

RES3DINV ver. 2.14

for Windows 98/Me/2000/NT/XP

Rapid 3D Resistivity & IP inversion using the least-squares method

(For 3-D surveys using the pole-pole,
pole-dipole, dipole-dipole, rectangular, Wenner,
Wenner-Schlumberger and non-conventional arrays)

On land, underwater and borehole surveys

Geoelectrical Imaging 2D & 3D

GEOTOMO SOFTWARE

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1 Introduction

RES3DINV is a computer program which will automatically determine a three-dimensional (3-D) resistivity model for the subsurface using the data obtained from a 3-D electrical imaging survey (Li and Oldenburg 1992, White et al. 2001). The electrodes for such a survey are arranged in a rectangular grid (Figure 1). It should first be emphasised that full 3D surveys are not merely a series of 2D surveys, but a different approach has to be used. More details on the practical use of the pole-pole, pole-dipole and dipole-dipole arrays for 3D surveys are given in Appendices A, B and C, as well as in the free Tutorial Notes on electrical imaging (Loke 2002). The most common arrays used for 3-D surveys are the pole-pole, pole-dipole and dipole-dipole arrays. Other arrays do not provide sufficient data coverage for a full 3-D inversion. On a computer with 1.5 GB RAM, this program can handle survey grids with up to 77 by 77 (or 5929) electrodes!

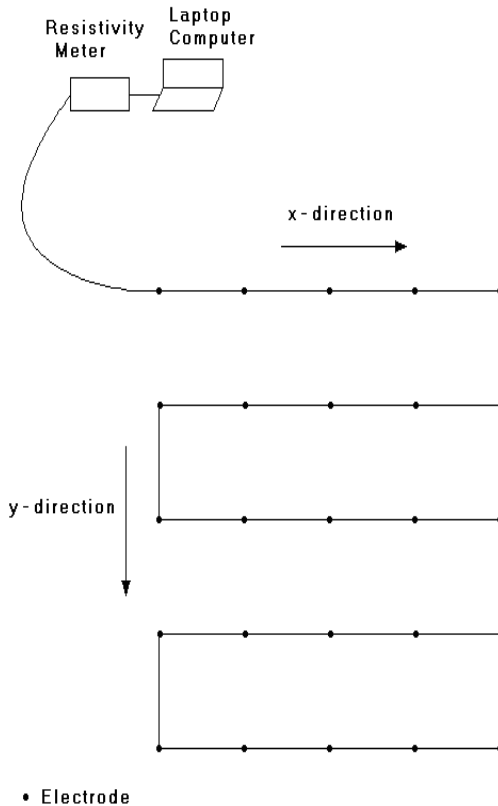


Figure 1. A schematic diagram for one possible layout for a 3-D survey.

2 Computer system requirements

RES3DINV is a 32-bit program that will run under Windows 95/98/Me/NT/2000/XP. You will need a Pentium (Pro, II, II, 4) or compatible based microcomputer to run this program. The minimum amount of RAM required is 64 MB, but 128 MB or higher is recommended. You will also need about 200 MB of free hard-disk space which 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. This is a 32-bit Windows program that can access up to 4 gigabytes of memory. The more RAM and free hard-disk space you have, the larger is the data set that you can process with this program.

It is also recommended that you use the 800 by 600 (for 14 and 15 inch monitors), or the 1024 by 768 (for 17 inch monitors), or the 1280 by 1024 (for 21 inch monitors) with 256 colours SVGA graphics mode. If you are using the SuperVGA modes with 16-bit or 24-bit colours, you should switch the display mode to 256 (i.e. 8-bit) colours using the Display option in the Control Panel folder in Windows 95/98/Me/NT/2000/XP if you encounter problems. Graphics operations with the 256 colours mode will be faster, and more memory will be available to your programs. If the graphics appear to be rather slow on your computer, please refer to Appendix F.

There should not be any background programs running (such as word processors, CAD programs) when executing the RES3DINV program. Please shut down the other programs to free the memory for this program. This will reduce memory to hard disc swapping which slows down the program. In Windows 95/98/Me/NT/2000/XP, the active programs are usually listed on the Start bar at the bottom of the screen.

The RES3DINV package comes in a single compressed installation file SETUP.EXE. It is a Windows based installation program that will install the program files. In Windows 95/98/Me/NT/2000/XP, click Start, and then Settings followed by Control Panel. Then click the icon to Add/Remove programs. After that, navigate to the subdirectory where the SETUP.EXE file is located.

In Windows NT/2000/XP, it is necessary to install a system driver for the dongle.

a). **For users with the Rainbow Technologies Sentinel SuperPro key**
Run the RainbowSSD5.39.2.exe file in the RAINBOW_SYSTEM_DRIVER subdirectory in the CDROM. This program will automatically install the system driver for the dongle. If you are using a Toshiba Laptop with the Win XP operating system, there are special instructions together with a patch file

Sentinel.sys in the Toshiba_XP.zip file. After installing the driver, restart the computer for the driver to take effect. If you are using Windows 95/98/Me, it is normally not necessary to install the system driver. However, if the program is unable to detect the dongle, installing the appropriate driver might help in situations with a non-standard configuration for the printer port. In case of problems, use the SuperProMedic.exe program to check the condition of the dongle. More information about the system drivers can be obtained at the following web site : www.rainbow.com.

b). For users with the Keylok key

Please run the INSTALL.EXE program in the found in the subdirectory for the Keylok system drivers. This program will install the appropriate driver for your operating system into your computer hard-disk. It is usually not necessary to run the INSTALL.EXE program for Win 95/98/Me, but if the RES3DINV consistently fails to detect the dongle, try running the INSTALL.EXE program to install the driver for Win 95/98/Me. More information about the system drivers can be obtained at the following web site : www.keylok.com

If you are using Windows 95/98/Me, it is normally not necessary to install the system driver. However, if the program is unable to detect the dongle, installing the appropriate driver might help in situations with a non-standard configuration for the printer port.

In Windows 95/98/Me/NT/2000/XP, a Recycle Bin program is sometimes used to save recently deleted files. This feature might prove to be a nuisance when inverting very large data sets as the program uses a number of temporary files. Although the program deletes the files, they might end up in the Recycle Bin, and quickly fill up your hard disc! The RES3DINV program will, by default, use the hard disc partition with the largest amount of free space as the buffer drive. It is recommended that you disable the Recycle Bin for this drive. This can be done by clicking the Recycle Bin icon with the right mouse button, and then click the Properties option. You can then configure the settings for each hard disc drive.

For both operating systems it is recommended that you remove the CD-ROM disc, if present, from the CD-ROM drive when using this program. Due to the multi-tasking nature of these systems, sometimes the program on the disc might be launched while RES3DINV is busy inverting a large data set!

It is also recommended that you disable the computer power management functions (in Windows as well as in the system CMOS setting) and the Windows Screen Saver program (in the Display Settings function within the Control Panel). Please refer to Appendix J for more details.

For all versions of Windows, it is recommended that you run the SCANDISK program occasionally to check the condition of the hard disc, and also the DEFRAG program to reduce file fragmentation.

Since RES3DINV is a Windows based program, all Windows compatible graphics cards or printers are automatically supported. It has been tested with video screen modes of up to 1600 by 1200 pixels and 256 colours.

3 Copy protection

The program uses a hardware key (dongle) for copy protection. Without the dongle, you can use the program to invert data sets with up to 50 electrodes. There is a limit of 3 iterations in the inversion routine. If you had purchase the 2D resistivity/IP inversion program, RES2DINV, you can process data sets with up to 100 electrodes (with a limit of 5 iterations) using the dongle provided. In both cases, topographic modelling cannot be carried out. With the RES3DINV dongle, both restrictions are removed and the maximum number of electrodes the program allows is 1849. This corresponds to a 43 by 43 electrodes survey grid that is much larger than those used in most field surveys.

The program should be able to detect the dongle if the parallel printer port follows the IBM PC specifications. If it is unable to find the dongle, the printer port is not completely IBM PC compatible. In this case, after connecting the dongle to the computer, connect a printer to the other end of the dongle. Turn on the printer and print out something, for example your AUTOEXEC.BAT file, to confirm that the printer port is working. Leave the printer on, and then try to run the RES3DINV.EXE program again. If the program is able to detect the dongle, you will need a special adapter from Rainbow Technologies to use the dongle without a printer (particularly for older laptop computers). If the computer is a desktop model, you could change the adapter card with the printer port, or set up a second printer port with another card. If you are still not able to solve the problem, please contact the Rainbow Technologies or the Keylok companies by email.

If you are using Windows NT/2000/XP, it is necessary to install a system driver for the dongle (please refer to the previous section). A more common problem is that the printer port was assigned to another device, such as a scanner port, and not as LPT1 that is the default printer port. In this case, you will need to reassign the parallel port as a printer port. In Windows 95/98/Me/NT/2000/XP, you have to select the Settings option on the Start menu bar to access the Control Panel or the Printers folder.

4 Theory

The inversion routine used by the program is based on the smoothness-constrained least-squares method (deGroot-Hedlin and Constable 1990, Sasaki 1992). A new implementation of the least-squares method based on a quasi-Newton optimisation technique (Loke and Barker 1996) can also be used. This technique can be more than 10 times faster than the conventional least-squares method for large data sets and requires less memory. The smoothness-constrained least-squares method is based on the following equation

$$(\mathbf{J}^T\mathbf{J} + u\mathbf{F})\mathbf{d} = \mathbf{J}^T\mathbf{g} \quad (1)$$

where $\mathbf{F} = \mathbf{f}_x\mathbf{f}_x^T + \mathbf{f}_z\mathbf{f}_z^T$

\mathbf{f}_x = horizontal flatness filter

\mathbf{f}_z = vertical flatness filter

\mathbf{J} = matrix of partial derivatives

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

u = damping factor

\mathbf{d} = model perturbation vector

\mathbf{g} = discrepancy vector

One advantage of this method is that the damping factor and flatness filters can be adjusted to suit different types of data.

In this program, you can also use the conventional Gauss-Newton method that recalculates the Jacobian matrix of partial derivatives after every iteration (Loke and Dahlin 2002). It is much slower than the quasi-Newton method, but in areas with large resistivity contrasts of greater than 10:1, it gives slightly better results. A third option in this program is to use the Gauss-Newton method for the first 2 or 3 iterations, after which the quasi-Newton method is used. In many cases, this provides the best compromise.

Besides the above smoothness-constrain method, other types of inversion methods are also available. The user can choose a method that will apply the smoothness-constrain directly on the model resistivity values. This method will produce an optimally smooth model (see section 8). On the other extreme, a robust model inversion method is also available which tends to produce models with sharp boundaries. 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 small rectangular prisms, and attempts to determine the resistivity values of the prisms so as to minimise the difference between the calculated and observed apparent resistivity values. One possible arrangement used by Loke and Barker

(1996) is shown in Figure 2a. Here, each block in the top layer has an electrode in each corner. Besides this basic arrangement, two other arrangements are supported by the program. One alternative is to divide the blocks in the top few layers by half in the horizontal directions only (Figure 2c). The third alternative is to divide the layers by half in the vertical direction as well (Figure 2b). Since the resolution of the resistivity method decreases rapidly with depth, it has been found that subdividing the blocks is only beneficial for the top two layers only. In many cases, subdividing the top layer only is enough. By subdividing the blocks, the number of model parameters and thus the computer time required to invert the data set can increase dramatically.

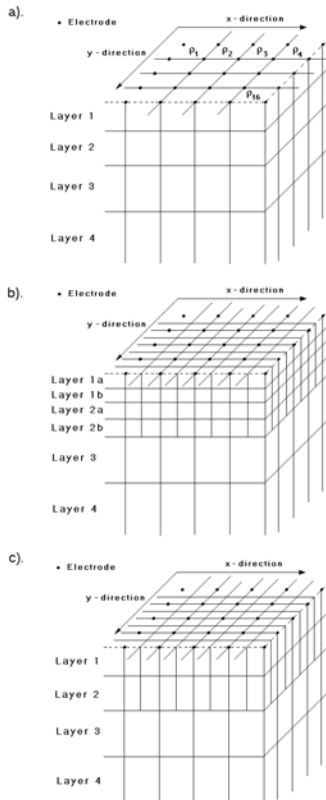


Figure 2. The models used in the inversion. (a) Standard model where the widths of the rectangular blocks are equal to the unit electrode spacings in the x- and y-directions. (b) A model where the top few layers are divided by half, both vertically and horizontally, to provide better resolution. (c) A model where the model blocks are divided in the horizontal directions but not in the vertical direction.

The optimisation method tries to reduce the difference between the calculated and measured apparent resistivity values by adjusting the resistivity of the model blocks. A measure of this difference is given by the root-mean-squared (RMS) error. However the model with the lowest possible RMS error can sometimes show large and unrealistic variations in the model resistivity values and might 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.

5 Disk contents

The package containing the program should have the following files :

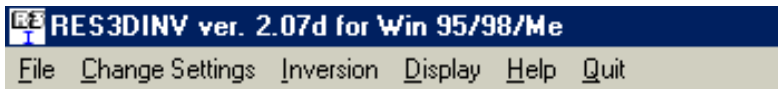
RES3DINV.EXE	Main inversion program
ROOTS7.DAT	A small field data set with a 7 by 7 survey grid.
SEPTIC.DAT	A field data set from a survey over a septic tank using an 8 by 7 grid.
PIPE3D.DAT	Data from a field survey over an underground pipe with an 8 by 9 grid.
GRID7X7.DAT	A synthetic data set with a 7 by 7 grid with all the possible measurements. (Pole-pole array).
BLK15PPL.DAT	A synthetic data set with a 15 by 15 grid. (Pole-pole array).
BLK15PDP.DAT	A synthetic data set with a 15 by 15 grid. (Pole-dipole array).
BLK15DDP.DAT	A synthetic data set with a 15 by 15 grid. (Dipole-dipole array).
MODEL3IP.DAT	An example data file with resistivity and IP data.
GRID8X8.DAT	A small synthetic data set with an 8 by 8 grid. (Pole-pole array).
MOD3DFIX.DAT	An example data file with where the resistivity of a section of the model is fixed by the user.
BLOCK26W.DAT	Example data set for the Wenner array
BLOCK26S.DAT	Example data set for the Wenner-Schlumberger array
BLOCK11T.DAT	Example input data file with topography.
RES3DINV.HLP	Windows help file for the program.
RES3DINV.CNT	Support file for help file.

