

# RES3DINV ver. 2.1

*for Windows 95/98/Me/2000/NT/XP*

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

(For E-SCAN type of surveys using the  
pole-pole, pole-dipole, dipole-dipole, rectangular,  
Wenner and Wenner-Schlumberger arrays)

## **Geoelectrical Imaging 2D & 3D**

**October 2001**

email : [info@terraplus.com](mailto:info@terraplus.com)

Internet : [www.terraplus.com](http://www.terraplus.com)

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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 E-SCAN type of survey (Li and Oldenburg 1992). 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. 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 sufficient memory, this program can handle survey grids with up to 43 by 43 (or 1849) electrodes!

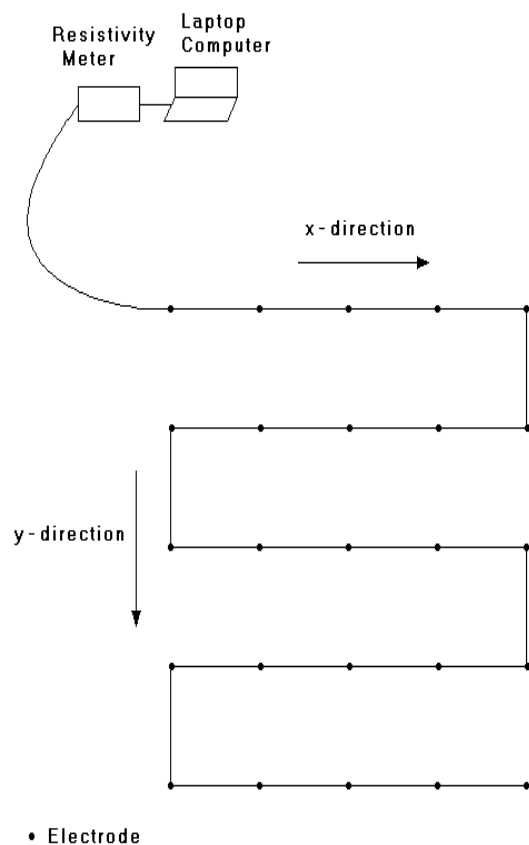


Figure 1. A schematic diagram for one possible layout for a 3D survey.

## 2 Computer system requirements

RES3DINV is a 32-bit Windows based program that will run under Windows 95/98 and NT. You will need a Pentium, Pentium Pro, Pentium II or Pentium III (or compatible) based microcomputer to run this program. The minimum amount of RAM is 32 megabytes, but 64 megabytes is recommended and 128 megabytes is preferred! You will also need about 200 megabytes 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/NT 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/NT, 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/ NT, 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 and 2000, it is necessary to install a system driver for the dongle.

**a). For users with the Rainbow Technologies Sentinel SuperPro key**  
The file SYSDRVR.EXE is a self-extracting file (in the same CD-ROM as the RES2DINV program files) which contains the system drivers for Windows 95/98 and Windows NT. Copy this file to a subdirectory, for example C:\SYSDRVR, and run this file from within Windows. The drivers for Windows NT and 95/98 will be extracted automatically. There is a README.TXT file which gives instructions on installing the driver (just substitute subdirectory for floppy drive

mentioned in this file). For the Windows NT operating system, change to the Win\_NT sub-subdirectory and run the SETUPX86.EXE file to install the NT driver. After that you will need to restart the computer for the driver to take effect. More information about the system drivers can be obtained at the following web site : [www.rainbow.com](http://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 RES2DINV 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](http://www.keylok.com)

If you are using Windows 95 or 98, 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 and Windows NT ver. 4.0, 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 RES2DINV 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 RES2DINV is busy inverting a large data set!

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 eg. 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 Keylok company by email.

If you are using Windows NT, 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 which is the default printer port. In this case, you will need to reassign the parallel port as a printer port. In Windows 95/98/NT, 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. It is much slower than the quasi-Newton method, but in areas with large resistivity contrasts of greater than 10:1, it gives slightly 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

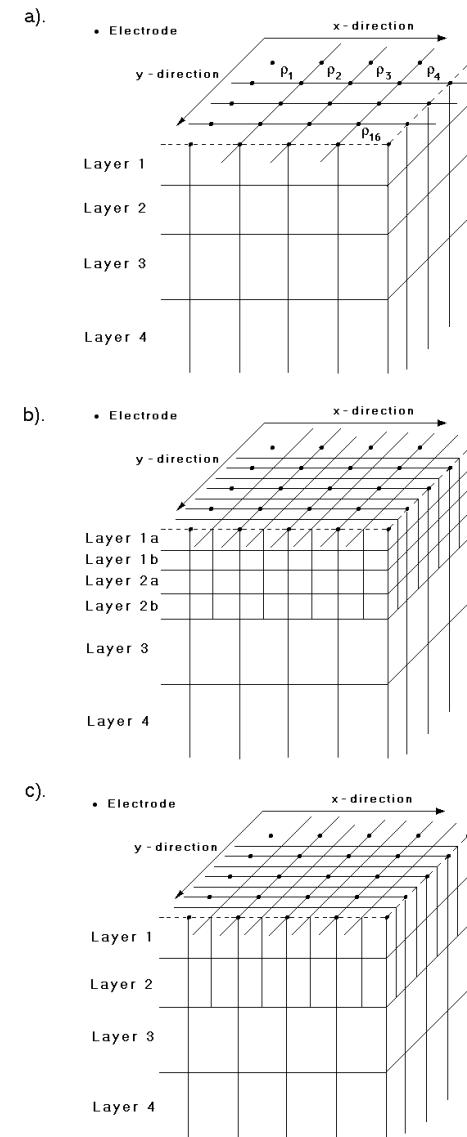


Figure 2. The models used in the inversion. (a) Standard model where the widths of the rectangular blocks are equal to the unit electrode spacings in the x- and y-directions. (b) A model where the top few layers are divided by half, both vertically and horizontally, to provide better resolution. (c)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

of model parameters and thus the computer time required to invert the data set can increase dramatically.

