

# **RES2DINV ver. 3.55**

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

## **Rapid 2-D Resistivity & IP inversion using the least-squares method**

Wenner ( $\alpha, \beta, \gamma$ ), dipole-dipole, inline pole-pole, pole-dipole, equatorial dipole-dipole, Wenner-Schlumberger and non-conventional arrays

*On land, underwater and cross-borehole surveys*

## **Goelectrical Imaging 2-D & 3D**

**GEOTOMO SOFTWARE**

**June 2005**

**This software is distributed by :**

**Geotomo Software,**

**5 Cangkat Minden Lorong 6,**

**Minden Heights, 11700 Gelugor,**

**Penang,**

**MALAYSIA**

**Tel : +60 4 6574525, Fax : +60 4 6588437**

**email : [geotomo@tm.net.my](mailto:geotomo@tm.net.my)**

**Internet : [www.goelectrical.com](http://www.goelectrical.com)**

## Table of Contents

	<b>Topic</b>	<b>Page No.</b>
1	Introduction	1
2	Computer system requirements and installation	3
3	Copy protection	7
4	Theory	7
5	Disc contents	9
6	Using the program	10
7	Data file operations and data format	11
8	Editing the data	16
9	Changing the program settings	19
10	Inversion options	25
11	Topographical modelling	33
12	Display the inversion results	36
13	Program settings	41
14	Help	41
15	Printing the pseudosections	41
16	Other useful programs	42
17	Pitfalls in 2-D inversion	43
18	Some field examples	45
19	Trouble shooting	49
	Acknowledgements	50
	References	51
	Appendix A : Dipole-dipole and pole-dipole surveys	54
	Appendix B : The Wenner-Schlumberger array	57
	Appendix C : Fixing Resistivities	59
	Appendix D : The Equatorial Dipole-Dipole array	61
	Appendix E : Underwater surveys	62
	Appendix F : IP data inversion	68
	Appendix G : New batch mode options	72
	Appendix H : Speed of graphics display	73
	Appendix I : Cross-borehole data inversion	74
	Appendix J : Remote electrodes	84
	Appendix K : Robust data and model inversion	88
	Appendix L : Non-conventional or general arrays	90
	Appendix M : Array types in RES2DINV	96
	Appendix N : Saving results in SURFER format	98
	Appendix O : Model refinement	101
	Appendix P : Combining 2-D files	104
	Appendix Q : Bedrock edge detection	108
	Appendix R : Time-lapse resistivity inversion	111
	Appendix S : Incorporating data noise estimates	119
	Appendix T : Incorporating boundaries of known layers	121
	Appendix U : Special topography information	

for mineral exploration	124
Appendix V : Plotting methods for the gradient array	125
Special OhmMapper Note	129
Disclaimer	130
Support	130

### **Notice of Copyright**

RES2DINV is copyrighted by © Geotomo Software, 2000-2004. All rights reserved. No part of this document may be reproduced without written permission of Geotomo Software.

## 1 Introduction

RES2DINV is a computer program that will automatically determine a two-dimensional (2-D) resistivity model for the subsurface for the data obtained from electrical imaging surveys (Griffiths and Barker 1993). Since it is a Windows based program, all Windows compatible graphics cards and printers are automatically supported. It has been tested with video screen modes of up to 1600 by 1200 pixels and 256 colours.

Figure 1 shows an example of the electrodes arrangement and measurement sequence that can be used for a 2-D electrical imaging survey. This program is designed to invert large data sets (with about 200 to 21000 data points) collected with a system with a large number of electrodes (about 25 to 16000 electrodes).

The 2-D model used by the inversion program, which consists of a number of rectangular blocks, is shown in Figure 2. The arrangement of the blocks is loosely tied to the distribution of the data points in the pseudosection. The distribution and size of the blocks is automatically generated by the program using the distribution of the data points as a rough guide. The depth of the bottom row of blocks is set to be approximately equal to the equivalent depth of investigation (Edwards 1977) of the data points with the largest electrode spacing. The survey is usually carried out with a system where the electrodes are arranged along a line with a constant spacing between adjacent electrodes. However, the program can also handle data sets with a non-uniform electrode spacing.

A forward modelling subroutine is used to calculate the apparent resistivity values, and a non-linear least-squares optimisation technique is used for the inversion routine (deGroot-Hedlin and Constable 1990, Loke and Barker 1996a). The program supports both the finite-difference and finite-element forward modelling techniques. This program can be used for surveys using the Wenner, pole-pole, dipole-dipole, pole-dipole, Wenner-Schlumberger and equatorial dipole-dipole (rectangular) arrays. In addition to these common arrays, the program even supports non-conventional arrays with an almost unlimited number of possible electrode configurations! You can process pseudosections with up to 16000 electrodes and 21000 data points at a single time on a computer with 1 GB RAM. The largest electrode spacing can be up to 36 times the smallest spacing used in a single data set. The program data limits will be extended in the future as larger field data sets are encountered.

Besides normal surveys carried out with the electrodes on the ground surface, the program also supports underwater and cross-borehole surveys!

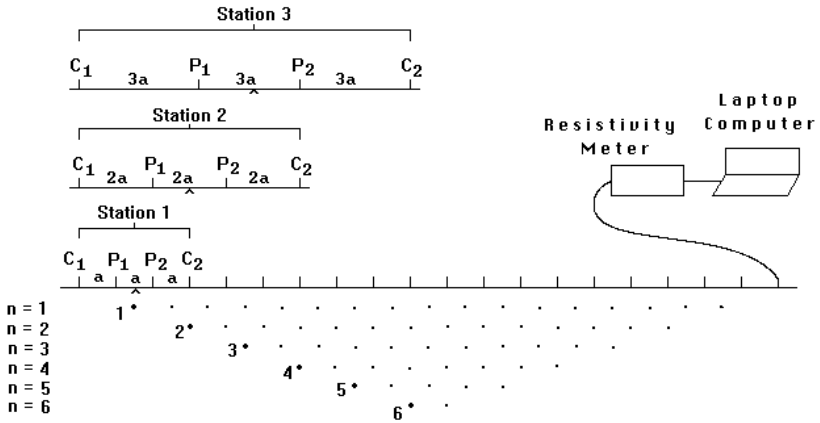
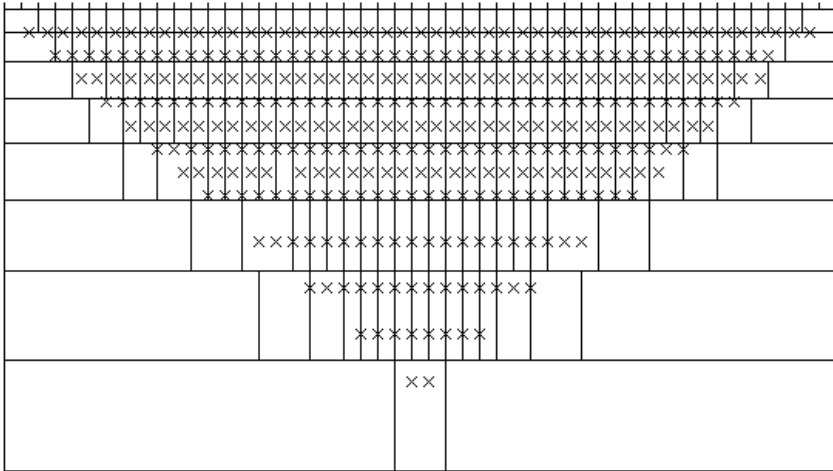


Figure 1. Sequence of measurements to build up a pseudosection using a computer controlled multi-electrode survey setup.

**ARRANGEMENT OF MODEL BLOCKS AND APPARENT RESISTIVITY DATUM POINTS**



□ MODEL BLOCK      × DATUM POINT

Figure 2. Arrangement of the blocks used in a model together with the data points in the pseudosection.

## 2 Computer system requirements and installation

This program is designed to run on IBM PC compatible microcomputers using the Windows 95/98/Me/2000/NT/XP operating systems. Due to the computational power required for the 2-D forward modelling and least-squares subroutines, it is written for 32-bit computer systems with at least 32 megabytes of RAM. On a Pentium computer, it will take a few minutes to invert the data set obtained from a survey with about 50 electrodes.

Minimum requirements : Hard disc with at least 64 megabytes free space, and motherboard with at least 32 megabytes RAM. SVGA colour graphics system with screen resolution of at least 800 by 600 pixels and 256 colours. Windows 95/98/2000/NT/XP operating system. Pentium, Pentium Pro, Pentium II, Pentium III or Pentium 4 CPU (or compatible CPUs).

However, it is recommended that you use it on a system with 64 (or more) megabytes of memory if you want to process very large data sets with more than 400 electrodes and 3000 data points. You should be able to process the largest example data set, DUFUYA.DAT that has 297 electrodes, on a system with 32 megabytes of RAM and 64 megabytes free hard disc space. However, it is recommended that your system has at least 128 megabytes free hard disc space. This is a 32-bit Windows program that can access up to 4 gigabytes of memory. The more RAM and free hard disc 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 and 19 inch monitors) or the 1280 by 1024 (for 21 inch monitors) with 256 colours SVGA graphics mode. You can change the graphics mode by clicking 'Start', and then 'Settings' followed by 'Control Panel' and then 'Display'. If you are using SVGA modes with 16-bit or 24-bit colours, please switch the display mode to 256 (i.e. 8-bit) colours if you encounter problems. Graphics operations with the 256 colours mode can be significantly faster, and more memory will be available to your programs. There should preferably not be too many background programs running before executing this program. The active background programs are usually shown on the 'Start' bar at the bottom of the screen. By shutting down the other programs, more memory will be available to this program. This will reduce memory to hard disc swapping that slows down the program.

The RES2DINV package comes in a single compressed installation file SETUP.EXE which is a Windows based installation program. To install the program, click Start, and then Settings followed by the Control Panel, and then Add/Remove Programs.

After installing the RES2DINV.EXE program, you should run the JACOBWIN.EXE program to create several support files. You only have to run the JACOBWIN.EXE program once after installing the RES2DINV program.

Practically all computers have an in-built power management system that 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 can interfere with the operation of the RES2DINV program if you are inverting a large data set since this program spends most of the time calculating using the CPU and coprocessor only. Windows also has an in-built screen saver functions which replaces the contents of the screen with a screen saver program. Before running the RES2DINV program, you will need to disable both the power management and screen saver programs. To disable them, 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.

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.

Before carrying out the inversion of a large data set with more than a thousand data points, please close down other active programs to free the system resources to RES2DINV alone. Also, using the "Set program priority" sub-option in the "File" option of the main menu, set the program priority to High or Highest to ensure that it is not interrupted by other programs while inverting the data set.

In Windows 95/98/Me/2000/NT/XP, it is necessary to install a system driver for the dongle.

a). **For users with the Rainbow Technologies Sentinel SuperPro key**  
Run the RainbowSSD5.39.2.exe file in the RAINBOW\_SYSTEM\_DRIVER subdirectory in the CDROM. This program will automatically install the system driver for the dongle. If you are using a Toshiba Laptop with the Win

XP operating system, there are special instructions together with a patch file Sentinel.sys in the Toshiba\_XP.zip file. After installing the driver, restart the computer for the driver to take effect. In case of problems, use the SuperProMedic.exe program to check the condition of the dongle. More information about the system drivers can be obtained at the following web site.

[www.rainbow.com](http://www.rainbow.com).

**b). For users with the Keylok key (parallel port or USB)**

Please run the INSTALL.EXE program in the KEYLOK\_SYSTEM\_DRIVER subdirectory for the Keylok drivers. This program will install the appropriate driver for your operating system into your computer hard-disk..

If you are using the **Keylok USB** key, please follow the steps below.

1). If the RES2DINV and RES3DINV software are already installed in your computer, you will need to replace the RES2DINV.EXE and RES3DINV.EXE files with the latest USB versions in the CD. You need to copy the RES2DINV.EXE and RES3DINV.EXE files from the Win\_Updates subdirectory to the appropriate folders in you computer (usually C:\RES2DINV and C:\RES3DINV).

2). If the RES2DINV and RES3DINV software have not yet been installed, run the SETUP.EXE files found in the RES2DINV and RES3DINV folders in the CD.

3). First, make sure that the USB dongle is not attached to the computer. You will now need to install the software driver for the Keylok dongle by running the INSTALL.EXE program in the KEYLOK\_SYSTEM\_DRIVER folder in the CD. Please note that in Windows NT/2000/XP you must have Administrator privileges in order to install the driver.

4). After installing the driver, switch off the computer and attach the USB dongle. It is recommended that you attach the USB dongle to the first USB port on the computer. Some older computer systems have trouble detecting it on the second USB port. Now switch on the computer. Windows will display a message saying that it has found a new hardware and it should then automatically copy the driver for the dongle.

5). Try running the RES2DINV and RES3DINV program, and they should be able to detect the dongle. If the programs still cannot detect the dongle, you will need to install the driver manually. Click the Control Panel under Settings, and then select the "Add New Hardware" option. Windows then searches for new Plug and Play devices. Click the "No the device isn't in the list" and then the "No I want to select the hardware from a list" options. Near the near bottom of hardware list, the "USB Dongle" will probably be displayed. Click it, and then the "Have Disk" option in the next dialog box. Then click "Browse" and change the folder to the KEYLOK\_SYSTEM\_DRIVER folder in the CD. A list of files with the ".inf" extension will then be displayed. For Windows



98/Me select the “usbkey98.inf” file, for Windows NT/2000/XP select the “Usbkey2K.inf” file. After that click “OK”, and a “Copying files” dialog box should be shown, and Windows should copy the drivers.

After copying the drivers, you need to restart the computer, and the RES2DINV/RES3DINV programs should then be able to detect the dongle.

More information about the system drivers can be obtained at the following web site : [www.keylok.com](http://www.keylok.com)

In Windows 95/98/2000/NT/XP, a Recycle Bin program is sometimes used to save recently deleted files. This feature might prove to be a nuisance when inverting very large data sets as the program uses a number of temporary files. Although the program deletes the files, they might end up in the Recycle Bin, and quickly fill up your hard disc! The RES2DINV program will, by default, use the hard disc drive 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, followed by 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.

### **3 Copy protection**

A hardware key (dongle) is supplied with the registered version of the program. Attach this key to the parallel printer port of your computer. You can attach the 25-pin connector of the printer to the other end of the key. The demonstration version of the program does not require a hardware key but some important features of the program cannot be used.

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 might 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 to confirm that the printer port is working. Leave the printer on, and then try to run the RES2DINV.EXE program again. If the program is not 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 using Windows NT, it is necessary to install a system driver for the dongle (please refer to previous section). If you are still not able to solve the problem, please contact the Rainbow Technologies or Keylok company by email.

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/Me/2000/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). 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

$u$  = 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. A detailed description of the different variations of the smoothness-constrained least-squares method can be found in the free tutorial notes by Loke (2001).

The program supports a new implementation of the least-squares method based on a quasi-Newton optimisation technique (Loke and Barker 1996a). This technique is more than 10 times faster than the conventional least-squares method for large data sets and requires less memory. You can also use the conventional Gauss-Newton method in this program. It is much slower than the quasi-Newton method, but in areas with large resistivity contrasts of greater than 10:1, it gives slightly better results. A third option in this program is to use the Gauss-Newton method for the first 2 or 3 iterations, after which the quasi-

Newton method is used. In many cases, this provides the best compromise (Loke and Dahlin 2002).

The 2-D model used by this program divides the subsurface into a number of rectangular blocks (Figure 2). The purpose of this program is to determine the resistivity of the rectangular blocks that will produce an apparent resistivity pseudosection that agrees with the actual measurements. For the Wenner and Schlumberger arrays, the thickness of the first layer of blocks is set at 0.5 times the electrode spacing. For the pole-pole, dipole-dipole and pole-dipole arrays, the thickness is set to about 0.9, 0.3 and 0.6 times the electrode spacing respectively. The thickness of each subsequent deeper layer is normally increased by 10% (or 25%). The depths of the layers can also be changed manually by the user.

The optimisation method basically 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 3rd and 5th iterations.

More information about the inversion method can be found in the free "Tutorial Notes" on electrical imaging (Tutorial : 2-D and 3-D electrical imaging surveys) that is available on the [www.geoelectrical.com](http://www.geoelectrical.com) web site.

## 5 Disc contents

The Res2dinv folder in the CD contains the main setup file SETUP.EXE. After installing this setup file, you should have the following files in the subdirectory containing the RES2DINV program.

RES2DINV.EXE	Main inversion program
JACOBWIN.EXE	Program to create some support files.
REGISTER.TXT	Registration file
LANDFILL.DAT	An example field data file for the Wenner array obtained by a survey with 50 electrodes. This example shows an interesting application of 2-D electrical imaging to map a pollution plume from a landfill site (Niederleithinger, 1994).
GRUNDFOR.DAT	Another field example for the Wenner array, but with a more irregular distribution of the data points.
ODARSLOV.DAT	A fairly large data set collected over a high resistivity dyke (Wenner array).
ROMO.DAT	Another fairly large data set (Wenner array).
DUFUYA.DAT	This is a large data set with nearly 300 electrodes and more than 1200 data points (Wenner array). On a 266 Mhz Pentium II it took about 23 minutes to invert this data set where the Jacobian matrix was recalculated after each iteration.
GLADOE2.DAT	An example data file with topographical information.
BLOCKWEN.DAT	Input test data file for Wenner array with a few bad data points.
BLOCKDIP.DAT	Example input data file for dipole-dipole array.
BLOCKTWO.DAT	Example input data file for pole-pole array.
RATHCRO.DAT	Wenner array data file from an archaeological survey which also contains topographical information.
PIPESCHL.DAT	Example field data set for the Wenner-Schlumberger array.
WATER.DAT	Example data file for an underwater survey.
MODEL101.DAT	A very large test data set for computer systems with at least 64 MB RAM.
DIPOLEN5.DAT	Example dipole-dipole data file with non-integer values for the "n" factor.
BLUERIDGE.DAT	Example dipole-dipole data set with different "a" and "n" combinations.
WENSCHN5.DAT	Example Wenner-Schlumberger data set with non-integer values for the "n" factor.
PDIPREV.DAT	Example pole-dipole data file with the "forward" and "reverse" arrangement of the electrodes.

POLDPIN5.DAT	Example pole-dipole data set with non-integer values for the “ $n$ ” factor.
OHMMAPPER.DAT	Example field data set from a mobile surveying system
KNIVSAS.DAT	Example data set using the gradient array
ITALY_CAVE.DAT	Example data set in general array data format but with the topography in a separate list
IPMODEL.DAT	IP with data set with chargeability values
IPSHAN.DAT	Field survey IP data set with PFE values
IPMAGUSI.DAT	Field survey IP data set with metal factor values.
IPKENN.DAT	Field survey IP data set with phase angle values
BOREHOLE.DAT	Example cross-borehole data set.
BOREHIP.DAT	Example cross-borehole data set with IP measurements.
BORELANC.DAT	Cross-borehole field data set.
BOREDIFF.DAT	Example cross-borehole data set where the electrodes in the two borehole are not at the same depths.
BORERES.DAT	Example cross-borehole data set with measurements given as resistance values.
BOREHOLE_TOPO.DAT	Example borehole data set with topography
RES2DINV.HLP	Help file for this program.
RES2DINV.CNT	A support file for the help file.
RES2DINV.INI	Configuration file for the RES2DINV program.
RES2DINV.IN2	Alternative configuration file.
README.TXT	Latest information about the current version of the 2-D inversion program.
RESIS.BTH	Example file for the batch processing mode option

## 6 Using the program

After running the SETUP.EXE installation program, and the JACOBWIN.EXE program, the main program RES2DINV.EXE and the support files (GRADWEN, GRADTWO and GRADDIP) and example data files should be in the same subdirectory in the hard disc. Please check the condition of the hard disc using the CHKDSK and SCANDISK programs, or similar programs in software utility packages such as Norton Utilities.

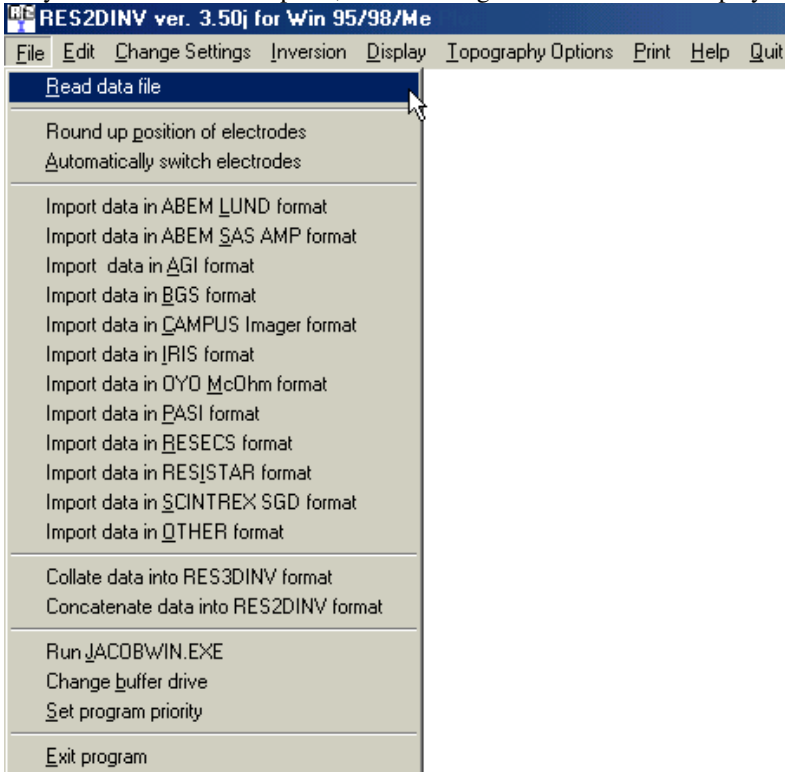
To run the resistivity inversion program, click the RES2DINV icon. The program will first check the computer system to ensure that it has the necessary resources that this program requires. It will check for the available memory and hard disc space. If the program displays a warning, you should quit 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 the resistivity data file LANDFILL.DAT provided with the program. Then select the inversion option to carry out an inversion of the data set. Figure 3 shows an example of the results from the inversion of this data set. After reading a data set, you should generally check for bad data points using the “Edit data” option. In the following sections, a more detailed description of each item in the above menu is given.

## 7 Data file operations and data format

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 that has an extension of .DAT will be displayed. 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 a 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 was arranged in a wrong format. An example of an input data set is given in the file LANDFILL.DAT. The initial section of this file with a description of the data format is given in the 'Comments' section below.

<u>LANDFILL.DAT file</u>	<u>Comments</u>
LANDFILL SURVEY	Line 1- Name of survey line
3.0	Line 2 - Smallest electrode spacing
1	Line 3 - Array type (Wenner = 1, Pole-pole = 2,  Dipole-dipole = 3, Pole-dipole = 6, Schlumberger = 7  Equatorial dipole- dipole - 8 )
334	Line 4 - Total number of data points
1	Line 5 - Type of x-location for data points.  Enter 0 if location of first electrode in array used to  indicate the x-location. Enter 1 if mid-point of the  array (i.e. location of data point in pseudosection)  is used.
0	Line 6 - Flag for IP data (enter 0 for resistivity data  only)
4.50 3.0 84.9	Line 7 - The x-location, electrode spacing and  measured apparent resistivity value for the first  data point.
7.50 3.0 62.8	Line 8 - The x-location, electrode spacing and  measured apparent resistivity value for the second  data point.

Subsequent lines give similar information for the other data points. This is followed by four 0's that are reserved flags for other features.

Subsequent lines give similar information for the other data points. This is followed by four 0's that are reserved flags for other features.

The **dipole-dipole**, **pole-dipole** and **Schlumberger** array data sets have a slightly different format since an extra parameter, the dipole separation factor, is needed. Please refer to **Appendices A** and **B** for a description of the data formats for these arrays. The file DIPOLEN5.DAT is an example data set for the dipole-dipole array.