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.

6 Using the program

After installing the program, just click the RES3DINV icon to start the program. The program will first check the computer system to ensure that it has the necessary resources that this program requires. 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. After checking the computer configuration, the program will then display the following Main Menu bar near the top of the screen.



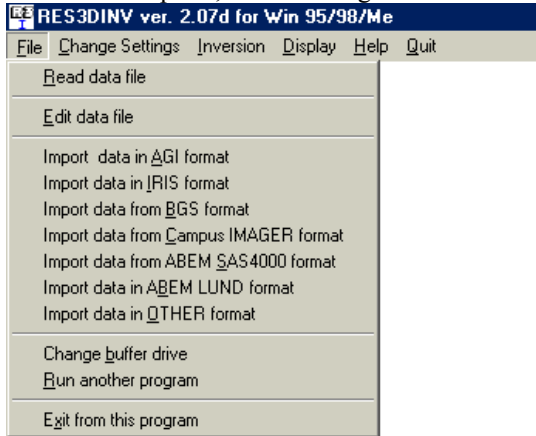
You can select an option by clicking it with the mouse cursor. If this is the first time you are using the program, try reading in one of the smaller files such as ROOTS7.DAT provided with the program. Click the File choice, followed by the "Read in data file" submenu choice. After that, if necessary, navigate to the subdirectory where the RES3DINV program is installed. After reading in the file, go to the "Inversion" option, and then choose the "Carry out inversion" option. The inversion subroutine will start. Wait for a few minutes for the data to be inverted. If you need to stop the inversion routine at any time, just press the "Q" key 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" suboption. 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.

The following sections will describe the different menu options in more detail.

7 File operations

When you select the “File” option, the following menu choices are displayed.



Read data file - When you select this option, the list of files in the current directory which has an extension of DAT will be displayed. It is assumed that the files follow the format required by this program. If not, you have to convert the raw data files using the conversion program for the particular resistivity meter system. You can use the mouse or keyboard to select the appropriate file, or to change the subdirectory.

The apparent resistivity values must first be typed into a text file. You can use any general purpose text editor, such as the Windows NOTEPAD program. 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. The program requires the data to be arranged in a certain format. If there is a problem in running this program, one possible cause is that the input data were arranged in a wrong format. The format of the input data file is as follows using the ROOTS7.DAT file as an example :-

<i>ROOTS7.DAT file</i>	<i>Comments</i>
garden-square-0.5m	Title
7	x grid size
7	y grid size
0.5	x unit electrode spacing
0.5	y unit electrode spacing
2	array type, enter 2 for pole-pole
467	Number of datum points
0.00 0.00 0.50 0.00 350.46	For each datum point, enter
0.00 0.00 1.00 0.00 398.05	x- and y- location of current elec., x- and y-
0.00 0.00 1.50 0.00 424.08	location of potential electrode, apparent

```

0.00  0.00  2.00  0.00  413.83  | resistivity value
0.00  0.00  2.50  0.00  373.76  |
.                                           | Repeat for all datum points
.                                           |
0                                           | Followed by a few 0's
0
0
0
0

```

In the local coordinate system used, the top-left electrode is located at (0.0,0.0). For the pole-dipole array, the x - and y - locations of the C1 electrode, followed by the x - and y - locations of the P1 electrode and then similar data for the P2 electrode are given. The file BLK15PDP.DAT is an example data file with the pole-dipole array. Note that the array type number for this array is 6.

For the dipole-dipole array, the x - and y - locations of the C1 electrode, followed by the x - and y - locations of the C2 electrode, followed by the x - and y - locations of the P1 electrode and then similar information for the P2 electrode are given. The file BLK15DDP.DAT is an example data file with the dipole-dipole array. Note that the array type number for this array is 3.

If the survey data has topography, the elevation of each electrode in the grid is entered in the data file after the data for 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 are given below.

BLOCK11T.PPL file										Comments	
8.000	10.000	10.000	10.000	10.000	113.3131					Last two resistivity	
9.000	10.000	10.000	10.000	102.7262						datum points	
Topography										Word indicates topography present	
2										Type of x - and y - coordinate	
0.00	0.00	0.00	-0.50	-1.00	-1.50	-1.00	-0.50	0.00	0.00	0.00	Height of electrodes in
0.00	0.00	0.00	-0.50	-1.00	-1.50	-1.00	-0.50	0.00	0.00	0.00	arranged row by row.
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	

The word “Topography” must be entered in the file immediately after the last apparent resistivity datum 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 x equals to 0 metres. 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.

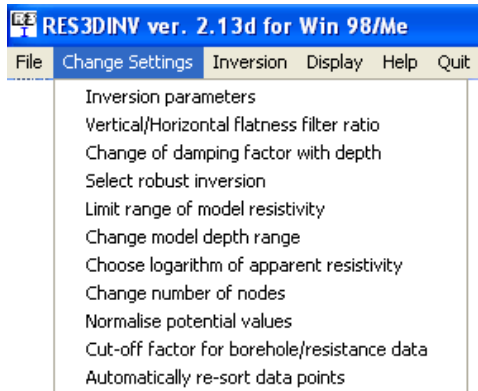
If the data set contains topography, the inversion subroutine will automatically incorporate the topography into the inversion model by using the finite-element method (Silvester and Ferrari 1990).

Edit data file - This option will call up a text editor which you can use to edit the data file.

Import data informat : This program also allows you to run other programs to convert data arranged in a propriety format into the format required by this program. This program is usually supplied by the manufacturer of the resistivity meter system you are using.

8 Change program settings

The program has a set of predefined settings for the damping factors and other variables that generally gives satisfactory results for most data sets. However, in some situations, you might get better results by modifying the parameters which control the inversion process. When you select this option, the following menu is displayed.



When you select the "Inversion parameters" suboption, the following dialog box is displayed. To change a particular setting, move the mouse cursor to the appropriate box and then just click it. Where appropriate, type in the required information into the box.

Initial Damping Factor and Minimum Damping Factor- In this section, you can set the initial value for the damping factor in equation (1), as well as the minimum damping factor. If the data set is very noisy, you should use a relatively larger damping factor (for example 0.3). If the data set is less noisy, use a smaller initial damping factor (for example 0.1). The inversion subroutine will generally reduce the damping factor in equation (1) after each iteration. However, a minimum limit for the damping factor must be set to stabilise the inversion process. The minimum value should usually set to about one-fifth to one-fifteenth of the value of the initial damping factor.

Change inversion parameters	
Initial Damping Factor:	0.150
Minimum Damping Factor:	0.010
<input type="checkbox"/> Directly smooth model resistivity	
<input checked="" type="checkbox"/> Line search on every iteration	
Minimum % RMS change for line search:	0.20
Thickness of first layer:	0.700
Factor to increase layer thickness:	1.150
HALF SIZE LAYERS OPTION	
Number of half size layers:	0
<input type="checkbox"/> Divide half size layers vertically	
Flatness filter factor for half size layers:	1.00
Number of iterations:	6
No. of iter. to recalculate Jacobian:	3
Convergence limit (in percent):	5.00
<input type="button" value="OK"/> <input type="button" value="Cancel"/>	

Directly smooth model resistivity - The least-squares formulation used in equation (1) applies a smoothness constraint on the model perturbation vector \mathbf{d} only, and not directly on the model resistivity values. In most cases, it will produce a model with a reasonably smooth variation in the resistivity values. In some cases, particularly for very noisy data sets, better results might be obtained by applying a smoothness constraint on the model resistivity values as well. The resulting least-squares equation is given by

$$(\mathbf{J}^T \mathbf{J} + u \mathbf{F}) \mathbf{d} = \mathbf{J}^T \mathbf{g} - u \mathbf{F} \mathbf{r} \quad (2)$$

where \mathbf{r} is a vector containing the logarithm of the model resistivity values. While for the same damping factors this will usually produce a model with a larger apparent resistivity RMS error, this modification will ensure that the resulting model shows a smooth variation in the resistivity values.

Line search on every iteration - The inversion routine determines the change in the model parameters by solving equation (1). Normally the parameter change vector \mathbf{d} will result in a model with a lower RMS error. In the event that the RMS error increases, you have two options. This option enables you to perform a line search using quartic interpolation (Fletcher 1987) to find the optimum step size for the change in the resistivity of the model blocks. This will usually give the optimum step size, but will require at least one forward modelling computation per iteration. In some cases, the extra forward computation could be worthwhile if it reduces the number of iterations needed to bring the RMS error down to an acceptable level.

This setting will only affect the inversion process for the third iteration onwards. For the first two iterations, where the largest change in the RMS error usually occurs, the program will always carry out a line search in an attempt to find the optimum step size to further reduce the RMS error.

Minimum % RMS change for line search - The line search method used can estimate the expected change in the apparent resistivity RMS error. If the expected change in the RMS error is too small, it might not be worthwhile to proceed with the line search to determine the optimum step size for the model parameter change vector. Normally a value between 0.1 and 1.0 % is used.

Thickness of first layer - This give the ratio of the thickness of the first model layer to the smallest unit electrode spacing. For the pole-pole array, this is set at 0.70 times the unit electrode spacing. For other arrays, the thickness of the first layer will be adjusted according to the depth of investigation of the array.

Factor to increase layer thickness - Since the resolution of the resistivity method decreases with depth, normally the thickness of the model layers are also increased with depth. By default, a factor of 1.15 is used to increase the thickness of the model layers. In this case, the thickness of each subsequent layer increases by 15%. However, you can modify this factor within a limited range. Normally, a value of between 1.05 to 1.25 is used.

Half Size Layer Option - This allows you to use a model where the widths and thickness of the top few layers are divided by half (see Figure 2 in the 'Theory' section). Here you can choose the number of layers which are to be subdivided, and also whether to subdivide them in the vertical direction as well (Figure 2b). You can also adjust the flatness filter damping factor for these layers. It has been found that the smaller the model blocks, the greater is the potential oscillation in the model values after inversion, especially for noisy data sets. To reduce the oscillations, you can use a slightly larger damping factor, for example 1.10, for these layers.

Number of iterations - This allows the user to set the maximum number of iterations for the inversion routine. By default the maximum number of iterations is set to 6. For most data sets, this is probably sufficient. When the inversion routine reaches this maximum limit, it will ask the user for the number of additional iterations if you wish to continue with the inversion process. It is usually not necessary to use more than 10 iterations.

Number of iterations to recalculate Jacobian - In the Gauss-Newton method, the Jacobian matrix is recalculated after each iteration, whereas in the quasi-Newton method the Jacobian matrix is never recalculated but estimated after each iteration (see 'Theory' section). The fastest method is to use the quasi-Newton method to estimate the Jacobian matrix (Loke and Barker 1996). In this case, put a value of 0 in the dialog box. This might be a good alternative to use in the field where a slower laptop computer with more limited memory is frequently used. The most accurate and slowest method is to recalculate the Jacobian matrix after every iteration. This requires a fast computer with preferably at least 32 megabytes of RAM, and about 256 megabytes free hard disc space for very large data sets. To choose this method, just put a very large value (for example 20) into the box. A third alternative is to recalculate the Jacobian matrix for the first few iterations only, and use the quasi-Newton updating method for subsequent iterations. The largest changes in the Jacobian matrix usually occurs in the first few iterations. So in many cases, a limited recalculation of the Jacobian matrix gives the best compromise between speed and accuracy. By default, the program will recalculate Jacobian matrix for the first 3 iterations only. However, the default settings can be changed by the user in this menu option. The quasi-Newton option is useful to get a quick look at the results, particularly in the field during the course of a survey using a laptop computer. Another situation where this should be used is when you want to remove the bad data points using the RMS Errors Statistics method (see the 'Display' section). For the final model, it is best to use the limited recalculation option on a faster desktop computer with more RAM and free hard disc space. In areas with large resistivity contrasts, where the largest apparent resistivity value is more than 10 times the smallest value, recalculating the Jacobian matrix produces models with boundaries which are sharper than those produced by the quasi-Newton method.

Convergence limit - This sets the lower limit for the relative change in the RMS error between 2 iterations. By default, a value of 5% is used. 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.

Select robust inversion - The conventional least-squares method will attempt to minimise the *square* of difference between the measured and calculated apparent resistivity values. The 'Robust data constrain' option will attempt to minimise the *absolute* difference (or the *first* power) between the measured and calculated apparent resistivity values is minimised can be used (Claerbout and Muir 1973). This method is less sensitive to very noisy data points. In a similar way, the 'Robust model constrain' option will attempt to produce where absolute spatial changes in the model resistivity values is minimised, compared to the normal smoothness-constrained method where the square of the changes is minimised. This robust model option tends to produce a model with sharper boundaries. The two options are shown in the following dialog box.

Select robust inversion

You can choose the standard least-squares constrain which attempts to minimise the square of the difference between the measured and calculated apparent resistivity values, or a robust constrain which is less sensitive to very noisy datum points but might give a higher RMS error.

Data Inversion

Standard least-squares constrain
 Robust data constrain

Enter robust constrain cutoff

Model Inversion

Standard least-squares constrain
 Robust model constrain

Enter robust constrain cutoff

Limit range of model resistivity - When you select this option, the following dialog box will be shown.

Limit range of model resistivity values

You can choose to limit the upper and lower values of the resistivity values the inversion model can take. In some cases, this might be necessary to ensure that the model resistivity values do not become too large or too small.