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.



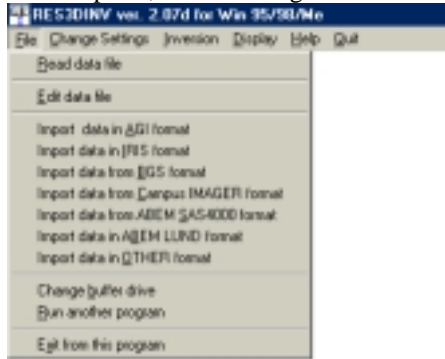
You can select an option by clicking it with the mouse cursor. If this is the first time you are using the program, try reading in one of the smaller files such as ROOTS7.DAT provided with the program. Click the File choice, followed by the "Read in data file" submenu choice. After that, if necessary, 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 which 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 :-

<u>ROOTS7.DAT file</u>	<u>Comments</u>
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  
 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.

<u>BLOCK11T.PPL file</u>	<u>Comments</u>
8.000 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	in x-direction.
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.

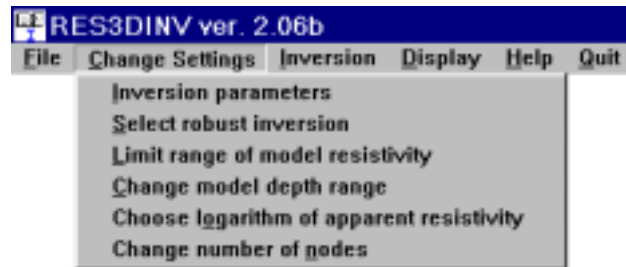
If the data set contains topography, the inversion subroutine will automatically incorporate the topography into the inversion model by using the finite-element method (Silvester and Ferrari 1990).

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

**Import data in .....format** : 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.

**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.

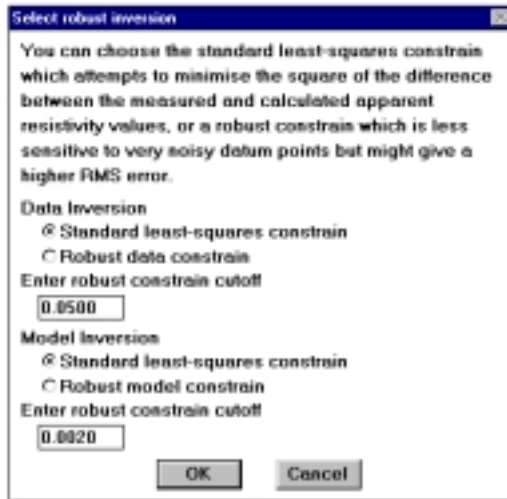
**Number of iterations to recalculate Jacobian** - In the Gauss-Newton method, the Jacobian matrix is recalculated after each iteration, whereas in the quasi-Newton method the Jacobian matrix is never recalculated but estimated after each iteration (see 'Theory' section). The fastest method is to use 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.

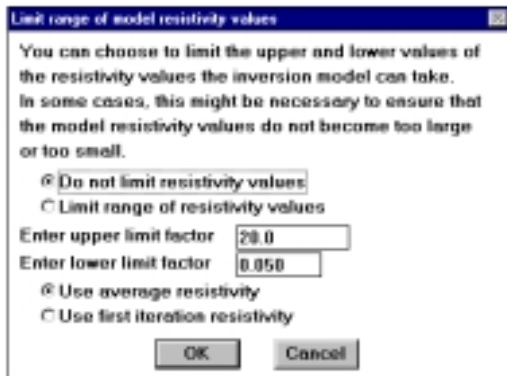
**Convergence limit** - This sets the lower limit for the relative change in the RMS error between 2 iterations. By default, a value of 5% is used. In this program the relative change in the RMS error, rather than an absolute RMS value, is used to accommodate different data sets with different degrees 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.





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



This option allows you to limit the range of resistivity values that the inversion subroutine will give. In the above example, the upper limit for is 20 times the average model resistivity value 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.

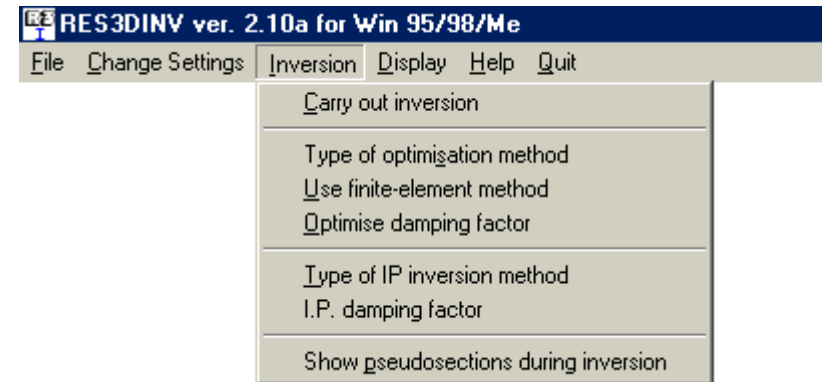
Change model depth range - This option allows you to increase or decrease the depth of the layers in the inversion model used by the program. The depths are multiplied by a scaling factor given by the user.

Chose 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 4 nodes between adjacent electrodes for greater accuracy.

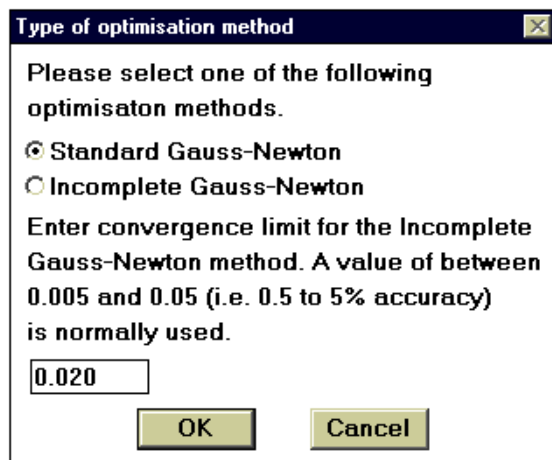
## 9 Inversion of data

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 5000), 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.