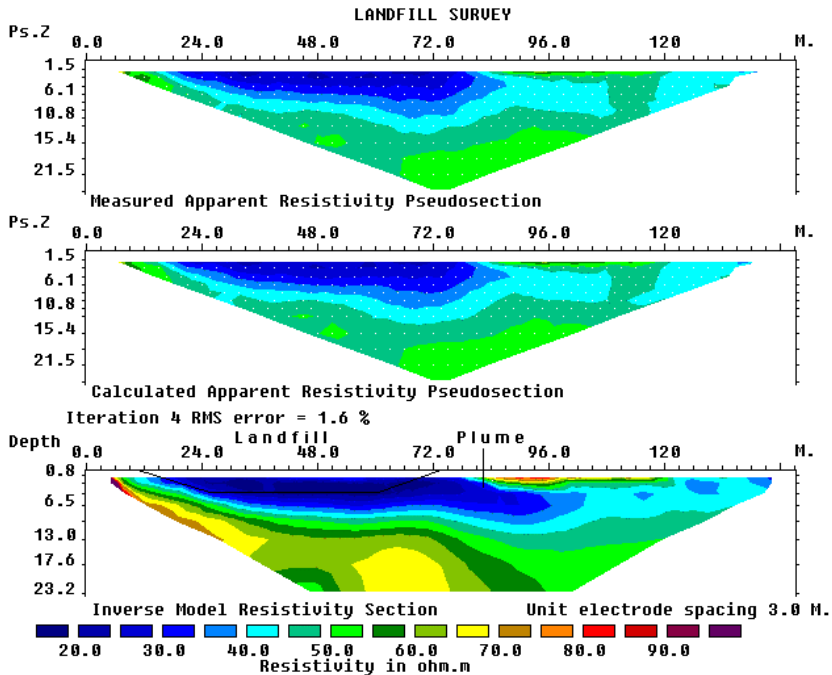


Figure 3 : The observed and calculated apparent resistivity pseudosection for the LANDFILL.DAT data set together with a model obtained by the inversion program.

Note that the program assumes that the x-location of the data points increases from the left to the right side of the pseudosection. If the x-locations in your data set are arranged in the other way, the pseudosection will appear to have undergone a left-to-right reversal when displayed on the screen!

The file GLADOE2.DAT is an example with topographical data. The bottom section of this file with a description of the format for topographical data is as follows :-

<u>GLADOE2.DAT file</u>	<u>Comments</u>
237 2 39.207	Last four data points
203 2 14.546	with x-location of the data point,
227 2 31.793	electrode spacing and
233 2 30.285	measured apparent resistivity values
2	Topography data flag. If no topography data, place 0 here.
26	Number of topography data points
-100 33	Horizontal and vertical coordinates of 1st,
-40 34.5	2nd topography data point



-20 35.0	This is followed by similar data for
0 35.209	the remaining topography data points
10 34.904	
20 33.678	
30 32.264	
40 31.191	
50 30.560	
60 29.905	
70 29.200	
80 28.774	
90 28.569	
100 28.473	
110 28.553	
120 28.462	
130 28.486	
140 28.601	
150 28.652	
160 28.825	
170 28.996	
180 29.284	
190 29.643	
200 29.563	
270 30.0	
300 33	Last topography data point
2	The topography data point number with the first electrode
0	Enter four 0s at the
0	end of the file
0	
0	

Note that the topography data is placed immediately after the apparent resistivity data points. The first item is a flag to indicate whether the file contains topography data. If there is no topography data, its value is 0. Enter 1 or 2 if topographical data is present. In the case where the actual horizontal and vertical coordinates of points along the survey line are given, enter 1. Even if the actual horizontal distances are given in the topography data section, you must still use the x-distance along the ground surface in the apparent resistivity data section. In most surveys the distances of the points along the ground surface, and not true horizontal distances, are actually measured with a tape. In this case, enter a value of 2 for the topography data flag. This is followed by the number of topographical data points.

It is not necessary to measure the elevation for each electrode. For example, the data in the GLADOE2.DAT file involves 161 electrodes but only the

elevations at 26 points are given. The maximum number of topographical data points you can have is 500. For each data point, the horizontal location and the elevation is entered into the data file. After the last topographical data point, the number of the topographical data point where the first electrode is located is given. In the above example, the first electrode was located at -40 metres, which corresponds to the 2nd topographical data point. Note that the elevation of the first electrode is required. If this was not measured in the field, you can estimate it from the elevations of the neighbouring data points. For data sets with IP measurements as well, please refer to Appendix F.

One common problem encountered in using this program is mistakes in the input data file. If the program stops with an error message it could be due to a mistake in the input data file. First check that the data in the file is arranged according to the format described above. The program will try to detect common mistakes, such zero or negative apparent resistivity values, but there might be some new exotic mistakes that the current version of this program cannot detect. Other possible problems are discussed in the "Pitfalls in 2-D inversion" section of this manual.

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 multielectrode resistivity meter system you are using.

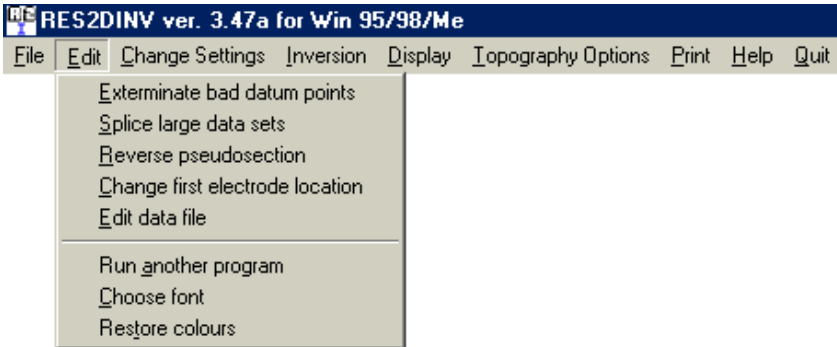
Collate data into RES3DINV format – Please refer to Appendix P for the details.

Run JACOBWIN program - This is a utility program that generates a number of support file required by the RES2DINV program. You should run this program after installing the RES2DINV program. You only need to run the JACOBWIN program once.

Change buffer drive - The program will automatically use the hard disc drive with the largest amount of free disc space as the buffer drive to store temporary files which it uses while inverting a data set. This option allows you to change the buffer drive used by the program.

## 8 Editing the data

This option enables you to make some changes to the data you have read from the input data file described in the previous option. It will enable you to remove bad data points, and to select a portion of the data set to invert for very large data sets. When you select this option, the following submenu will be displayed:

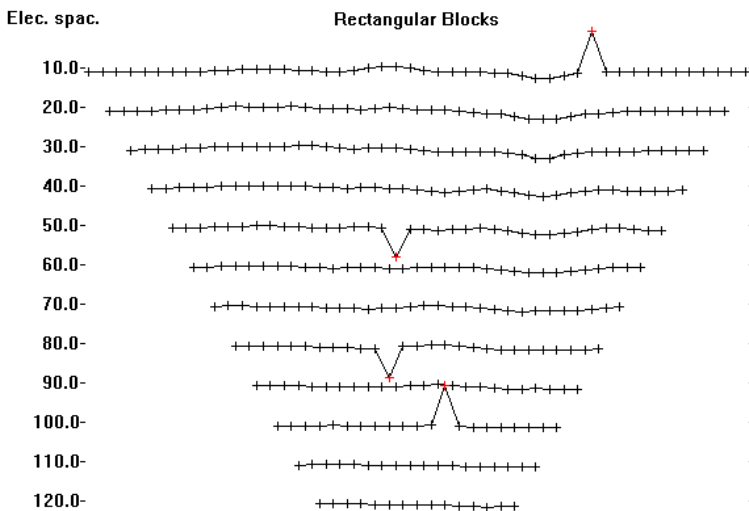


**Exterminate bad datum points** - In this option, the apparent resistivity data values are displayed in the form of profiles for each data level. You can use the mouse to remove any bad data point. The main purpose of this option is to remove data points that have resistivity values which are clearly wrong. Such bad data points could be due to the failure of the relays at one of the electrodes, poor electrode ground contact due to dry soil, or shorting across the cables due to very wet ground conditions. These bad data points usually have apparent resistivity values that are obviously too large or too small compared to the neighboring data points. The best way to handle such bad points is to drop them so that they do not influence the model obtained. Figure 4 shows an example of a data set with a few bad points. To remove a bad data point, move the cross-shaped cursor with the mouse to the data point and click the left mouse button. The colour of the data point should change from black to purple. If you click the same data point again, it will not be removed from the data set. To quit from this option, just press the **Q** key or click the Exit option.

**Splice large data set** - This option enables you to choose a section of the full data set (which is too large to be processed at a single time) to invert. After choosing this option, the distribution of the data points in a pseudosection will be displayed. You can select a section of the data set to invert by using the arrow keys. Full instructions on the keys to use are displayed on the screen. The data points selected will be marked by purple crosses or dots, whereas the remaining data points are black. At the top of the display, the left and right limits of the section selected are marked by yellow vertical lines. If there are

too many data points in the lower levels, you can reduce the number of data points by selecting only odd or even points in a level. To do this, move the horizontal yellow marker on the left side of the display up or down to the level you want to decimate using the up and down arrow keys. Then press D to decimate the data points in that level. The program allows you to read in a file which involves up to 15000 electrodes. Using this option, you can select a section of the data set (which covers up to a maximum of 500 electrodes and 8000 data points for a system with 64 megabytes RAM) to invert. The entire data set can then be inverted by inverting successive subsections of the data set. After selecting the data set subsection you want invert, you should select the "Exterminate bad data points" option to check for bad data points. In general, it is recommended that you try to invert the entire data set at one go. In most cases, this can be easily done by adding more RAM and free hard disc space to your computer.

Reverse pseudosection - This option flips the pseudosection horizontally from left to right. This is helpful when you have parallel survey lines but the surveys were started from different ends.



+ Measured data + Removed data

Figure 4 : Example of a data set with a few bad data points. The data is displayed using the "Exterminate bad data points" option.

Change location of first electrode - This allows you to change the location of the first electrode in the survey line. It is basically intended for plotting

purposes, so that overlapping survey lines have the same  $x$ -locations for electrodes which coincide.

Edit data file - When you select this option, the text editor (by default NOTEPAD) will start up. To return to the RES2DINV program, you must first exit from the text editor program.

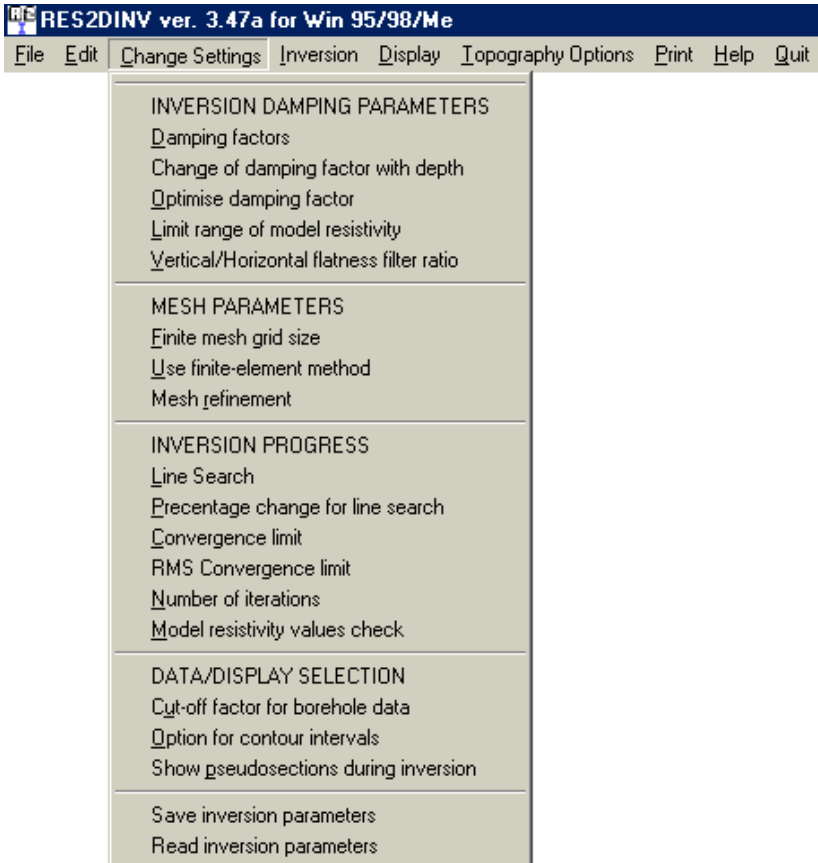
Run another program - This option enables you to run another program. It is mainly intended for cases where the program had not been installed and thus not in the list of programs recorded in the Windows Start and Program option.

Choose font - In this option, you can choose the type of font used by the program when it draws the pseudosections. The default font is an Arial font. The other choice is the system font. With the default Arial font the program should be able to fit everything into the screen when drawing the pseudosections, even with the 800x600 graphics mode. The system font usually has bolder characters when might be better when making printouts of the images. It is recommended that you use the 1024x768 or higher resolution graphics mode when you use the system font.

Restore colours - This option restores the default colour scheme used by the program.

## 9. Changing the program settings

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



To change a particular setting, move the mouse cursor to the appropriate line and then just click it. A message will then appear which gives some information about the values you can use, and the type of information you need to enter.

## INVERSION DAMPING PARAMETERS

The following options modify the use of the damping factor  $u$  in equation (1).

Damping factors - In this option, 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 be set to about one-fifth the value of the initial damping factor.

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

Optimise damping factor - If you select this option, the program will attempt to find the optimum damping factor  $u$  in equation (1) that 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 1000 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). In practice, the improvement in the results by optimising the damping factor for most data sets is rather small.

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

**Limit range of model resistivity values**

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

Do not limit resistivity values  
 Limit range of resistivity values

Enter upper limit factor   
 Enter lower limit factor

Use average resistivity  
 Use first iteration resistivity

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

Vertical to horizontal flatness filter ratio - You can select the ratio of the damping factor for the vertical flatness filter ( $f_z$ ) to the horizontal flatness filter ( $f_x$ ). By default, the same damping factor is used for both. However, if the anomalies in the pseudosection are elongated vertically, you can force the program to produce models that are also elongated vertically by selecting a higher value (for example 2.0) for the ratio of the vertical to horizontal flatness filter. For anomalies that are elongated horizontally, choose a smaller value (e.g. 0.5).

## MESH PARAMETERS

These set of options change the finite-difference or finite-element mesh used in the forward modelling subroutine.

Finite mesh grid size - You can choose a mesh grid used by the forward modelling program to have 2 or 4 nodes between adjacent electrodes. With 4 nodes per electrode spacing, the calculated apparent resistivity values would be more accurate (particularly for large resistivity contrasts). However, the computer time and memory required are correspondingly larger. By default, the



program will use the 2 nodes option if the data set involves more than 90 electrodes.

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.

Mesh refinement - This option allows you to use a finer mesh (in the vertical direction) for the finite-difference or finite-element method. The apparent resistivity values calculated by either method will be more accurate with a finer mesh, but the computer time and memory required will be greater. The use of a finer mesh can give better results for cases where subsurface resistivity contrasts of greater than 20:1 is expected. This is particularly useful in areas where a low resistivity layer lies below a high resistivity layer.

## INVERSION PROGRESS

The following set of options control the path the inversion subroutine takes during the inversion of a data set.

Line search - 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. One option is to perform a line search using quartic interpolation to find the optimum step size for the change in the resistivity of the model blocks. The program will attempt to reduce the RMS error, but it can also be trapped in a local minimum. The alternative is to ignore the increase in the RMS error, and hope that the next iteration will lead to a smaller RMS error. This might enable you to jump out of a local minimum, but it could also lead a further increase in the RMS error. A third alternative is to perform a line search at each iteration. This will usually give the optimum step size, but will require at least one forward computation per iteration. In some cases, the extra forward computations could be worthwhile if it reduces the number of iterations needed to bring the RMS error down to an acceptable level. To select a particular setting, just click the appropriate button. This setting will only affect the inversion process for the third iteration onwards. For the first two iterations, where the largest changes in the RMS error usually occurs, the program will always carry out a line search to find the optimum step size to further reduce the RMS error.

Percentage 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.

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.

RMS convergence limit – This sets the percentage RMS error in the inversion of the apparent resistivity data where the program will stop after the model produce has an RMS error less than this limit. Normally a value of between 2% and 5% should be used, depending on the quality of the data.

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 5. 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.

Model resistivity values check - The program will display a warning if after an iteration in the inversion of the data set, a model resistivity value becomes too large (more than 20 times the maximum apparent resistivity value) or too small (less than 1/20 the minimum apparent resistivity value). This option allows you to disable the warning.

## DATA/DISPLAY SELECTION

Minor options for pre-processing of data files and display of the sections during the inversion.

Cutoff limit for borehole resistance readings - In cross-borehole measurements, certain combinations of the current and potential electrodes could result in extremely low potential values. This could result in readings with very low signal to noise ratios. To filter out such potentially noisy readings, the program estimates the potential per a unit input current, that would be measured by each electrode configuration used in the data set. If the estimated potential falls below a certain limit, compared with the combination which gives the maximum potential, the reading is rejected. For example, if you choose a value of 0.001, this means configurations which will result in potential values that are a thousand times smaller than the maximum potential measured will be rejected. Normally a value of between 0.008 and 0.0007 is used. The program also allows you to enter the measurements as resistance values, and carry out the inversion with the resistance (rather than apparent resistivity) values. In this

case, the cutoff limit option is not used. For more details, please refer to Appendix I.

Option for contour intervals - By default, the program will use logarithmic contour intervals for the pseudosections and model sections when displaying the results in the “Inversion” option in the Main Menu. This is usually the best choice for most data sets. However, you can choose to use the linear or the user defined contour intervals options if you wish.

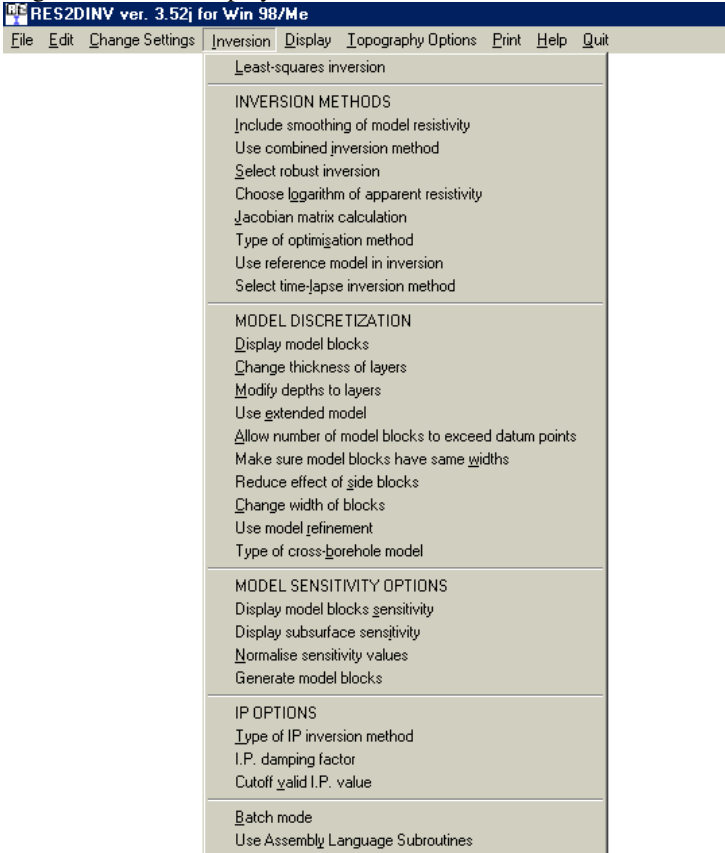
Show pseudosections during inversion - You can choose to display the pseudosections during the data inversion, or just display the model RMS values. It is recommended that you display the sections unless the Windows driver for your graphics card is extremely slow. In the long run, it is recommended that you download a new version of the Windows driver.

Save inversion parameters – This option saves the inversion parameters into a file RES2DINV.IVP.

Read inversion parameters –This option reads back the parameters stored in the RES2DINV.IVP files and uses them in the program. RES2DINV\_NEW.IVP is an example file that contains more inversion parameters. These files can also be used by the ‘Batch mode’ option. Please refer to Appendix G for the new format for the ‘Batch mode’ script file.

## 10. Inversion options

This option enables you to carry out the inversion of the data set that you had read in using the "File" option. You can also display the arrangement of the blocks used by the inversion model, as well as to change some of the parameters that control the inversion process. On selecting this option the following menu will be displayed.



**Least-squares 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, and the contour intervals for the pseudosections if you had chosen the user defined option for the contour intervals. You can stop the inversion by pressing the Q key, and then wait for a short while.

### INVERSION METHODS

These set of options allow you to select the type of regularised inversion method to use.

Include smoothing of model resistivity values - 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.

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

Select robust inversion – This allows you to select the robust or blocky inversion method. It should be used when sharp boundaries are expected to be present. Please refer to Appendix K for further details.

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

Jacobian matrix calculation - In this program you have three options in the calculation of the Jacobian matrix  $\mathbf{J}$  in equation (1). The fastest method is to use the quasi-Newton method to estimate the Jacobian matrix (Loke and Barker 1996a). 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 for all iterations. This requires a fast computer with preferably at least 32 megabytes of RAM, and about 64 megabytes free hard disc space for very large data sets. A third alternative is to recalculate the Jacobian matrix for the first 2 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 choose the limited recalculation option for the Jacobian matrix. 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. 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 for all iterations produces models with boundaries which are a shade sharper than those produced by the quasi-Newton method.

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.

**Type of optimisation method**

Please select one of the following optimisation methods. The Incomplete Gauss-Newton method is recommended for data sets with more than 2000 data points where it can greatly reduce the computer time required for the inversion.

Standard Gauss-Newton     Incomplete Gauss-Newton

Enter convergence limit for the Incomplete Gauss-Newton method. A value of between 0.001 and 0.01 (i.e. 0.1 to 1% accuracy) is normally used.

The data compression option can significantly reduce the computer memory required for very large data sets. It is used together with the Incomplete Gauss-Newton method. Use data compression method with the Incomplete Gauss-Newton method to reduce computer memory required?

No     Yes

Do you want the program to automatically use sparse inversion techniques? This is recommended for very long data sets with more than 2000 electrodes. This method will only be used together with the above data compression method.

No     Yes

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 2000), 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 0.5% (i.e. a convergence limit of 0.005 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 0.1%, will in theory give a result that is even closer to the ‘Standard Gauss-Newton’ method but this is at the expense of a longer inversion time. For very large data sets and models (usually over 10000 data points/model cells), a “data compression” option is provided with the ‘Incomplete Gauss-Newton’ method. This can significantly reduce the computer memory required.

For data sets from very long survey lines (over 2000 electrode positions), a “sparse inversion” option is provided that can greatly reduce the computer time and memory required. For example, the inversion of an underwater survey data set with nearly 7500 electrode positions was reduced by a factor of 10 (to about 101 minutes hours on a 3.2GHz P4 computer) with the sparse inversion option. This method inverts the entire data set and model at a single time to produce a continuous and seamless model.

## MODEL DISCRETIZATION

These option allows you to modify the way the program subdivides the subsurface into cells that is used as the inversion model.

Display model blocks - This option will display the distribution of the model blocks and data points. The data points will be plotted at the median depth of investigation (Edwards 1977) for the array used. The program has a maximum limit of 24 model layers. If you had chosen the 10% option for the increase in the layers thickness, and the bottom layer is above the bottom row of data points, you should change to the 25% option.

Change thickness of layers - In this option you can choose a model where the thickness of the layers increase by 10% or by 25% with each deeper layer. Choose the 10% option if there are only a small number (8 or less) of data levels. If there are a large number of sparse data levels, the 25% option might be better. Within this option, you can also allow the number of model blocks to exceed the number of data points. The program normally uses a model where the depth to the deepest layer does not exceed the maximum pseudodepth in the data set. To use a model that spans a deeper depth range, you can change the factor to increase model depth range, for eg. from 1.0 to 1.30 to increase the model depth range by 30%.

Modify depths to layers - This option allows you to change the depth of the layers used by the inversion model. You can adjust the depths so that some of the boundaries coincide with known depths from borehole and other data.

Use extended model – This option extends the model cells to the edges of the survey line (Figure 5c).

Allow number of model blocks to exceed datum points - By default, the program will try to arrange the position and size of the model cells such that they do not exceed the number of data points. This is probably the best option for large and medium size data sets collected with more than about 50 electrodes, particularly where the distribution of the data points with the larger spacings is more sparse. In some cases, the width of the model cells in the lower layers might be larger than those in the upper layers. However, for smaller data sets, it might be useful to relax this constraint, and allow the number of model parameters to exceed the number of data points. This will produce a model where the interior cells in all layers have a uniform width that is equal to the smallest electrode spacing (Figure 5b).

Make sure model blocks have same widths –The model shown in Figure 5b have model cells that are wider at the edges. This option will ensure that all the cells have the same width that is equal to the unit electrode spacing.

Reduce effect of side blocks – This option affects the calculation of the Jacobian matrix values for the model blocks located at the sides and bottom of the model section. Normally, for a block located at the side, the contributions by all the mesh elements associated with the model block are added up right to the edge of the mesh. This gives a greater weight to the side block compared to the interior blocks. In some cases, particularly when the robust inversion option is used, this can result in unusually a high or low resistivity value for the side block. This option leaves out the contribution of the mesh elements outside the limits of the survey line to the Jacobian matrix values for the side blocks.

Change width of blocks – This option allows the user to force the program to use model cells which are wider than one unit electrode spacing for all the layers.

Use model refinement – Please refer to Appendix P for the details.