Do not limit resistivity values
 Limit range of resistivity values

Enter upper limit factor
 Enter lower limit factor

Use average resistivity
 Use first iteration resistivity

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 for the previous iteration while the lower limit is 0.05 times (i.e. 1/20 times). The program uses “soft” limits that allows 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.

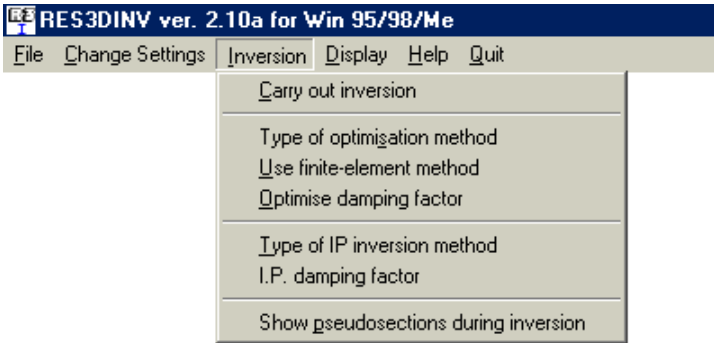
Change model depth range - This option allows you to increase or decrease the depth of the layers in the inversion model used by the program. The depths are multiplied by a scaling factor given by the user.

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

Change number of nodes - By default, the program uses a finite-difference or finite-element grid with 2 nodes 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 modelling subroutine, but the computer time and memory required will also increase.

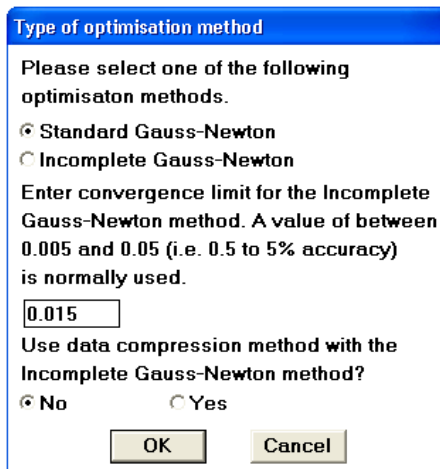
9 Inversion of data

This option enables you to carry out the inversion of the data set that you had read in using the "File" option. A default set of inversion parameters that control the inversion process is normally used. You can change the settings using the "Change Settings" menu described earlier. On selecting this option the following menu will be displayed.



Carry out inversion - This option will start the least-squares inversion routine. You will be asked for the name of the output data file in which to store the results. After the inversion process has started, you can stop it by pressing the Q key, and then wait for a short while.

Type of optimisation method – This option allows you to choose two different methods to solve the least-squares equation (1). On selecting this menu option, the following dialog box will be shown.



By default the program uses the ‘Standard Gauss-Newton’ least-squares method, particularly if the number of data points and/or model cells is small (less than a few thousand), where an exact solution of the least-squares equation is calculated. If the number of data points and/or model cells is large (more than 3000), 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 using the ‘Incomplete Gauss-Newton’ method can be used. The user can set the accuracy of the solution. For most data sets, an accuracy of about 1% to 2% (i.e. a convergence limit of 0.01 to 0.02 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. For very large data sets and models (over 15000 data points/cells), a “data compression” option is provided with the ‘Incomplete Gauss-Newton’ method. This can significantly reduce the inversion time. As an example, the inversion of a model with about 30000 cells and 60000 data points was reduced from more than a week to less than 2 days on a 2 GHz P4 computer with 1 GB RAM.

Use finite-element method - This program allows you to use either the finite-difference or finite-element method to calculate the apparent resistivity values. By default, the program will use the finite-difference method, which is faster, if the data set does not contain topography. If the data set contains topography, the default choice is the finite-element method. The finite-element method is significantly slower than the finite-difference method, so it is recommended that you use the finite-difference method if the data set does not have topography.

Optimise damping factor - If you select this option, the program will attempt to find the optimum damping factor u in equation (1) which gives the lowest RMS error in each iteration. By optimising the damping factor, the number of iterations the program requires to converge can be significantly reduced. However, the time taken per iteration will be increased. For small to medium size data sets, this can significantly reduce the overall computer time needed to invert the data set. For very large data sets with more than 2000 data points, the time taken in each iteration could be significantly increased as it is necessary to solve the least-squares equation more than once per iteration. Use this option with care as the model with the lowest RMS error is not always the “best” model, particularly for very noisy data sets (see the “Theory” section).

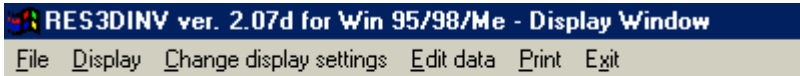
Type of IP inversion method - To invert a combined resistivity and IP dataset, you can choose to invert both data sets concurrently in each iteration or to invert the IP data sequentially after the inversion of the resistivity data.

IP damping factor – The damping factor used in the inversion of IP 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 IP inversion routines. Normally a much smaller value of about 0.05 to 0.25 is used. Alternatively, you can choose the option to let the program automatically calculate the damping factor.

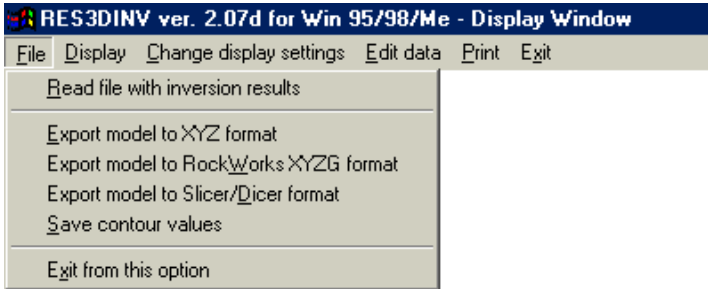
10 Display results

In this option, you can read in a data file or the output file produced by the inversion subroutine and display the measured apparent resistivity pseudosections and the model sections. Within this option, you can change the contour interval used for drawing the pseudo and model sections and the vertical scale of the pseudosections. You can also change the colour scheme used by the program. Two methods to remove bad data points from a 3D data set is also provided.

If you had earlier read in an input data file or used the inversion option in the Main Menu, the program will first read the last file used. After selecting this option on the Main Menu bar, the program will switch to the Window for displaying the pseudosections and model section. To return to the Main menu, you will need to Exit from this window. This window has the following top menu bar.



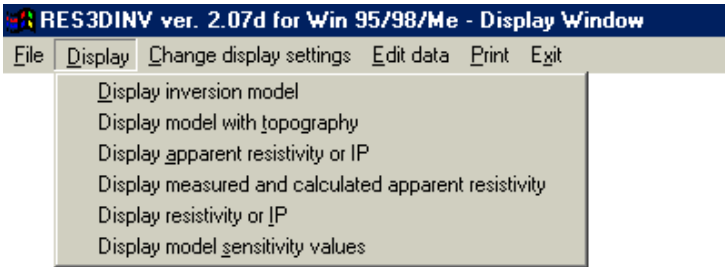
The “File” option will bring up the following submenu.



Read data file with inversion results - You can read in the output data file produced by the inversion subroutine or an input data file.

Save model in XYZ format - You can save the inversion results into a disc file with a format used by many contouring programs, such as Geosoft. This is a separate program sold by GEOSOFT Inc. which enables you to use more sophisticated contouring techniques than that used by the RES3DINV program.

Clicking the “Display” option on the top menu bar will bring up the following submenu.

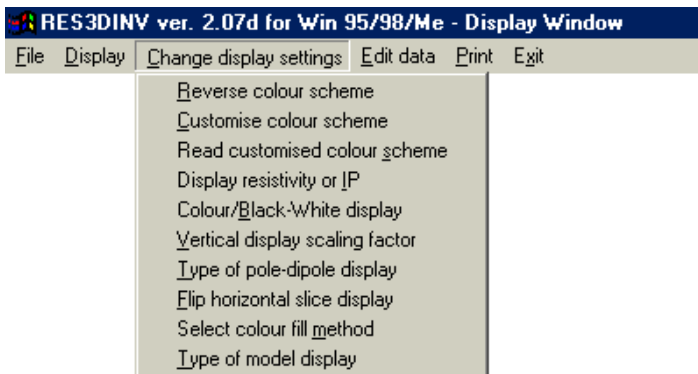


Display inversion model - Select this option to plot the model. You can plot the model in the form of horizontal or vertical slices through the earth.

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

Display apparent resistivity - This option allows you to display the apparent resistivity (or IP) pseudosections for measurements made in the x- or y-directions.

The “Change display settings” option enables you to change the parameters which control the way the apparent resistivity pseudosections and the model sections are displayed. The following submenu will be displayed when you click this option.



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 use to reverse the colour scheme so that blue is used for the high resistivity values and red for the low resistivity values.

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

Read customise colour scheme - You can change the colour scheme to a set of customise 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.

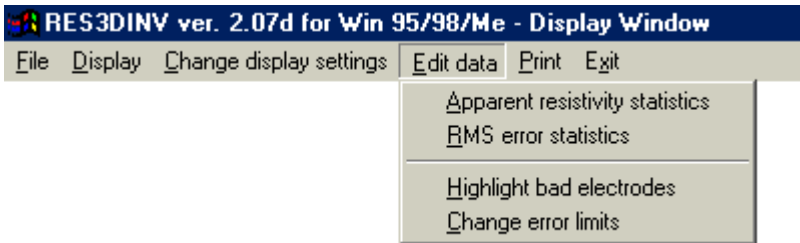
Display resistivity or IP - You can choose to display the resistivity or IP in the model sections or pseudosections if the data set contains IP measurements as well.

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, possibly for making printouts on normal laser printers. The program provides two choices for the black and white display. The first choice is to use pure black and white colours together with a dithering method to provide the different tones. Such screen images can be printed on almost any printer. The second choice is to use a grey scale where different shades of grey, ranging from pure white to pure black, is used. You will probably need a laser printer to make reasonably good printouts of the grey scale images.

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

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

The “Edit” option will bring up the following submenu.

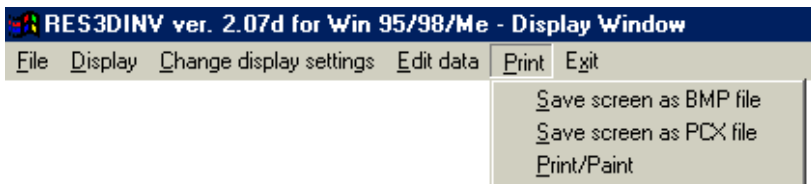


Large 3D surveys can involve many thousands of datum points. In the most general case, the array for a particular measurement can be orientated in any direction. To obtain a good inversion model, the “bad” data points must be removed from the data set. One possible way of removing the “bad” data points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

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

RMS error statistics - This suboption just displays the distribution of the percentage difference between the logarithms of the observed and calculated apparent resistivity values. It can only be used after carrying out a trial inversion of the data set. In this case, you should set the “Number of iterations to recalculate Jacobian matrix” in the “Change Inversion Parameters” dialogue box (described earlier in section 8) to 0. In this case, the program will use the quasi-Newton inversion method. On selecting this suboption, the distribution of the RMS errors will be displayed in the form of a bar chart. It is expected the “bad” data points will have relatively large “errors”, for eg. above 100 percent. To remove the points with large errors, just move the green cursor line to set the cut-off error limit to remove the “bad” datum points.

The “Print” option will bring up the following submenu.



This option enables you to save the screen image as a BMP or PCX graphics file, or make a direct printout with a printer by using the Windows Paintbrush program. After the program has completed drawing the model or pseudosection (selected from the “Display” option described earlier), click the Print option. This will display options to save the screen as a BMP file, a PCX file or to call

up the PaintBrush program to print the file. If you need to print the screen image together with some text, it might be more convenient to save the screen image as a BMP or PCX file. You can later insert the picture directly into the document if the word processor, such as Microsoft Word for Windows or Lotus Amipro or WordPerfect, allows you to import graphics files.

11 Topography

If the data set contains topography, the effect of the topography is automatically incorporated into the inversion model by using a distorted 3D finite-element grid. This is probably the most accurate method if the near surface regions contain significant resistivity variations, although it is probably the slowest method. Techniques based on the “correction factors” of a homogeneous earth model with surface topography, in theory, will only be exact if the actual subsurface is also homogeneous. The “correction factors” method will correct for changes in the geometric factor caused by the topography, but will not correct for changes in the distances of the electrodes from the subsurface bodies. If there are large resistivity variations near the surface, the “correction factors” method can cause significant distortions in the results (Tong and Yang, 1990; Loke, 2002). In any case, the “correction factors” method cannot be used for underwater surveys with topography.

12 Help

This option allows you to call the Windows help file for the program.

13 Some field examples

Some examples of field data sets that were inverted with this program are given below :-

Birmingham field test survey - UK

This field test was carried out using a multielectrode system with 50 electrodes commonly used for 2-D resistivity surveys. The electrodes are arranged in a 7 by 7 square grid with a unit electrode spacing of 0.5 metre (Figure 3). The two far electrodes were placed at more than 25 metres from the grid to reduce their effects on the measured apparent resistivity values. To reduce the survey time, the cross-diagonal survey technique was used (Appendix A). The subsurface is known to be highly inhomogeneous consisting of sands and gravels. Figure 3 shows the horizontal and vertical sections of the model obtained at the 6th iteration. The two high resistivity zones in the upper left quadrant and the lower right corner of Layer 2 are probably gravel beds (Loke and Barker 1996). The two low resistivity linear features at the lower edge of Layer 1 are due to

roots from a large sycamore tree just outside the survey area. The vertical extent of the gravel beds is more clearly shown in the vertical cross-sections across the model. The inverse model shows that the subsurface resistivity distribution in this area is highly inhomogeneous and can change rapidly within a short distance. In such a situation a simpler 2-D resistivity model (and certainly a 1-D model from conventional sounding surveys) would probably not be sufficiently accurate.

