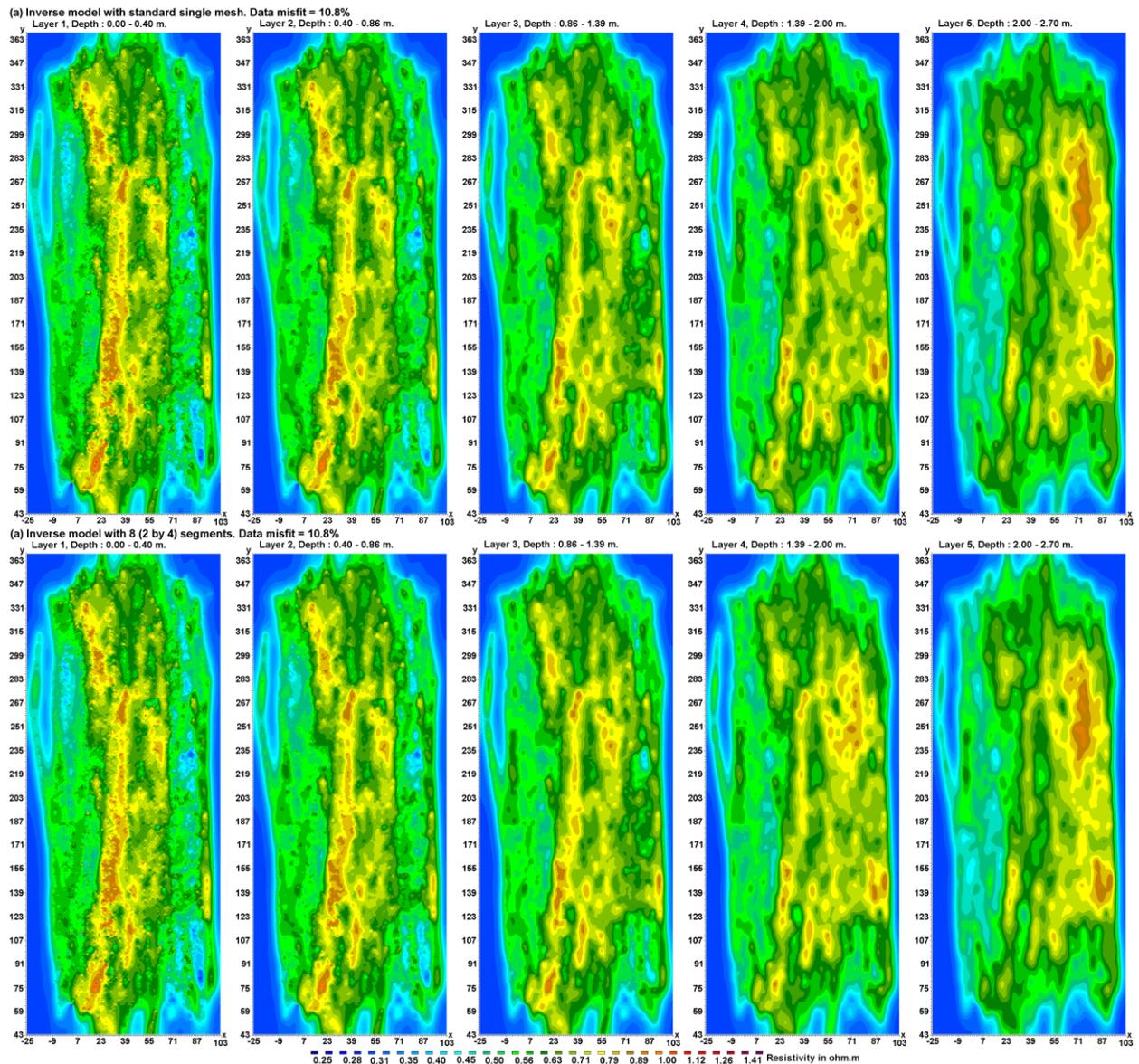


Figure 35. Inverse models of Lambayanna field data set using (a) normal inversion method with a single mesh, (b) subdivision in 8 (2 by 4) segments.

Appendix M : Vector array survey data inversion (Enterprise).