Type of cross-borehole model - There are two choices for the type of model you can use for the inversion of cross-borehole data. You can choose to use the Standard Model where the dimensions of the model blocks are the same as the spacing between the electrodes on the ground surface and in the boreholes. Alternatively, you can use a model with smaller blocks where the size of the blocks is half that of the Standard Model (see Figure 20 in Appendix I).



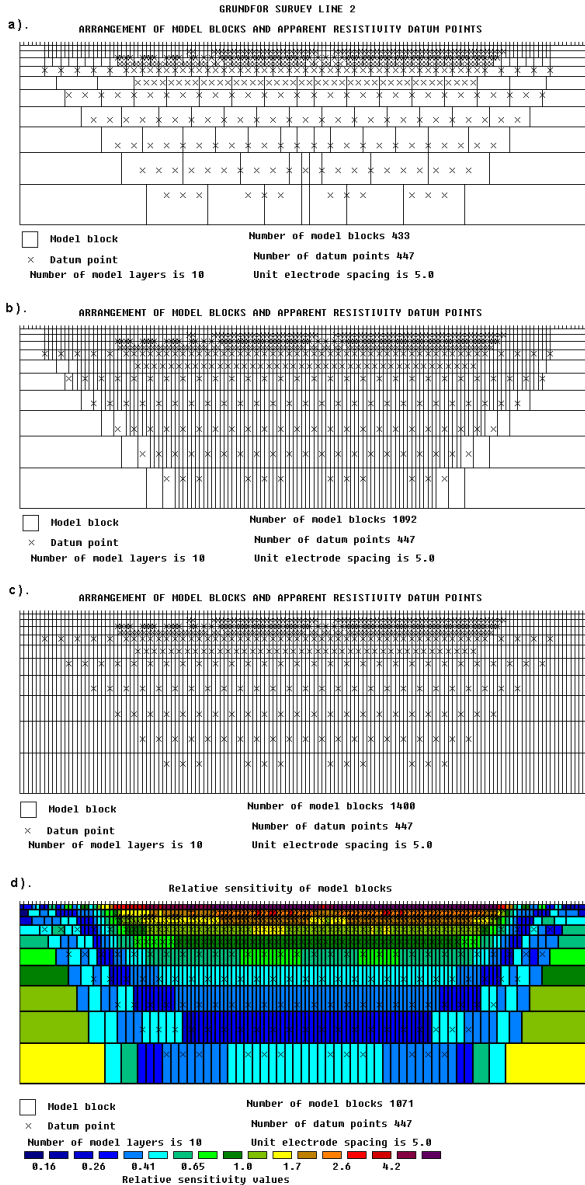


Figure 5. Different methods to subdivide the subsurface into 2-D rectangular cells. Models obtained with (a) the default algorithm, (b) by allowing the number of model blocks to exceed the number of data points, (c) a model which extends to the edges of the survey line and (d) using the sensitivity values for a homogeneous earth model.

## MODEL SENSITIVITY OPTIONS

**Display blocks sensitivity** - This will show a plot of the sensitivity of the blocks used in the inversion model. The sensitivity value is a measure of the amount of information about the resistivity of a model block contained in the measured data set. The higher the sensitivity value, the more reliable is the model resistivity value. In general, the blocks near the surface usually have higher sensitivity values because the sensitivity function has very large values near the electrodes. The blocks at the sides and bottom also have high sensitivity values due to the much larger size of these blocks that are extended to the edges of the finite-difference or finite-element mesh. If you had carried out an inversion of the data set before calling this option, the program will make use of the Jacobian matrix of the last iteration. Otherwise, it will calculate the Jacobian matrix for a homogenous earth model.

**Display subsurface sensitivity** - This shows a plot of the sensitivity of the subsurface for blocks of equal size. This basically eliminates the effect of changes in the model block size so that it shows more clearly the change of the subsurface sensitivity with depth and location.

**Normalise sensitivity values** – By default, the calculated sensitivity values are normalised by dividing with the average sensitivity value. In this option, you can choose not to normalise the sensitivity values.

**Generate model blocks** – This option generates the model cells by making use of the model sensitivity values. Please refer to Appendix L for a description of this option.

## IP OPTIONS

**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.

**Batch mode** - In this option, you can invert a number of data sets automatically. The name of the input data files, and other information, is provided through a file. It must be emphasised that before inverting the data sets, you should check the data for bad data points using the **Edit Data** option discussed earlier. When

you select the batch mode suboption, you will first be asked for the name of the data file containing the information required. An example file provided is RESIS.BTH which enables the inversion of 3 data sets using the batch mode. The format of this file is as follows :-

*Line 1* - Number of data files to process.

*Lines 2 to 16* - This contains the information for the first data file in the following format. The corresponding values used in the example RESIS.BTH for the first data file is also listed below to help clarify matters.

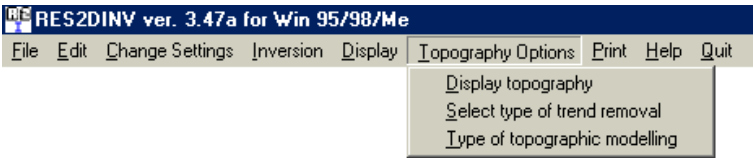
<u>Type of information</u>	<u>Value in RESIS.BTH</u>
Header	DATA FILE 1
Name of input data file	RATHCRO.DAT
Name of output data file	RATHCRO.INV
Starting damping factor	0.15
Minimum damping factor	0.03
Line Search option to be used	ALWAYS
Convergence limit	5.0
Percentage change for line search	0.4
Number of iterations	6
Vertical/Horizontal flatness filter ratio	1.00
Thickness of model layers increase	10
Finite-difference grid size	4
Include smoothing of model resistivity	NO
Reduce number of topographical datum points	YES
Carry out topographical correction	YES
Type of linear trend to remove	END-TO-END
Type of Jacobian matrix calculation	LIMITED RECALCULATION

If you do not wish to carry out the topographical corrections, just enter “No” at the appropriate line. To remove a linear least-squares or average trend, enter Linear or Average in the file. Even if the data set does not contain topographical data, you still must enter the topographical processing information. Although in this case the topographical processing information will be ignored by the program, you must still type in something at the appropriate lines or else the program cannot read in the parameters for the following data files in the correct sequence. The other options for the type of Jacobian matrix calculation are “Quasi-Newton” and “Recalculate”. The information for the other data files to be processed follow the same format. Please refer to the example file RESIS.BTH. An example of an extended batch file that includes more inversion parameters is the file RESIS\_NEW.BTH.

A new ‘Batch mode’ script file format is also described in Appendix G which makes use of the IVP files that are created by the RES2DINV program. It is easier to use since the user does not need to deal with the details about the format of file containing the inversion parameters.

## 11. Topographical modelling

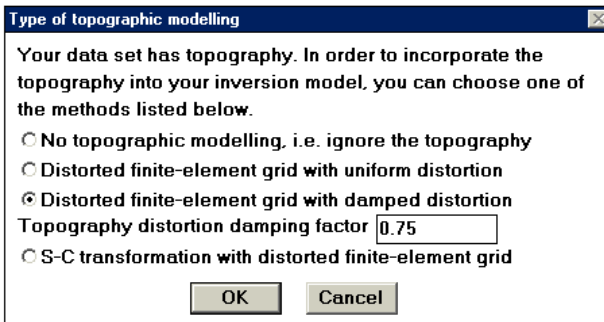
If there is significant topographical relief along the survey line, the effect of the topographical effects can be accounted for if the horizontal and vertical coordinates of a number of points along the survey line are known. When the program reads in a data file with topography data (please refer to section 7 for the data format), it will automatically select the finite-element method that incorporates the topography into the modelling mesh used. In this case, the topographic modelling will be automatically carried out by the program when you invert the data set. When you select the “Topography Option” menu, the following submenu will be displayed:



**Display topography** - This option simply plots the topography, such as in Figure 6.

**Select type of trend removal** - You can choose to remove the average elevation, a least-squares linear trend, or a straight line joining the first and last topography data points. If the ground surface along the survey line is generally flat except for a few points, use the option to subtract a constant value from the heights of the electrodes locations. If the survey points are on a slope, choose either a least-squares or an end-to-end straight line for the linear trend. Figure 6 shows an example with topography where the end-to-end straight line trend was removed.

**Type of topographic modelling** - Selecting this option will show the following dialog box where you can choose 3 different topographic modelling methods.



**Distorted finite-element grid with uniform distortion** : This method, and the next two methods, use a distorted finite-element grid such that the surface

nodes of the mesh match the actual topography. This gives more accurate results than the older method of using the correction factors for a homogeneous earth model calculated with the finite-element method (Fox *et al.* 1980) which can cause distortions in cases where large resistivity variations occur near the surface (Tong and Yang 1990, Loke 2000). In this particular option, the nodes below the surface (and thus also the model layers) are shifted to the same extent as the surface nodes.

**Distorted finite-element grid with damped distortion :** In this option, the subsurface nodes are shifted to a lesser extent compared with the surface nodes, i.e. the effect of the topography is “damped” with depth. This option is probably a reasonable choice if the amplitude of the curvature of the topography is less than the depth of the deepest model layer. A damping factor that controls the degree of damping with depth (Figure 7) can be modified by the user.

**S-C transformation with distorted finite-element grid :** This method uses the Schwarz-Christoffel transformation method to calculate the distortion in the subsurface layers. It is probably the best method that produces a more ‘natural’ looking model section in cases with a comparatively large topography curvature. In such cases, the damped topography approach might produce unusually thick model layers under areas where the topography curves upwards. In some unusual cases where the topography has very sharp acute peaks and sparse topography data points, the Schwarz-Christoffel transformation method might not work. If this happens, add a few extra topography data points near the peak.

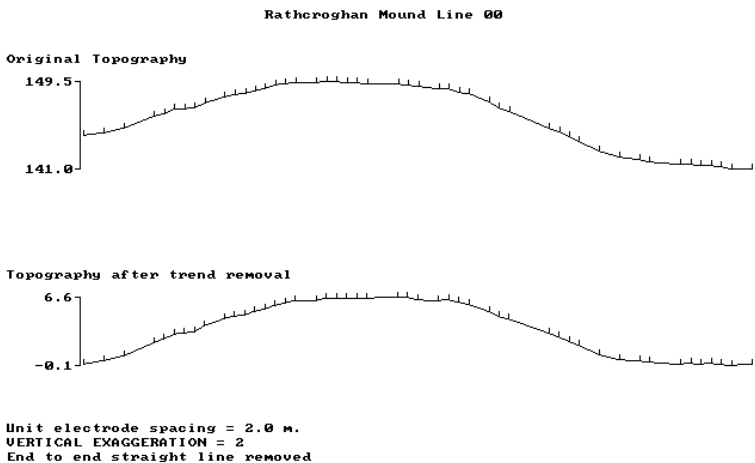
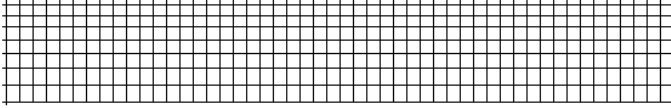
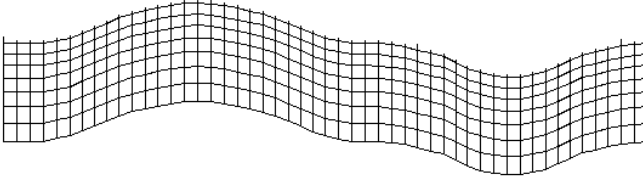


Figure 6. Topography linear trend removal for the Rathcroghan mound data set.

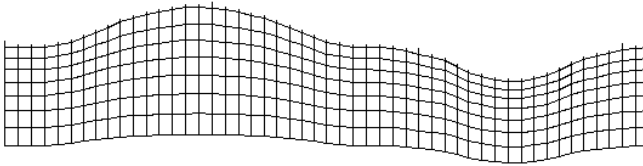
a). Arrangement of model blocks without topography



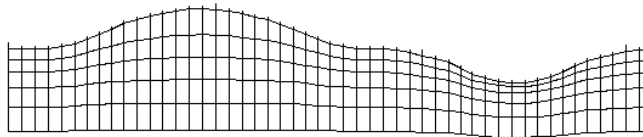
b). Arrangement of model blocks with a uniformly distorted grid



c). Arrangement of model blocks with a moderately damped distorted grid



d). Arrangement of model blocks with a highly damped distorted grid



e). Arrangement of model blocks with the inverse Schwartz-Christoffel transformation

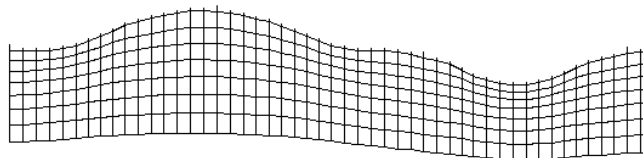


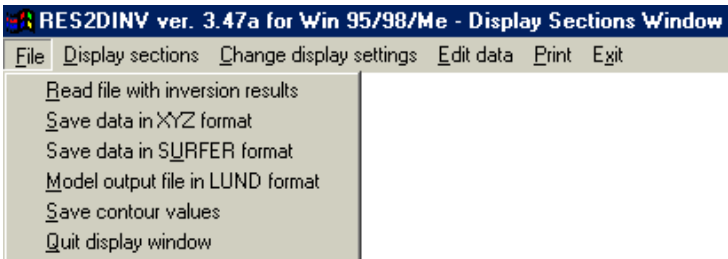
Figure 7. Different methods to incorporate topography into a 2-D inversion model. (a) Schematic diagram of a typical 2-D inversion model with no topography. A finite-element mesh with four nodes in the horizontal direction between adjacent electrodes is normally used. The near surface layers are also subdivided vertically by several mesh lines. Models with a distorted grid to match the actual topography where (b) the subsurface nodes are shifted vertically by the same amount as the surface nodes, (c) the shift in the subsurface nodes are gradually reduced with depth or (d) rapidly reduced with depth, and (e) the model obtained with the inverse Schwartz-Christoffel transformation method.

## 12. Displaying the inversion results

In this option, you can read in a data file or the output file produced by the inversion subroutine and display the measured and calculated apparent resistivity pseudosections and the model section. Within this option, you can change the contour interval used for drawing the pseudo and model sections, the vertical scale of the sections, and include topography in the model section. You can also change the colour scheme used by the program. 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 data 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 those used by the RES2DINV program.

Save data in SURFER format – This saves the data and model sections in SURFER format. Please refer to Appendix N for the details.

Model output in LUND format - This is a data format used by the LUND Imaging System produced by ABEM. You can save the model resistivity values in the .RHO and .RMS files used by the MODSEC program.

Save contour values - This option saves the values used to draw the contours in the pseudo and model sections.

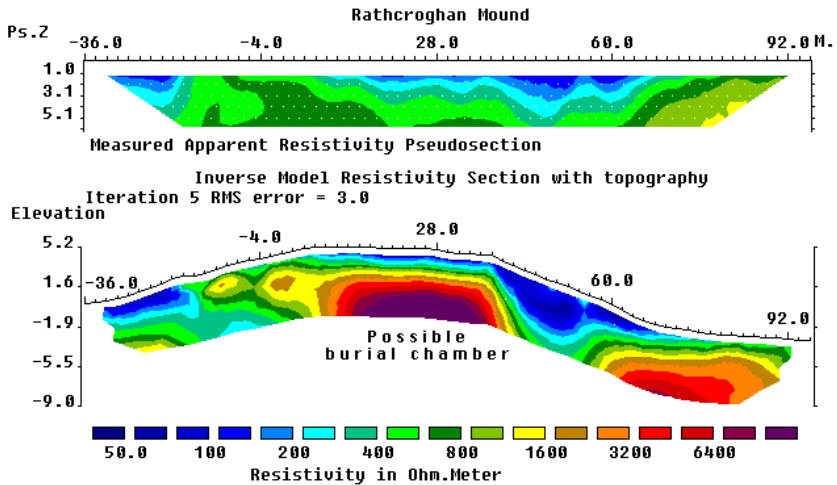
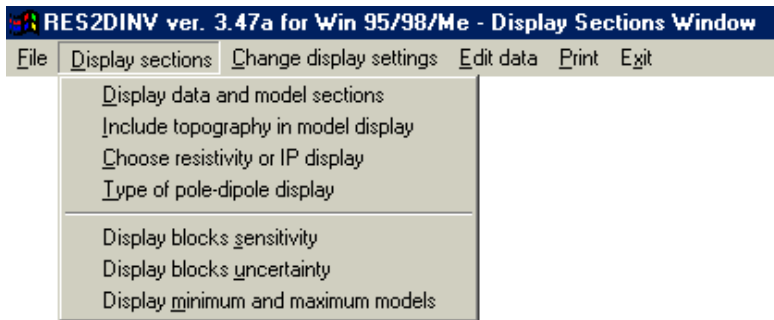


Figure 8. The observed apparent resistivity pseudosection from the Rathcroghan mound survey together with the model section. The topography has been incorporated in the model section.

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



**Display data and model sections** - Select this option to plot the model and apparent resistivity pseudosections on the screen.

**Include topography in model display** - For inversion results where topographic modelling were earlier carried out, you can incorporate the topography into the model section by calculating that the true depth and location of the model blocks below the surface. Figure 8 shows an example of a model section with the topography. The field data for this survey (as well as the Landfill example in Figure 3) was measured using a Campus Geopulse resistivity imaging system manufactured by Campus Geophysical Instruments Ltd.

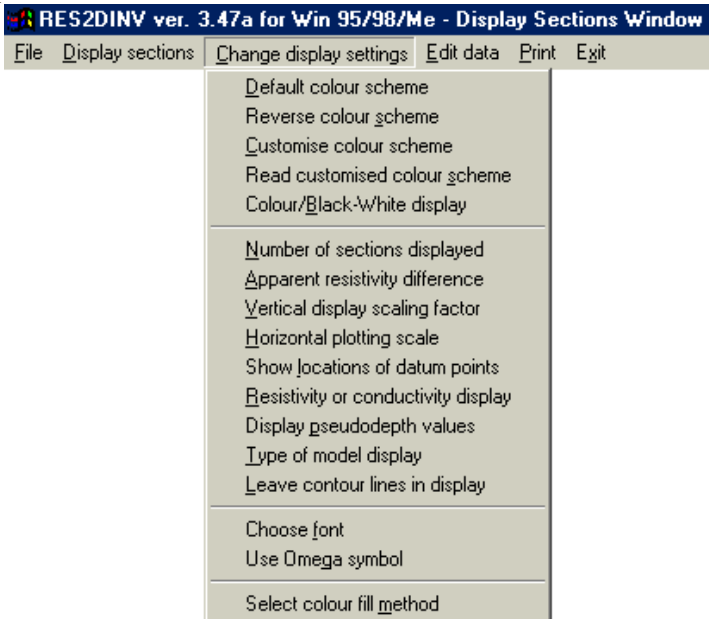


For both display options, you will be asked to enter the iteration number and the contour intervals. After the section is displayed, you can display the results for the next iteration by pressing the PgDn key. Similarly, pressing the PgUp key will display the results for the previous iteration.

Choose resistivity or IP display - If the data set has IP data as well, this option allows you to choose to display the resistivity or IP sections. You can also display both the resistivity and IP model sections at the same time.

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

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



Default colour scheme - This will reset the colour scheme used for colouring the sections to a default system used by the program.

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.

Number of sections to display - You can choose to display 1, 2 or 3 sections on the screen. By default, all the 3 sections (the observed and calculated apparent resistivity pseudosections and the model section) are displayed.

Apparent resistivity difference - You can choose to display either the calculated apparent resistivity pseudosection itself, or the percentage difference between the logarithms of the calculated and observed apparent resistivity values.

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. If you enter a value of 0.0, the program will use a default scaling factor so that the display can fit into the display screen.

Horizontal plotting scale - This allows you to change the horizontal scale, in terms of number of pixels per unit electrode spacing. This option is useful when you want to plot the results from different survey lines with different numbers of electrodes, with the same scale.

Show locations of datum points - By default, the location of the data points (and centres of the model blocks) will be shown by white dots in the colour pseudosection display. You can choose not to display the dots with this option.

Resistivity or conductivity display - The resistivity pseudosections and model sections are normally displayed. However, you can display the sections using conductivity values (i.e. the reciprocal of the resistivity) which is more commonly used in certain fields, such as hydrogeology.

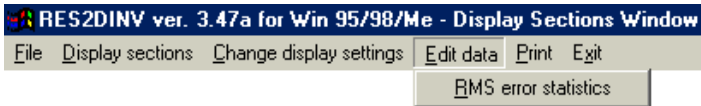
Display pseudodepth values - For the apparent resistivity pseudosections, you can display the pseudodepth values on the vertical scale, or display the electrode spacing and “n” factors (where applicable).

Colour/Black-White display - By default, the program will display the pseudosections and model section 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.

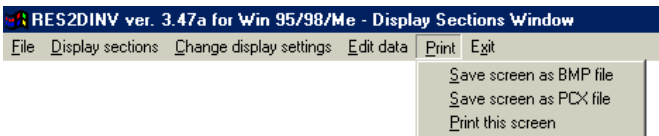
Type of model display - In this option, you can display the resistivity values in the model section in the form of contours (the default choice), or in the form of rectangular blocks which constitute the inversion model. The contoured section makes it easier to visualise geological structures, while finer features might be more easily detected in the rectangular blocks section.

When the “Edit data” option is selected, the following “RMS error statistics” submenu is displayed. This option provides another means of removing bad data points from the data set. In fact, for cross-borehole or certain types of non-conventional arrays data where the apparent resistivity values cannot be conveniently displayed in the form of a pseudosection or profiles, this is the primary method to remove the bad data points.



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. To save some time, you could use the quasi-Newton method to carry out the trial inversion (see section 10). 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 example above 100 percent. To remove the points with large errors, just move the green cursor line to set the cut-off error limit to remove the “bad” data points.

The “Print” option on the main menu bar enables you to save the screen image as a BMP or PCX graphics file, or to make a direct printout with a printer by using the Windows Paintbrush program. On selecting this option, the following submenu will be displayed.



Saving the screen image into the form of a BMP or PCX graphics file allows you to edit the picture with a bit-mapped graphics program, such as the Windows PaintBrush program, before printing it (see section 15).

### 13. Program settings

By default, the Windows Paintbrush is used as the program to manipulate and print the BMP or PCX graphics file, and the NOTEPAD program is used as the text editor. You can change these default choices by changing the appropriate lines in the RES2DINV.INI file which should be located in the same subdirectory as the RES2DINV.EXE program.. For example, a configuration file with the following contents :-

```
[programs]
paint=c:\psp\psp.exe
editor=c:\gwd\gwd.exe
[files]
extension=*.lok
input=c:\res2dinv\
output=c:\res2dinv\
```

will use the Paint Shop Pro graphics program (located in the subdirectory C:\PSP) and the GWD text editor (in the C:\GWD subdirectory). It will also look for files with the extension LOK when you choose the option to read in a data file. The default subdirectory with the data files is C:\RES2DINV, and the same subdirectory is used for the output files.

### 14. Help

If you click the “Help” option, the Windows help file for the program will be displayed. Clicking the “Info” option will display the copyright notice.

### 15. Printing the pseudosections

Besides displaying the pseudosections on the screen, you can make a printout of the model sections. There are three methods of making a printout.

The simplest method is to use the RES2DINV.EXE to display the pseudosection and model sections that you want to print by using the “Display inversion results” option in the Main Menu. After the program has completed drawing the pseudosection, 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.

Another method is to save the information into a XYZ file (see “File” section), which is a general format supported by a number of dedicated graphics contouring/plotting program. With such a program, you can redraw the model sections and print them. This is particularly useful if you want to combine the results from different survey lines within the same area to make a pseudo 3-D plot of the structures. If you want to include topography in the model values saved in the XYZ file, you will need to first run the “Include topography in model section” option before saving the XYZ file. In this case, the XYZ file will contain the model values without the topography, followed by a section with the model after incorporating the topography.

The third method is to save the model information into SURFER format, and use the SURFER for Windows program to draw and print the sections. Please refer to Appendix N for details about this option.

## **16 Other useful programs**

Two shareware programs that have been found to be useful are the Paint Shop Pro image processing program, and the GWD text editor program. Both are Windows based programs. The Paint Shop Pro program enables you to carry out a number of sophisticated processing to enhance the BMP and PCX bit-mapped graphics files. For example, you can convert the files to a GIF format which takes up much less space compared to the BMP and PCX files. The GWD text editor is a professional level editor which enables you to carry out many operations not possible with the NOTEPAD program. You can make use of these programs, instead of the default Microsoft Paintbrush and NOTEPAD program, by modifying the appropriate lines in the RES2DINV.INI file. The file RES2DINV.IN2 gives such an example.