Sludge deposit - Sweden

Most commercial 3D surveys will probably involve grids of at least 16 by 16 in order to cover a reasonably large area. A 16 by 16 grid will require 256 electrodes which is larger than many multi-electrode resistivity meter systems. One method to survey such large grids with a limited number of electrodes is to extend the roll-along technique used in 2D surveys to 3D surveys. In the 3-D roll-along method used by Dahlin *et al.* (2002), a number of parallel multi-electrode cables were used. A survey was carried out at Lernacken in Southern Sweden over a covered sludge deposit. Seven parallel multi-electrode cables were used to cover a 21 by 17 grid with a 5 metres spacing between adjacent electrodes. Initially the cables are laid out in the x-direction, and measurements were made in the x-direction only. After each set of measurements, the cables were shifted step by step in the y-direction until the end of the grid. Next, the measurements were made with the cables laid out in the y-direction. In surveys with large grids, such as in this example, it is common to limit the maximum spacing for the measurements. The maximum spacing is chosen so that the survey will map structures to the maximum depth of interest. In this case, the maximum spacing was 40 metres compared to the total length of 100 metres along a line in the x-direction. The model obtained from the inversion of this data set is shown in Figure 4. The former sludge ponds containing highly contaminated ground water show up as low resistivity zones in the top two layers (Dahlin *et al.* 2002). This was confirmed by chemical analysis of samples. The low resistivity areas in the bottom two layers are due to saline water from a nearby sea.

Birmingham garden field test

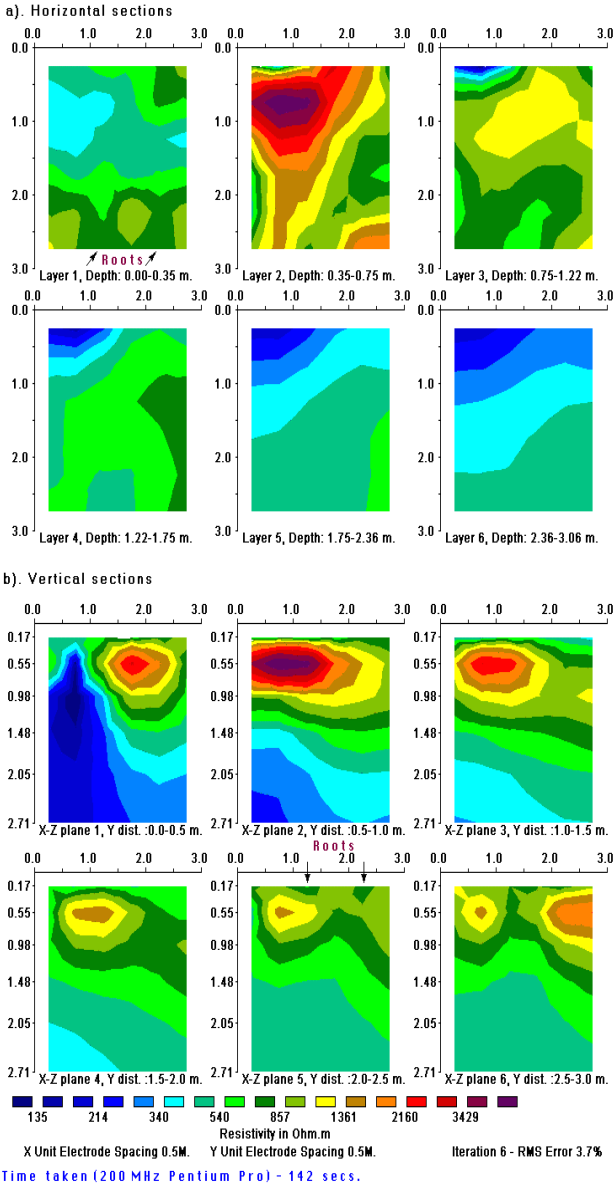
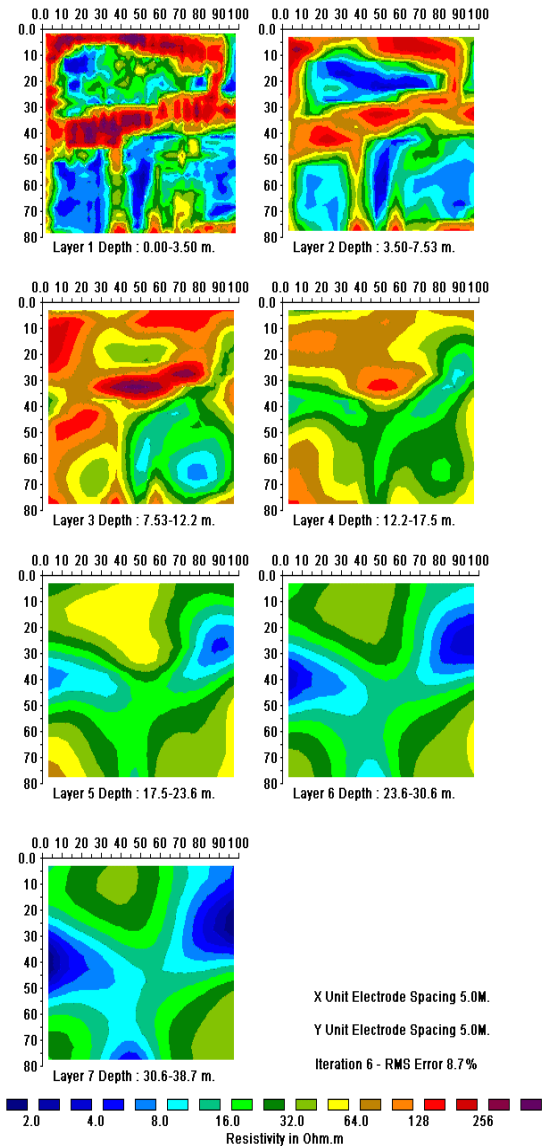


Figure 3. Horizontal and vertical cross-sections of the model obtained from the inversion of the Birmingham field survey data set. The location of observed tree roots on the ground surface are also shown.

Lernacken Sludge Deposit survey



Time taken (200 MHz Pentium Pro) - 15162 secs.

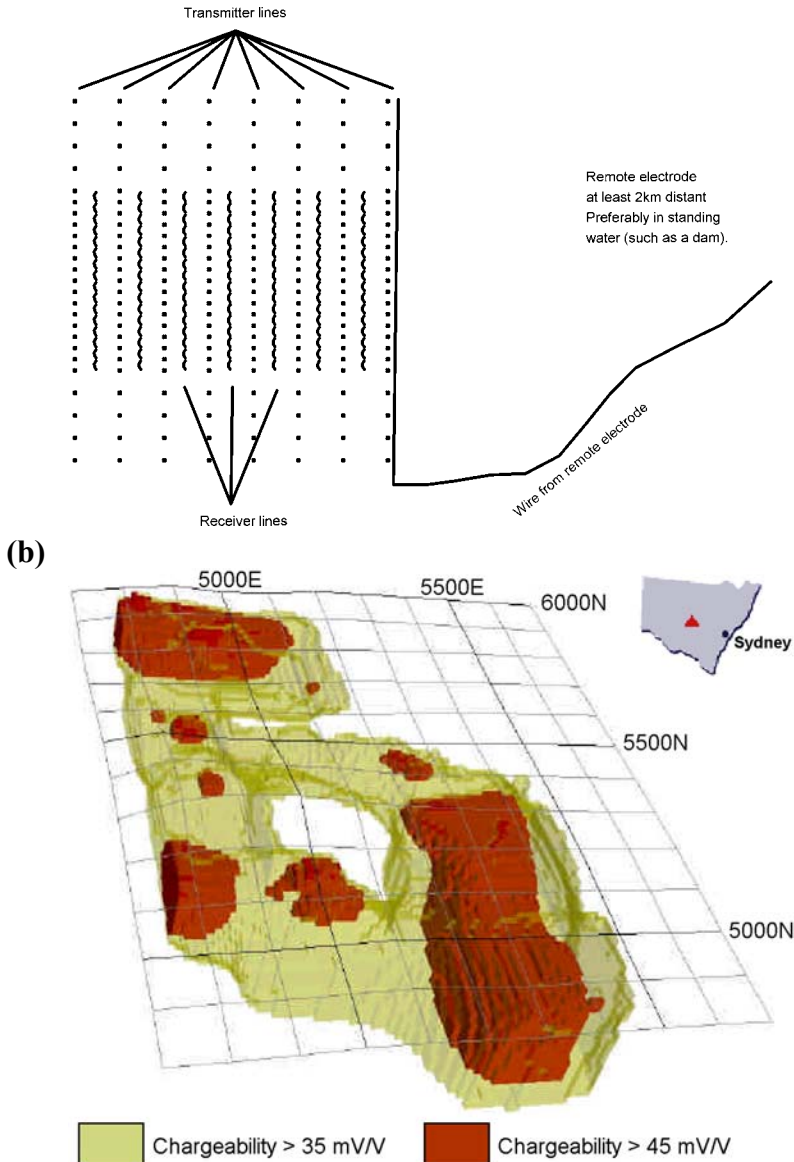
Figure 4. The 3D model obtained from the inversion of the Lernacken Sludge deposit survey data set. The model is shown in the form of horizontal slices through the earth.

Copper Hill - 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 IP survey and 7 drill-holes (White at 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 IP survey using the pole-dipole array was used. The survey covered a large (1.6 x 1.1km) area using a series of 1.6 km lines with a spacing of 25m between adjacent electrodes. Figure 5a 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 at al. (2001).

The data was inverted with the RES3DINV program that produced a 3-D resistivity as well as a 3-D IP model for the area. The 3-D IP model that shows the location of the mineralized zones more clearly is shown in Figure 5b. The inversion model output from the RES3DINV program was rearranged into a VRML format that could be read by a 3-D visualization program (please contact Arctan Services at www.arctan.com.au for the details) that enables the user to display the model from any direction. The 3D IP model in Figure 5b 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 IP model. A drill-hole, CHRC58, intersected a 217m 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 low 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. Further surveys, including drilling, is presently being carried out.



Courtesy of Golden Cross Resources and Arctan Services Pty.

Figure 5. (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).

14 Troubleshooting

A brief compilation of possible problems and their possible causes and solutions is given in this section.

Insufficient memory : If the program cannot find sufficient memory, one possible reason is that it has been reserved for other programs. In this case, you will need to remove the other active programs. In Windows 95/98/NT, the active programs are usually shown on the Start menu bar at the bottom of the screen. If you have less than 64 megabytes RAM, it is recommended that you buy some RAM.

Program crashes when it tries to invert the data set : This could be due to data arranged in the wrong format or other errors in the data set. When the program reads the data file, it will check for some common errors such as zero or negative apparent resistivity values. However, there might be some new unexpected errors. If you still cannot find the error, please send a copy of the data set to the company who sold you this program (or the author of this program) by email or by post using a 3.5" disc.

Program cannot find dongle : If the program cannot find the hardware key, it will run as a demonstration program. If you had securely attached the dongle provided to the printer port and the program still cannot detect it, please refer to section 2 for a method to check for the source of the problem. The two most likely causes are a faulty printer port, or one which is not completely IBM PC compatible (this problem is more common in older laptop computers). Another possibility is that the parallel port has been reconfigured by a program as another port instead of as a printer port. If you are using Windows NT, it is necessary to install a system driver for the dongle (please refer to sections 2 and 3). The system driver file provided (SYSDRVR.EXE) also contains the drivers for Windows 3.1 and Windows 95. Install this driver if the program is unable to detect the dongle with Win 95/98.

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Appendix A : 3D surveys with the pole-pole array

The pole-pole electrode configuration is commonly used for 3D surveys, such as the E-SCAN method (Li and Oldenburg 1992). The apparent resistivity value for the pole-pole array is given by

$$\rho = 2 \pi a R$$

where R is the measured resistance, a is the spacing between the C1 and P1 electrodes.

For a given number of electrodes, the pole-pole array gives the maximum number of independent measurements, n_{max} , which is given by

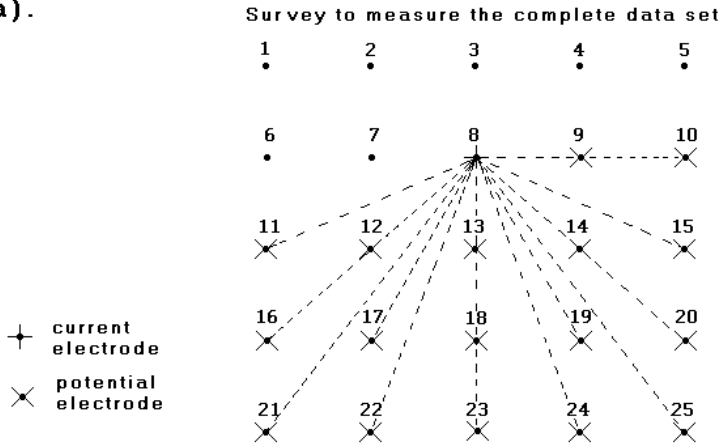
$$n_{max} = n_e (n_e - 1) / 2.$$

Where n_e is the number of electrodes. In the measurement sequence shown in Figure 6a, each electrode in turn is used as a current electrode and the potentials at all the other electrodes are measured. Note that because of reciprocity, it is only necessary to measure the potentials at the electrodes with a higher index number than the current electrode in Figure 6a. For a 5 by 5 electrode grid, a complete data set (Xu and Noel 1993) will have 300 datum points. For 7 by 7 and 10 by 10 electrode grids, the numbers of measurements are 1176 and 4500 respectively. It can be very time-consuming to make such a large number of measurements with typical single-channel resistivity meters commonly used for 2D surveys. For example, it could take several hours to make the 1176 measurements for a 7 by 7 survey grid with a standard low frequency earth resistance meter. To reduce the number of measurements required without seriously degrading the quality of the model obtained, an alternative measurement sequence has been tested (Figure 6b). In this proposed "cross-diagonal survey" technique, the potential measurements are only made at the electrodes along the horizontal, vertical and the 45 degrees diagonal lines passing through the current electrode. The number of datum points with this arrangement for a 7 by 7 grid is reduced to 476. For large survey grids, such as the sludge deposit field example described earlier, it is also common to limit the maximum spacing used in the measurements to about 8 to 10 times the minimum electrode spacing.