A conventional ERT survey usually has a pair of potential electrodes at each receiver station. The vector array layout uses triplets of potential electrodes at each station that measure two components of the electric field that are approximately at right angles (Zonge 1994; Truffert et al. 2018; Loke et al. 2019). Figure 35a shows a possible field survey layout. At each receiver station two measurements are made using the C1-C2-P1-P2_a and C1-C2-P1-P2_b electrodes combinations giving two resistance values r_a and r_b (Figure 35b). The amplitude of the two resistance values will vary depending on the orientation of the potential dipoles with respect to the current dipole. An example of the data format is given in Table 36 for the example data file *vector_ip.dat*. The initial section before the main data section with the measurements is similar to that used for the arbitrary electrodes data format. Note the sub-array number of 16 is used to indicate this is a vector array data set. The input data must always be in the two components format with the resistance values measured with the P1-P2_a and P1-P2_b potential dipoles. A more detailed description of each data line is given below with the contents of each column. The first number '4' indicates the number of electrodes used for each measurement. If the pole-dipole array is used it should be '3'. The x-y positions of both P2 potential electrodes are listed, followed by the two resistance values, and the two apparent I.P. values (if I.P. data is present).

<i>N</i>	<i>C1</i>	<i>C2</i>	<i>P1</i>	<i>P2_a</i>	<i>P2_b</i>	<i>r_a</i>	<i>r_b</i>	<i>ip_a</i>	<i>ip_b</i>
4	0.25, 0.25	30.00, 2.50	1.00, 1.00	1.00, 2.00	2.00, 1.00	6.45167, 6.48840		0.964, 0.985	

Table 36. Part of the vector *ip.dat* file with data format for the vector array.

<i>vector_ip.dat</i>	<i>Comments</i>
Vector array data set	<i>Name of survey</i>
31,14	<i>Model grid is 31 x 14 in x and y directions</i>
Nonuniform Grid	<i>Type of model grid</i>
X-location of grid lines	<i>Header for x grid lines</i>
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 ...	<i>X grid values</i>
Y-location of grid lines	<i>Header for y grid lines</i>
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 ...	<i>Y grid values</i>
11	<i>General array data format</i>
16	<i>Sub-array 16 for vector array</i>
Type of measurements (Two component values=0, Apparent resistivity amplitude and resistance ratio =1)	<i>Header for vector array data type</i>
0	<i>Indicates 2 components format</i>
Point Electrodes outside grid present	<i>Header to indicate arbitrary point electrodes</i>
Number of point electrodes	<i>Header for number of point electrodes</i>
9	<i>Number of point electrodes</i>
Compressed format used for point electrodes coordinates	<i>Header to indicate compressed format used</i>
1 0.25, 0.25, 0.00	<i>First point electrode</i>
2 11.50, 0.25, 0.00	<i>Index, x, y, elevation, depth below surface</i>
...	<i>Same for other point electrodes</i>
9 30.00, 2.50, 0.00	<i>Last point electrode</i>
2024	<i>Number of data points</i>
IP present	<i>Flag to indicate I.P. data present</i>
Chargeability	<i>Type of I.P. data</i>
mV/V	<i>Unit for I.P. data</i>
0.1000, 1.0000	<i>Parameters for I.P. data</i>
4 0.25,0.25 30.00,2.50 1.00,1.00 1.00,2.00 2.00,1.00 6.45167, 6.48840 0.964, 0.985	<i>First data point</i>
..	
..	
4 24.50,0.50 30.00,2.50 23.00,11.00 23.00,12.00 24.00,11.00 0.03130,0.07142 1.333,0.933	<i>Last data point</i>
0,0,0,0	<i>End with a few 0s</i>