There are also a number of fine shareware paint programs and text editors which you can download directly from Internet shareware sites. Besides Paint Shop Pro, the paint programs I have tested are Lview Pro, VuePrint and Graphics Workshop for Windows. All of these programs allow you to change the BMP and PCX files to the GIF format which can dramatically reduce the size of the graphics files. You can download these shareware programs from most Internet shareware sites, such as [www.softseek.com](http://www.softseek.com).

The SURFER 2-D drawing program from Golden Software Inc. ([www.golden.com](http://www.golden.com)) has a large variety of useful options for drawing sections.

The RES2DINV program has an option to export the data to the SURFER format.

## **17 Pitfalls in 2-D inversion**

If the program still does not give a satisfactory model (assuming that the input data is in the correct format), it could be due to one of the following problems.

***Garbage In - Garbage Out*** : One common problem is bad data points. Check for unusually low or high apparent resistivity values. These anomalous values can be caused by instrumentation errors during the field survey, poor electrode contact in dry, sandy or stony ground, shorting of electrodes due to very wet conditions or metal objects (such as fences, pipes etc.) or mistakes such as attaching electrodes to the wrong connectors. You can easily pick out these anomalous values using the "Edit data" option described earlier. Remember, a good model requires good data.

***Non-uniqueness*** : It is well known in the inversion of resistivity sounding data that it is possible for the calculated apparent resistivity values for slightly different models to be almost the same. The same thing holds for 2-D inversion of resistivity data. However, while the finer features in the different models obtained for a single data set can be different, the major features should be similar. Also, bear in mind that the resolving power of the resistivity method itself decreases exponentially with depth. This program allows you to modify some of the parameters, such as the damping factor and the flatness filters, that will influence the inversion process. By using different inversion parameters, you will probably end up with slightly different models.

***Unusual ground conditions*** : If the top ground layer is very dry, you might not be able to pump enough current into the ground. In this case, the resistivity technique itself might not be suitable and you should consider alternative geophysical methods (such as EM). Another similar situation is a very conductive top layer. In this case, the voltage difference measured by the potential electrodes might be too small (perhaps even below the background noise level). In this situation, try to get more current into the ground and check the actual voltage difference measured. If you are using the dipole-dipole array, try again with another array such as the Wenner-Schlumberger that gives larger potential values. If this still does not work, try using another geophysical method such as seismic refraction!

***3-D geology*** : It should be noted that a basic limitation of this program is the assumption of a 2-D subsurface model. For surveys carried out across the strike of elongated geological structures, this assumption is reasonably accurate. However, if there are significant variations in the subsurface resistivity in a

direction perpendicular to the survey line (i.e. the geology is 3-D), this could cause distortions in the lower sections of the model obtained. Measurements made with larger electrode spacings are not only affected by the deeper sections of the subsurface, they are also affected by structures at a larger horizontal distance from the survey line. This effect is most pronounced when the survey line is placed near a steep contact with the line parallel to the contact.

A 3-D resistivity inversion (Loke and Barker 1996b) program, RES3DINV, is now available. To invert a 3-D data set with a reasonable number of data points, a fast Pentium microcomputer with at least 64 megabytes of RAM is recommended! With 64 megabytes of RAM, the 3-D inversion program can handle surveys grids of up to 32 by 32 electrodes and a maximum of about 11,000 data points. A free 3-D resistivity and IP forward modelling program RES3DMOD is also available. You can use this program to calculate the apparent resistivity and IP values for a variety of 3-D structures for different electrode arrays. This will give you an idea of the extent of the 3-D effects.

There is a discussion on other interesting pitfalls in the free “Tutorial notes” on electrical imaging that is available on the [www.geoelectrical.com](http://www.geoelectrical.com) web site.

## 18 Some field examples

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

**Grundfor Line 2** - This survey was carried out by the Department of Earth Sciences, University of Aarhus, Denmark to map the lithology of the near-surface unconsolidated sediments and aquifers in the Grundfor area (Christensen and Sorensen 1994). The low resistivity zones in the inversion model (Figure 9) consist of more clayey Quaternary glacial deposits while the high resistivity areas consist of more sandy deposits. The model obtained was confirmed by a number of boreholes along this line. This is a moderately large data set with 447 data points and 141 electrodes. On a 90 MHz Pentium it took about 1033 seconds (17.2 minutes) to invert this data set, while on a 266 MHz Pentium II it took about 158 seconds (2.6 minutes).

**Odarslov Dyke** - The dyke causes a prominent high apparent resistivity zone near the middle of the pseudosection (Dahlin 1996) in the upper part of Figure 10. This is a particularly difficult data set to invert as the width of the high resistivity dyke is smaller than the depth to the lower section of the dyke. Thus the lower part of the dyke is not well resolved. If the damping factor used is too small, this will result in oscillations in the resistivity values in the model section. To invert this data set, the weight of the vertical flatness filter was set at twice that of the horizontal filter since the dyke has a predominantly vertical direction. The robust data inversion option (see Appendix K) was used to reduce the effect of a few data points that might be more noisy on the inversion results. Since there is a sharp and distinct contrast between the resistivity of igneous dyke and the surrounding sedimentary rocks, the robust model inversion option (Appendix K) was also used. In the model section, the dyke shows up as a prominent high resistivity body with vertical sides. This data set has 701 data points and 181 electrodes. The Grundfor and Odarslov dyke surveys were carried out using the LUND Automatic Resistivity Imaging System produced by ABEM Instrument AB.



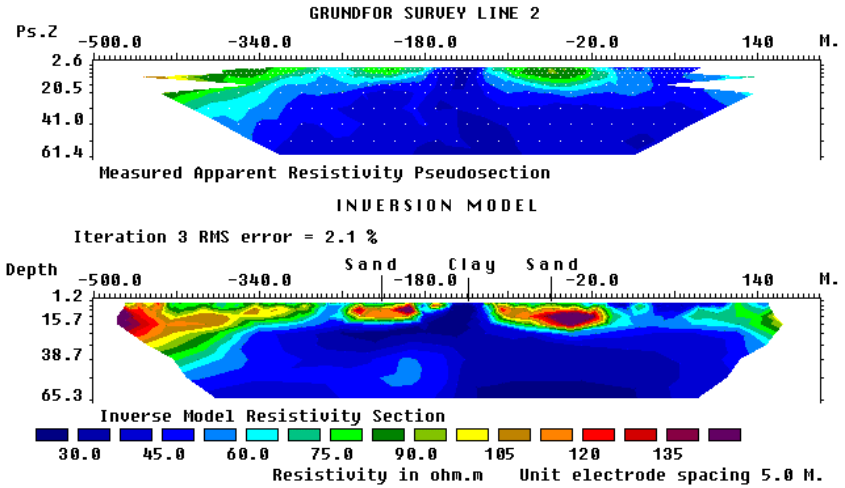


Figure 9 : The observed apparent resistivity pseudosection for the Grundfor Line 2 survey together with an inversion model.

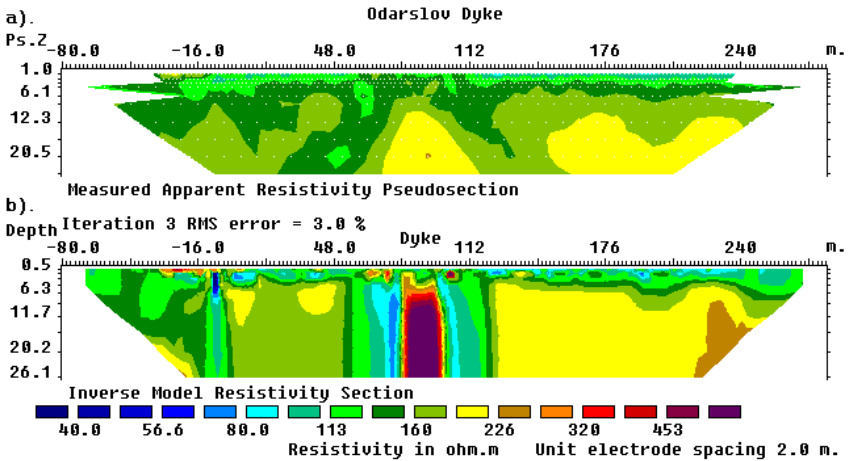


Figure 10: The observed apparent resistivity pseudosection for the Odarslov dyke survey together with an inversion model.

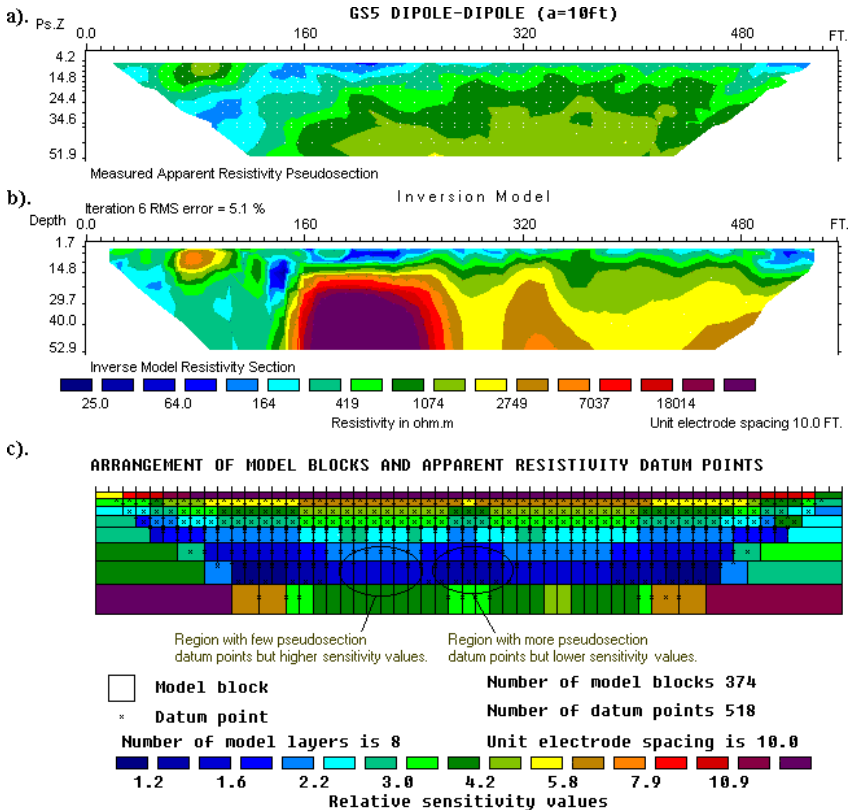


Figure 11. Mapping of holes in a clay layer, U.S.A. (a) Apparent resistivity pseudosection for the survey to map holes in the lower clay layer. (b) Inversion model and (c) sensitivity values of the model cells used by the inversion program.

### Holes in clay layer - U.S.A.

This survey was carried out for the purpose of mapping holes in a clay layer that underlies 8 to 20 feet of clean sand (Cromwell pers. comm.). The results from the electrical imaging survey were subsequently confirmed by boreholes. The pseudosection from one line from this survey is shown in Figure 11a. The data in the pseudosection was built up using data from horizontally overlapping survey lines. One interesting feature of this survey is that it demonstrates the misleading nature of the pseudosection, particularly for the dipole-dipole array. In the inversion model, a high resistivity anomaly is detected below the 200 ft. mark, which is probably a hole in the lower clay layer (Figure 11b). This feature falls in an area in the pseudosection where there is an apparent gap in the data. However, a plot of the sensitivity value of the cells used in the inversion model shows that the model cells in the area of the high resistivity

body have higher sensitivity values (i.e. more reliable model resistivity values) than adjacent areas at the same depth with more data points in the pseudosection plot (Figure 11c). This phenomenon is due to the shape of the contours in the sensitivity function of the dipole-dipole array, where the areas with the highest sensitivity values are beneath the C1C2 and P1P2 dipoles, and not at the plotting point below the center of the array. If the model cells are placed only at the location of the data points, the high resistivity body will be missing from the inversion model, and an important subsurface feature would not be detected!

**Bauchi groundwater survey** - A groundwater survey using the Wenner Alpha, Beta and Wenner arrays was carried in the Bauchi area of Nigeria (Acworth 1987). In this region, groundwater is frequently found in the weathered layer above the crystalline bedrock. The weathered layer is thicker in areas with fractures in the bedrock, and thus such fractures are good targets for groundwater. The Wenner Gamma array data set is shown in Figure 12 as an example. To emphasize the boundary between the soil layer and the bedrock, the robust inversion option was used (Appendix K). The thickness of the lower resistivity weathered layer is generally about 10 to 20 metres. There is a narrow vertical low resistivity zone with a width of less than 20 metres below the 190 metres mark that is probably a fracture zone in the bedrock. A borehole well that was placed at the 175 metres mark that lies at the edge of the fracture zone had yields that were lower than expected. The placement of the well was largely based on resistivity and EM profiling measurements using the Geonics EM34-3, and before fast 2-D resistivity inversion microcomputer software was widely available.

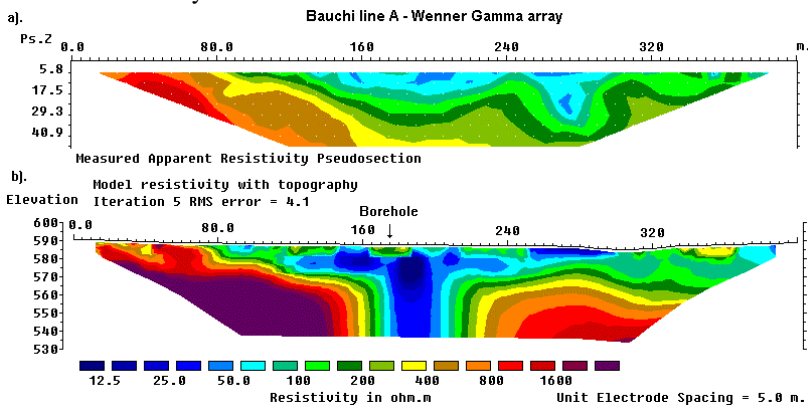


Figure 12. Bauchi Wenner Gamma array survey. (a). Apparent resistivity pseudosection. (b) The inversion model with topography.

## 19 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 near the bottom of the screen. If you have less than 64 megabytes RAM, it is recommended that you buy some RAM.

### **Program stops when it tries to calculate the partial derivatives :**

The partial derivative values are stored in the files GRADWEN.10, GRADTWO.10, GRADDIP.10, GRADWEN.25, GRADTWO.25 and GRADDIP.25. First check that these files are in the same sub-directory of your hard disc as the RES2DINV.EXE files. If they are there, one possible problem could be due to bad sectors in the hard disc. You need to scan the hard disc to check for possible unmarked bad sectors. Also, check that the hard disc has at least 64 megabytes of free space that the program needs to store temporary files for large data sets.

**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. One preliminary check you could make is to view the data using the "Edit data" option described in section 8. 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.

**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 3 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 for the Rainbow Technologies dongle and INSTALL.EXE for the Keylok dongle) also contains the drivers for Windows 95/98. Install this driver if the program is unable to detect the dongle with 95/98.

If you are using the USB dongle, the Keylok system driver must be installed. During the installation of the driver, the program will copy the necessary system (SYS) files needed by Windows to detect the USB dongle. Please refer to the installation note provided with the USB dongle for further details.

### **Acknowledgements**

Dr. Torleif Dahlin of Lund University in Sweden provided the interesting and challenging Odarslov Dyke, Gladkvarn and Knivsas data sets. The Grundfor data set was kindly provided by Dr. Niels B. Christensen of the University of Aarhus in Denmark and Dr. Torleif Dahlin. The Rathcroghan data set was kindly provided by Dr. Kevin Barton and Dr. Colin Brown from data collected by the Applied Geophysics Unit of University College Galway, Ireland. Dr. Andrew Binley of Lancaster University kindly provided the cross-borehole field data set. Mr. Ernst Neiderleithinger of Buro Fur Geophysik Lorenz (Germany) supplied the Landfill data set that provided the initial motivation to write this program to handle large 2-D data sets. I am also grateful to Prof. Douglas Oldenburg of the University of British Columbia in Canada for pointing out some of the possible advantages of using equation (2). The Bauchi data was provided by Dr. Ian Acworth of School of Civil and Environmental Engineering, The Un. of New South Wales, Australia. Many thanks to Richard Cromwell and Rory Retzlaff of Golder Assoc. (Seattle) for the survey example to map holes in a clay layer. Bill Seaton of ATS, Virginia kindly provided the BLUERIDGE.DAT data set. Dr. Fabrizio Cara of the Istituto Nazionale di Geofisica e Vulcanologia, Italy generously supplied the ITALY\_CAVE.DAT data set. I would also like to thank Ron Kaufman of Technos Inc. for his permission to use the Lake Lelia underwater field survey example. I would like to acknowledge Michel Ritz of IRD, France for kindly providing the BOREHOLE\_TOPO.DAT example data set. Finally, a special thanks to Rob Barker of The University of Birmingham (U.K.) for the Birmingham time-lapse, Stud Farm bedrock survey and the Clifton (with Julian Scott) data sets, and his advice through the years.

## References

- Acworth, R. I., 1987. The development of crystalline basement aquifers in a tropical environment: *Quarterly Journal Engineering Geology*, **20**, 265-272.
- Barker, R. and Moore, J., 1998. The application of time-lapse electrical tomography in groundwater studies. *The Leading Edge*, **17**, 1454-1458.
- Christensen N.B. and Sorensen K.I., 1994. Integrated use of electromagnetic methods for hydrogeological investigations. *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems*, March 1994, Boston, Massachusetts, 163-176.
- Claerbout, J.F. and Muir, F., 1973. Robust modeling with erratic data. *Geophysics*, **38**, 826-844.
- Dahlin, T., 1996. 2D resistivity surveying for environmental and engineering applications. *First Break*, **14**, 275-284.
- Dahlin, T. and Zhou, B., 2004. A numerical comparison of 2D resistivity imaging using ten electrode arrays. *Geophysical Prospecting*, **52**, 379-398.
- Dahlin, T. and Zhou, B., 2005. Multiple gradient array measurements for multi-channel 2D resistivity imaging. *Near Surface Geophysics*, in review.
- deGroot-Hedlin, C. and Constable, S., 1990, Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysics*, **55**, 1613-1624.
- Edwards, L.S., 1977, A modified pseudosection for resistivity and induced-polarization. *Geophysics*, **42**, 1020-1036.
- 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.
- Griffiths, D.H., Turnbull, J. and Olayinka, A.I., 1990, Two-dimensional resistivity mapping with a computer-controlled array. *First Break*, **8**, 121-129.
- Hallof, P.G., 1990, Reconnaissance and detailed geophysical results, Granite Mountain Area Pershing County, Nevada. 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.
- Keller G.V. and Frischknecht F.C., 1966. *Electrical methods in geophysical prospecting*. Pergamon Press Inc., Oxford.

- Loke, M.H., 1999. Time-lapse resistivity imaging inversion. 5th Meeting of the Environmental and Engineering Geophysical Society European Section Proceedings. Em1.
- Loke, M.H., 2000. Topographic modelling in resistivity imaging inversion. 62nd EAGE Conference & Technical Exhibition Extended Abstracts, D-2.
- Loke, M.H., 2001. Tutorial : 2-D and 3-D electrical imaging surveys. Geotomo Software, Malaysia.
- Loke, M.H. and Barker, R.D., 1996a, Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophysical Prospecting*, **44**, 131-152 .
- Loke, M.H. and Barker, R.D., 1996b, Practical techniques for 3D resistivity surveys and data inversion. *Geophysical Prospecting*, **44**, 499-523.
- Loke, M.H. and Dahlin, T., 2002. A comparison of the Gauss-Newton and quasi-Newton methods in resistivity imaging inversion. *Journal of Applied Geophysics*, **49**, 149-162.
- Loke, M.H., Acworth, I. and Dahlin, T., 2003. A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. *Exploration Geophysics*, **34**, 182-187.
- Nelson, G.D. and Van Voorhis, 1973, Letter to the editor regarding the paper "Complex resistivity spectra of porphyry copper mineralization". *Geophysics*, **38**, 984.
- Niederleithinger, E., 1994, Use of high resolution geomagnetics, 2D-DC-geoelectrics and induced polarisation in environmental investigations. Paper presented at SAGEEP '94, Boston, USA.
- Olivar, A., de Lime, L. and Sharma, M.M., 1990. A grain conductivity approach to shaly sandstones. *Geophysics*, **55**, 1347-1356.
- Robain, H., Albouy, Y., Dabas, M., Descloitres, M., Camerlynck, C., Menchler, P. and Tabbagh, A., 1997, The location of infinite electrodes in pole-pole electrical surveys: consequences for 2D imaging. *Journal of Applied Geophysics*, **41**, 313-333.
- Sasaki, Y., 1992, Resolution of resistivity tomography inferred from numerical simulation. *Geophysical Prospecting*, **40**, 453-464.
- Scott, J.B.T., Barker, R.D. Peacock, S., 2000. Combined seismic refraction and electrical imaging. Procs. 6th Meeting of the European Association for Environmental and Engineering Geophysics, 3-7 Sept. 1997, Bochum, Germany, EL05.
- Seaton, W.J. and Burbey, T.J., 2000. Aquifer characterization in the Blue Ridge physiographic province using resistivity profiling and borehole geophysics : Geologic analysis. *Journal of Environmental & Engineering Geophysics*, **5**, no. 3, 45-58.
- Silvester P.P. and Ferrari R.L., 1990, Finite elements for electrical engineers (2nd. ed.) . Cambridge University Press.

- Slater, L., Binley, A.M., Zaidman, M.D. and West, L.J., 1997, Investigation of vadose zone flow mechanisms in unsaturated chalk using cross-borehole ERT. Proceedings of the EEGS European Section 3rd Meeting, Aarhus, Denmark, 17-20.
- 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.
- Turnbull, J., 1986. A field and interpretation technique for resistivity surveying over two dimensional structures. Unpubl. PhD thesis, Un. of Birmingham, U.K.
- 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.



### Appendix A : Dipole-dipole and pole-dipole surveys

The format for the data points for a dipole-dipole survey is slightly different from that used for the Wenner and pole-pole surveys. The arrangement of the electrodes for the dipole-dipole survey is shown in the following figure.

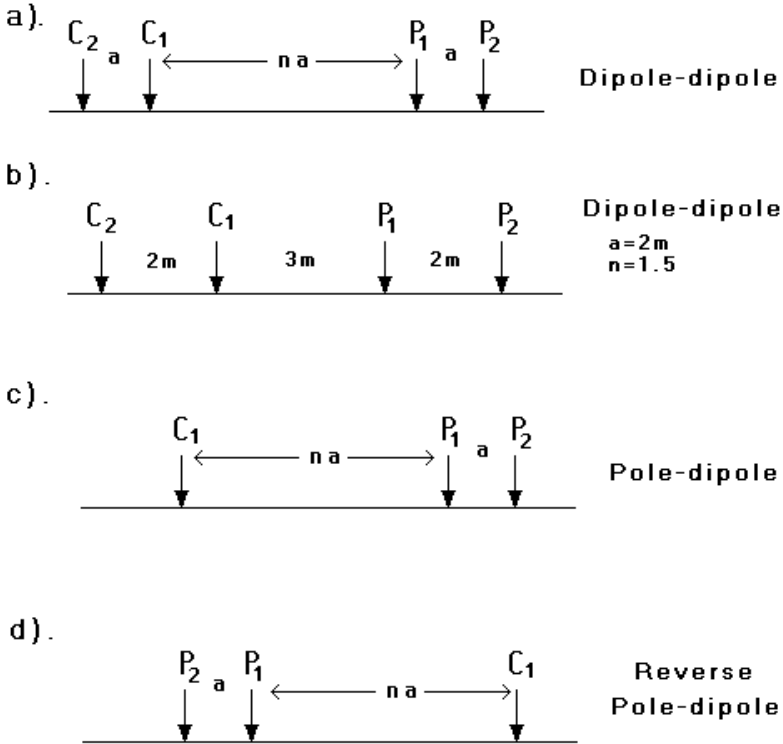


Figure 13 : (a) Arrangement of the electrodes for the dipole-dipole array. (b) Example of dipole-dipole array with non-integer “ $n$ ” value. Arrangement of the electrodes for (c) the “forward” and (d) “reverse” pole-dipole arrays.