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).

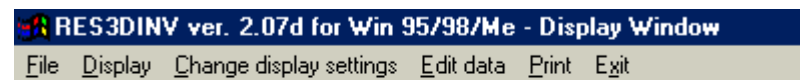
Type of IP inversion method - To invert a combined resistivity and IP dataset, you can choose to invert both data sets concurrently in each iteration or to invert the IP data sequentially after the inversion of the resistivity data.

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.

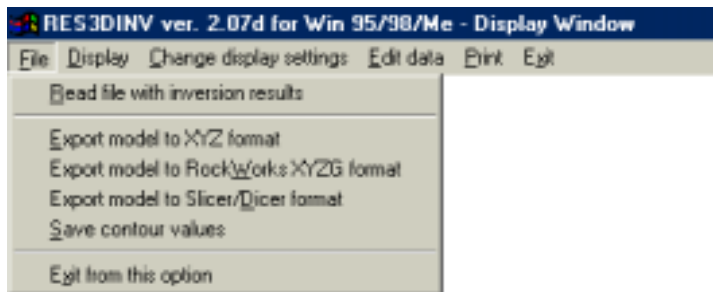
## 10 Display results

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.



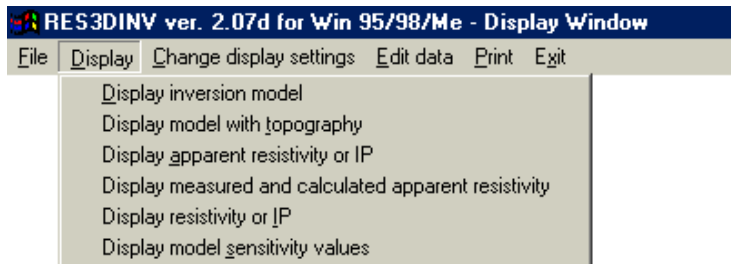
The “File” option will bring up the following submenu.



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.

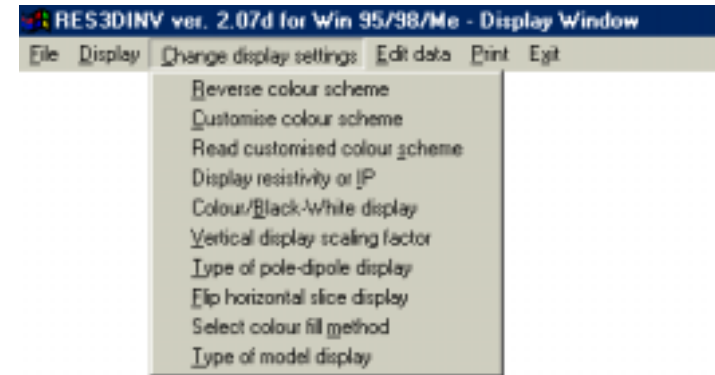


Display inversion model - Select this option to plot the model. You can plot the model in the form of horizontal or vertical slices through the earth.

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.

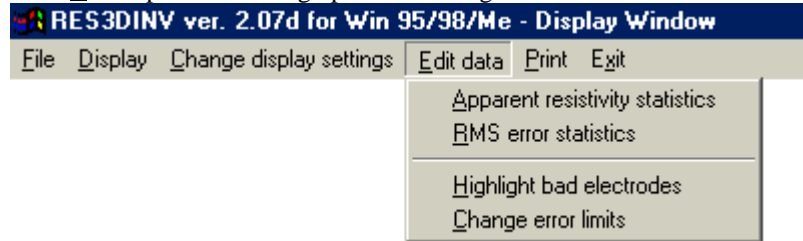
Display resistivity or IP - You can choose to display the resistivity or IP in the model sections or pseudosections if the data set contains IP measurements as well.

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.



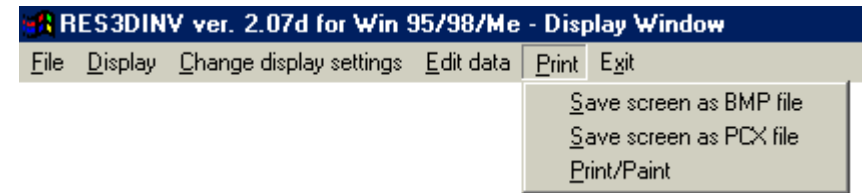
Large 3D surveys can involve many thousands of datum points. In the most general case, the array for a particular measurement can be orientated in any direction. To obtain a good inversion model, the “bad” data points must be removed from the data set. One possible way of removing the “bad” data points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

## 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 are 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.

#### Septic tank survey - Texas

This field survey was carried out using a 8 by 7 grid of electrodes over a buried septic tank. A Sting/Swift multi-electrode resistivity meter system (Lagmansson pers. comm.) was used for this survey. The distance between adjacent electrodes in the grid was 1 metre. All the possible measurements with the pole-pole array were made which gave a total of 1470 data points. The result from the computer inversion of this data set is shown in Figure 4. For the inversion of this data set, the model blocks in the top 2 layers are subdivided into smaller blocks. The results are given in the form of horizontal slices through the subsurface. The septic tank appears as a large high resistivity area in the bottom left quadrant of survey area in Layers 2, 3 and 4. The topmost layer (Layer 1a in Figure 4) has a few areas with relatively large resistivity variations over short distances. In comparison, Layer 2b that extends from a depth of 1.1 to 1.5 metres shows more gradual lateral variations in the model resistivity values. In general, the deeper is the layer, the smoother is the lateral variations in the model resistivity values. This is probably partly caused by the decrease of the resolution of the resistivity surveying method with depth. The location of the septic tank as indicated in the model sections was subsequently confirmed by excavating the overlying soil (Lagmansson pers. comm.).