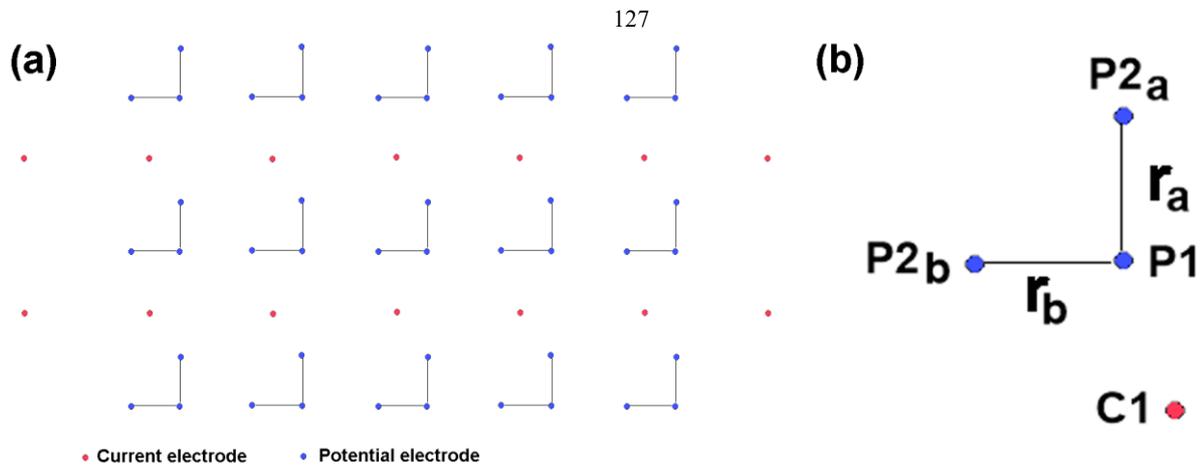


Figure 36. (a) Example of vector I.P. survey layout. (b) Measured potential components at a receiver station.

The layout for an I.P. vector array survey by Iris Instruments using interleaved lines of current and potential electrodes is shown in Figure 37 (Loke et al. 2019). The angle between the two potential dipoles in the vector triplets range from 82° to 98° . When treated as conventional pole-dipole arrays, the geometric factors range from about 200 to 70,000,000 m with a number of negative apparent resistivity values. The higher geometric factors are due to some arrays where the potential dipoles are almost on an equipotential line. Such arrays will have very low potential signal values from the current electrode and will be very sensitive to background noise. The equivalent combined vector array data set had significantly lower geometric factors of 200 to 180,000 m.

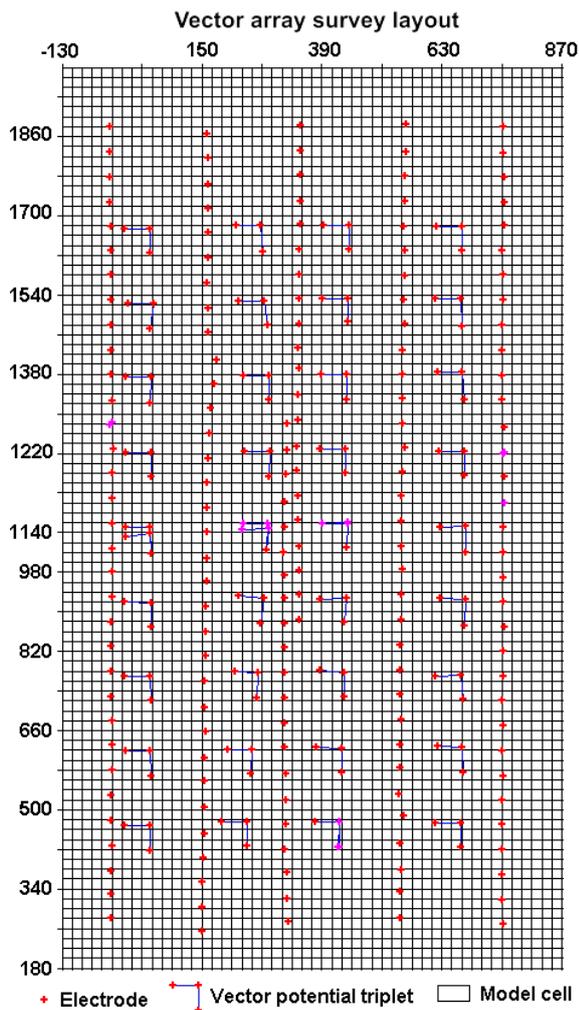


Figure 37. Example of layout of a field survey with vector array.