The distance,  $a$ , between the two current electrodes,  $C_1$  and  $C_2$ , is the same as that between the potential electrodes. The distance between the current electrode  $C_1$  and the potential electrode  $P_1$  (the dipole separation factor) is usually an integer multiple,  $n$ , of the distance between the current or potential electrode pair. Initially, the dipole separation factor ( $n$ ) is set to 1. Then it is increased to 2, 3 and so on until a maximum value of between 4 and 6. When the dipole separation factor is increased, the potential measured between  $P_1$  and  $P_2$  decreases rapidly with increasing  $n$ . For this reason, it is not advisable to use a value of  $n$  greater than 6. Using larger values of  $n$  could result in rather noisy data. In some surveys, the distance ( $a$ ) between the current and potential

electrode pairs is doubled or tripled (Edwards 1977) to increase the signal strength. Thus both the dipole separation factor ( $n$ ) and the spacing between the current electrode pair ( $a$ ) has to be recorded. Using the BLOCKDIP.DAT file as an example, the data file format for the dipole-dipole array is as follows :-

<i>BLOCKDIP.DAT file</i>	<i>Comments</i>
TWO RECTANGULAR BLOCKS	Title
1.0	Unit electrode spacing
3	Array number (dipole-dipole=3)
356	Number of data points
0	x-location given in terms of first electrode   use 1 if mid-point location is given
0	0 for no IP, use 1 if IP present
0.0 1.0 1 30.1	For each data point; enter x-location, "a"
1.0 1.0 1 30.1	spacing, "n" factor value, apparent
2.0 1.0 1 30.1	resistivity
.	
.	
39.0 1.0 8 30.3	Last 2 data points
40.0 1.0 8 30.4	
0,0,0,0,0	Put a few zero's at the end

The first value (in each line with the data point values) gives the x-location of the data point. The second value gives the separation between the potential electrode pair P<sub>1</sub> and P<sub>2</sub>. This value is usually an integer multiple (of between 1 to 5 times) the unit electrode spacing. In some 2-D resistivity surveys, the separation between the current electrode pair is fixed. In this case, this factor will have a constant value (as in the file BLOCKDIP.DAT). The third value is the dipole separation factor ( $n$ ) with a maximum value of 8. The fourth value is the measured apparent resistivity value.

The data filed BLUERIGDE.DAT is an example field data set where different "a" and "n" combinations (Seaton and Burbey 2000) in order to increase the depth of penetration without greatly reducing the signal strength.

The pole-dipole array has an array number of 6. The format of the data points is similar to that for the dipole-dipole array. The file BLOCKPDI.DAT gives an example of a pole-dipole data set. Compared to the dipole-dipole array, the signal strength measured with the pole-dipole array decreases less rapidly when the dipole separation factor ( $n$ ) is increased. Unlike the other common arrays, the pole-dipole is a non-symmetrical array which gives rise to somewhat more complicated anomalies in the pseudosection. The centre point of this array is defined as the mid-point between the C<sub>1</sub> and P<sub>2</sub> electrodes. This program

assumes that the x-location of C1 electrode is less than that of the P1 and P2 potential electrode pair (on the left side in Figure 13c). If the location of the first electrode is given in the input data file, then the location of the C1 electrode is used.

The pole-dipole array is an asymmetrical array, and over symmetrical structures the apparent resistivity anomalies in the pseudosection 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 13d). By combining the measurements with the “forward” and “reverse” pole-dipole arrays (Figures 13c and 13d), any bias in the model due to the asymmetrical nature of this array would be removed. The file PDIPREV.DAT is an example field data set that combines measurements made with the “forward” and “reverse” pole-dipole arrays. For the reverse pole-dipole measurement, the location of the first electrode is given by the position of the P2 electrode. A negative value for the  $n$  factor is used to indicate that the reverse pole-dipole arrangement is used.

In this program, the maximum allowed dipole separation factor  $n$  is 10 while the largest spacing between the P1-P2 electrode pair is 5 times the unit electrode spacing for the dipole-dipole array. For the pole-dipole array,  $n$  can have a maximum value of 10 while the P1-P2 spacing can be up to 5 times the unit electrode spacing. In most cases, the  $n$  dipole separation factor is an integer value. However it is possible for the  $n$  factor to have non-integer values although all the electrodes still have a constant inter-electrode spacing. This can occur when the spacing  $a$  between the C1-C2 pair is twice (or more) the unit electrode spacing. For the example shown in Figure 13b, the unit electrode spacing for the survey line is 1 metre. The  $a$  spacing has a value of 2 metres, while the distance between the C1 and P1 electrodes is 3 metres. In this case, the  $n$  factor has a value of 1.5. The data file, DIPOLEN5.DAT, gives an example of a dipole-dipole data set with non-integer  $n$  values. For cases where the fractional part of the  $n$  factor has is an infinite series in decimal notation, the  $n$  value should be given to at least four decimal places. For example, if the  $n$  value is one and one-third, it should be given as 1.3333.

### Appendix B : The Wenner-Schlumberger array

In areas with limited open space for a long survey line, the conventional Wenner array has a disadvantage in that there is a large reduction in horizontal coverage when the electrode spacing is increased in order to achieve a deeper depth of investigation. For example, in order to increase the depth of investigation by two times, the electrode spacing  $a$  has to be increased to  $2a$  (Figure 14). In this case, the total length of the array is increased from  $3a$  to  $6a$ . At the same time, the width of the pseudosection decreases by  $3a$  with each level of measurement (Figure 15). In comparison, the width of the pseudosection decreases by  $2a$  for the Wenner-Schlumberger array.

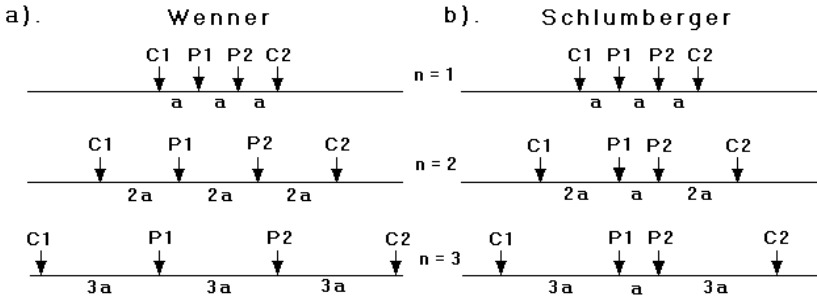


Figure 14 : The steps used by the (a) Wenner and the (b) Wenner-Schlumberger arrays to increase the depth of investigation.

The apparent resistivity value for the Wenner-Schlumberger array is given by

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

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-P1 and the P1-P2 electrodes. This array effectively becomes the Schlumberger array when the  $n$  factor is greater than 2. Thus it is actually a combination of the Wenner and Schlumberger arrays adapted for use for an arrangement with a line of electrodes with a constant spacing (as normally used in 2-D electrical imaging). Besides better horizontal coverage, the maximum depth of penetration of this array is about 15% larger than the Wenner array. Note that the normal Wenner array is actually a special case of the Wenner-Schlumberger array where the  $n$  factor is equals to 1.

In practice, since the potential between the P1 and P2 electrodes decreases when the electrode spacing factor  $n$  is increased, the maximum value of  $n$  used in actual field surveys is about 8. To increase the depth of investigation, the spacing between the P1-P2 electrodes is increased to  $2a$  and the measurements

are repeated for  $n$  equals to 1, 2, 3, 4, 5 and 6. Next, the P1-P2 spacing is increased to  $3a$ , and the same sequence of measurements is made. The file PIPESCHL.DAT gives an example of a field data set using this array.

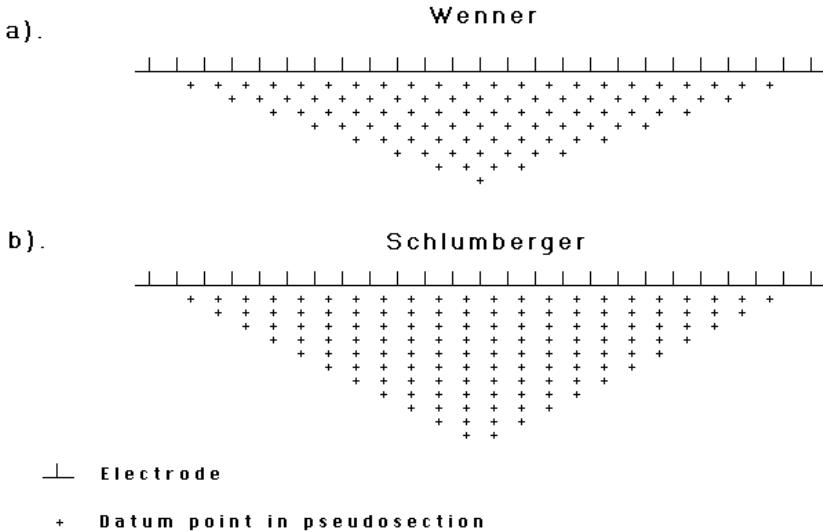


Figure 15 : Arrangement of data points in the pseudosections for the (a) Wenner and the (b) Wenner-Schlumberger arrays.

While the  $n$  factor usually has integer values, the program can also accept non-integer values for this factor. The data file, WENSCHN5.DAT, is an example with non-integer values for the  $n$  factor.

One advantage of the normal Wenner array is that it has the highest signal-to-noise ratio among the conventional arrays. To be on the safe side, you should include all the normal Wenner array measurements when carrying out a survey with the Wenner-Schlumberger array. The resulting pseudosection might look a little messy with overlapping data measurement levels, but RES2DINV can handle such a data set. In very noisy areas, the Wenner array measurements should be the most reliable.

### Appendix C : 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 256 sections of the subsurface. The shape of the section to be fixed must be rectangular or triangular. The data to fix the model resistivity values are entered into the input data file after section with the topography information. As an example, part of the example data file MODELFIX.DAT is listed below.

```

0      | Topography flag
2      | Number if regions to fix, put 0 if none
R      | Type of first region, R for rectangular
24,0.7 | X and Z coordinates of top-left corner of rectangle
28,2.3 | X and Z coordinates of bottom-right corner of rectangle
2.0    | Resistivity value of rectangular region
2.0    | Damping factor weight
T      | Type of second region, T for triangular
30,0.0 | X and Z coordinates of first corner of triangle
30,3.0 | X and Z coordinates of second corner of triangle
45,3.0 | Coordinates of third corner of triangle
10.0   | Resistivity value of triangular region
2.0    | Damping factor weight

```

The first item after the topography data section is the number of regions where the resistivity is to be specified. In the example above, 2 regions are specified. If a value of 0 is given (default value), then there are no regions where the resistivity is specified by the user. Next, the shape of the region is given, R for rectangular or T for triangular. If a rectangular region is specified, then the X and Z coordinates of the top-left and bottom-right corners of the rectangle are given, as shown in Figure 16.

If a triangular region is chosen, the X and Z coordinates of the 3 vertices of the triangle must be given in an anti-clockwise order. 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

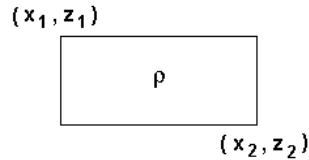
The larger the damping factor weight is used, the smaller is the change that is allowed in the resistivity of the "fixed" region. Normally, a value of about 1.5 to 2.5 is used. If a relatively large value is used, for example 10.0, the change in the resistivity of the region would be very small during the inversion process. Such a large value should only be used if the resistivity and shape of the region is accurately known.

### Fixing model resistivities

#### Data format

R  
 $x_1, z_1$   
 $x_2, z_2$   
 $\rho$   
 2.0

#### Rectangular regions



#### Data format

T  
 $x_1, z_1$   
 $x_2, z_2$   
 $x_3, z_3$   
 $\rho$   
 2.0

#### Triangular regions

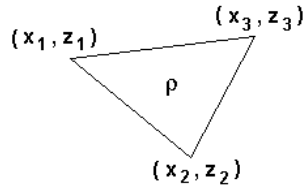


Figure 16 : Fixing the resistivity of rectangular and triangular regions of the inversion model.

### Appendix D : The Equatorial Dipole-Dipole array

The arrangement of the electrodes for this array is shown in the following figure.

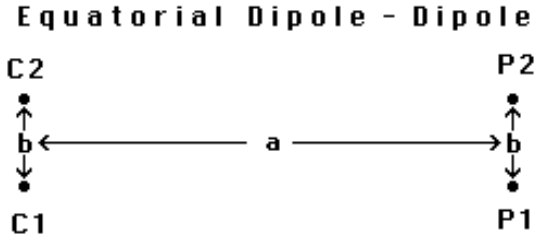


Figure 17 : The arrangement of the electrodes for the equatorial dipole-dipole array.

The apparent resistivity value for this array is given by

$$\rho = 2 \pi a s R / (s - a)$$

where

$$s = (a^2 + b^2)^{0.5}$$

and R is the measured resistance. This array differs from the other arrays where the electrodes are arranged in a single line. Each reading is characterised by two spacings. The first spacing, a, is the distance between the current electrodes pair C1-C2 and the potential pair P1-P2. The second spacing, b, is the spacing between the C1 and C2 electrodes. This program has a restriction that the spacing between the P1-P2 pair must be the same as that between the C1-C2 pair. An example of a data file for this array is the data file FAULTEQU.DAT. The initial part of the file is shown below with comments :-

FAULTEQU.DAT file			Comments
Equatorial dipole-dipole array			Title
1.00			The unit electrode spacing
8			Array number 8 for this array
1.50			The spacing b between the C1-C2 pair
285			The number of data points
1			Flag for mid-point of array
0			No IP data
0.50	1.00	2.74	x-location, spacing a, app. resis.
1.50	1.00	2.74	Repeat for all the other points

Note that for this array, it is necessary to include the spacing b between the C1-C2 electrodes pair after the array number.



## Appendix E : Underwater surveys

The possible situations for underwater surveys are shown in the following figure.

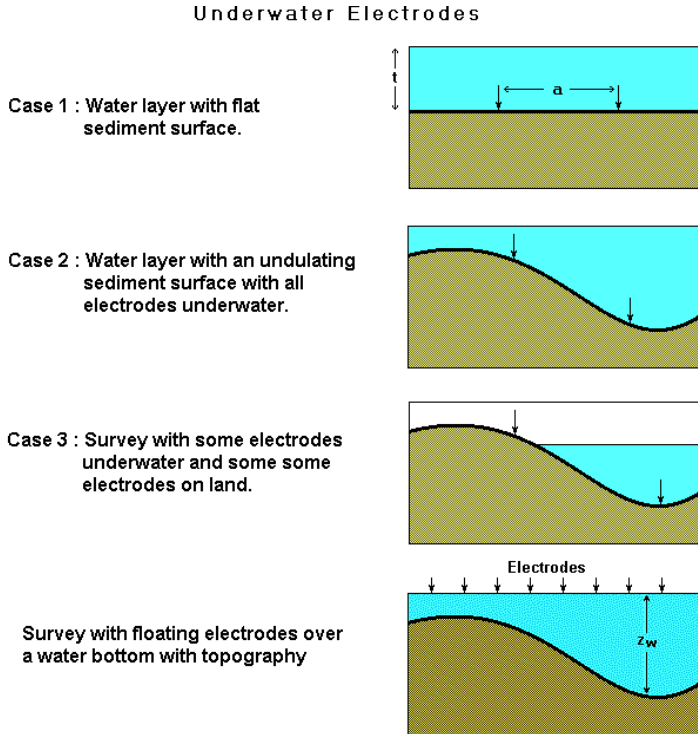


Figure 18 : Three possible situations for underwater surveys, and a survey with floating electrodes.

In the first situation, there is a water layer with a constant thickness over a flat sediment surface (i.e. there is no topography). An example of such a data set is given in the file WATER.DAT. The bottom section of this file with comments is as follows :-

WATER.DAT file			Comments
39.00	1.00 16	51.36	Last 3 data points
40.00	1.00 16	52.09	
41.00	1.00 16	54.29	
0			0 for no topography
0			0 for no fixed regions
1			1 to indicate water layer present
50.00, -100.00, 200.00			Resistivity of water layer, left and right limits of water layer
4.00			Thickness of water layer

1 | Surface geometric factor used to calculate  
 0 | apparent resistivities  
 |

While the left and right limits of the water layer are included in the data format, this is at present not used by the program. It is included for future use for surveys with some of the electrodes above the water layer, for example a survey across a river. Note that a flag is included to indicate that the normal geometric factor (as used for a surface survey) is used to calculate the apparent resistivity values. If a value of 0 is used for this flag, the exact geometric factor (which includes the thickness of the water layer) must be used to calculate the apparent resistivity values. For actual field surveys, it is expected that the normal surface geometric factor will be used.

If the river or sea bottom has topography, the topography information is entered immediately after the data set as in a normal land surface survey. The bottom section of the files is as follows :-

Underwater survey file wth topography			Comments
39.00	1.00 16	51.36	Last 3 data points
40.00	1.00 16	52.09	
41.00	1.00 16	54.29	
2			2 for topography with surface x-   distances
7			Number of topography data points
0.0, 3.0			The x-location and elevation of each
10.0, 4.0			topography data point
15.0, 4.5			
25.0, 5.0			
30.0, 5.1			
35.0, 4.5			
45.0, 4.6			
0			0 for no fixed regions
1			1 to indicate water layer present
50.00, -100.00, 200.00			Resistivity of water layer, left and right   limits of water layer
4.00			Elevation of water surface with respect to   local datum
1			1 to indicate normal surface geometric factor   used

The program will automatically calculate the thickness of the water layer from the elevation of the sea or river bottom and the elevation of the water surface. Note that is format also allows for the where some of the electrodes are above the water surface (i.e. on normal dry land) and some of the electrodes

underwater. In the example above, the electrodes between 0 and 10 meters are above the water surface. A common situation where this occurs is a survey that crosses a river. In this case, the program will assume that an electrode with an elevation that is less than the elevation of the water surface is underwater. For the case when some of the electrodes are above the water surface, the surface geometric factor must be used for calculating the apparent resistivity values for all the data points.

The topographic modelling is automatically carried out by the program when you invert the data set. The program will automatically adjust the surface of the finite-element grid used to model the subsurface so that it matches the surface of the sediment below the water layer.

There is a fourth possible situation with a confined body of water that is so far not supported. One possible situation is a river or lake with dykes. In this case, some points with elevations below the water surface level are not underwater. Support will probably be added in the future when such situations are more frequently encountered.

Many underwater surveys are carried out by dragging a cable or streamer behind a boat. In this case, the electrode locations are unlikely to be equally spaced. This situation is best handled by entering the data in the general array format that is described in Appendix L. The data file LAKELELIA.DAT is an interesting field survey by Technos Inc. with data in the general array format (Appendix L) and underwater topography. Parts of the file are highlighted below to illustrate the data format used.

<u>LAKELELIA.DAT file</u>	<u>Comments</u>
LAKE LELIA UNDERWATER SURVEY	Title
1.50	Unit electrode spacing
11	General array format
1	Note Wenner sub-array type
Type of measurement (0=app. resistivity, 1=resistance)	Header
0	Data is in apparent resistivity
291	Number of data points
2	Surface x-distances
0	No IP
4 82.37,0.0 91.37,0.0 85.37,0.0 88.37,0.0 43.137	First four data points
4 89.55,0.0 98.55,0.0 92.55,0.0 95.55,0.0 36.599	Note the electrode
4 96.74,0.0 105.74,0.0 99.74,0.0 102.74,0.0 36.458	elevation is 0.0 here
4 103.92,0.0 112.92,0.0 106.92,0.0 109.92,0.0 37.019	because it is given later
.	Other data points
.	Other data points
4 1050.25,0.0 1077.25,0.0 1059.25,0.0 1068.25,0.0 93.072	Last two data
4 1056.35,0.0 1083.35,0.0 1065.35,0.0 1074.35,0.0 95.383	points
Topography in separate list	Special header to indicate elevations

	are given separately from the main   data section
2	2 to indicate surface x-distances
38	Number of topography data points
26.12 999.09	First two topography   data points
30.48 999.09	Other topography   data points
.	data points
1127.76 999.09	Last topography data point
1	First electrode coincides with first   topography data point
0	Put zero here in place of usual   surface topography
0	No fixed regions
1	1 to indicate water layer present
58.00,-2000.00,2000.00	Resistivity of water layer, left and   right limits of water layer
1000	Elevation of water surface
1	Surface geometric factor used to   calculate apparent resistivities
0,0,0	End with a few zeros

Figure 19 shows the apparent resistivity pseudosection and inversion model for this data set. Mobile surveying systems typically produce survey lines that are very long compared to the depth of investigation of the cable array system used.

### Surveys with floating electrodes

Another possible arrangement for a survey using a boat dragging a cable is where the electrodes are floating on the water surface. The main disadvantage of this arrangement is that a large part of the current flows within the water layer, compared to the portion of the current that flows into the material below the water bottom. The main advantage is that it is easier and faster to carry out and avoids problems such as the cable being snagged by obstacles on the river bottom. It could be an efficient method in shallow areas where the screening effect due to the water layer is not too large. One possible way of interpreting such a data set is to treat it as a standard surface data set where the water layer is included as part of the model. This probably gives acceptable results where there is a strong contrast between the water layer and the topmost layer of the sub-bottom materials, and where the data has a low noise level. However if the depth of the water bottom was measured during the course of the survey (usually with an echo sounder), and the water resistivity was also measured, the effect of the water layer could be calculated and included in the model. The file WATER\_FLOAT.DAT is a synthetic data set which gives an example of the data format. The initial part of the file is identical with that used for normal

surface surveys or surveys with electrodes on the water bottom. The difference is in the final section of the file where the water layer parameters are given.

<u>WATER_FLOAT.DAT file</u>	<u>Comments</u>
Survey on water layer and floating electrodes	Title
2.0	Unit electrode spacing
11	General array format
0	No sub-array type
Type of measurement (0=app.resistivity, 1=resistance)	Header
0	Data is in apparent resistivity
942	Number of data points
1	True horizontal distances
0	No IP
4 2.0,0.0 0.0,0.0 4.0,0.0 6.0,0.0 1.86738	First three data points
4 4.0,0.0 2.0,0.0 6.0,0.0 8.0,0.0 1.86843	Note water surface is assumed to be
4 6.0,0.0 4.0,0.0 8.0,0.0 10.0,0.0 1.87070	at 0.0 metres
.	Other data points
.	
4 46.0,0.0 34.0,0.0 94.0,0.0 106.0,0.0 14.91776	Last two data points
4 48.0,0.0 36.0,0.0 96.0,0.0 108.0,0.0 15.51526	
0	No topography information
0	No fixed regions
3	3 to indicate floating electrodes survey
Water resistivity	Header
1.5	The water resistivity in ohm.m
Water elevation	Header
0.0	Elevation of water surface
18	Number of water bottom depth points
0 -1.5	x-location and elevation of water bottom below water surface
10 -1.5	Second depth point
20 -1.5	
26 -1.5	
28 -2.0	
30 -2.5	
.	Other bottom elevation data lines
.	
100 -1.5	
108 -1.5	Last depth point
1	Indicates first electrode is at first depth point
0,0,0	A few zeros to end the data file

While the above example gives the data in the general array format (Appendix L), the program can also accept data in the index based format. For example, the above data set is for the dipole-dipole array. An index based format (see Appendix A) will give the location of the data point, the 'a' dipole length and the 'n' dipole separation factor.

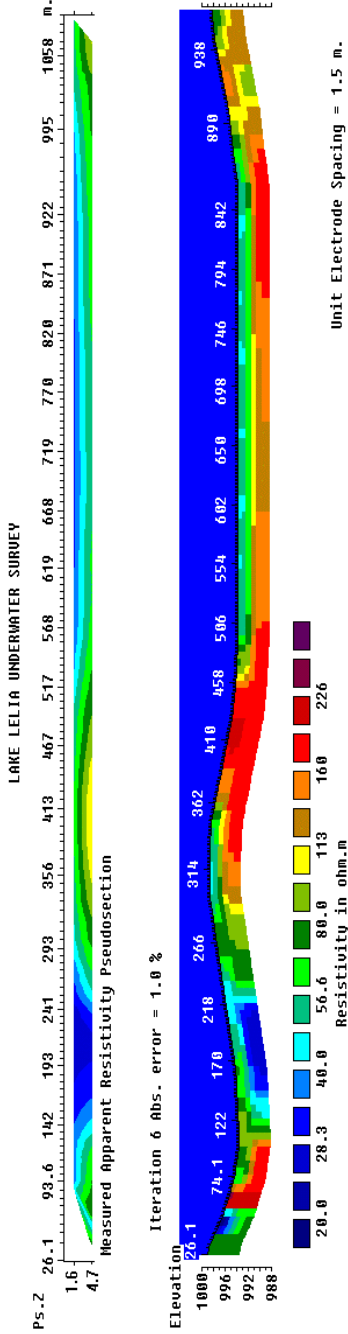


Figure 19. The apparent resistivity pseudosection and inversion model section from the Lake Lelia underwater survey. A vertical exaggeration factor of 5 was used in drawing the sections. This is typical for a survey using a mobile measurement system that tends to produce a very long survey lines compared to the depth of investigation.

Courtesy of Tecnos Inc., USA

## Appendix F : 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 data 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 data points. The distortion becomes worse when the data contains noise. Many users tend to use a large number of iterations together with small 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 program provides two methods to invert the IP data. In the first method the inversion of the resistivity and IP data are carried out concurrently. Immediately after an iteration of the inversion of the resistivity data, an iteration of the IP inversion is carried out. In the second method, the inversion of the IP data is carried out only after the completion of the resistivity inversion. In this case, only the resistivity of the model obtained at the last resistivity iteration is saved.