The file GRID7X7.DAT is an synthetic data file for a pole-pole survey over a 7 by 7 grid with all the possible measurements. The file ROOTS7.DAT is from a field survey with a 7 by 7 grid where the cross-diagonal measurement sequence was used.

To map large areas with a limited number of electrodes in a multi-electrode resistivity meter system, the roll-along technique can be used (Dahlin *et al.* 2002). Figure 7 shows an example of survey using a multi-electrode resistivity-meter system with 50 electrodes to survey a 10 by 10 grid.

a).



b).

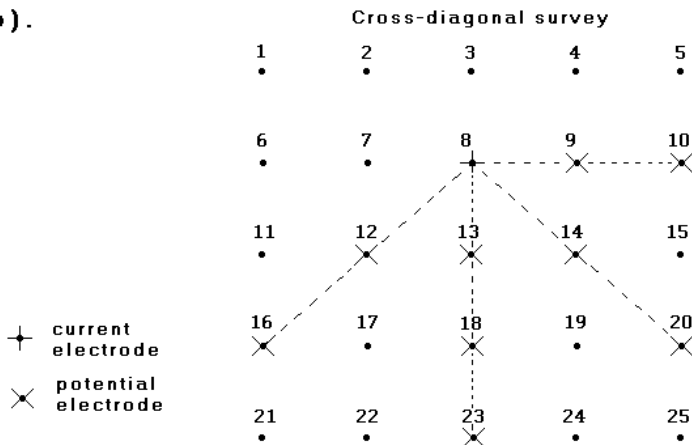


Figure 6. The location of potential electrodes corresponding to a single current electrode in the arrangement used by (a) a survey to measure the complete data set and (b) a cross-diagonal survey.

Initially the electrodes are arranged in a 10 by 5 grid with the longer lines orientated in the x-direction (Figure 7a). Measurements are made primary in the x-direction, with some possible measurements in the diagonal directions. Next the entire grid is moved in the y-direction so that the 10 by 5 grid now covers the second half of the 10 by 10 grid area. The 10 by 5 grid of electrodes is next orientated in the y-direction and the measurements are made between the electrodes in the y-direction (Figure 7b).

The file PIPE3D was from a survey using such a roll-along technique. It was carried out with a resistivity-meter system with only 25 electrodes, with the electrodes arranged in an 8 by 3 grid. The long axis of this grid was orientated perpendicularly to two known subsurface pipes. The measurements were made using three such 8 by 3 grids so that the entire survey covers an 8 by 9 grid. For each 8 by 3 sub-grid, all the possible measurements (including a limited number in the y -direction) for the pole-pole array were made. In this survey, the second set of measurements in the y -direction (as in Figure 7b) was not carried out to reduce the survey time, and also because the pipes have an almost two-dimensional structure.

For practical reasons, the number of field measurements in some surveys might be even less than the cross-diagonal technique. Another common approach is to just make the measurements in the x - and y - directions only, without the diagonal measurements. This is particularly common if the survey is made with a system with a limited number of independent electrodes, but a relatively large grid is needed.

For relatively small grids of less than 12 by 12 electrodes, the pole-pole array has a substantially larger of possible measurements compared to other arrays. The loss of data points near the sides of the grid is kept to a minimum, and provides better horizontal data coverage compared to any other array. This is an attractive array for small survey grids with relatively small spacings (less than 10 metres) between the electrodes. However, it has the disadvantage of requiring two “far” electrodes that must be placed at a sufficiently large distance (at least 10 times the maximum electrode spacing used) from the survey grid. Due to the large distance between the two potential electrodes, this array is more sensitive to telluric noise.

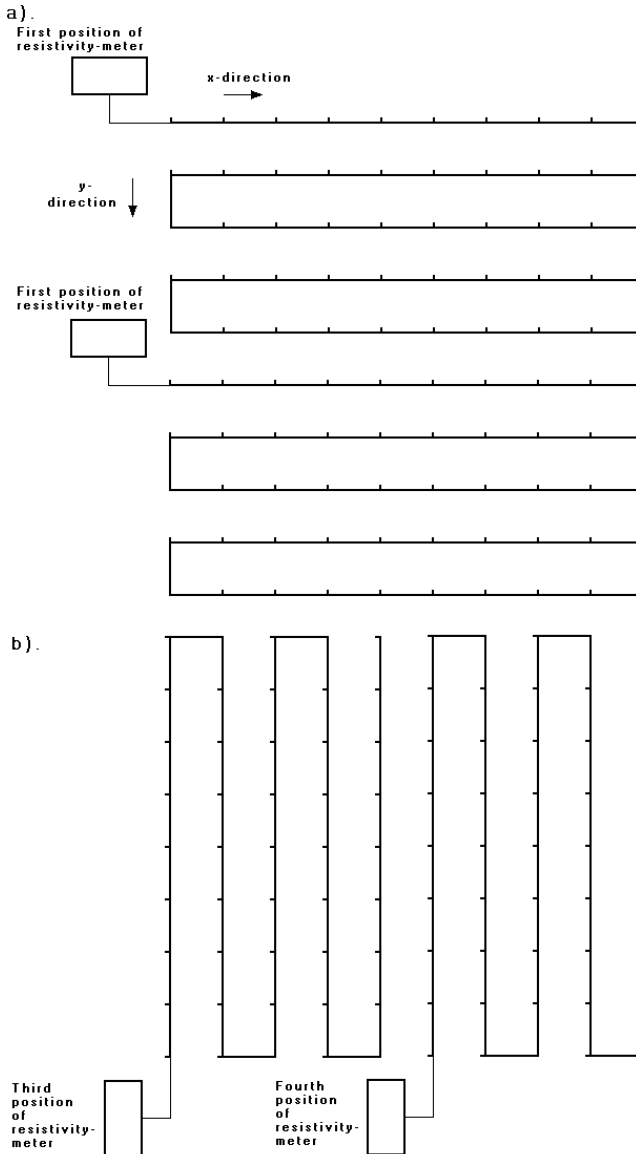


Figure 7. Using the roll-along method to survey a 10 by 10 grid with a resistivity-meter system with 50 electrodes. (a) Surveys using a 10 by 5 grid with the lines orientated in the x-direction. (b) Surveys with the lines orientated in the y-direction.

Appendix B : 3D surveys with the pole-dipole array

This array is an attractive alternative to the pole-pole array for surveys with medium and large survey grids (12 by 12 and above). It has a better resolving power than the pole-pole array, and is less susceptible to telluric noise since both potential electrodes are kept within the survey grid. Compared to the dipole-dipole array, it has a significantly stronger signal strength. The arrangement of the electrodes is shown below.

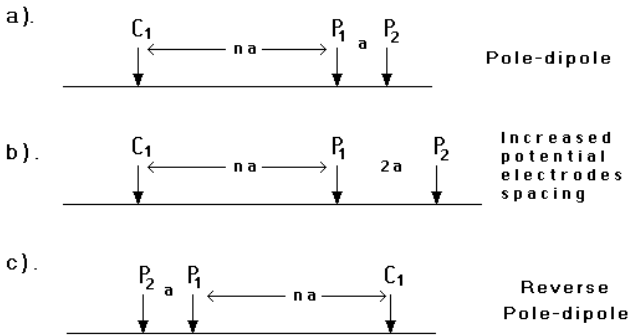


Figure 8. The arrangement of the electrodes for the pole-dipole array for measurements in the (a) “forward” direction, (b) with a larger spacing between the potential electrodes and (c) in the “reverse” direction.

Unlike other common arrays, it is an asymmetrical array. Over symmetrical structures the apparent resistivity anomalies are also asymmetrical. In some situations, the asymmetry in the measured apparent resistivity values could influence the model obtained after inversion. One method to eliminate the effect of this asymmetry is to repeat the measurements with the electrodes arranged in the reverse manner (Figure 7c). By combining the measurements with the “forward” and “reverse” pole-dipole arrays (Figures 7a and 7c), any bias in the model due to the asymmetrical nature of this array would be removed.

The apparent resistivity value for the pole-dipole array is given by

$$\rho = 2 \pi i n (n+1) a R$$

where R is the measured resistance, a is the spacing between the P_1 and P_2 electrodes and n is the ratio of the distances between the C_1 and P_1 electrodes to the P_1 - P_2 spacing. The voltage measure between the potential electrodes decreases with the square of the n factor. For large values of the n factor, the signal to noise ratio might become too small for a reliable measurement to be

made. To increase the signal strength, the distance between the P1 and P2 electrodes is increased (Figure 7b). One possible field technique is to make all the possible measurements with the P1-P2 spacing equals to $1a$ (i.e. the unit electrode spacing), followed by measurements with P1-P2 spacing equals to $2a$. This will increase the data density. In some cases, particularly in noisy areas, it has been found by having such redundant measurements improves the resolution of the resulting inversion model.

Concerning the data format, the upper part of the example data file BLK10PDP.DAT is shown below with some comments. Note that the array number is 6 for the pole-dipole, and the coordinates of the C1, P1 and P2 (i.e. three electrodes compared to only two electrodes for the pole-pole array) are given.

<i>BLK10PDP.DAT file</i>							<i>Comments</i>
2	BLOCKS						<i>Title</i>
10							<i>x grid size</i>
10							<i>y grid size</i>
1.00							<i>x unit electrode spacing</i>
1.00							<i>y unit electrode spacing</i>
6							<i>array type, enter 6 for pole-dipole</i>
1466							<i>Number of data points</i>
0.00	0.00	1.00	0.00	2.00	0.00	29.9669	<i>For each data point, enter</i>
0.00	0.00	2.00	0.00	3.00	0.00	30.0220	<i>x- and y- location of C1 current elec.,</i>
0.00	0.00	3.00	0.00	4.00	0.00	30.2216	<i>x- and y-location of C2 current elec.,</i>
0.00	0.00	4.00	0.00	5.00	0.00	30.3957	<i>x- and y-location of P1 potential elec.,</i>
0.00	0.00	5.00	0.00	6.00	0.00	30.4765	<i>apparent resistivity value</i>
0.00	0.00	6.00	0.00	7.00	0.00	30.4459	

Appendix C : 3D surveys with the dipole-dipole array

This array can be recommended only for grids that are larger than 12 by 12 due to the poorer horizontal data coverage at the sides. The arrangement of the electrodes are shown below.

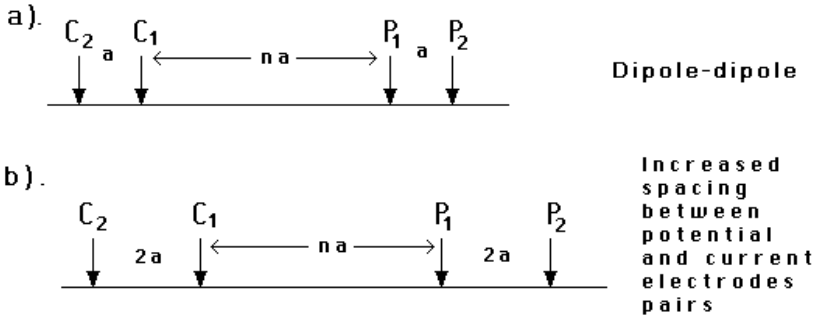


Figure 9. (a) The arrangement of the electrodes for the dipole-dipole array. (b) The use of a larger spacing between the C1-C2 (and P1-P2) electrodes to increase the signal strength.

The apparent resistivity value for the dipole-dipole array is given by

$$\rho = \pi n (n+1) (n+2) a R$$

where R is the measured resistance, a is the spacing between the P1 and P2 electrodes and n is the ratio of the distances between the C1 and P1 electrodes to the P1-P2 spacing. This array has the advantage of very good horizontal resolution, but its main disadvantage is its relatively low signal strength. The voltage measured by the P1-P2 pair is inversely proportional to the cube of the n factor. Normally, the maximum value for the n factor is 6. To get a deeper depth of penetration, the spacing between the C1-C2 (and P1-P2) pair is increased. One method to reduce the effect of noise is to make redundant measurements using different combinations of the n factor and the a spacing.

As an example, consider the case where the unit electrode spacing is 1 meter. First make all the possible measurements with a equals to 1 meter, and with n equals to 1, 2, 3, 4, 5 and 6. Next make the measurements with a equals to 2 meters and also with n equals to 1, 2, 3, 4, 5 and 6. If the grid is sufficiently large, another series of measurements with a equals to 3 meters can be carried out.

The file BLK10DDP.DAT is an example dipole-dipole array data file. Note that the array number is 3, and that the x- and y-coordinates of the C1, C2, P1 and P2 electrodes are given in that order.

Appendix D : Fixing resistivities

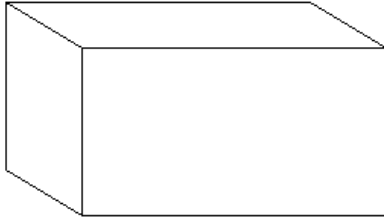
In some cases, the true resistivity of a section of the subsurface might be known, for example from borehole resistivity measurements. This program allows you to fix the resistivity of up to 10 sections of the subsurface. The shape of the section to be fixed must be rectangular.

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 10 : Fixing the resistivity of a rectangular region of the inversion model.

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

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

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 regions 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 the above diagram. After the coordinates of the region to be fixed are given, 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 control the degree in which the inversion subroutine can change the resistivity of the region. There is usually some degree of uncertainty in 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 is used, the smaller is the change that is 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.

Appendix E : IP data inversion

The data collected from IP (Induced Polarization) surveys consists of two sets, the normal apparent resistivity measurements and an apparent IP data set. So, the number of datum points is twice the number for a normal resistivity survey.