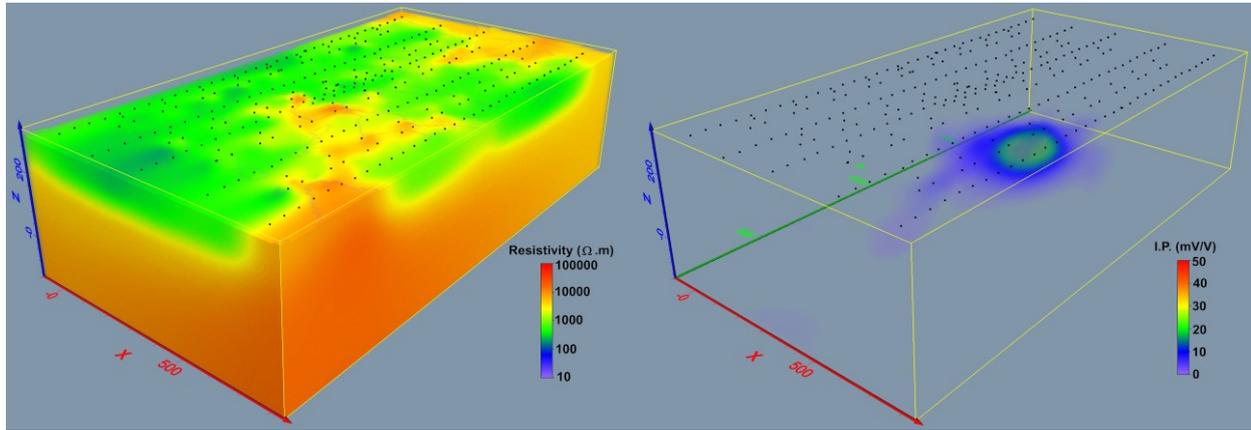


Figure 38. 3-D resistivity and I.P. models from inverse model of vector array data set.

Figure 38 shows the inverse resistivity and I.P. models for the field data set. The model resistivity generally increases with depth. A single compact I.P. anomaly with values of over 40 mV/V and average diameter of about 150 m is detected at about 30 to 160 m below the surface in the right side of the survey area. There are higher resistivity values in the upper 200 m near the location of the high I.P. anomaly.

Ideally the two arms of the potential dipoles should be orientated at 90° with each other. This ensures that the combined signal amplitude is the maximum possible regardless of the orientation of the dipoles with respect to the current dipole. However, in some situations (such as rugged terrain covered with thick jungle) it might not be possible to arrange the dipoles at 90° degree between the potential dipoles. Nevertheless, it would help if there can be even a slight angle between the dipoles. If a 30° (or 150°) angle is used, the signal strength will be at least 50% the maximum possible. Even if a 10° (170°) degree is used, the signal will be at least 17% of the maximum which is better than the worst possible case of 0% with the two dipoles in exactly the same orientation. Putting even a small angle helps to ensure the two measurements give some independent information.

The vector array data inversion is only supported in the Res3dinvx64 'Enterprise' version. Users with the 'Professional' license can convert data from the vector array format to the normal single component format after filtering out data points with low resistance values (section 8.5.8).

Appendix N : Volume of investigation (VOI) calculations (Enterprise).

N.1 Theory

While the model resolution (section 9.4.11) is a more quantitative method to determine whether the data has significant information at a region of the model, it might not be practical to use for very large data sets and models. The memory required is proportional to the n^2 and the calculation time is proportional to n^3 (where n is the number of model parameters). If model has more than a hundred thousand cells, it might exceed the available RAM in the PC, or it could take a very long time to calculate the model resolution. The ‘depth of investigation’ (DOI) proposed by Oldenburg and Li (1999) carries out the inversion of a data set using two different background reference models. In section 9.4.5, the least-squares equation that uses a reference model is given below.

$$(\mathbf{J}^T\mathbf{J} + \lambda(\mathbf{F} + \mu\mathbf{I}))\Delta\mathbf{q}_k = \mathbf{J}^T\mathbf{g} - \lambda\mathbf{F}\mathbf{q}_{k-1} - \lambda\mu(\mathbf{q}_{k-1} - \mathbf{q}_m)$$

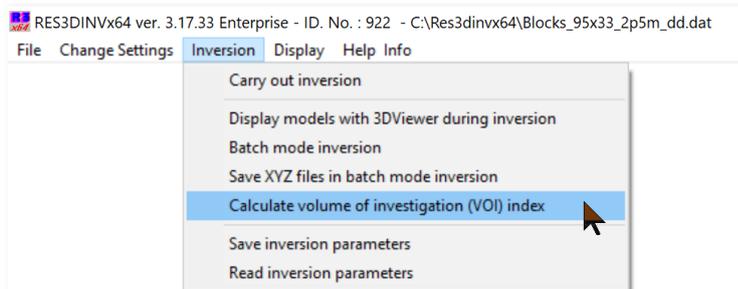
The reference model, \mathbf{q}_m , is usually a homogenous model with the average apparent resistivity value. In the DOI method, two separate inversions are carried out using different reference models. Typically, the two reference models have resistivities of 0.1 and 10 times the average apparent resistivity value. In regions of the model that are not well constrained by the data, the inverse model value will tend towards the reference model used. From the model resistivity values, the following depth of investigation (DOI) index is calculated.