The files IPMODEL.DAT, IPMAGUSI.DAT, IPSHAN.DAT and IPKENN.DAT are example data files with both resistivity and IP data. This program supports four different types of IP data; (i) time domain chargeability measurements, (ii) frequency domain percent frequency effect measurements, (iii) phase angle measurements and (iv) metal factor IP values. The file IPMODEL.DAT has the IP data as chargeability values. The first part of the files with comments are as follows :-

<u>IPMODEL.DAT file</u>	<u>Comments</u>
Fault and block model	Title
1.00	Unit electrode spacing
3	Array type
432	Number of data points
1	Location of centre of array given
1	1 to indicate IP present

Chargeability					<i>Type of IP data</i>
msec					<i>IP unit</i>
0.1,1.0					<i>Delay, integration time</i>
1.50	1.00	1	12.04	7.2038	<i>x-loc., a, n, app. res., app. IP</i>
2.50	1.00	1	12.03	7.1983	<i>2nd data point</i>

A value of “1”, instead of “0”, is entered into the sixth line to indicate that IP data is present. This is followed by 3 data lines that gives information about the nature of the IP data. The seventh line with 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.

IP surveys have traditionally been used in the mineral exploration industry, particularly for metal sulfides, where generators producing high currents of the order of 10 Amperes are used. The apparent IP values from such surveys are usually less than 100 msec. (or mV/V). One recent development is the addition of IP capability to battery based systems used in engineering and environmental surveys where currents of 1 Ampere or less are normally used. An accompanying phenomenon is the observation of IP values of over 1000 msec. (or less than -1000 msec.) in some data sets. Such values are almost certainly caused by noise due to a very weak IP signal. To check whether such high IP values are real, first check the apparent resistivity pseudosection. If it shows unusually high and low values that vary in an erratic manner, the data is noisy. If the apparent resistivity values are noisy, then the apparent IP values are almost certainly unreliable. Next check the apparent IP pseudosection. If the apparent IP values show an erratic pattern (frequently with anomalous values lined up diagonally with an apex at a doubtful electrode), then the IP values are too noisy to be interpretable.

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. The file IPSHAN.DAT is an example of a frequency domain IP



data set. In the seventh line, the type of IP data is given as “Percent Frequency Effect”. The ninth data line contains the values of the low and high frequencies used in the measurement. This data set is from a field survey in Burma where the measurements were made with 20 metres and 40 metres dipoles (Edwards 1977). Like many field data sets, it has a very complex distribution of the data points in the pseudosection. This is a relatively noisy data set. It is advisable to use the option to “Include smoothing of model resistivity values” described in section 9 for the inversion of this data set to avoid extremely large and small model resistivity values. The survey target is a galena deposit in meta-sediments. The geology is rather complex with massive galena deposits together with quartz veins, silicified marbles and clay zones. There is a very wide range of resistivity values.

IP values are also given as phase angles. In this case the unit normally used is milli-radians (mrad). An example of an IP data set with phase angles is given in the file IPKENN.DAT with values from the paper by Hallof (1990). In the seventh line, the type of IP data type is given as “Phase Angle”. The second parameter in the ninth data line contains the values of the frequency at which the phase angles were measured. The first parameter is not used and is normally set to 0. Many modern IP survey instruments can measure the phase angle for several frequencies. In this case, the inversion of is repeated for the phase angle data at each frequency. This will give an idea of the change of the subsurface IP phase angle with frequency for complex resistivity studies.

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

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

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

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

The file IPMAGUSI.DAT is from a survey over the Magusi River ore body (Edwards 1977) where the survey was conducted with 30.5 metres (100 feet), 61.0 metres (200 feet) and 91.4 metres (300 feet) dipoles. Again the resulting pseudosection has a very complex distribution of the data points. The measured apparent resistivity and IP pseudosections, together with the model sections obtained are shown in Figure 20. The ore body shows up as a distinct low resistivity body with high IP values near the middle of the survey line in the model sections. In the inversion of this data set, the robust inversion method was used (see Appendix K) to sharpen the boundary between ore body and the surrounding rocks.

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 involves a resistivity value. The model that 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.

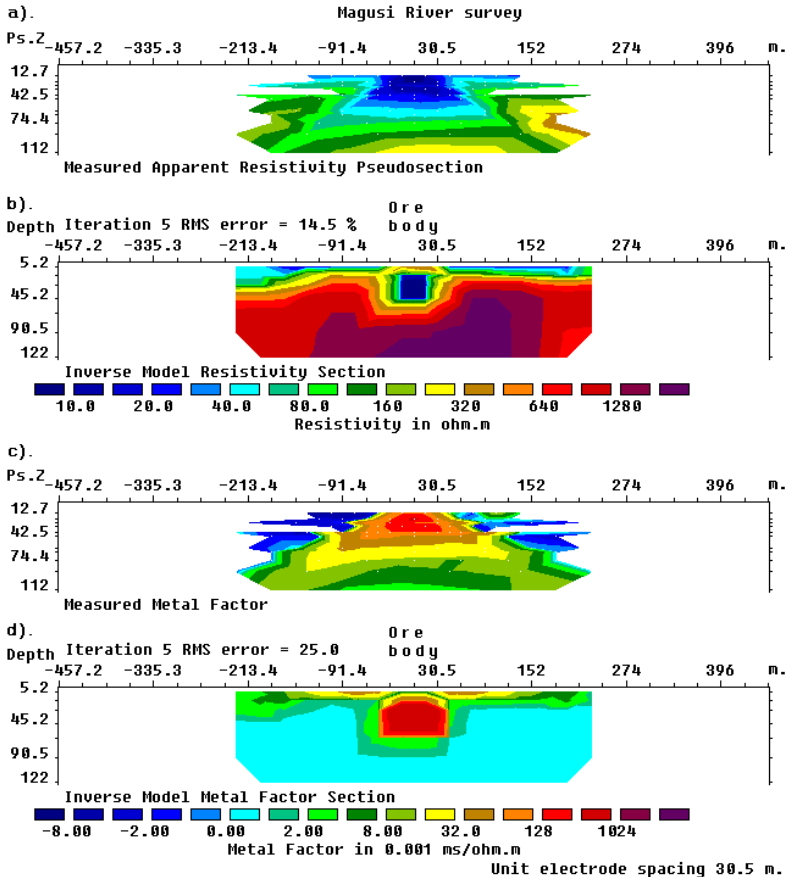


Figure 20. Magusi River ore body (a) Apparent resistivity pseudosection, (b) resistivity model section, (c) apparent metal factor pseudosection and (d) metal factor model section.

### Appendix G : New batch mode options

This option is intended for users who might wish to invert a large number of data sets at one go by remote control. It allows you to launch the batch mode from another Windows program, or from a command line. In the batch mode option a script file, for example RESIS.BTH, is used to inform the program of the data files which need to be processed and the various inversion options used. In Windows, you can access the command line option by clicking the “Start” button, followed by the “Run” option. If the RES2DINV program is located in the C:\R2DINV subdirectory, and the batch script file RESIS.BTH is located in the D:\DATA subdirectory, the following command is typed into the “Run” dialog box.

```
C:\R2DINV\RES2DINV D:\DATA\RESIS.BTH
```

This command will launch the RES2DINV program that will automatically process the list of data files in the RESIS.BTH. In the RESIS.BTH file, it is recommended that you type in the full drive and path for all the files. After the program has processed all the data files, it will automatically shut down. You can process up to 40 data files using a single batch script file.

Starting with version 3.53, a new and simpler file format for the batch mode option which makes use of the inversion parameters files (IVP) that are created by the RES2DINV program itself. The file RESIS\_IVP.BTH is an example, with the following format.

RESIS_IVP.BTH file	Comments
3	Number of files to invert
INVERSION PARAMETERS FILES USED	Header to indicate new batch mode
DATA FILE 1	Header for first file
C:\RES2DINV\RATHCRO.DAT	Data file to invert
C:\RES2DINV\RATHCRO_L2.INV	Output file with inversion results
C:\RES2DINV\RES2DINV_L2.IVP	File containing the inversion settings
DATA FILE 2	Header for second file
C:\RES2DINV\RATHCRO.DAT	Data file to invert
C:\RES2DINV\RATHCRO_L1.INV	Output file with inversion results
C:\RES2DINV\RES2DINV_L1.IVP	File with different inversion settings
DATA FILE 3	Header for third file
C:\RES2DINV\LANDFILL.DAT	Third data file to invert
C:\RES2DINV\LANDFILL_L2.INV	Output file with inversion results
C:\RES2DINV\RES2DINV_L2.IVP	File containing the inversion settings

Since the IVP files are created by the RES2DINV program, it is not necessary for the user to deal with the details about the file format. To create them, the user just needs to click the appropriate inversion options within the RES2DINV program, and then select the “Save inversion parameters” option under the “Change Settings” menu to save the parameters into an IVP file.

**Appendix H : Speed of graphics display**

As RES2DINV 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 data 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 RES2DINV program, but will also improve the response of practically all graphics intensive Windows programs (such as CAD and animation programs).

### Appendix I : Cross-borehole data inversion

The resolution of electrical surveys carried out with electrodes on the ground surface decreases exponentially with depth. One method to obtain reasonably good resolution at depth is by making measurements with the electrodes in boreholes. Cross-borehole surveys are much less frequently carried out compared to surface based surveys, so unlike surface surveys, there are at present no common standards with regards to the arrangement of the electrodes. The cross-borehole option in this program is intended for shallow surveys with the arrangement of the electrodes placed in a certain general pattern (Sasaki 1992). The basic arrangement of the electrodes is shown in the Figure 21.

The electrodes are divided into 3 sets with (i) the surface electrodes, (ii) electrodes in borehole 1 and (iii) electrodes in borehole 2. It is assumed that the boreholes do not have a metal casing which would severely alter the pattern of the current flow. The program divides the subsurface into a number of quadrilateral blocks (Figure 21). Note that the positions of the surface and borehole electrodes control the manner in which the subsurface is divided into the model blocks. The file BOREDIF.F.DAT is an example data file with cross-borehole measurements. A description of the format used is given below in the comments section. Note that in this example, the measurements are made with the pole-dipole array where only the C1, P1 and P2 electrodes are used.

<i>BOREDIFF.DAT file</i>	<i>Comments</i>
Borehole electrodes at different depths	Title
1.0	Smallest electrode spacing
12	Array number 12 for cross-borehole survey
840	Number of data points
2	2 to indicate XYZ location format is used
0	0 for no IP data
Surface Electrodes	Header for surface electrodes
16	Number of surface electrodes
0.0, 0.0	x- and z-location of first surface electrode
1.0, 0.0	location of second surface electrode
2.0, 0.0	Note location values are given for the
3.0, 0.0	electrodes in ascending order starting
4.0, 0.0	from the left.
5.0, 0.0	Note a zero value for the depth for the
6.0, 0.0	surface electrodes.
7.0, 0.0	
8.0, 0.0	
9.0, 0.0	
10.0, 0.0	
11.0, 0.0	
12.0, 0.0	
13.0, 0.0	

```

14.0, 0.0 |
15.0, 0.0 |
Borehole 1 Electrodes | Header for first borehole
10 | Number of electrodes in first borehole
4.0 1.0 | x- and z-location of first electrode
4.0 2.0 | x- and z-location of second electrode
4.0 3.0 | Note locations of electrodes
4.0 4.0 | are given from the topmost electrode
4.0 5.0 | below the surface.
4.0 6.0 | Also note a constant x-location for
4.0 7.0 | vertical borehole.
4.0 8.0 |
4.0 9.0 |
4.0 10.0 |
Borehole 2 Electrodes | Header for second borehole
10 | Number of electrodes in second borehole
11.0 1.5 | x- and z-location of first electrode
11.0 2.5 | location of other electrodes are then given.
11.0 3.5 |
11.0 4.5 |
11.0 5.5 |
11.0 6.5 |
11.0 7.5 |
11.0 8.5 |
11.0 9.5 |
11.0 10.5 |
Measured Data | Header for section with the measurements
3 0.00 0.00 1.00 0.00 2.00 0.00 101.5718 | The format for each data point is :-
3 0.00 0.00 2.00 0.00 3.00 0.00 99.5150 | Number of electrodes used in
3 0.00 0.00 3.00 0.00 4.00 0.00 99.2303 | measurement, x- and z-location of
3 0.00 0.00 4.00 0.00 5.00 0.00 99.1325 | C1 electrode, x- and z-location of
3 0.00 0.00 5.00 0.00 6.00 0.00 101.0616 | P1 electrode, x- and z-location of
3 0.00 0.00 6.00 0.00 7.00 0.00 105.7333 | P2 electrode, apparent resistivity
3 0.00 0.00 7.00 0.00 8.00 0.00 112.6745 | value.
3 0.00 0.00 8.00 0.00 9.00 0.00 118.5223 |

```

The array number is 12 for cross-borehole survey data with the measurements given as apparent resistivity values. You can also enter the data as resistance measurements, in which case the array number is 13. This might be more convenient as most resistivity meters give the readings as a resistance value in ohm, and furthermore the geometric factor for arrays with subsurface electrodes is different from the geometric factor for conventional surface arrays. The file BORERES.DAT gives an example where the measurements are given as resistance values. An interesting field data set where the pole-pole array was used, and the measurements are also given as resistance values, is BORELUND.DAT from Lund University, Sweden.

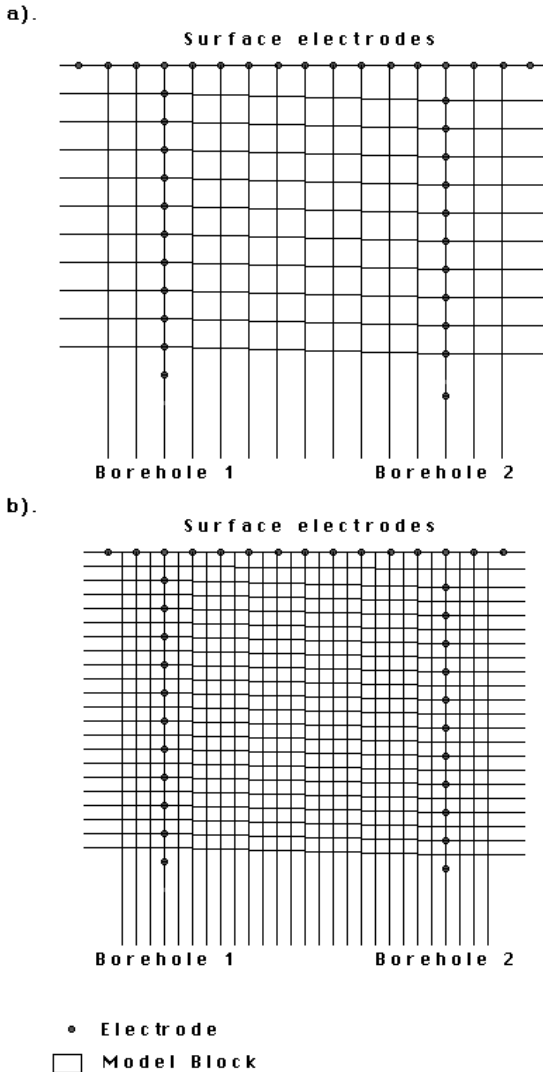


Figure 21. Arrangement of the electrodes in a cross-borehole survey. (a) The default Standard Model where the dimensions of the model blocks are equal to the spacing between the electrodes. (b) An alternative model with finer blocks with dimensions about half the spacing between the electrodes.

If only two electrodes are used in a measurement, only the x- and z-locations of the C1 and P1 electrodes are given in the data file (see the file BOREHIP.DAT

which also contains IP measurements). However, if all four electrodes are used, the x- and z-locations of the C1, C2, P1 and P2 electrodes must be given in this order. You can combine measurements made with different numbers of electrodes in the same data file.

When the programs reads in a file with resistance values, you have a choice of inverting the data set using apparent resistivity values, or directly use the resistance values. Using resistance values directly in the inversion has the advantage of allowing you to use readings where the apparent resistivity value does not exist, or is negative. After reading in a data file, the program will attempt to filter out suspicious readings with potentially high noise levels if the measurements are given as apparent resistivity values, or if you had chosen the option to use apparent resistivity values in the inversion. If you choose to carry out the inversion using resistance values, the readings are not filtered.

The geometric factor for subsurface electrodes is different from that used for surface electrodes. As an example, the geometric factor for a measurement where only two electrodes is used is as follows. If the C1 and P1 electrodes are located at  $(x_1, z_1)$  and  $(x_2, z_2)$  respectively, the geometric factor  $k$  is then given by

$$k = 4 \pi i / (1/r_1 + 1/r_1')$$

where

$$\begin{aligned} r_1 &= \text{sqrt}(dx^2 + dz^2) & r_1' &= \text{sqrt}(dx^2 + Dz^2) \\ dx &= x_1 - x_2 & dz &= z_1 - z_2 \\ Dz &= z_1 + z_2 \end{aligned}$$

Similar equations for measurements with 3 or 4 electrodes can be easily obtained by adding the appropriate terms.

The depth of the electrodes in Borehole 1 can be different from the corresponding electrodes in Borehole 2. In practice, to get the best results the depths should not differ too much.

This program requires that the number of electrodes in both boreholes must be the same. In practice, this restriction is not a significant problem. You can be easily overcome this restriction by inserting dummy electrodes into the data set if the number of electrodes in one borehole is less (in the section where the x- and z-location of the electrodes in the borehole are given).

The program also requires that a surface electrode is located at the top of both boreholes. If they do not physically exist, just insert dummy electrodes at the appropriate locations in the data file. Also there should be at least a few surface electrodes between the two boreholes, as well as at least two surface electrodes to the left of borehole 1, and another two to the right of borehole 2. Again, if



the such electrodes were not used in the field survey, just insert dummy electrodes into the data file to satisfy the requirements of this program. One significant restriction of the present version of the program is that the boreholes must be vertical, i.e. inclined boreholes are not allowed. If there is a significant number of actual field surveys with inclined boreholes, this restriction might be removed in future versions of the program.

By default, the program will subdivide the subsurface into quadrilateral blocks such that the dimensions of the blocks are equal to the spacing between the electrodes (Figure 21a). However, you can also choose to use a model where the dimensions of the blocks is about half the spacing between the electrodes (Figure 21b). Using the model with a finer discretisation could significantly improve the inversion results in some cases (Sasaki 1992). To select the type of model to use, click the 'Change Settings' options on the Main Menu top bar, followed by 'Type of cross-borehole model'. In theory, it is possible to further subdivide the subsurface into even smaller blocks. However, since the resolution of electrical measurements decreases rapidly with distance from the measuring electrodes, this is unlikely to significantly improve the results. In fact, it could result in unnatural oscillations in the model resistivity values, particularly near the electrodes. This is as a result of the well known trade-off between model resolution and model variance in geophysical inversion.

Figure 22 shows the model obtained after the inversion of the BOREHOLE.DAT data set. This is a synthetic data set produced by a forward modelling program with a high resistivity block in between the two boreholes. The option to use finer blocks with half the size of the spacing between the electrodes was used in the inversion of this data set.

Figure 23 shows the inversion results from an interesting field data set. This data set is one from a number that were collected by a survey to study the flow of fluids through the UK Chalk aquifer in east Yorkshire by using a saline tracer (Slater et al 1997). There is a low resistivity zone near the surface where the saline solution was irrigated onto the ground, and also prominent low resistivity zones below a depth of 7 metres due to the saline tracer that had flowed downwards. Another interesting feature of this data set is that no surface electrodes were used. So all the surface electrodes given in the BORELANC.DAT data file are dummy electrodes. The inversion of this data set took about 15 minutes on a 200 Mhz Pentium Pro computer. the left of borehole 1, and another two to the right of borehole 2. Again, if the such electrodes were not used in the field survey, just insert dummy electrodes into the data file to satisfy the requirements of this program. One significant restriction of the present version of the program is that the boreholes must be vertical, i.e. inclined boreholes are not allowed. If there is a significant number

of actual field surveys with inclined boreholes, this restriction might be removed in future versions of the program.

If IP measurements were also made, you need to enter a value of 1 at the 6th line in the data file, and two more data lines after that which gives the type of IP measurement used and the two parameters associated with it (see Appendix F). Next, enter the IP value after the apparent resistivity value for each data point. The file BOREHIP.DAT is an example cross-borehole data file with IP measurements.

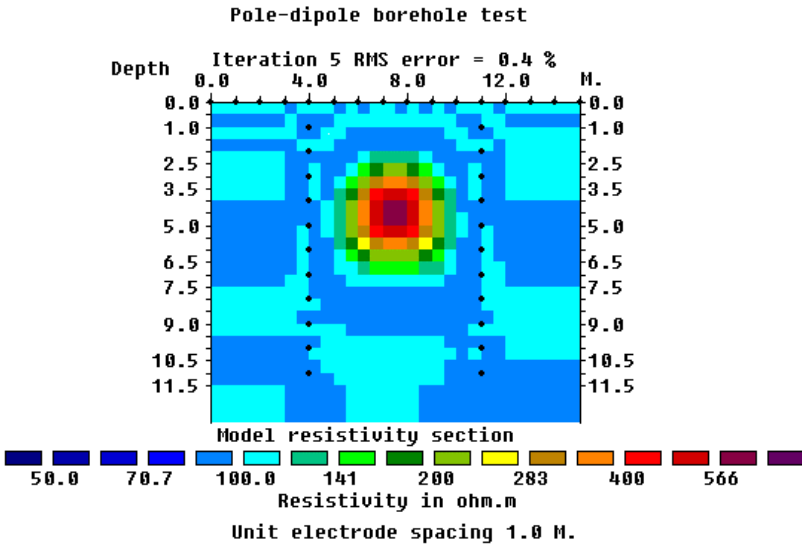


Figure 22. The model obtained after the inversion of the BOREHOLE.DAT data set. The option to use finer blocks with half the size of the spacing between the electrodes was used.

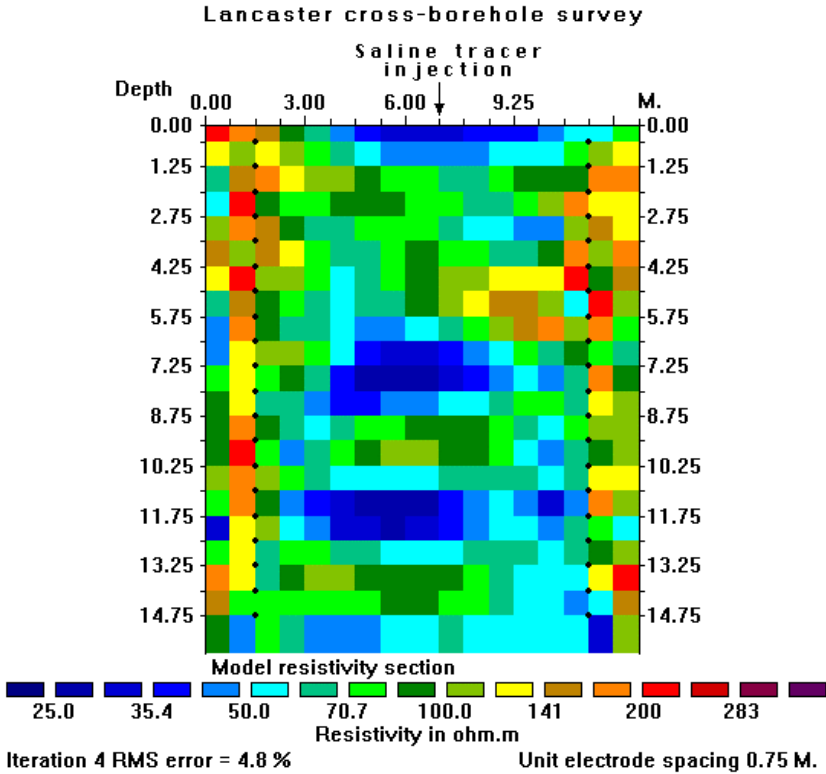


Figure 23. Model obtained from the inversion of data from a cross-borehole survey to map the flow of a saline tracer in between two boreholes. Note the low resistivity zones near the surface (where the tracer was injected) and below a depth of 7 metres. The locations of the borehole electrodes are shown by small black dots.

The RES2DINV program supports up to 10 boreholes (20 boreholes if your computer has at least 256 MB RAM) along a survey line. This limit might be increased in future when the need arises. A possible situation where more than 2 “boreholes” exists is when a current electrode is placed at the end of a borehole driller or penetrometer. The file BOREHOLE3.DAT gives an example of the data format with more than 2 boreholes. A description of the format is as follows.