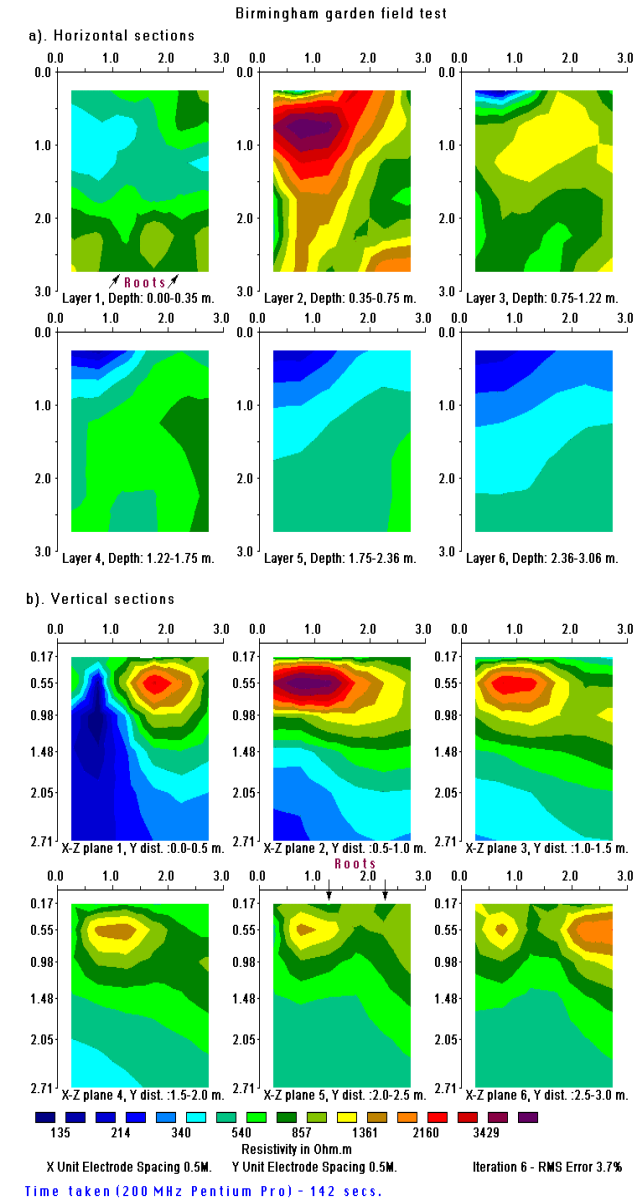


Figure 3. Horizontal and vertical cross-sections of the model obtained from the inversion of the Birmingham field survey data set. The location of observed tree roots on the ground surface are also shown.

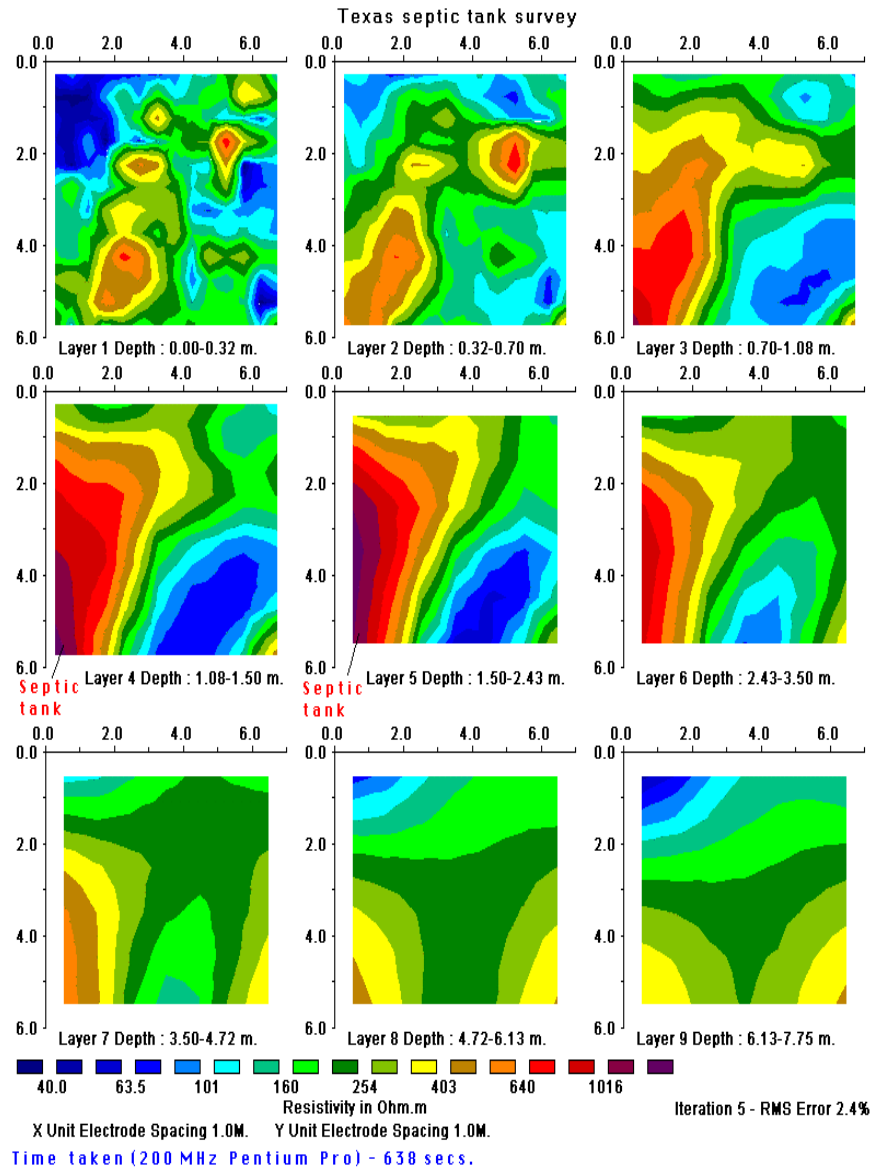


Figure 4. The model obtained from the inversion of the septic tank field survey data set.