$$R(x, z) = \frac{q_{m1}(x, z) - q_{m2}(x, z)}{q_{1r} - q_{2r}} \quad (\text{N.1})$$

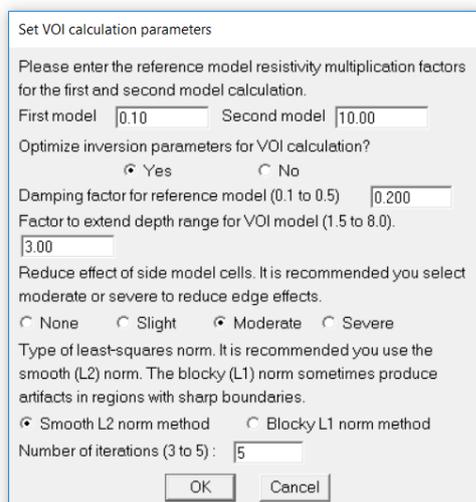
q_{1r} and q_{2r} are the resistivity of first and second reference models, $q_1(x, z)$ and $q_2(x, z)$ are model cell resistivity obtained from the first and second inversions. R will approach a value of zero where the inversion produces the same cell resistivity regardless of the reference model resistivity. In such areas, the cell resistivity is well constrained by the data. In areas where the data do not have much information about the cell resistivity, R will approach a value of one as the cell resistivity will be similar to the reference resistivity. Thus, the model resistivity in areas where R has small values is considered to be “reliable”, while in areas with high R values are not reliable.

N.2 Calculating the VOI

To carry out the VOI calculation, after reading in the data file, select the ‘Inversion-Calculate volume of investigation (VOI) index’ menu option. The VOI calculation option is only available in the ‘Enterprise’ version of the program.



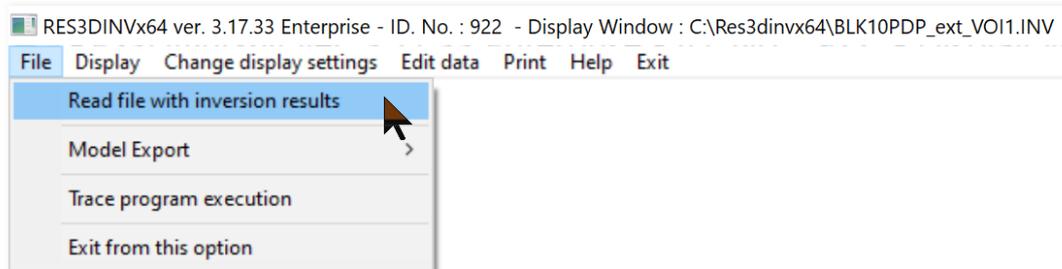
On selecting this option, the following dialog box will be shown.



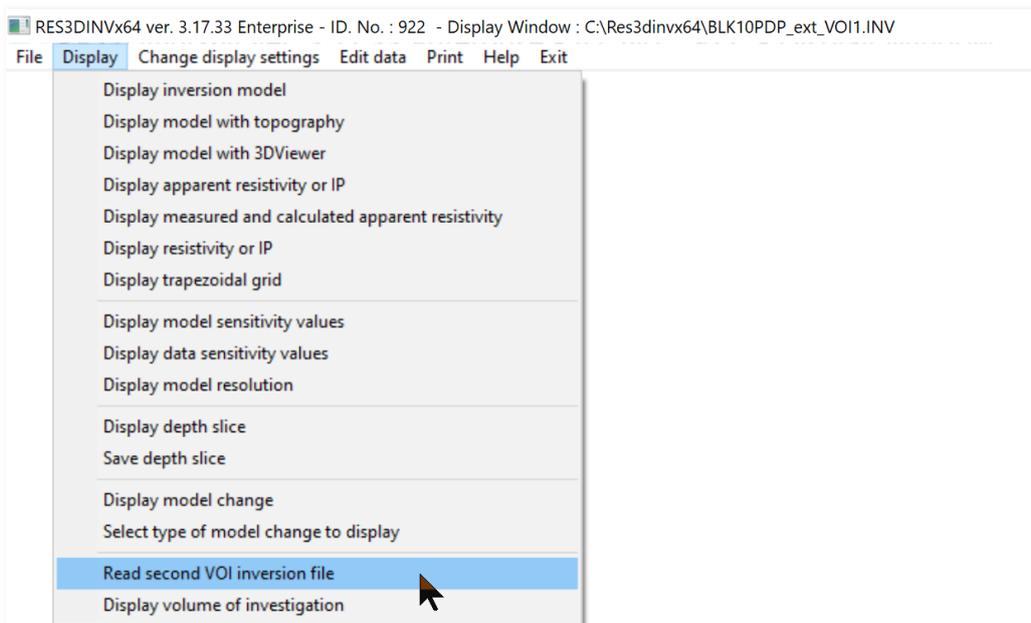
The ‘Factor to extend depth range for VOI model’ should be at least 2.0 so that the deepest layer in the model is well below the maximum median depth of investigation of the data set. This ensures that the deepest layer will have minimal information and should tend towards the reference resistivity value in the inverse model. After setting the inversion parameters, click ‘OK’ and the program will automatically carry out 2 inversions of the data set using the difference reference models and the results saved into different files. As an example, if the BLK10PDP_ext.dat data file was selected, the results will be saved in BLK10PDP_ext_VOI1.INV and BLK10PDP_ext_VOI2.INV files.