<i>BOREHOLE3.DAT file</i>	<i>Comments</i>
Pole-dipole borehole test	Title
1.0	Smallest electrode spacing
12	Array number 12 for cross-borehole survey
908	Number of data points
2	2 to indicate XYZ location format is used
0	0 for no IP data
Surface Electrodes	Header for surface electrodes
16	Number of surface electrodes
0.0, 0.0	x- and z-location of first surface electrode
1.0, 0.0	location of second surface electrode
2.0, 0.0	Note location values are given for the
3.0, 0.0	electrodes in ascending order starting
4.0, 0.0	from the left.
5.0, 0.0	Note a zero value for the depth for the
6.0, 0.0	surface electrodes.
7.0, 0.0	
8.0, 0.0	
9.0, 0.0	
10.0, 0.0	
11.0, 0.0	
12.0, 0.0	
13.0, 0.0	
14.0, 0.0	
15.0, 0.0	
Number of boreholes	New header for more than 2 boreholes
3	Number of boreholes here
Borehole 1 Electrodes	Header for first borehole
11	Number of electrodes in first borehole
4.0 1.0	x- and z-location of first electrode
4.0 2.0	x- and z-location of other electrodes
4.0 3.0	
4.0 4.0	
4.0 5.0	
4.0 6.0	
4.0 7.0	
4.0 8.0	
4.0 9.0	
4.0 10.0	

```

4.0 11.0      |
Borehole 2 Electrodes | Header for second borehole
11           |
11.0 1.0     |
11.0 2.0     |
11.0 3.0     |
11.0 4.0     |
11.0 5.0     |
11.0 6.0     |
11.0 7.0     |
11.0 8.0     |
11.0 9.0     |
11.0 10.0    |
11.0 11.0    |
Borehole 3 Electrodes | Header for third borehole
11           |
13.0 1.0     |
13.0 2.0     |
13.0 3.0     |
13.0 4.0     |
13.0 5.0     |
13.0 6.0     |
13.0 7.0     |
13.0 8.0     |
13.0 9.0     |
13.0 10.0    |
13.0 11.0    |
Measured Data | The apparent resistivity values start after this
3  0.00 0.00 1.00 0.00 2.00 0.00 101.5718 | Note 3 electrodes for
3  0.00 0.00 2.00 0.00 3.00 0.00 99.5150  | a pole-bipole array
.
.
3  11.00 11.00 11.00 5.00 11.00 4.00 110.7175 | Last two data
3  11.00 11.00 11.00 4.00 11.00 3.00 118.4761 | points
0,0,0,0,0 | End with 5 zeros

```

Note that the format is essentially the same as that used earlier for two boreholes, except for the header after the list of surface electrodes and the value for the number of boreholes.

The file BOREHOLE\_TOPO.DAT is a field example of a cross-borehole data set with topography. The initial part of this data file with a description of the format is as follows.

<i>BOREHOLE TOPO.DAT file</i>	<i>Comments</i>
BOREHOLE WITH TOPOGRAPHY	Title
1.00000	Smallest electrode spacing
12	Array number 12 for cross-borehole survey
570	Number of data points
2	2 to indicate XYZ location format is used
0	0 for no IP data
Topography Present	Header to indicate topography is present
Topography information mode	(0=wrt to surface electrodes)   Header
0	Indicates depths of borehole electrodes are given wrt   the surface electrode at the top of the borehole
Type of x-distances	Header
2	2 to indicate x-distances are along the surface
Surface Electrodes	Header
31	Number of surface electrodes
-14.0000 0.00	x-location and elevation of first electrode
-13.0000 0.03	x-location and elevation of second electrode
-12.0000 0.05	Same for the rest
-11.0000 0.08	
-10.0000 0.11	
-9.0000 0.13	
.	
.	
15.0000 0.85	
16.0000 0.95	Last surface electrode
Borehole 1 electrodes	Header for first borehole
17	Number of electrodes in borehole
-14.0000 1.0000	x-location and depth of first borehole electrode
-14.0000 2.0000	x-location and depth of first borehole electrode
.	Same for the rest
.	The format is the same as for normal borehole data files

Note that the topography information is given in the z-coordinates of the surface electrodes.

### Appendix J - Remote electrodes of the pole-pole and pole-dipole arrays

In theory, the pole-pole array has only 2 electrodes, the positive current electrode C1 and the positive potential electrode P1. In practice such an array does not exist since all field measurements are made using an array with 4 electrodes (Figure 24).

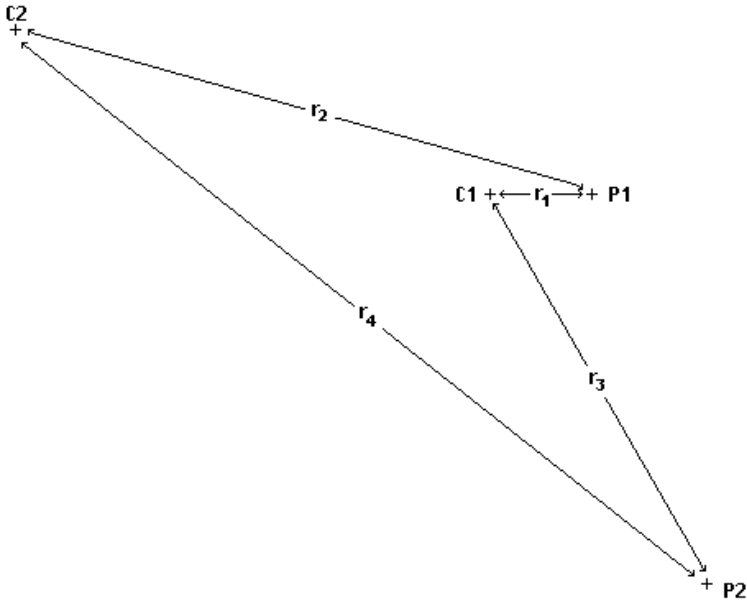


Figure 24. A schematic diagram of the arrangement of the electrodes in an actual field pole-pole measurement.

To minimise the effects of the C2 and P2 electrodes, it is generally recommended that the distance of these two electrodes from the C1 and P1 electrodes must be at least 10 times (and preferably 20 times) the C1-P1 spacing  $r_1$ . In some cases, when large spacings between the C1 and P1 electrodes are used, this requirement is not met for all measurements. This could lead to distortions in the inversion model (Robian et al. 1997). To overcome this problem, the RES2DINV program allows the user to incorporate the effects of the C2 and P2 electrodes in the inversion.

To calculate the apparent resistivity value measured with the non-ideal pole-pole array, two possible geometric factors can be used. One method is to use the same equation as the ideal pole-pole array. This gives an approximate geometric factor since the resulting apparent resistivity value is not the same as the true resistivity for a homogeneous half-space. Alternatively, the exact

geometric factor that takes into account the positions of the C2 and P2 electrodes can be used.

Approximate Geometric factor (ideal pole-pole array) =  $2 \cdot \pi \cdot r_1$

Exact Geometric factor =  $2 \pi / [ (1/r_1) - (1/r_2) - (1/r_3) + (1/r_4) ]$

The program supports both conventions.

A possible arrangement of the electrodes in a pole-pole survey is shown in Figure 25. In this case, the C2 and P2 electrodes are fixed throughout the survey. The measurements are made by using different pairs of electrodes along the survey line as the C1 and P1 electrodes. For a survey line with  $n$  electrodes, there are  $n(n+1)/2$  possible combinations. For example, if there are 25 electrodes in the survey line, there are 300 possible combinations. In practice, not all the possible measurements are made. Instead a maximum distance between the C1 and P1 electrodes is set depending on the maximum depth of investigation needed (Edwards 1977). In many cases, this maximum distance is 6 to 10 times the unit electrode spacing along the survey line. To avoid the possibility of negative or zero apparent resistivity values, the distance of the C2 and P2 electrodes must be at least 2.5 times (and preferably 3 times) the maximum C1 to P1 spacing used. For example, if the unit electrode spacing is 1 metre, and the maximum C1-P1 spacing is 10 metres, then the C2 and P2 electrodes must be at least 25 metres from the survey line. Note that as the distance of the C2 and P2 electrodes from the survey line decreases, the effective maximum depth of investigation of the survey also decreases. It might be significantly less than the depth of investigation for the ideal pole-pole array (Edwards 1977).

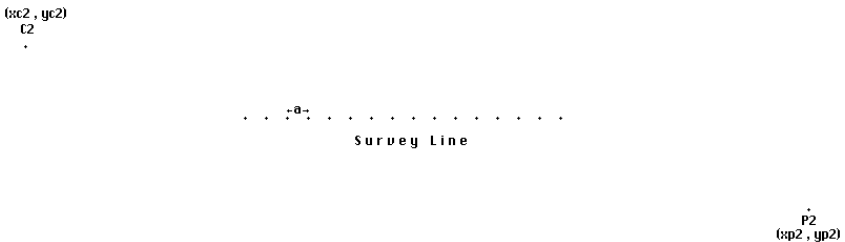


Figure 25. A schematic diagram of the arrangement of the C2 and P2 electrodes and the electrodes along the survey line in a pole-pole survey. To incorporate the effects of the C2 and P2 electrodes in the data inversion, their x- and y-coordinates with respect to the survey line must be recorded.



The file POLPOLFX.DAT is an example data file with pole-pole measurements where the locations of the C2 and P2 remote electrodes are specified. A description of the format used is given below in the comments section. Although the z-locations of the electrodes are also included in the file data format for completeness, the values are presently not used by the program. The program at present estimates the heights at the remote electrodes from the heights of the electrodes along the survey line. However, in future, they might be used to accommodate extreme cases where slope of the ground at the remote electrodes is very different from that along the survey line.

POLPOLFX.DAT file	Comments
Blocks Model	Title
2.00	Smallest electrode spacing
2	Array number 2 for pole-pole.
Remote electrodes included	Header to indicate position of remote electrodes included in data file
C2 remote electrode X, Y and Z location	Header for second current electrode location
-50.000,20.000,0.0	x-, y- and z-location of C2 electrode
P2 remote electrode X, Y and Z location	Header for second potential electrode location
120.000,0.000,0.0	x-, y- and z-location of P2 electrode
Exact Geometric factor used	Type of geometric factor used
295	Number of data points
1	1 to indicate x-location of centre of array is given
0	0 for no IP
1.00 2.00 10.13	The x-location, electrode spacing   apparent resistivity for first data point
3.00 2.00 10.18	Second data point

The data format is the same as that for normal pole-pole surveys except for the section (after the array number) which contains information about the location of the second current and potential electrodes. The data line “Exact Geometric factor used” is used to indicate that the apparent resistivity values in the data file were calculated using the exact geometric factor. If the approximate geometric factor was used, this data line should be given as “Approximate Geometric factor used”. The file POLDPLFA.DAT is an example data file for a pole-dipole survey where the approximate geometric factor was used in calculating the apparent resistivity values. Note that in this file, only the location of the second current electrode C2 is given.

For the pole-pole array, the effect of the C2 electrode is approximately proportional to the ratio of the C1-P1 distance to the C2-P1 distance. If the effects of the C2 and P2 electrodes are not taken into account, the distance of these electrodes from the survey line must be at least 20 times the largest C1-

P1 spacing used to ensure that the error is less than 5%. In surveys where the inter-electrode spacing along the survey line is more than a few metres, there might be practical problems in finding suitable locations for the C2 and P2 electrodes to satisfy this requirement. Thus the error in neglecting the effects of the remote electrodes is greatest for the pole-pole array. As a general guide, if the distances of the C2 and P2 electrodes from the survey line is more than 20 times the largest C1-P1 spacing used, the array can be treated as an ideal pole-pole array for interpretation purposes. Otherwise, the coordinates of the C2 and P2 electrodes should be recorded so that their effects can be determine by this program. However, it should be noted that as the distance of the P2 electrode from the survey line increases, the telluric noise picked up by the P1-P2 pair also increases. This factor should also be taken into account when positioning the P2 electrode.

For the pole-dipole array, the effect of the C2 electrode is approximately proportional to the *square* of ratio of the C1-P1 distance to the C2-P1 distance. Thus the pole-dipole array is less affected by the C2 remote electrode. If the distance of the C2 electrode is more than 5 times the largest C1-P1 distance used, the error caused by neglecting the effect of the C2 electrode is less than 5% (the exact error also depends on the location of the P2 electrode for the particular measurement). So, as a general guide, if the distance of C2 electrode from the survey line is more than 5 times the largest C1-P1 spacing, it can be treated as an ideal pole-dipole array. Otherwise, enter the coordinates of the C2 electrode into the data file.

### Appendix K : Robust data and model inversion

The conventional least-squares method will attempt to minimise the *square* of difference between the measured and calculated apparent resistivity values. This method normally gives reasonable results if the data contains random or “Gaussian” noise. However if the data set contains “outlier” data points (where the noise comes from non-random sources such mistakes or equipment problems), this criteria is less satisfactory. Such “outlier” data points could have a great influence on the resulting inversion model. To reduce the effect of such “outlier” data points, an inversion method where the *absolute* difference (or the *first* power) between the measured and calculated apparent resistivity values is minimised can be used (Claerbout and Muir 1973).

In the RES2DINV program, this inversion method can be selected by clicking the “Select robust inversion” option under the “Change settings” menu. In the “Select robust inversion” dialog box, click the “Robust data constrain” option. There is a cut-off factor which controls the degree in which this robust data constrain is used. If a value of 0.05 is used, this means the effect of data points where the differences in the measured and calculated apparent resistivity values are much greater than 5 percent will be greatly reduced.

The conventional smoothness-constrained least squares method (deGroot-Hedlin and Constable 1990) also attempts to minimise the *square* of the changes in the model resistivity values. This will produce a model with a smooth variation in the resistivity values. Such a model is most suitable where subsurface resistivity also changes in a smooth manner, such as the pollution plume example shown in Figure 3. However if the subsurface bodies have sharp boundaries, such as the soil-bedrock interface or massive homogeneous bodies, the conventional least-squares smoothness-constrain method tends to smear the boundaries.

If the robust model constrain inversion method is used on the model resistivity values, the program will attempt to minimise the *absolute* changes in the resistivity values. This constrain tends to produce models with sharp interfaces between different regions with different resistivity values, but within each region the resistivity value is almost constant. This might be more suitable for areas where such a geological situation exists, such as the soil-bedrock interface over certain types of bedrock. As an example, Figure 26 shows the inversion results for a synthetic model with a faulted block (with a resistivity of 50 ohm.m) and a small rectangular block (1 ohm.m) within a surrounding medium with a resistivity of 10 ohm.m. The model produced by the standard least-squares method has a gradational boundary for the faulted block. In comparison, the model produced by the robust model inversion method has sharper and straighter boundaries.

A field example with sharp boundaries was shown earlier in Figure 20 for the Magusi River resistivity and IP data set. The main structure, the massive sulphide ore body, by nature has a distinct and sharp resistivity/IP contrast with the surrounding igneous/metamorphic country rocks.

In the RES2DINV program, this robust model option can be selected by clicking the “Robust model constrain” option in the “Select robust inversion” dialog box. There is a cut-off factor which controls the degree in which this robust model constrain is used. If a large value is used, for example 1.0, the result is essentially that of the conventional smoothness-constrained least-squares inversion method. If a very small value is used, for example 0.001, the result is close to the true robust constrained inversion method.

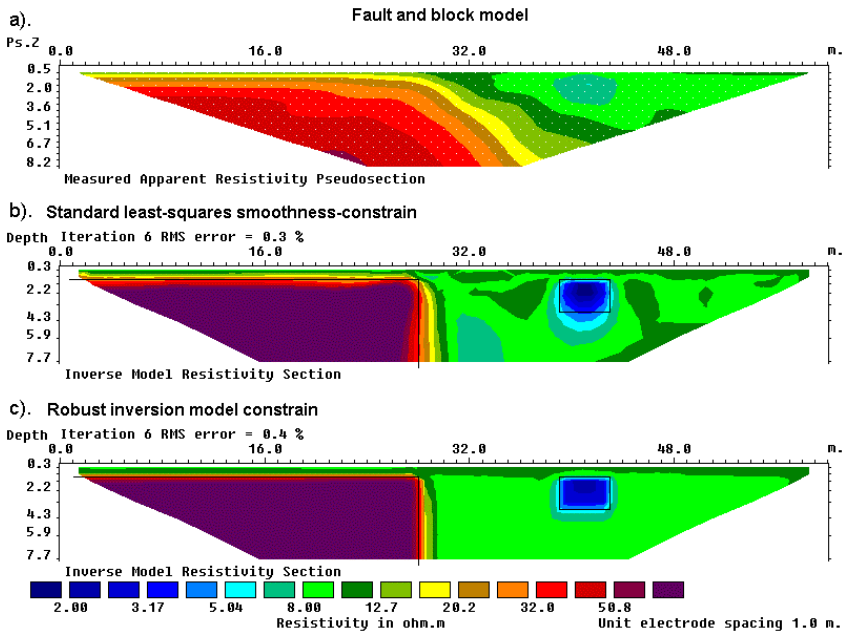


Figure 26. Example of inversion results using the smoothness-constrain and robust inversion model constrains. (a) Apparent resistivity pseudosection (Wenner array) for a synthetic test model with a faulted block (100 ohm.m) in the bottom-left side and a small rectangular block (2 ohm.m) on the right side with a surrounding medium of 10 ohm.m. The inversion models produced by (b) the conventional least-squares smoothness-constrained method and (c) the robust inversion method.

### Appendix L : Non-conventional or general arrays

This feature is to cater for electrode arrangements that do not fall under the usual array types or electrode arrangements, or unusual ways of carrying out the surveys. There are probably an infinite number of possible electrode configurations that are limited only by the imagination of the user, but in most cases they are likely to be slight variations of the standard arrays. Figure 27 shows four possible non-standard configurations.

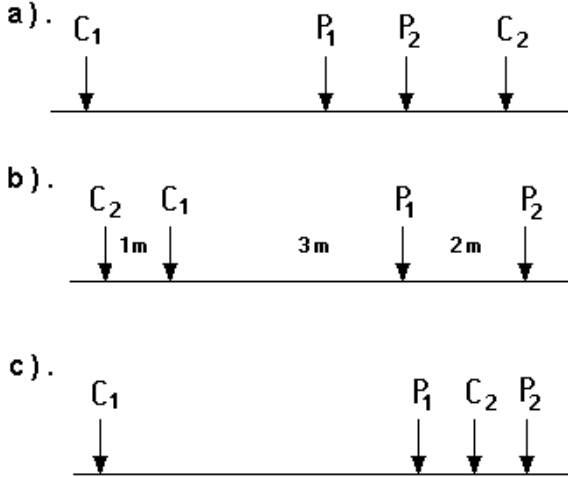


Figure 27. Some possible non-conventional arrays. (a) Non-symmetrical four-electrode Wenner-Schlumberger type of array. (b) Dipole-dipole array with dipoles of unequal size. (c) A possible but probably non-viable electrode configuration.

One possibility is a non-symmetrical variation of a symmetrical array, such as the Wenner-Schlumberger or the dipole-dipole array (Figures 27a and 27b). Such a configuration could arise from surveys with multi-channel resistivity meters where measurements are made with several pairs of potential electrodes for a common pair of current electrodes.

While the program gives the user greater latitude in the electrode arrangement, some arrays that are technically possible but would have very low potential signals should be avoided.

To accommodate the various possibilities, a data format which is similar to that used for cross-borehole surveys (Appendix I) is used. The x-location as well as the elevation of all the electrodes used in a measurement must be given. The file MIXED.DAT is an example data file with such a format. This is actually a synthetic data set with a mixture of measurements using the Wenner-

Schlumberger and dipole-dipole arrays. The initial part of this data file with comments about the format is given below.

<i>MIXED.DAT file</i>	<i>Comments</i>
Mixed array	Title
1.0	Unit electrode spacing
11	Array type (11 for general array)
0	Sub-array type
Type of measurement (0=app. resistivity, 1=resistance)	Header
0	0 here to indicate apparent resistivity values
407	Number of data points
1	Indicator for type of x-location
0	No IP values, 1 if I.P present
4 0.00 0.00 3.00 0.00 1.00 0.00 2.00 0.00 10.158	The format for each data point is
4 1.00 0.00 4.00 0.00 2.00 0.00 3.00 0.00 10.168	Number of electrodes used in
4 2.00 0.00 5.00 0.00 3.00 0.00 4.00 0.00 10.184	measurement, x- and z-location of
4 3.00 0.00 6.00 0.00 4.00 0.00 5.00 0.00 10.225	C1 electrode, x- and z-location of
4 4.00 0.00 7.00 0.00 5.00 0.00 6.00 0.00 10.337	C2 electrode, x- and z-location of
4 5.00 0.00 8.00 0.00 6.00 0.00 7.00 0.00 10.708	P1 electrode, x- and z-location of
4 6.00 0.00 9.00 0.00 7.00 0.00 8.00 0.00 11.668	P2 electrode, apparent resistivity
4 7.00 0.00 10.00 0.00 8.00 0.00 9.00 0.00 12.542	or resistance value.

The sub-array type indicator is used when the electrode configuration follows one of the conventional arrays, for example the Wenner-Schlumberger array. As an example, the file MIXEDWS.DAT has the data for a Wenner-Schlumberger array only but the information is arranged in a general array format. In this case the sub-array number is 7. The file RATHCMIX.DAT has the data for the Rathcrogan mound (described earlier in Figure 8) for the Wenner array but in a general array format (thus it has sub-array number of 1). For these data sets, the apparent resistivity values can be displayed in the form of a pseudosection. The file MIXED.DAT is a combined data set with a mixture of measurements with the Wenner-Schlumberger and dipole-dipole array. In this case, there is no consistent array type, so the sub-array number is given as 0.

Concerning the indicator for the type of x-location, there are two possible values. A value of 1 is used if the x-location values are the true horizontal distances, while a value of 2 is used if it is the distance along the ground surface. This is similar to the convention used for topography data (Section 7).

In the RATCMIX.DAT file, the topography information is included as the elevation for each electrode in every data line. In some cases, it might be more convenient to enter the topography information in a separate list, much like for data in the normal format. One example with data in the general array format but with the topography in a separate list after the apparent resistivity data lines is given in the file ITALY\_CAVE.DAT. Part of the file is shown below.

<i>ITALY CAVE file</i>	<i>Comments</i>
Italy cave survey	Title
1.00	Unit electrode spacing
11	Array type (11 for general array)
3	Sub-array type (dipole-dipole)
Type of measurement (0=app. resistivity.1=resistance)	Header
0	0 here to indicate apparent resistivity values
584	Number of data points
2	Indicator for type of x-location (surface   distance)
1	Note presence of I.P. data
Chargeability	IP data in chargeability
mV/V	IP unit
0.16,0.5	IP measurement parameters
4 2.00 0.00 0.00 0.00 4.00 0.00 6.00 0.00 126.16 0.23	First 2 data lines
4 2.00 0.00 0.00 0.00 6.00 0.00 8.00 0.00 169.15 -2.80	Note 0.0 for elevation
.	Other data lines
.	
4 88.00 0.00 86.00 0.00 92.00 0.00 94.00 0.00 44.73 1.71	Last 2 data lines
4 90.00 0.00 88.00 0.00 92.00 0.00 94.00 0.00 42.93 1.37	
Topography in separate list	Header to indicate the topography information
2	is in a separate list after the data lines. Format
85	for topography data is same as for data in
0.94,158	normal format. First 2 topography points.
2,94,269	
.	Other topography data points
.	
94,101.948	Last 2 topography data points
95,102.062	
1	Indicates first electrode coincides with first
0	topography point
0	Ends with a few zero's
0	

Note the addition of a header line “Topography in separate list” that indicates the topography information is in a separate list after the apparent resistivity data lines. Note also in the data lines, the elevation for each electrode is given as 0.00. The program will calculate the elevation for the electrodes from the topography information.

The measurement can be given in terms of resistance or apparent resistivity. If there is no topography, i.e. the z-locations are all equal to zero or the same, the conventional formula can be used to calculate the apparent resistivity. The geometric factor  $k$  is given by the following equation

$$k = 2 \pi / (1/r1 - 1/r2 - 1/r3 + 1/r4)$$

where  $r_1$  is the distance between the C1 and P1 electrodes,  $r_2$  is the distance between the C1 and P2 electrodes,  $r_3$  is the distance between the C2 and P1 electrodes and  $r_4$  is the distance between the C2 and P2 electrodes. In the case when there is no topography, the distance between two electrodes is simply the difference in the x-locations of the two electrodes.

In the case where topography is present, there is no widely accepted convention. To be consistent with the format used earlier, two different conventions are used depending on the type of x-location given in the data file. If the x-locations are given as distances along the surface (i.e. not true horizontal distances), the distance between two electrodes is calculated by using the difference in the values of the x-locations only.

If the x-locations are true horizontal distances, the true distance between two electrodes is used in the calculation of the geometric factor. For example, if the C1 and P1 electrodes are located at  $(x_1, z_1)$  and  $(x_2, z_2)$  respectively, then

$$r_1 = \sqrt{dx^2 + dz^2}$$

where

$$dx = x_1 - x_2$$

$$dz = z_1 - z_2$$

In the case where the ground surface has a constant slope, both conventions will give the same geometric factor.