### 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 and Bernstone (1997), 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 5. The former sludge ponds containing highly contaminated ground water show up as low resistivity zones in the top two layers (Dahlin and Bernstone 1997). 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.

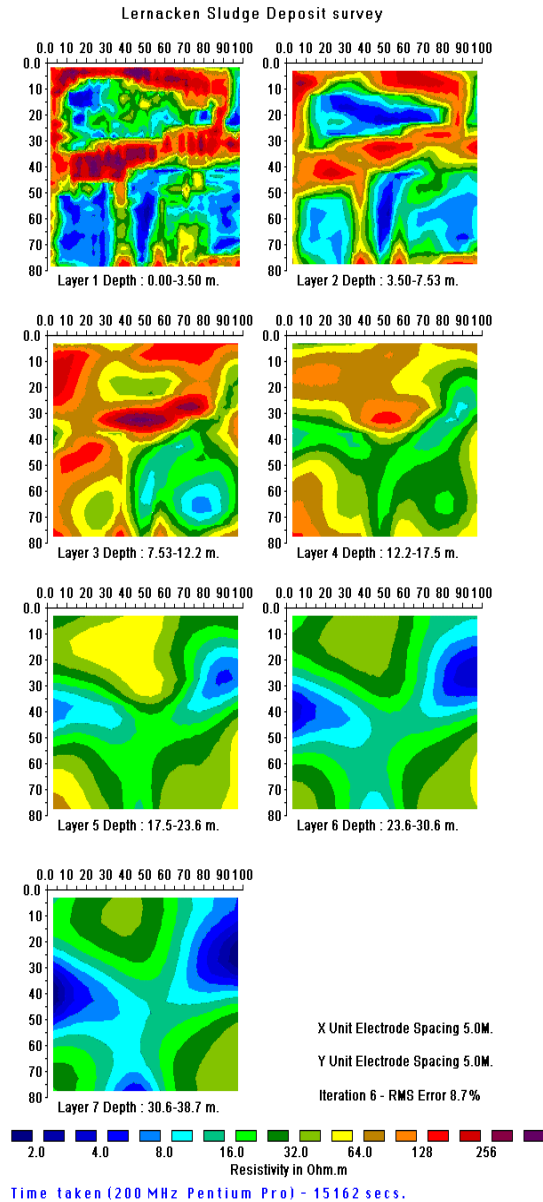


Figure 5. The 3D model obtained from the inversion of the Lernacken Sludge deposit survey data set. The model is shown in the form of horizontal slices through the earth.

## 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.

## Acknowledgements

Dr. Torleif Dahlin of Lund University in Sweden kindly provided the Lernacken field example. Mr. Mats Lagmanson of Advanced Geosciences Inc. generously contributed the Septic tank data set. Finally, a special acknowledgement to Ron Barker of the School of Earth Sciences, University of Birmingham for the 3D Birmingham field test data set. Rockworks and Slicer/Dicer are registered trademarks of Rockware Earth Science Software and Visualogic Inc.

### References

- Claerbout, J.F. and Muir, F., 1973. Robust modeling with erratic data. *Geophysics*, **38**, 826-844.
- deGroot-Hedlin C. and Constable S.C. 1990. Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysics*, **55**, 1613-1624.
- Dahlin, T. and Bernstone, C., 1997, A roll-along technique for 3D resistivity data acquisition with multi-electrode arrays, *Procs. SAGEEP'97 (Symposium on the Application of Geophysics to Engineering and Environmental Problems)*, Reno, Nevada, March 23-26 1997, vol 2, 927-935.
- Dey A. and Morrison H.F. 1979. Resistivity modeling for arbitrarily shaped three-dimensional shaped structures. *Geophysics*, **44**, 753-780.
- Fletcher R. 1987. *Practical methods of optimization*. John Wiley & Sons.
- Fox, R.C., Hohmann, G.W., Killpack, T.J. and Rijo, L., 1980, Topographic effects in resistivity and induced polarization surveys. *Geophysics*, **45**, 75-93.
- Griffiths D.H. and Barker R.D. 1993, Two-dimensional resistivity imaging and modelling in areas of complex geology. *Journal of Applied Geophysics*, **29**, 211-226.
- Li Y. and Oldenburg D.W. 1992, Approximate inverse mappings in DC resistivity problems. *Geophysical Journal International*, **109**, 343-362.
- Loke M.H. and Barker R.D., 1996, Practical techniques for 3D resistivity surveys and data inversion. *Geophysical Prospecting*, **44**, 499-523.
- Nelson, G.D. and Van Voorhis, 1973, Letter to the editor regarding the paper "Complex resistivity spectra of porphyry copper mineralization". *Geophysics*, **38**, 984.
- Silvester P.P. and Ferrari R.L., 1990, *Finite elements for electrical engineers* (2nd. ed.) . Cambridge University Press.
- Summer, J.S., 1976, *Principles of induced polarization for geophysical exploration*. Elsevier Scientific Publishing Company.
- Tong, L. and Yang, C., 1990, Incorporation of topography into two-dimensional resistivity inversion. *Geophysics*, **55**, 354-361.
- Van Voorhis, G.D. Nelson, P.H. and Drake, T.L., 1973, Complex resistivity spectra of porphyry copper mineralization. *Geophysics*, **38**, 49-60.
- Witherly, K.E. and Vyselaar, J, 1990, A geophysical case history of the Poplar Lake Copper-Molybdenum deposit, Houston Area, British Columbia. in Fink, J.B., McAlister, E.O., Sternberg, B.K., Wieduwilt, W.G. and Ward, S.H. (Eds), 1990, *Induced polarization : Applications and case histories : Investigations in Geophysics No. 4*, Soc. Expl. Geophys.
- Xu, B. and Noel, M. 1993. On the completeness of data sets with multielectrode systems for electrical resistivity survey. *Geophysical Prospecting* **41**, 791-801.