One possible method to invert such a joint data set is to treat the two data sets as completely separate data sets. The inversion of the resistivity data is completed before starting on the inversion of the IP data set. In this case, the resistivity model obtained at the last iteration of the inversion of the resistivity data set (which usually has the lowest RMS error) is used in the inversion of the IP data set. This is probably the most efficient method if the resistivity model is a good representation of the true subsurface resistivity. However, it has been found that even in the inversion of computer generated data sets, the model obtained can contain distortions particularly if a large number (more than 5) of iterations is used in the inversion of the resistivity data set. This is because the inversion is based on a finite number of datum points. The distortion becomes worse when the data contains noise. Many users tend to use a large number of iterations together with relatively low damping factors in an effort to reduce the RMS error to the lowest possible value. If a resistivity model with distortions is used in the inversion of the IP data, then the distortions will affect the IP models for all iterations of the IP inversion.

The inversion method used in this program is a step-wise refinement of IP inversion model. The inversion of the resistivity and IP data sets are still carried out separately. However, immediately after an iteration of the inversion of the resistivity data, an iteration of the IP inversion is carried out. The resistivity model obtained at the particular iteration of the resistivity data is used for the inversion of the IP data at the same iteration. Since the resistivity models at the earlier iterations are less distorted by noise in the data, the corresponding IP models are also less influenced by the distortions in the resistivity models.

The files MODEL3IP.DAT is an example data files with both resistivity and IP data. This program supports three different types of IP data; (i) time domain chargeability measurements, (ii) frequency domain percent frequency effect measurements and (iii) metal factor IP values. The file MODEL3IP.DAT has the IP data as chargeability values. The first part of the file with comments is as follows :-

<i>MODEL3IP.DAT file</i>	<i>Comments</i>
RESISTIVITY & IP MODEL	<i>Title</i>
8, 8	<i>x and y grid size</i>
1.00, 1.00	<i>x and y unit electrode spacing</i>

2							<i>Code for pole-pole array</i>
712							<i>Number of datum 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, integration time</i>
0.000	0.000	1.000	0.000	10.0544	0.3702		For each data line, the x- and y-
							location of the C1 electrode
0.000	0.000	2.000	0.000	10.1311	0.8952		followed by the x- and y-location of
							the P1 electrode, then
0.000	0.000	3.000	0.000	10.1860	1.3004		the apparent resistivity value and the
							apparent IP value
0.000	0.000	4.000	0.000	10.1808	1.3179		

The word *IP*, placed after the data line with the number of datum points, is used to indicate the data set contains IP measurements. This is followed by the type of IP data. The word *Chargeability* shows that the IP data is given in terms of chargeability. Many IP instruments measured the chargeability by integrating the area under the IP 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 IP unit, in this case in mV/V. If the IP 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.

IP 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).

For frequency domain measurements, the IP 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 follows :-

IP present	<i>Word IP to indicate IP is present</i>
Chargeability	<i>Type of IP data</i>

PFE	<i>IP unit</i>
0.3,5.0	<i>Lower and upper measurement frequencies</i>

IP values are also given as phase angles. In this case the unit normally used is milli-radians (mrad). In this case, the IP data section would be given as follows :-

IP present	<i>Word IP to indicate IP is present</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>

IP 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

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

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

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

An example format for metal factor measurements is as follows :-

IP present	<i>Word IP to indicate IP is present</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 minimise the difference between the observed and calculated equivalent apparent chargeability values. IP values in percent frequency effect and phase angles are directly proportional to the equivalent chargeability values. However, the metal factor value also involve 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.

Appendix F : Speed of graphics display

As RES3DINV is a Windows based program, graphics operations by the program are handled via the Windows display driver for the computer graphics card. Thus the program will work with any graphics card as long as it has a Windows driver. This is different from DOS based programs where compatibility problems with the high resolution Super VGA graphics modes are common. One big advantage of this program is that high resolution graphics modes, such as the 1024 by 768 pixels with 256 colours graphics mode, can be easily used by this program. This is important for data collected from surveys with more than several hundred to several thousand electrodes (a survey with about 5000 electrodes, 65000 data points and 32000 model cells now holds the record) where the standard VGA 640 by 480 pixels graphics mode is clearly inadequate.

Since graphics operations are carried out via the display driver, the speed of the graphics display is dependent on the efficiency of the display driver. For some graphics cards, the earlier versions of the drivers are relatively inefficient which results in painfully slow graphics operations such as in drawing the pseudosections. If this happens on your computer, the cause is almost certainly due to an early version graphics driver for the display card. The best way to overcome this problem is to replace the Windows graphics card driver with a newer version that should be more efficient. The drivers can be downloaded via the Internet from many shareware sites or from the manufacturer's web site. Using the latest version of the display driver can result in significant improvements in the speed of the graphics operations. This will affect not only the speed of the graphics display in the RES3DINV program, but will also improve the response of practically all graphics intensive Windows programs (such as CAD and animation programs).

Appendix G : Non-uniform survey grids

In some areas, it might not be possible to place the survey lines at exactly the same distance apart. One possible situation is shown in Figure 11 where the inner survey lines are 0.5 metres apart while the lines at the edge are 1.0 metres 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 :-

<i>NUGRID.DAT file</i>	<i>Comments</i>
2 BLOCKS	<i>Title</i>
9,9	<i>x and y grid size</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</i>
992	<i>Number of datum points</i>
0.000 0.000 1.000 0.000 29.934	<i>First datum point</i>
0.000 0.000 1.500 0.000 29.918	<i>Second datum point</i>
.	<i>Format of the rest of the data file is</i>
.	<i>the same as normal data file</i>
.	
.	
4.000 5.000 5.000 5.000 29.820	<i>Last data point</i>
0	
0	
0	
0	<i>End of file</i>

The program will check whether the x- and y-locations of each data point must fall on one of the grid lines when it reads in the file. If the difference is significant (more than 0.1%), the program will reject the data point.

This feature can also be used to modify the arrangement of the model blocks so as to add extra belts of blocks at the edges of the survey grid. This might be useful if there are strong anomalies near the sides of the survey grid. This is done by adding dummy electrodes outside the actual survey grid.

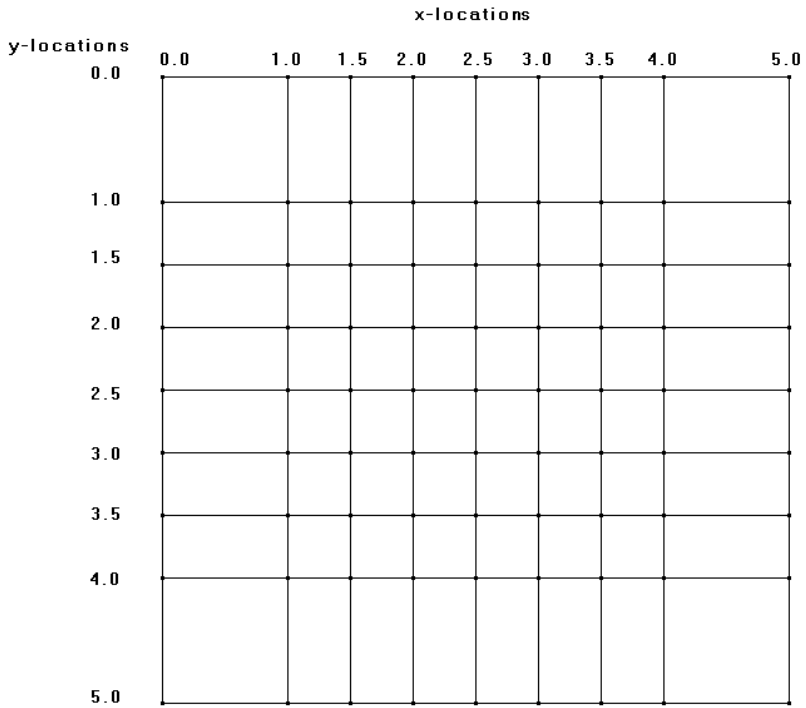


Figure 11. Arrangement of the survey grid lines in the data file NUGRID.DAT. Note the wider spacing at the sides.

Appendix H : The equatorial dipole-dipole (rectangular) array

This array differs from other arrays in that the electrodes are not arranged in a straight line but in a rectangular manner (Figure 12). This rectangular arrangement appears to fit in with the rectangular grid electrode arrangement used for 3D surveys. For a 3D grid of electrodes, it appears to have a better coverage at the sides compared to the inline dipole-dipole array, so it might be useful for small survey grids, particularly if high resolution at shallow depths is needed. The file EQUADIP3.DAT is an example data with this array for a 10 by 10 electrodes survey grid.

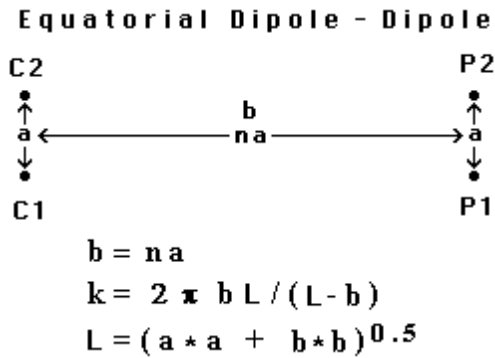


Figure 12. The arrangement of the electrodes and geometric factor “k” for the equatorial dipole-dipole or rectangular array.

Appendix I : Export model to Rockworks and Slicer/Dicer formats

In the "File" option within the "Display" window, there is a suboption to save the model resistivity or I.P. values into the format used by two 3D graphics display and modelling programs, the Rockworks 99 program by Rockware Earth Science Software (www.rockware.com) and the Slicer/Dicer program by Visualogic Inc. (www.visualogic.com).

For the Rockworks program, the model values are saved in the XYZG format that is very similar to the usual XYZ format (section 10). In this case, the file is read in as a text data file by the Rockworks program. In the XYZG file, the X, Y, and Z coordinates of the centre of each model block together with the resistivity is given. In place of the resistivity, you can also save the model conductivity or I.P. values.

For the Slicer/Dicer program, the data is saved as a generic metadata text file with a "gm" extension. The following dialog box is displayed when this option is selected.

Export data to Slicer/Dicer format

This option saves the model in the Slicer/Dicer generic data file format.
Please select the type of model parameter to save.

Save model resistivity
 Save model conductivity
 Save model I.P.

Number of iterations is 6. Please select an iteration number.

For resistivity or conductivity values, you can choose to save the values directly or the logarithm (base 10) of the values.

Save values directly
 Save logarithm of values

Slicer/Dicer assumes that the spacing in all directions, including the Z direction, are the same. The model is likely to have layers with different thicknesses, so the model drawn by Slicer/Dicer might look compressed in the vertical direction. To overcome this problem, you can choose to interpolate the layers using layers with a constant thickness. In this case, the program will replace the original layers with up to 32 interpolated layers.

Use actual layers
 Use interpolated layers

If you had chosen 'Use interpolated layers in the above option, you can choose to use uniform spacings in the X and Y directions as well. Using a uniform spacing in all directions will result in a larger file, but you do not have to adjust the scales in Slicer-Dicer to correct for differences in the sampling intervals in the different directions.

Use non-uniform spacing
 Use uniform spacing

You can choose to save the model values in a single file using a text format, or to save the information in two files using a binary format. In the binary format option, a small text metadata file is used to save information about the model parameters while the model values are saved in a binary file. This is recommended if you have a large model.

Use a single text file
 Save model values in binary file

The Slicer/Dicer program assumes that the unit spacing in all 3 directions are the same. This is not a problem in the X and Y directions if the survey is carried out with electrodes arranged in a rectangular grid with a constant unit spacing in the X and Y directions (i.e. a uniform grid).

If the unit spacing in the Y-direction is different from that in the X-direction, you can set different plotting scales within the Slicer/Dicer program so that the correct relative dimensions are obtained for the resulting display. The main problem lies in the Z-direction since the RES3DINV program normally uses a model where the thickness of the layers increases with depth. To overcome this problem, the RES3DINV program has an option to subdivide the model into layers with a constant spacing in the Z-direction. The program subdivides the model into layers that are thinner than the actual layers in the model. In the comment section of the generic metadata file, the appropriate relative scale factors to use in the X-, Y- and Z-directions for the display within the Slicer/Dicer program is also given.

There are two options for the type of output file in the Slicer-Dicer format. In the first option, all the information is stored in a single text file. The main advantage of this option is that the file can be copied to other drives or subdirectories, and still be directly read by the Slicer-Dicer program. The main disadvantage is that the size of the file becomes very large if there are a large number of model values, or if you choose option to use a uniform sampling spacing in all directions. In the second option, the model values are stored in a binary file (with a "bin" extension) while a small text metadata file with a "gm" extension stores information about the model values. The second line of this metadata file has the location (drive and subdirectory) of the binary file. If the files are moved to a different drive or subdirectory, you will need to edit the metadata text file so that the second line shows the correct drive and subdirectory where the corresponding binary file is located.

The file ROOTS7.GM is an example output Slicer/Dicer generic metadata format file for the Birmingham field test (section 13) inversion model. Note that in this file, the base 10 logarithms of the model resistivity values are stored. Figure 13 shows a 3D plot of the Sludge deposit (section 13) inversion model obtained with the Slicer/Dicer program.

Slicer-Dicer normally displays units for the labels on the x , y and z axes in units of pixels. To change it into the true units used, for example meters, click the 'Names and Units' option under the 'Options' menu. In the top half of the dialog box under 'Coordinates', change the starting and ending values for the x , y and z coordinates to the actual values. Lastly, click the 'Show values' option in the 'Coordinates' section, and select 'in dimensional units'.