N.3 Displaying the VOI

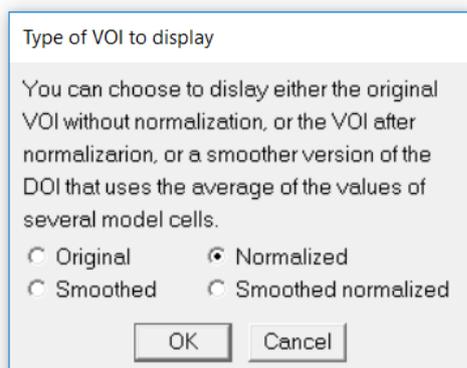
The VOI values are displayed in the ‘Display’ window used for displaying the inverse models. The first step is to read in the file with the inversion results from the first VOI inversion, such as the BLK10PDP_ext_VOI1.INV file using the ‘File-Read file with inversion results’.



To calculate the VOI the second inversion file, such as BLK10PDP_ext_VOI1.INV much now be read using the ‘Display-Read second VOI inversion file’ option.



Next select the ‘Display-Display volume of investigation’ option to VOI values.



The ‘Original’ option shows the VOI values calculated by equation N1. At a sufficiently large depth, the VOI values should approach 1.0. It is usually less than 1.0 unless the depth range is extended to a large value. The ‘Normalized’ option divides the VOI values by the maximum value so that the largest VOI value display is 1.0. Figure 39 shows the ‘Normalized’ VOI values for the BLK10PDP_ext.dat data set. It suggests that the maximum depth of investigation is about 4 m after which the VOI values increases rapidly.