### 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 number 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 although speed is partly determined by the grid spacing and the magnitude of the measured resistances (Griffiths and Barker 1993). 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 and Bernstone 1997). Figure 7 shows an example of survey using a multi-electrode resistivity-meter system with 50 electrodes to survey a 10 by 10 grid.

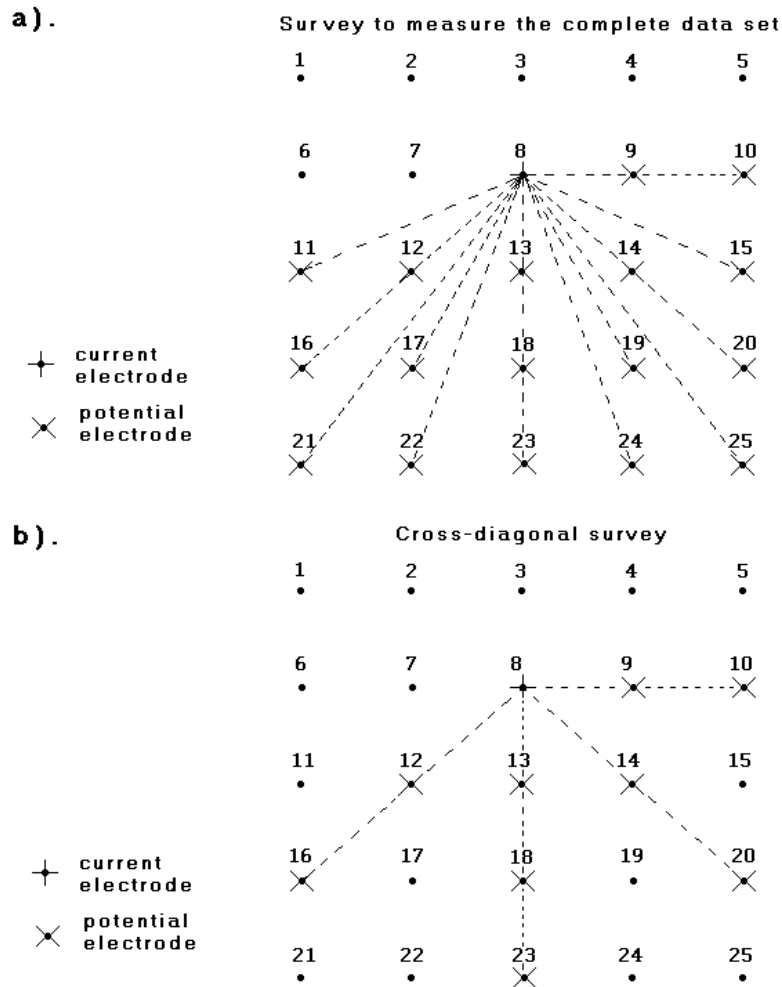


Figure 6. The location of potential electrodes corresponding to a single current electrode in the arrangement used by (a) a survey to measure the complete data set and (b) a cross-diagonal survey.

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 subgrid, all the possible measurements (including a limited number in the y-direction) for the pole-pole array was 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 datum points near the sides of the grid is kept to a minimum, and provides a 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 which 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 noise, between the two potential electrodes, this array is more sensitive to telluric noise.

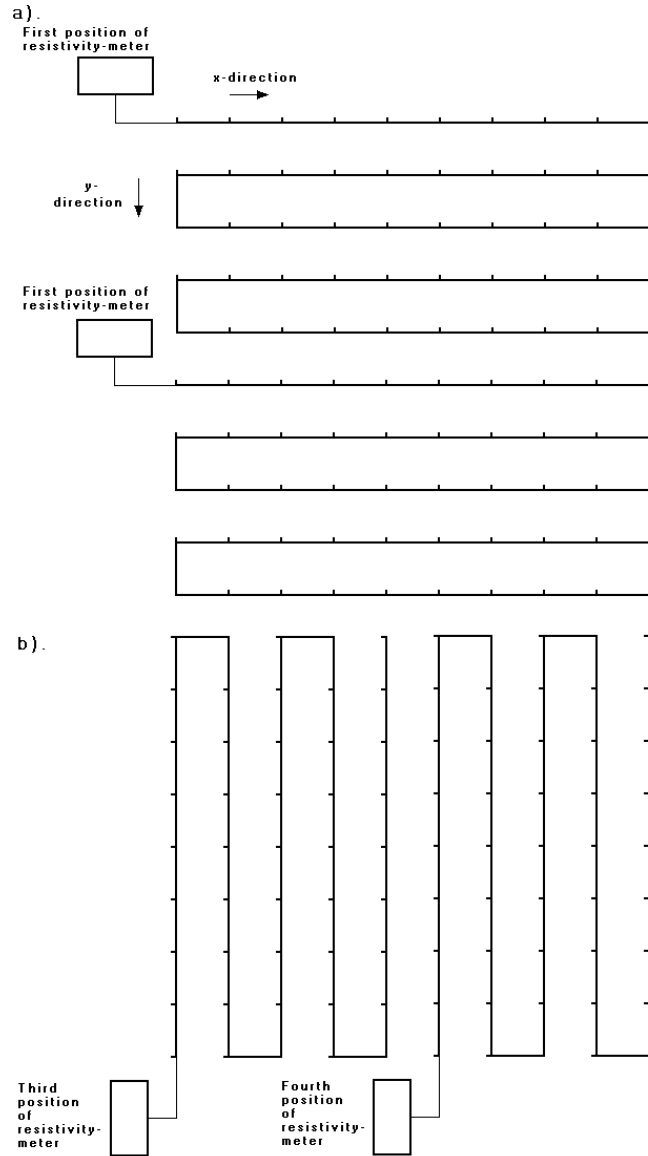


Figure 7. Using the roll-along method to survey a 10 by 10 grid with a resistivity-meter system with 50 electrodes. (a) Surveys using a 10 by 5 grid with the lines orientated in the x-direction. (b) Surveys with the lines orientated in the y-direction.