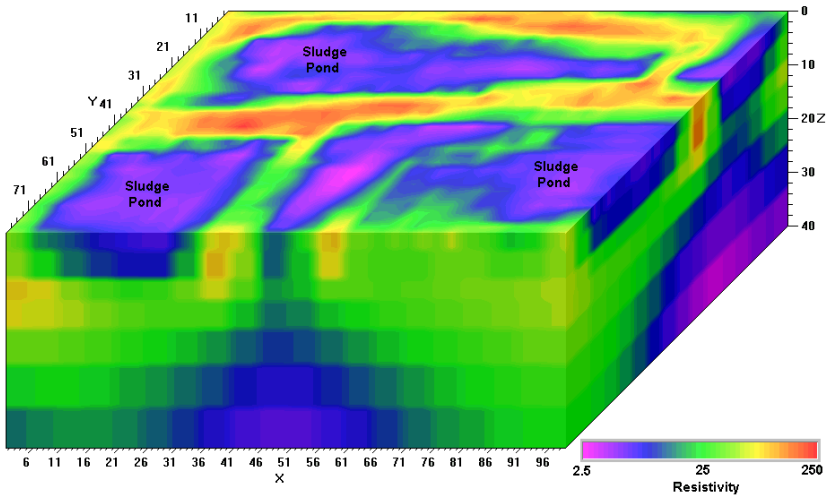


Figure 13. A 3-D view of the model obtained from the inversion of the Lernacken Sludge deposit survey data set displayed with the Slicer/Dicer program. A vertical exaggeration factor of 2 is used in the display to highlight the sludge ponds. Note that the colour contour intervals are arranged in a logarithmic manner with respect to the resistivity.

Appendix J : Disabling computer power management and screen saver

Practically all computers have an in-built power management system which slows down and eventually shuts down the computer system if the keyboard/mouse or hard disc is not accessed after a certain time limit. This might be a bit inconvenient if you are inverting a large data set since this program spends most of the time calculating using the CPU and coprocessor only. You will need to disable the power management feature in your computer to stop the computer from automatically slowing or shutting down. If the computer shuts down the system automatically, it will normally start again from the last program used, the next time it is switched on again. If this happens, you should exit from the program and restart it before using any of the program options. In some computer systems, the contents of all the memory might not be fully restored which could cause the program to crash. A similar, but fortunately less severe problem, exists with screen savers which kick in after a period of time if the keyboard or mouse is not used. Normally, a setting of several minutes is used for the screen saver. Since the calculations for a large model can take longer, it is recommended that you disable the screen saver. To disable the power management and screen saver, you need to take the following steps.

- 1). Shortly after the computer is switched on, it usually runs a memory check. During this time, you need to go to the CMOS Setup program in the computer BIOS. For most computers, this is done by pressing the "Del" key. The CMOS setup screen will next be shown. Go to the section which concerns power management, and disable the power management options for the computer. This is to ensure that the computer does not shut down or slow down automatically if the keyboard or mouse is not used after a fixed time.
- 2). After Windows starts up, go to the Control Panel. Click the Power Management icon. Here it will probably show the number of minutes after which Windows will automatically shut down the computer if the mouse or keyboard is not used. Disable this feature.
- 3). Next, still within the Control Panel, click the Display icon. In the Display program, click the Screen Saver option and disable the screen saver. This will ensure that Windows does not automatically run a screen saver.

After disabling the power management and screen saver options, you can physically switch off the monitor if the computer is left running overnight.

Please also shut down other active programs (such as word processors, CAD programs, spreadsheets) before running the RES3DINV program. This will ensure that the maximum amount of memory is available to the RES3DINV program, and also it will not be interrupted by another program during the course of inverting a large data set.

Appendix K : Inversion of large data sets, hard-disk file format and recommended PC systems

Recent advances in microcomputer technology and numerical algorithms have made it possible to carry out the inversion of very large data sets and grid models (over 30,000 data points and model cells). Even as recently as 5 years ago, 3D inversion of such large data sets would have required a fast mainframe or workstation computer system. Now it can be carried out on commonly available microcomputers with RES3DINV.

While carrying out the inversion of such large data sets, the RES3DINV program stores some of the information into temporary files on the computer hard-disk. In some cases, the size of such a file could exceed 4 GB (gigabytes). The Windows 98/Me operating systems use a file format system called FAT32 that has a maximum limit of 4 GB for files. So, the inversion of large data sets that require temporary files of greater size cannot be done efficiently under the Windows 98/Me operating systems. Windows NT4/2000/XP supports a newer file format system called NTFS that allows the use of much larger files. The maximum possible size of a file under the NTFS system presently exceeds that largest hard-disk commercially available for microcomputers. Computers using Windows NT4/2000 can use either the older FAT32 or the newer NTFS file format system. If the FAT32 system is used, the 4 GB file size limit still remains. According to Microsoft, it is possible to convert the file format system from FAT32 to NTFS without losing the data in the hard-disk by using a utility program supplied with Windows NT4/2000. The details can be found at the following web site.

<http://www.microsoft.com/windowsxp/pro/using/itpro/managing/convertfat.asp>

Windows XP is the latest Windows operating system, so the hard-disk that comes with this operating system is usually formatted with the NTFS file format system.

The recommended microcomputer system for the inversion of very large data sets is as follows.

Intel P4 CPU with speed of at least 2 GHz

40GB hard-disk with at least 16GB free hard-disk space (80 GB recommended)

At least 1 GB RAM (2 GB recommended)

Windows NT4/2000/XP operating system with NTFS file format system

There have been some reports of problems with systems using the AMD Athlon processors when running inversions that take more than a few hours. It

is recommended that you use a PC with an Intel P4 CPU together with an Intel motherboard.

Please remember that you need to install the driver for the dongle so that the RES2DINV/RES3DINV program can detect the dongle under Windows NT/2000/XP.

Appendix L : Non-conventional or general arrays

This feature is to cater for electrode arrangements that do not fall under the usual array types or electrode arrangements (such as the gradient array) or a mixture of data from different arrays. There are two main differences in the data format. Firstly the array type number is 11, and it also has a sub-array type to accommodate the case where the data is from one of the conventional arrays. The second difference is that in each data line, the number of electrodes used in the measurement is given. The file `3d_mixed_arrays.dat` gives an example of the data format. This file contains a mixture of data from the dipole-dipole and pole-dipole arrays.

<i>3d mixed arrays.dat file</i>	<i>Comments</i>
Mixed dipole-dipole and pole-dipole data	Title
10	X grid size
10	Y grid size
1.00	X unit electrode spacing
1.00	Y unit electrode spacing
11	Array type 11
0	Sub-array type
Type of data (0=apparent resistivity,1=resistance)	Header
0	Data in apparent resistivity
2480	Number of data points
4 1.0 0.0 0.0 0.0 2.0 0.0 3.0 0.0 29.968	Each data line has Number of electrodes,
4 1.0 0.0 0.0 0.0 3.0 0.0 4.0 0.0 30.096	X and Y loc. of C1,C2,P1,P2 electrodes
4 1.0 0.0 0.0 0.0 4.0 0.0 5.0 0.0 30.438	followed by the apparent resistivity value.
4 1.0 0.0 0.0 0.0 5.0 0.0 6.0 0.0 30.810	
.	
.	
.	
3 0.0 0.0 1.0 0.0 2.0 0.0 29.964	Note number of electrodes is 3 for
3 0.0 0.0 2.0 0.0 3.0 0.0 30.022	pole-dipole array
.	
.	
3 9.0 9.0 9.0 7.0 9.0 6.0 29.947	Last 2 data points
3 9.0 9.0 9.0 8.0 9.0 7.0 30.013	
0,0,0,0,0	Ends with a few zero's

Note that the sub-array number is 0 since there is no single fixed array type in this data set.

To accommodate the gradient array, the non-uniform grid option (Appendix G) can be used to add extra survey grid lines so as to include the remote C1 and C2 electrodes into the survey grid. In this case, two of the outer grid lines are likely to have a wider spacing from the interior grid lines.

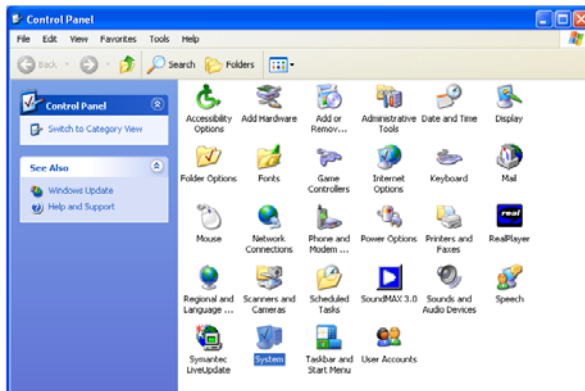
Appendix M : Using more than 1 GB RAM

For the inversion of some data sets, even 1 GB RAM might not be sufficient! This situation occurs with large surveys grids (with more than one thousand electrodes) in an area with topography together with use of the 3 nodes or 4 nodes between adjacent electrodes option. The 3 or 4 nodes option is used for greater accuracy. It is necessary to use the finite-element method when the data set has topography. For the inversion of such large data sets, the Windows NT/2000/XP operating system must be used so that temporary files larger than 4 GB can be used by the program (see Appendix K).

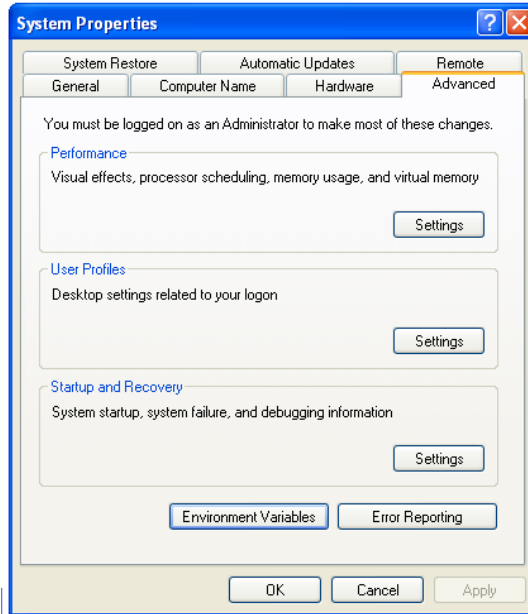
There are two main obstacles in using more than 1 GB RAM on standard PCs. The first obstacle is the number of memory slots on the motherboard. Most PCs have two or three memory slots which can accept 512 MB or 1 GB RAM modules. At the present time (March 2003), 512MB RAM modules are fairly common and inexpensive, while 1 GB RAM modules are comparatively rare and much more expensive. If there are three memory slots, then a maximum of 1.5 GB can be installed using the 512 MB RAM modules. A problem arises if there are only two memory slots. Then there is a choice of limiting the maximum RAM to 1 GB using 512 MB RAM modules, or using the more expensive 1 GB RAM modules.

In order for a program to access more than 1 GB memory, the virtual memory setting in Windows NT/2000/XP must be modified. Windows probably has a 1 GB virtual memory default setting. To use memory above 1 GB, the SDVIRTUALMAXMEMORY environment variable in Windows must be changed. The following section describes the steps needed in Windows XP to change this setting. Similar steps are used in Windows NT and 2000.

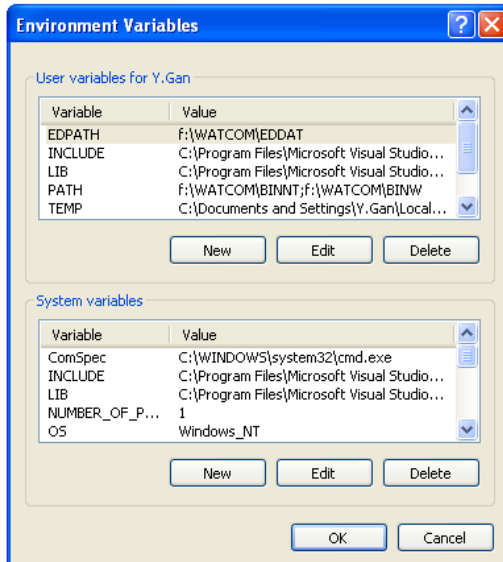
First click the ‘Start’ button and then ‘Control Panel’ icon. In the ‘Control panel, click the ‘System’ icon, as shown below.



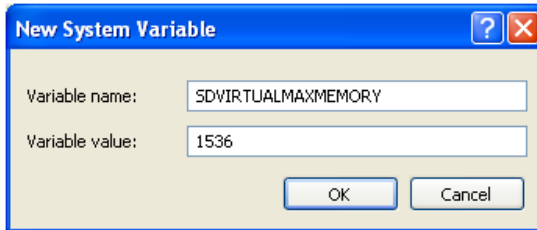
In the 'System Properties' window, click the 'Advanced' tab, and the following settings will be shown.



In this window, click the 'Environment Variables' option, after which the following window is displayed.



In the 'System variables' section, click the 'New' button. Fill in the 'New System Variable' dialog box as shown below. The variable name should be set to 'SDVIRTUALMAXMEMORY', while the variable value is the size in megabytes for the virtual memory setting. The example below uses a value of 1536 for a system with 1.5 GB RAM.



After filling in the box, click the OK button for this box, follow by the OK buttons for the 'Environment Variables' and 'System Properties' windows. After that, restart the computer so that the new setting will be used by Windows.

While 32-bit processors such as the Pentium series can physically address up to 4 GB RAM, only the bottom 2 GB can be used by application programs in Windows. The upper 2GB memory address space is reserved for Windows.

Appendix N : Underwater 3-D 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 hand-held 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 below.