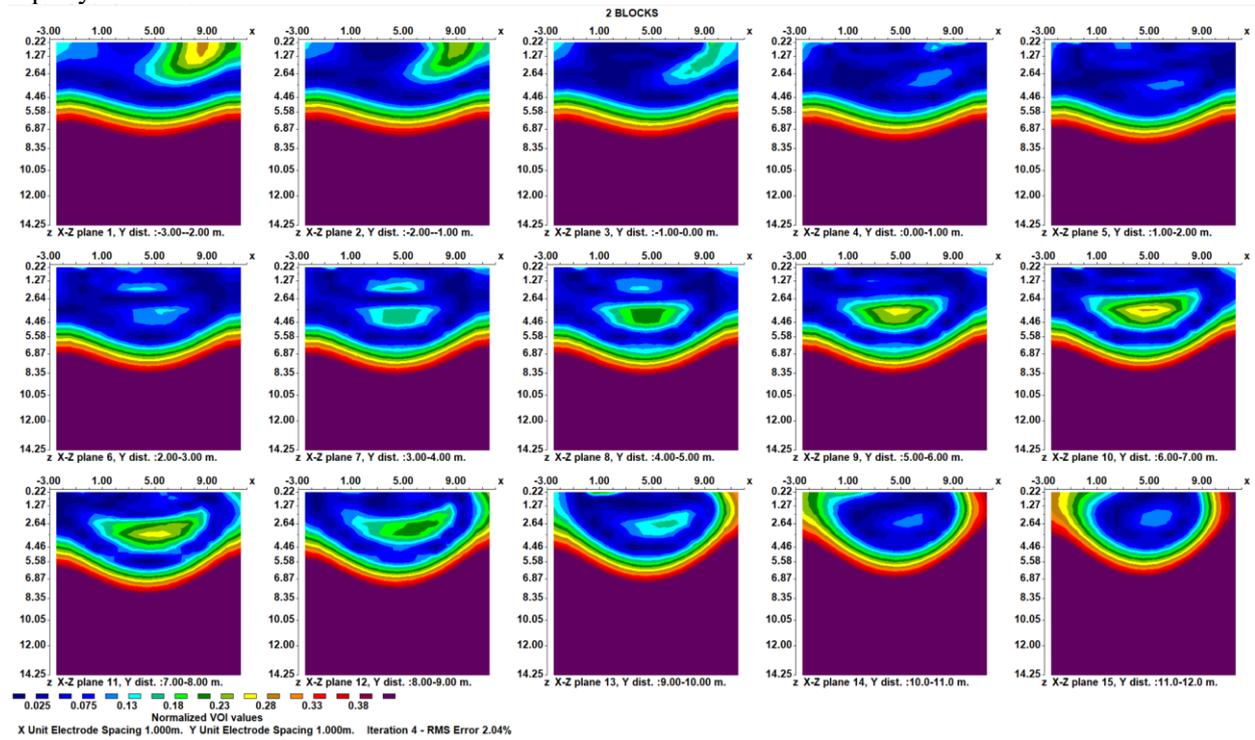


Figure 39. Volume of investigation (VOI) vertical sections for the BLK10PDP_ext.dat data set.

As a comparison, Figure 40 shows the model resolution index (section 11.2.8) for the same data set. If a cut-off value of 10 is used, the estimated maximum depth of investigation would be slightly less than 4 meters. Note it is free of local anomalies shown in the VOI section.