**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.

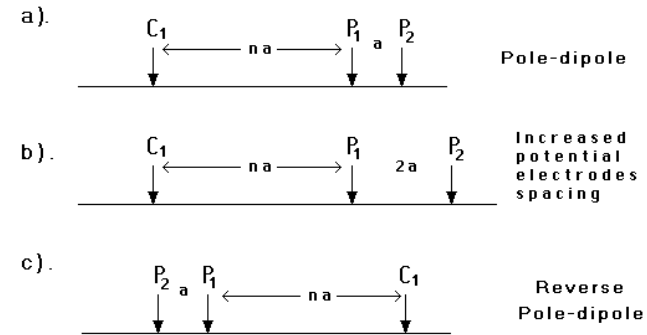


Figure 8. The arrangement of the electrodes for the pole-dipole array for measurements in the (a) “forward” direction, (b) with a larger spacing between the potential electrodes and (c) in the “reverse” direction.

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 P1 and P2 electrodes and  $n$  is the ratio of the distances between the C1 and P1 electrodes to the P1-P2 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	Title
10	x grid size
10	y grid size
1.00	x unit electrode spacing
1.00	y unit electrode spacing
6	array type, enter 6 for pole-dipole
1466	Number of data points
0.00 0.00 1.00 0.00 2.00 0.00 29.9669	For each data point, enter
0.00 0.00 2.00 0.00 3.00 0.00 30.0220	x- and y- location of C1 current elec.,
0.00 0.00 3.00 0.00 4.00 0.00 30.2216	x- and y-location of C2 current elec.,
0.00 0.00 4.00 0.00 5.00 0.00 30.3957	x- and y-location of P1 potential elec.,
0.00 0.00 5.00 0.00 6.00 0.00 30.4765	apparent resistivity value
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.

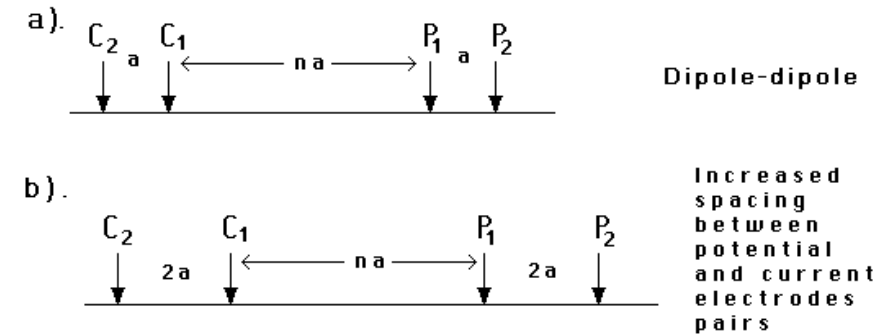


Figure 9. (a) The arrangement of the electrodes for the dipole-dipole array. (b) The use of a larger spacing between the C1-C2 (and P1-P2) electrodes to increase the signal strength.

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.

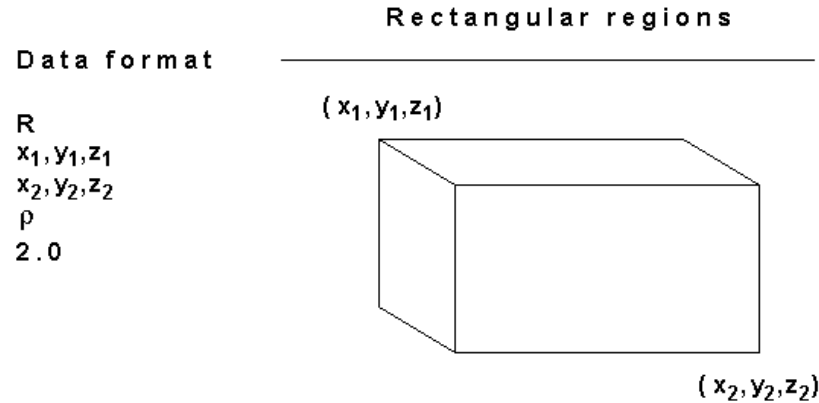


Figure 10 : Fixing the resistivity of a rectangular region of the inversion model.

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

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

where  $\rho_{DC}$  and  $\rho_{AC}$  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 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 electrodes (a survey with about 650 electrodes and nearly 5200 datum points now holds the record for land surveys) 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. For example, the SEPTIC.DAT data set shows a large high resistivity anomaly at the bottom-left edge of the grid (Figure 4). The data file SEPTICX.DAT has the same apparent resistivity measurements but it has been modified so as to add extra belts of models blocks at the sides. This is done by adding dummy electrodes outside the actual survey grid.