<i>WATER3D.DAT file</i>	<i>Comments</i>
Underwater survey example	<i>Title</i>
12	<i>12 electrodes in x-direction</i>
12	<i>12 electrodes in y-direction</i>
2.00	<i>Unit electrode spacing in x-direction</i>
2.00	<i>Unit electrode spacing in y-direction</i>
3	<i>3 for dipole-dipole array</i>
1440	<i>Number of data points</i>
2.0 0.0 0.0 0.0 4.0 0.0 6.0 0.0	<i>106.811 x- and y-locations of C1, C2, P1, P2</i>
2.0 0.0 0.0 0.0 6.0 0.0 8.0 0.0	<i>84.895 electrodes, followed by the apparent</i>
2.0 0.0 0.0 0.0 8.0 0.0 10.0 0.0	<i>97.331 resistivity value.</i>
.	<i>Note same format as land survey.</i>
.	<i>Other data points</i>
22.0 8.0 22.0 2.0 22.0 14.0 22.0 20.0	<i>101.143 Last 2 data points</i>
22.0 10.0 22.0 4.0 22.0 16.0 22.0 22.0	<i>97.808 </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 x-row by x-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	
0.1 0.0 0.0 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 0.0 0.0 0.0	
0.0 0.0 -0.1 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 0.0 0.0 0.0	
0.0 0.0 -0.2 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 0.0 0.0 0.0	
0.0 -0.1 -0.2 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 0.0 0.0 0.0	
-0.1 -0.2 -0.3 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 -0.2 -0.1 0.0	
-0.2 -0.3 -0.4 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 -0.4 -0.2 -0.1	
-0.3 -0.4 -0.5 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 -0.4 -0.3 -0.2	
-0.4 -0.5 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 -0.4 -0.3 -0.3	
-0.5 -0.5 -0.5 -0.5 -1.0 -1.5 -1.5 -1.0 -0.5 -0.5 -0.4 -0.4	
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 | Header
-0.2                       | The elevation of the water surface
Type of geometric factor (1=surface,0=exact) | Header
1                           | 1 to indicate surface geometric factor
0,0,0,0                   | End with a few zeros

```

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 (Appendix D), 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 following figure.

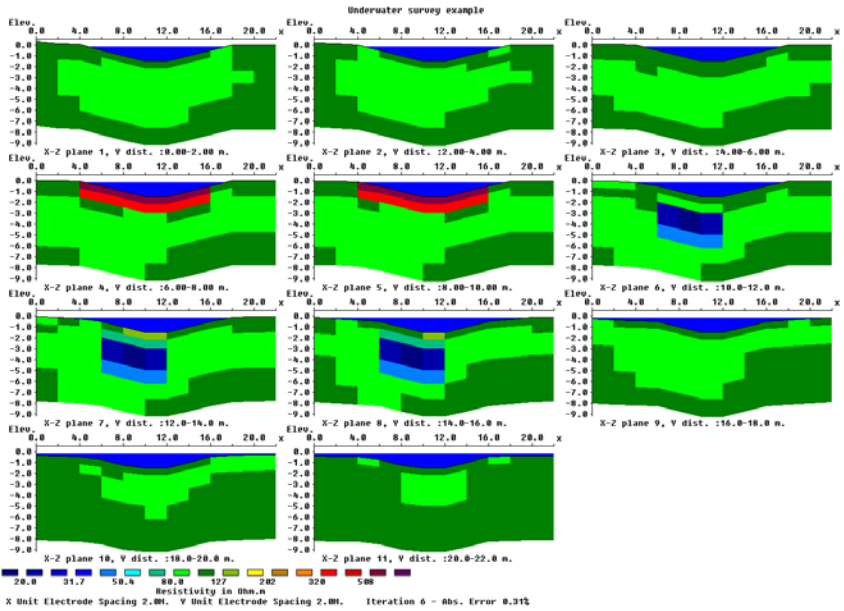


Figure 14. Plot of the model sections with topography from the WATER3D.INV file. The water layer is indicated by the blue zone at the top part of the sections. Note that some of the electrodes are above the water level, i.e. this data set has electrodes below as well as above the water layer.

Appendix O : Cross-borehole data inversion

The resolution of electrical surveys carried out with electrodes on the ground surface decreases exponentially with depth. One method to obtain reasonably good 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 cross-borehole option in this program is intended for shallow surveys with the arrangement of the electrodes placed in a certain general pattern. The surface electrodes must be arranged in a rectangular grid. The x and y location of a borehole must coincide with the location of one of the surface electrodes in the grid.

The program divides the subsurface into a number of quadrilateral blocks. The x and y location of the boundaries of the blocks are set using the surface grid of electrodes (Figure 2a). The vertical position of the boundaries are set at the depths where the borehole electrodes are located. The program has the restriction that the number of electrodes in all the boreholes must be the same, and the borehole electrodes are located at the same depths from the surface.

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 the comments section. 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.

<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>
1.00	<i>x unit electrode spacing</i>
1.00	<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 electrode in borehole</i>
2.0 2.0 3.0	<i>x, y and z location of 3rd electrode in borehole</i>
2.0 2.0 4.0	
2.0 2.0 5.0	
2.0 2.0 6.0	

2.0 2.0 7.0	
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 location</i>
6.0 2.0 2.0	<i>of the borehole electrodes starting from the first</i>
6.0 2.0 3.0	<i>borehole electrode.</i>
6.0 2.0 4.0	
6.0 2.0 5.0	
6.0 2.0 6.0	
6.0 2.0 7.0	
6.0 2.0 8.0	
Borehole 3	<i>Header for 3rd borehole</i>
8	
6.0 6.0 1.0	
6.0 6.0 2.0	
6.0 6.0 3.0	
6.0 6.0 4.0	
6.0 6.0 5.0	
6.0 6.0 6.0	
6.0 6.0 7.0	
6.0 6.0 8.0	
Borehole 4	<i>Header for 4th borehole</i>
8	
2.0 6.0 1.0	
2.0 6.0 2.0	
2.0 6.0 3.0	
2.0 6.0 4.0	
2.0 6.0 5.0	
2.0 6.0 6.0	
2.0 6.0 7.0	
2.0 6.0 8.0	
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 datum point, the first parameter is</i>
2 0.0 0.0 0.0 2.0 0.0 0.0 98.50	<i>the number of electrodes used (2 for pole-pole).</i>
2 0.0 0.0 0.0 3.0 0.0 0.0 97.63	<i>This is followed by the x, y and z location of the</i>
2 0.0 0.0 0.0 4.0 0.0 0.0 97.14	<i>current electrode C1, and then the x, y and z</i>
2 0.0 0.0 0.0 5.0 0.0 0.0 97.23	<i>location of the potential electrode P1.</i>
2 0.0 0.0 0.0 6.0 0.0 0.0 97.73	
2 0.0 0.0 0.0 7.0 0.0 0.0 98.35	
2 0.0 0.0 0.0 8.0 0.0 0.0 98.92	
2 0.0 0.0 0.0 0.0 1.0 0.0 99.39	
2 0.0 0.0 0.0 1.0 1.0 0.0 98.76	

```

.
.
.
2 2.0 6.0 7.0 2.0 6.0 8.0 99.38 | Last datum point, followed
0                               | by a few 0's. If there is topography,
0                               | the topographical information should be entered
0                               | after the apparent resistivity data using the same
0                               | format as for standard surface surveys.

```

The file BORHOLE3D.DAT gives an example where the pole-dipole array is used. The format for the initial section is the same as for the above example, the only difference is the x, y and z location of the P2 electrode is also entered in the data section. Below part of the data section is shown with comments.

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

If 4 electrodes are used in a measurement, the x-, y- and z- location 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 IP data is present, the format is similar to that used for normal surface surveys. The type of IP information is entered after the number of data points and before the apparent resistivity and IP values.

For a computer system with 512MB RAM, the maximum number of boreholes allowed is 12. The maximum total number of electrodes in the boreholes is 500. For example, if there are 10 boreholes, then each borehole can have a

maximum of 50 electrodes. These limits are higher for systems with more RAM.

Appendix P : Non-rectangular (trapezoidal) survey grids

In areas with rugged and forested terrain, it is frequently not possible to place the survey lines in a perfect rectangular grid. This option allows moderate departures from a perfectly rectangular arrangement of the electrodes. Figure 15 gives a sketch of a possible electrodes arrangement that deviate from a rectangular grid and effectively forms a trapezoidal grid. Along each survey line, the number of electrode still must be the same. The example has a 7 by 5 grid, so there still must be 7 electrodes in each row. The survey lines need not be orthogonal, but deviations of greater than 30 degrees will probably not be advisable.

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 horizontal coordinates, and not distances along the ground surface, while the z coordinate is the elevation. The file TRAPEZOIDAL.DAT gives an example of the data format used.

<i>TRAPEZOIDAL.DAT file</i>	<i>Comments</i>
2 BLOCKS with Shifted Y lines	Title
14	x grid size
14	y grid size
Trapezoidal Grid used	Header to indicate trapezoidal survey grid
Location of electrodes given line by line	Header
Line 1	Header for Line 1
0.0,0.0,0.0	(x,y,z) coordinate of first electrode on Line 1
3.0,0.0,0.0	(x,y,z) coordinate of second electrode on Line 1
6.0,0.0,0.0	Same for other electrodes on Line 1
9.0,0.0,0.0	
12.0,1.0,0.0	Note shift of 1 m. for
15.0,1.0,0.0	these 3 electrodes
18.0,1.0,0.0	in y-direction
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	(x,y,z) coordinate of last electrode on Line 1
Line 2	Header for line 2
0.0,3.0,0.0	(x,y,z) coordinate of first electrode on Line 2
3.0,3.0,0.0	(x,y,z) coordinate of second electrode on Line 2
.	Similar information is given for all
.	electrode and survey lines until last line
.	
36.0,39.0,0.0	(x,y,z) coordinate of second last electrode on Line 14
39.0,39.0,0.0	(x,y,z) coordinate of last electrode on last Line
Type of geometric factor (0=horizontal, 1=linear, 2=user defined)	Header

```

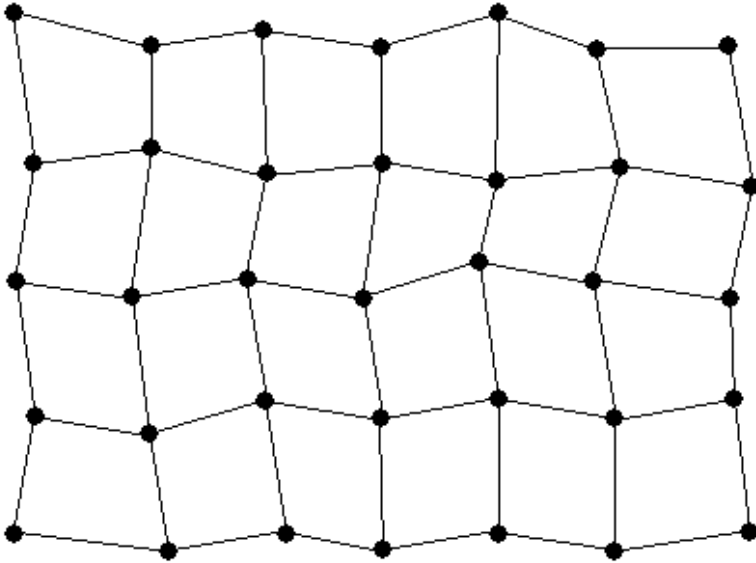
0          | 0 to indicate horizontal distance used to calculate geometric factor
2          | Array type. Pole-pole in this case. Rest of data follows the
          | standard format.
1274      | Number of data points
0.00, 0.00 0.00, 3.00 101.4090 | Location of electrodes and apparent resistivity
0.00, 0.00 0.00, 6.00 102.4530 | Same for the rest
0.00, 0.00 0.00, 9.00 103.3240 |
.
.

```

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 by the user in calculating the apparent resistivity value from the potential and current values. In the data format, the type of geometric factor used must be specified to avoid any ambiguity. Most survey will probably calculate the distance between the electrodes using the (x,y) coordinates only, which can usually be derived from GPS readings. In the above example, a value of 0 is used to indicate that the geometric factor is calculated using horizontal distances. Another possibility is to use the linear distance between the electrodes by using the (x,y,z) coordinate (value of 1 in the above data format) of each electrode.

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

In the above 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.



● **Electrode**

Figure 15. Schematic diagram of a survey where the electrodes are displaced from a rectangular grid pattern.

Appendix Q : Special topography information for mineral exploration surveys

The RES3DINV software was originally written for surveys by engineering and environmental geophysicists. Thus the default settings in the program follow the practices in this field. One important difference is that in engineering/environmental surveys, the electrodes are laid out such that the distance along the ground surface is constant by using a multicore cable with a constant spacing between the takeouts. This saves time and the expense of carrying out a detailed topographical survey before the resistivity survey. The RES2DINV program assumes that the x-locations of the electrodes are given in terms of distances along the ground surface.

However for mineral exploration surveys (with bigger budgets) it is common to carry out a detailed topographical survey before the resistivity and IP survey, and the electrodes are placed such that the true horizontal distance (rather than the surface distance) between the electrodes is constant. In areas with steep topography, it is possible for the vertical distance between two adjacent electrodes to exceed the horizontal distance (but still less than the surface distance). For surveys where the true horizontal distance is used for the x- and y- locations of the electrodes, the indicator in the topography data section for the type of x- and y- coordinates must be given as 1 instead of 2 (which indicates surface distances are used). A description is given in pages 10 and 11 of this manual.

In very rugged areas, it is possible that the survey grid is not exactly rectangular in shape. For such a situation, the non-rectangular or trapezoidal survey grid data format must be used (see Appendix P). In this data format, the true horizontal x-, y- and z- coordinates of all the electrodes must be given.

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 for a nominal charge to cover postage and handling. Faulty dongles or program disks will be replaced free of charge within the first 6 months from the date of purchase to registered users. Registered users are entitled to free updates and support within the first year.

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) (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. It is not possible to provide technical support for users of the demo version of this software. For technical support, you can contact the software provider by email at the following addresses. Please attach a copy of your data file to your email.

geotomo@tm.net.my
support@geoelectrical.com

The following information will be required before technical support is provided.

- 1). Your dongle ID number. This ID number is displayed near the bottom of the initial information box when the RES3DINV program starts up if the dongle is attached to the computer.
- 2). The name of your company or institution.
- 3). Approximate date (month/year) your company or institution purchased the software.

What's New

Version 2.00 - Upgrade to Windows 3.1 and 95.

Version 2.01 - Code optimisations 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 IP 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. Optimisation 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.