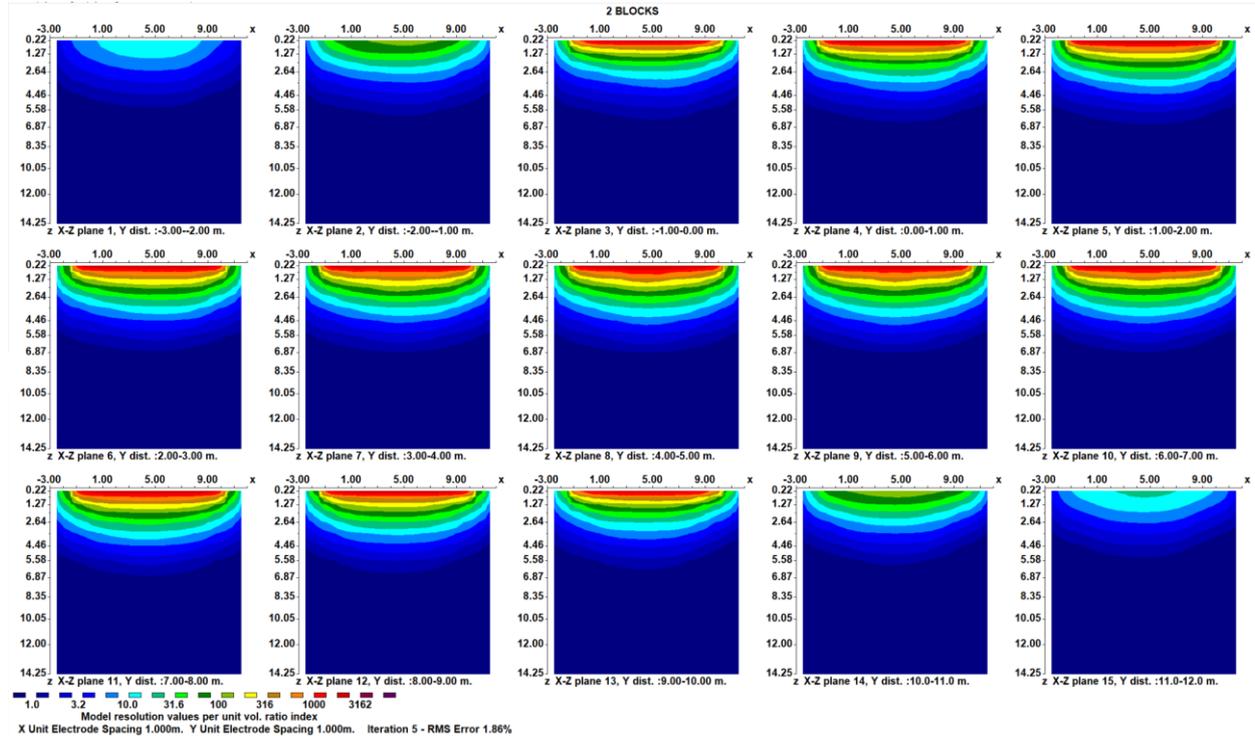


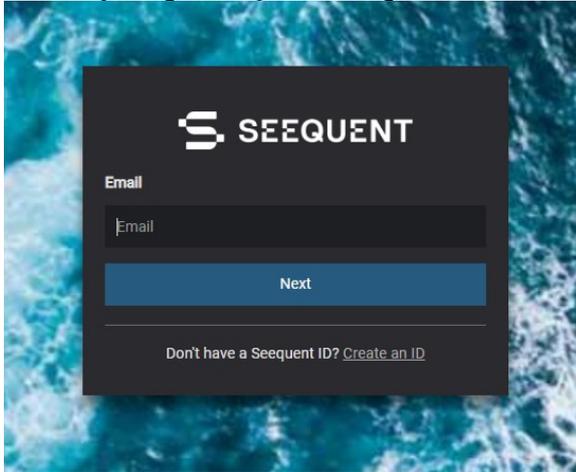
Figure 40. Model resolution index vertical sections for the BLK10PDP_ext.dat data set.

The VOI values are also saved in the model export files to the xyz, Paraview vtk and Voxler formats.

Appendix O: Setup for GDB import/export

Importing or exporting from GDB files requires installation of a set of files (Geosoft redistributables). An installer for these files can be downloaded from <https://www.aarhusgeosoftware.dk/download-additional-software>. Furthermore, in some cases it will also be necessary to install the Microsoft Visual C++ Redistributable. This is often the case, if Res2DInv reports that one or dll-files are missing. The redistributable can be downloaded from here: <https://docs.microsoft.com/en-us/cpp/windows/latest-supported-vc-redist?view=msvc-170> (choose the installer for x64 architecture).

First time a GDB file is attempted imported or exported, the conversion program will start a licensing program called Seequent Connector. This will take the user to a web browser showing a login form requiring a Seequent ID login:



If the user does not already have a Seequent ID, it can be created for free by using the provided link. After signing in, accept the web browser's attempt to open Seequent Connector. Once this step is completed, GDB import/export will work without the need for additional Seequent Connector logins.

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 original software version 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 email to sales.ags@seequent.com 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 ags.support@seequent.com

The following information will be required for technical support.

1. Your software 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, you will need to update the software license (contact sales.ags@seequent.com) to be eligible for technical 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.

Version 3.14 – Aarhus Geosoft online copy protection system implemented to replace USB dongle system. Function to automatically disable removal of negative calculated apparent resistivity values if logarithm of apparent resistivity is not used as inversion data parameter added. Fixed bugs in options to set the thickness of the first layer, the depth range of the model and number of layers. Option to convert data file in boreholes format to subsurface point electrodes. Changes to option to save model values to VTK format, I.P. model values automatically saved with resistivity values, second file automatically generated if global coordinates present. Finite-element mesh size limit for Res3dinvx64 Basic increased to 1.6 million nodes. Support for 256GB RAM.

Version 3.15 – Option to use 2 or 3 nodes per model mesh line spacing for data in arbitrary electrodes data format. Option to use AGS 3DViewer to view model in 3-D mode. Support for up to 220,000 arbitrary electrodes positions for PCs with at least 256 GB RAM.

Version 3.16 – Option to display the apparent resistivity and apparent I.P. data misfits as histogram plots together to filter out data points with high resistivity and/or high I.P. misfits.

Version 3.17 – Borehole data sets automatically converted to subsurface points electrodes format. Option to adjust the cutoff factor for L1-norm model constraint automatically. The fast ‘incomplete Gauss-Newton’ (linear conjugate gradient) method can now be used for the main inversion iterations if the option to calculate the model resolution is selected. Previous versions automatically select the full Gauss-Newton method which can be significantly slower for very large data sets and models. The user can select the iteration number in the ‘RMS error statistics’ option to display the misfits for any iteration in the file with the inverse model.

New options added for ‘Enterprise’ version. (i) Option to subdivide large finite-element mesh into segments to reduce computer time, memory and disk space required. (ii) Support for vector arrays data sets. (iii) Calculation of VOI. (iv) Calculation of point-spread-function.

Version 3.18 – New improved version of the AGS 3D viewer with new color scale module. Option to automatically combine repeated data points by taking the average of the apparent resistivity and IP values. Option to select number of CPU cores used in inversions.