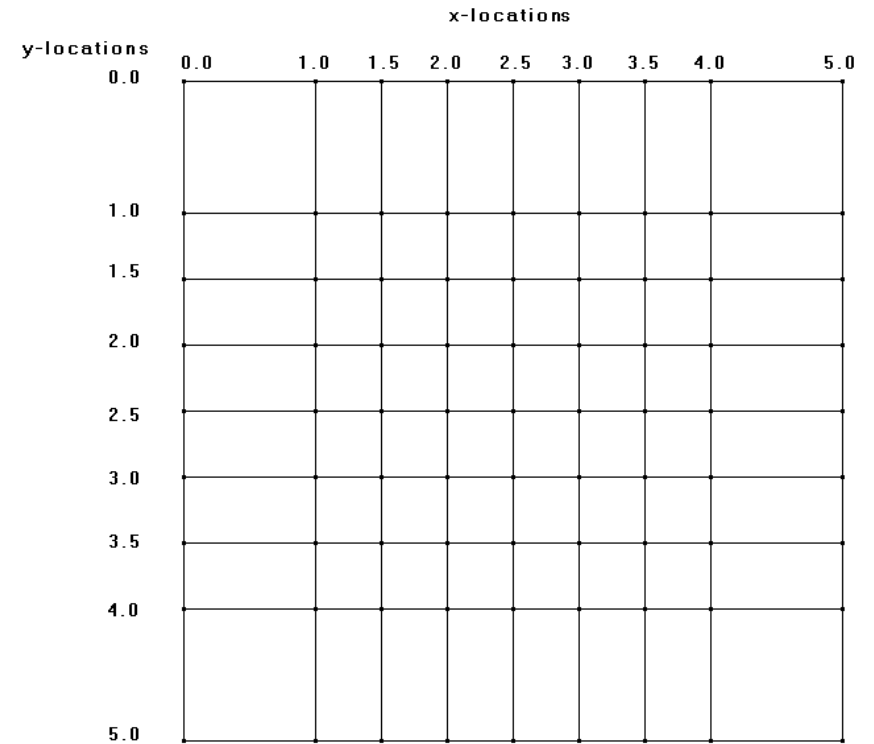


Figure 11. Arrangement of the survey grid lines in the data file NUGRID.DAT. Note the wider spacing at the sides.

### 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.

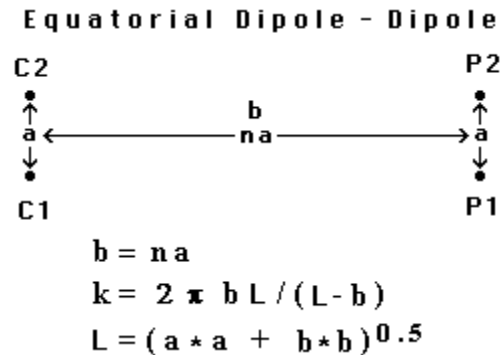


Figure 12. The arrangement of the electrodes and geometric factor “k” for the equatorial dipole-dipole or rectangular array.

This array has better resolution than the pole-pole array but a shallower depth of investigation. Like the inline dipole-dipole array it suffers from the problem of low signal strengths when the dipoles are far apart. The potential measured by the P1-P2 dipole is proportional to  $(L-b)/bL$ , so if the “b” distance between the two dipoles is much greater than the “a” dipole length, the signal strength drops rapidly. To obtain a deeper depth of investigation, the “a” distance has to be increased so that the “n” factor, i.e. the ratio of the “b” and “a” distances in Figure 12, does not exceed 6 (and preferably does not exceed 4).

The data file EQUADIP3.DAT gives an example of the data format for this array. Note that the array number is 8, and like the inline dipole-dipole array the x- and y-coordinates of the C1, C2, P1 and P2 electrodes are given.

### 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](http://www.rockware.com)) and the Slicer/Dicer program by Visualogic Inc. ([www.visualogic.com](http://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 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. The file SEPTIC.GM is an example output Slicer/Dicer generic metadata format file for the Septic tank (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 septic tank inversion model obtained with the Slicer/Dicer program. A similar Slicer/Dicer 3D display of the Sludge deposit model (section 13) is shown in section 3.6.3 of my free lecture notes "Electrical imaging surveys for environmental and engineering studies : *A practical guide to 2-D and 3-D surveys*" which is available in PDF format.



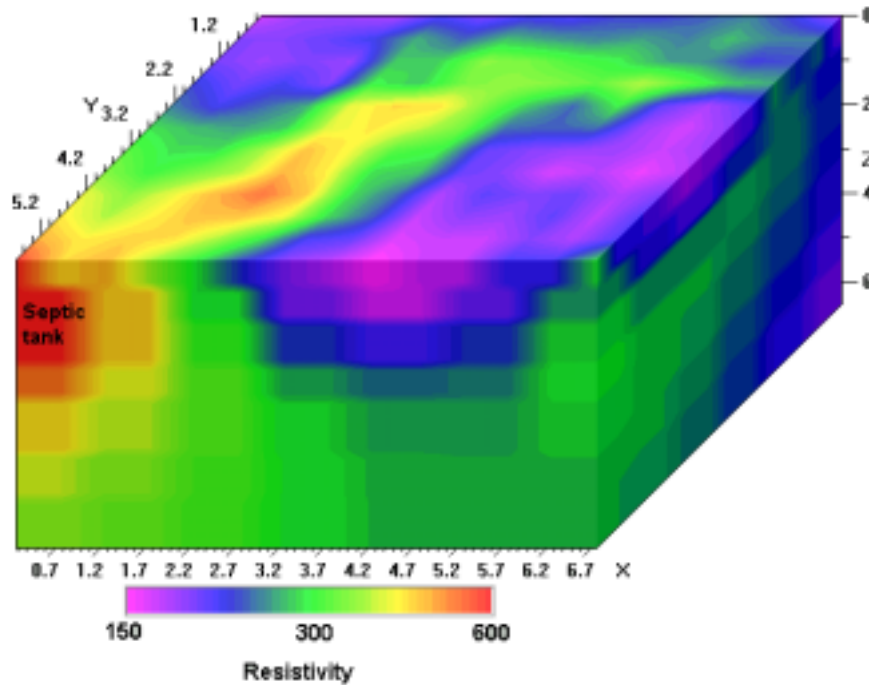


Figure 13. A 3D plot of the septic tank inversion model obtained with the Slicer/Dicer program. The septic tank appears as a high resistivity region at the upper left-front corner of the model. Note that the colour contour intervals are arranged in a logarithmic manner with respect to the resistivity.

### 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.

## 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 three months from the date of purchase to registered users. Registered users are entitled to free updates 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 RES2DINV 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@time.net.my  
support@geoelectrical.com

## 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.