Note that in the general array data format, the z-location is the elevation of the electrode which is positive in the upwards direction. This unfortunately is different from the format for the borehole data set where the z-values are positive in the downwards direction.

Figure 28 shows an interesting arrangement where the electrodes are arranged such that the *true horizontal* distances between adjacent electrodes are constant. When the slope of the ground surface is not constant, this results in an arrangement where the distance between adjacent electrodes as measured along the ground surface is not constant but depends on the slope. In areas where the slope is steeper, the distance between adjacent electrodes along the ground surface is greater. To accommodate such an arrangement, the general array format can be used. In this case, the indicator for the type of x-location must be 1 since the true horizontal distances are given in the data. Very often, the survey is carried out with one of the conventional arrays, such as the Wenner-Schlumberger, so the appropriate sub-array number should also be given.



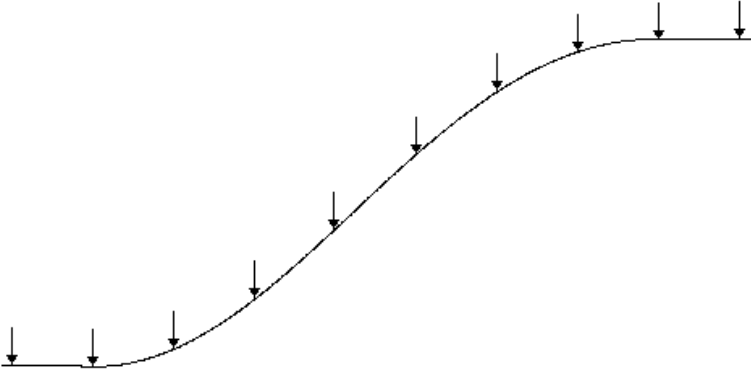


Figure 28. Arrangement of the electrodes along a survey line such that the true horizontal distance between adjacent electrodes is constant regardless of the slope of the ground surface. Note that the distance between adjacent electrodes along the ground surface is greater at the steeper part of the slope.

In some cases, the 2-D data set is generated from a series of collinear 1-D sounding lines. In such a situation, the distance between adjacent electrodes is not constant, whether as measured along the surface or in the true horizontal direction. For such a case, the general array format (with a sub-array type of 0) can be used.

For data sets with a sub-array type of 0, the data cannot be displayed in the form of a pseudosection, nor can it be edited with the "Exterminate bad data points" option. To remove bad data points from the data set, you need to first carry out an inversion of the entire data set. However, you need to use the "Robust data constrain" (see Appendix K) to ensure that bad data points do not have a large effect on the inversion results. Next, go to the "Display" window and read in the file with the inversion results. Select the "RMS error statistics" sub-option under the "Edit data" menu. This will display a histogram where the data points are grouped according to the difference between the measured and calculated apparent resistivity values. This allows you to remove the data points where a large difference occurs, for example more than 100 percent. After removing the more noisy data points, save the trimmed data set in a file and carry out the inversion again with the trimmed data set.

The suboption "Generate model blocks" under the "Inversion" option on the main menu allocates the arrangement of the blocks in the model using the sensitivity values as a guide. Figure 29 shows the sensitivity values of the MIXEDWS.DAT data set using the default extended model, and for the "Generate model blocks" option. Note that this option increases the width of the blocks near the sides in the deeper parts of the model section in order to increase the sensitivity values of the blocks. This option can also be used for

normal data sets with the standard arrays. By default, the program uses a heuristic algorithm partly based on the position of the data points to generate the size and position of the model blocks. The "Generate model blocks" uses a more quantitative approach based the sensitivity values of the model blocks. However, in practice, the simpler and faster heuristic algorithm gives reasonably good results for most data sets.

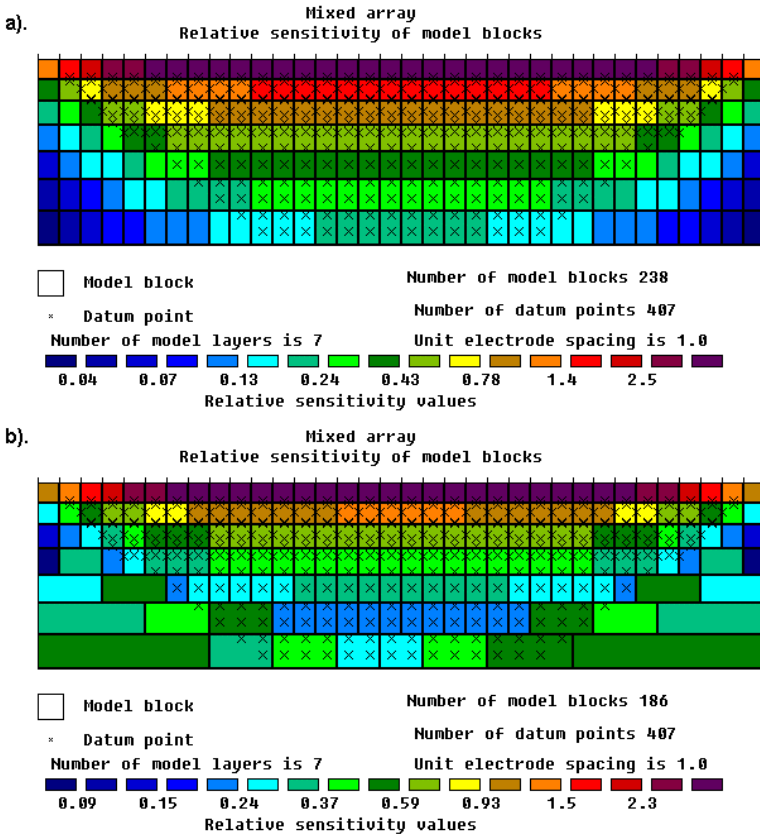


Figure 29. The arrangement of the model blocks used by the program for the inversion of the MIXEDWS.DAT data set using (a) the default extended model and (b) a model generated so that any single block the does not have a relative sensitivity value that is too small.

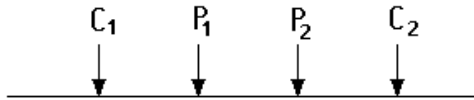
### Appendix M : Array types in RES2DINV

A list of the arrays supported by the RES2DINV program together with their number codes are given below.

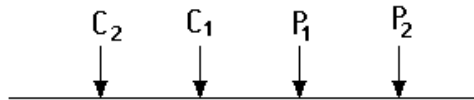
<u>Array name</u>	<u>Number code</u>
Wenner (alpha)	1
Pole-pole	2
Inline dipole-dipole	3
Wenner (beta)	4
Wenner (gamma)	5
Pole-dipole	6
Wenner-Schlumberger	7
Equatorial dipole-dipole	8
Non-conventional/General array	11
Cross-borehole survey (apparent resistivity values)	12
Cross-borehole survey (resistance values)	13
Gradient array (only used as sub-array number with data in the general array format)	15

Note that the Wenner array has three different variations (Figure 30). The "normal" Wenner array is actually the Wenner alpha array.

#### a) . Alpha



#### b) . Beta



#### c) . Gamma

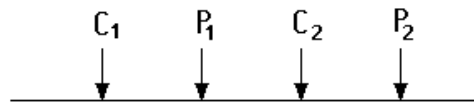


Figure 30. Arrangement of the electrodes for the Wenner alpha, beta and gamma arrays.

The Wenner beta array is a special case of the dipole-dipole array where the "n" factor is always 1. The RES2DINV program will automatically convert a Wenner beta array data file into a dipole-dipole array data set.

The Wenner gamma array is not frequently used but it has direct support in RES2DINV. The file GAMMA.DAT is an example data file for this array. A case history of a field survey in Africa using this array is given in section 18 of this manual.

## Appendix N – Saving results in SURFER format

This option allows the user to save the apparent resistivity pseudosections and model sections in the XYZ format used by the SURFER graphics 2-D plotting program. After reading in an INV file containing the inversion results in the 'Display' window, it is recommended that you display the pseudosections at least once before using the option to save the results in SURFER format. If the inversion file contains topographical data, such as the example RATCHRO.INV file provided with this software package, you will need to use select option 'Include topography in model display' to display the model section with the topography. After that, you can click 'Save data in SURFER format' option under the File menu. For the RATCHRO.INV file, the following dialog box will be displayed.

**Saving inversion results in SURFER format**

Please select iteration number

You can save the resistivity values directly or the logarithm of the resistivity values.

Save resistivity values directly

Save logarithm of resistivity values

SURFER provides two methods to blank out the area outside the region of interest. Please select one of the methods.

Use BLANK function

Use base map overlay method

Please select the sections which you want to save in SURFER format by clicking the appropriate buttons.

Type of section.	Available (?)
<input type="checkbox"/> Measured apparent resistivity	<input checked="" type="radio"/>
<input type="checkbox"/> Calculated apparent resistivity	<input checked="" type="radio"/>
<input checked="" type="checkbox"/> Model resistivity	<input checked="" type="radio"/>
<input type="checkbox"/> Model conductivity	<input checked="" type="radio"/>
<input type="checkbox"/> Model resistivity with topography	<input checked="" type="radio"/>
<input type="checkbox"/> Model conductivity with topography	<input checked="" type="radio"/>
<input type="checkbox"/> Measured apparent I.P.	<input type="radio"/>
<input type="checkbox"/> Calculated apparent I.P.	<input type="radio"/>
<input type="checkbox"/> Model I.P.	<input type="radio"/>
<input type="checkbox"/> Model I.P. with topography	<input type="radio"/>

In this dialog box, you can select the iteration number for which you want to save the inversion results. Also, you can choose to save the resistivity values directly, or the logarithm of the resistivity values which might be more suitable if the resistivity values have a large range. SURFER will plot the sections as a rectangular section. In many cases, especially a model section with topography, this might not be appropriate. To remove the sections outside of the model section, SURFER provides two methods of blanking part of the displayed contoured section. The default and normally better method is to use the Base

Map Overlay feature in SURFER. In the bottom half of the dialog box, all the various possible data or model sections are displayed. For a particular inversion file, not all the possible sections are available. For example, the RATHCRO.INV file does not have IP data, so the circles to the right of the dialog box are not checked. As an exercise, click the 'Model resistivity with topography' option for the RATHCRO.INV file. After clicking the OK button, the program will then save the various sections. For a particular section, the program will save 5 different files that are used for different functions in SURFER. As an example, follow the following steps to plot the resistivity (logarithm) model section with topography for the RATHCRO.INV file. The different files are provided in the RES2DINV software package.

- 1). Create contour file. Click 'Grid' on the top menu bar, and then 'Data' to read in the RATCHRO\_TOPRESLOG.DAT file. After reading in the data file, SURFER will show the 'Scattered Data Interpolation' dialog box. In the 'Grid Line Geometry' section, the number of lines that SURFER uses to interpolate the data values into a rectangular grid is shown. For this data set, the default values are probably 50 lines in the X direction and 6 lines in the Y direction. In most cases, you should increase the default values by a factor of 4 to 10 times to improve the accuracy of the interpolation. For this example, try changing the number of lines in the X and Y directions to 250 and 30 respectively (i.e. increase the default values by a factor of 5). The SURFER program will create a corresponding RATCHRO\_TOPRESLOG.GRD file. Next click 'Map' on the top menu bar and then 'Contour'. In the 'Contour' option, read in the RATCHRO\_TOPRESLOG.GRD file. Next the 'Contour Map' dialog box will be shown. In this dialog box, click the 'Fill Contours' option. Next click the 'Load' button, and then read in the RATCHRO\_TOPRESLOG.LVL file to set the contour values and colours. If you wish to display the colour scale and smooth the contours, click the 'Color Scale' and 'Smooth Contours' options. Next click OK.

- 2). Next you need to mask out sections of the contour display. In the 'Map' menu, click 'Load Base Map'. Choose the RATCHRO\_TOPRESLOG.BLN as the base map file. In the 'GS Blanking Import Options', just click OK. Do not use the 'Areas to Curves' option. Next press F2, and then click the 'Overlap Maps' option in the 'Map' menu. This will combine the contour map and the base blanking map into a single map. Select the overlay by clicking near one of the corners of the rectangle containing the contour map, and then select the 'Edit Overlays' command from the 'Map' menu. In the 'Edit Components' dialog box, click the 'Base' and then click 'Move to Front' button. Next hold down the CTRL key on the keyboard and click the overlay until the base map is selected (as shown by the status indicator 'Map:Base' near the bottom left corner of the screen). Next click the 'Draw' menu, and then choose the 'Fill Attributes' option. Select the blank or white colour as the colour for the fill

attributes. Next click the 'Line Attributes', and also select the white colour so that the overlay lines are not visible in the display.

3). Click the 'Post' command in the 'Map' menu, and then read in the RATCHRO\_TOPRESLOG\_POST.DAT file (which contains the location of the electrodes) in the 'Open Data' dialog box. After reading in this file, the 'Post Map' dialog box will be shown. In this dialog box, select the symbol shape and size and other options you want to use, and then click OK. After that, press F2, and then click the 'Overlay Maps' command in the 'Map' menu. Next click the figure and then the 'Edit Overlays' command in the 'Map' menu. Click 'Post' and the 'Move to Front', and the electrodes will be drawn on top of the model section.

After drawing the section in the SURFER window, you can use other options within SURFER to improve the model section, such as changing the font, labels, titles etc., before printing the results or exporting it to another format. SURFER supports a large variety of formats, including bit-mapped graphics formats such as PCX, BMP, GIF etc.; and well as vector-based formats such as the AUTOCAD DXF format.

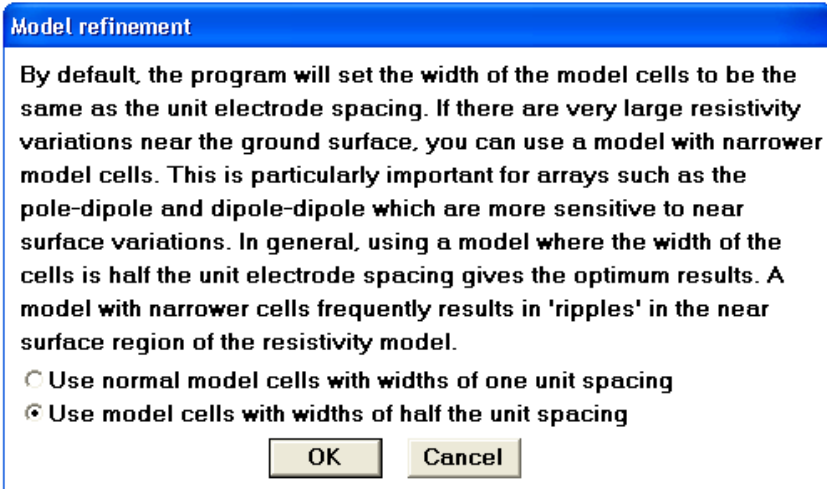
For model sections without topography, step (3) where the post data map is read is probably not necessary. However, you might need to adjust the tick marks on the vertical scale on the left side of the contour plot. The depths are given as negative values so that SURFER will plot the figure in the correct orientation with the ground surface on top. As an example, draw the model section for the Sting Cave example using the CAVE\_MODRESLOG.DAT, CAVE\_MODRESLOG.LVL and CAVE\_MODRESLOG.BLN files provided. After you have drawn the model section, it is likely that you will only see the 0.0 mark on the left vertical axis for the depth scale. Click the left axis with the right mouse button and the 'Left Axis' dialog box will be shown. Next click the 'Scaling' button in the dialog box. In the 'Axis Scaling' dialog box, change the 'Major Interval' value to 10 and the 'First Major Tick' to -40. Click OK to save the values, and the left axis model section should then show ticks at depth intervals of 10.

There will be slight differences in the contour sections drawn by SURFER and RES2DINV due to the differences in the interpolation methods used. SURFER does not use the original data points, but an interpolated rectangular grid of points to draw the contours. The differences will probably be more obvious in areas with very rapid changes in the resistivity. One way to reduce the differences is to increase the number of grid lines used by SURFER for the interpolation grid.

### Appendix O : Model refinement

The RES2DINV program by default uses a model where the width of the interior model cells is the same as the unit electrode spacing (for example as in Figure 2). This works well in most cases. In some situations, particularly where there are large resistivity variations near the ground surface, better results can be obtained by using narrower model cells. There are two possible ways to reduce the width of the model cells.

The first is by using the “Use model refinement” option on the ‘Inversion’ menu. Clicking this option will show the following dialog box.



This allows you to choose model cells with widths of half the unit electrode spacing. In almost all cases, this gives the optimum results. After selecting this option, you must read in the data file. The program will then automatically reduce the unit electrode spacing it uses by half of that given in the data file.

The second method is to modify the data file directly using a text editor. The unit electrode spacing is given in the second line of the apparent resistivity data file. For example, the first few lines of the PIPESCHL.DAT file are reproduced below.

Underground pipe survey

1.00

7

173

1

0



```
1.50  1.00  1  641.1633
```

In the second data line, the unit electrode spacing is given as 1.0 metre that is the actual spacing used in this survey. When the RES2DINV reads in this data file, it will set the width of the model cells to 1.0 metre. The file PIPESCHL\_HALF.DAT has the same data except that the unit electrode spacing is now defined as 0.5 metre. The upper part of this file is shown below.

Underground pipe survey - half actual electrode spacing

```
0.5
7
173
1
0
  1.50  1.00  1  641.1633
```

When the RES2DINV program reads this file, it will set the model cells to a 0.5 metre width. Figure 31 shows the inversion models for this data set using cells with widths of 1.0 and 0.5 metre. The model with the 0.5 metre cell width is able to more accurately model the high resistivity anomalies near the surface between the 3 and 12 metres marks above the low resistivity pipe, and thus has a slightly lower apparent resistivity RMS error. The Wenner-Schlumberger array was used for this survey.

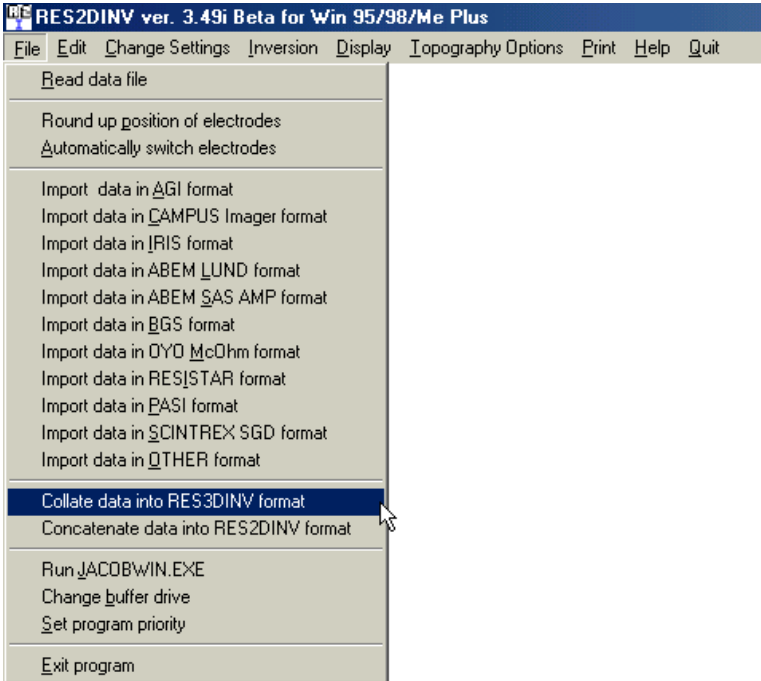
In most cases with large resistivity variations near the surface, using a model with a cell width of half the actual unit electrode spacing is sufficient. In some cases, using a narrower cell width of one-third or one-quarter the unit might be justified, particularly if the survey was carried out using a pole-dipole or dipole-dipole array with very high ‘n’ factors. If the cell width is one-quarter the true unit electrode spacing, or less, oscillations in the model resistivity values in the first few layers can occur. Thus the use of a cell width of less than one-quarter the true unit electrode spacing is not advisable.

It is recommended that you refer to section 4.7j of the free notes “Tutorial : 2-D and 3-D electrical imaging surveys” that can be downloaded from the [www.geoelectrical.com](http://www.geoelectrical.com) web site. This section has a discussion on the effect of using high ‘n’ factors with the pole-dipole array on the sensitivity of the array to near-surface anomalies.



## Appendix P : Combining 2-D files

The RES2DINV program has 2 options for combining 2-D data files. In one option, intended for a series of parallel survey lines, you can combine a number of 2-D data files into a single 3-D data file. This is the “Collate data into RES3DINV format” option under the “File” menu. In the second option, intended for several roll-along survey lines, you can combine them into a single 2-D data file. This is the “Concatenate 2-D data files” option under the “File” menu.



### *Collate data into RES3DINV format*

Ideally, a 3-D survey should be carried out using a rectangular grid of electrodes with measurements in different directions (Loke and Barker 1996b). However, for various reasons, this is sometimes not possible. In some surveys a number of parallel 2-D survey lines, with possibly some tie lines in a perpendicular direction, are used. This option enables the user to combine the 2-D lines with data in the RES2DINV format into a single data file in the format used by the RES3DINV program. While the RES3DINV program will carry a true 3-D inversion (in that the resistivity values are allowed to vary in all 3 directions simultaneously during the inversion process), whether the data set contains sufficient 3-D information so as to produce a reasonably accurate 3-D model is a different matter. A discussion of the

various factors that influence the amount of 3-D information in a data set is given by Loke (2001).

A script file is used to combine the 2-D files. The file COLLATE\_2D\_3D.TXT is an example script file. The contents of this file together with a description of the format used is given below.

<u>COLLATE 2D 3D.TXT file</u>	<u>Comments</u>
Conversion of RES2DINV data files	Title
Number of files to collate	Header for no. of data files
3	Number of data files
File 1 parameters	Header for first file
Name of data file in RES2DINV format	Header for name of file
d:\test\FILE2D_1.DAT	Full name plus path of file
X and Y location of first electrode along this line	Header
0.0,0.0	Coordinates of the first electrode
Line direction (0=X,1=Y)	Header
0	Number specifying line direction
Line sign (0=positive,1=negative)	Header
0	Specify whether electrode   coordinates increase or decrease   along line
File 2 parameters	Same set of parameters
Name of data file in RES2DINV format	for second file
d:\test\FILE2D_2.DAT	
X and Y location of first electrode along this line	
0.0,-0.5	
Line direction (0=X,1=Y)	
0	
Line sign (0=positive,1=negative)	
0	
....	Same for third
....	file
Name of Output file in RES3DINV format	Header
d:\test\FILE_3D.dat	Name of 3-D data file
End of file	Header for end of file

The format used allows for the possibility that the survey had lines in 2 perpendicular directions.

A 2-D survey line has only one horizontal direction, and the coordinate of an electrode along the survey line is given as the distance along the line, starting from the first electrode. To determine the coordinate of the electrode in the X-Y plane for a 3-D survey, we need to determine the coordinate of the first electrode in the 2-D survey line within the X-Y survey grid. This gives a reference point for which the coordinates of the other electrodes along the same survey line can be calculated.

Secondly, it is necessary to know the orientation of the line, i.e. whether is along the X-direction or Y-direction in the X-Y grid. Note that diagonal lines are not allowed.

In a 2-D survey line, it is always assumed that the coordinate of the electrode always increases starting from the first electrode (i.e. from left to right in a typical pseudosection). However, the direction of increasing coordinate value along the 2-D survey line might not always be the same as the positive X or Y direction in the 3-D survey X-Y grid. The 'Line sign' parameters allows for the possibility that the direction of the 2-D survey line is opposite to the direction of the positive X or Y axis in the X-Y grid.

While it is possible to combine a number of 2-D lines into a 3-D data set, it might not always be worthwhile to do so. Firstly, it is recommended that there should be at least 5 parallel lines. Furthermore, the separation between the lines should not be more than twice the unit electrode spacing along the lines. For further details, please refer to Chapter 8 of the free "Tutorial : 2-D and 3-D electrical imaging surveys" by M.H.Loke. If you do not have a copy, it can be downloaded from the [www.geoelectrical.com](http://www.geoelectrical.com) web site.

### ***Concatenate data into RES2DINV format***

This option enables the user to combine roll-along data files measured along the same line into a single data file. All of the electrodes used in the survey lines line along a single straight line. The file CONCATENATE\_2D.TXT an example script file. The contents of this file together with a description of the format used is given below.

<u>CONCATENATE 2D.TXT file</u>	<u>  Comments</u>
Concatenation of several data files in RES2DINV	Title
Number of files to concatenate	Header
3	Number of data files
File 1 parameters	Header
Name of data file in RES2DINV format	Header
c:\data\file1.DAT	Full name plus path of file
X location of first electrode along this line	Header
0.0	Coordinate of the first electrode
Line sign (0=positive,1=negative)	Header
0	Specify whether electrode   coordinates increase or decrease   along line
File 2 parameters	Similar information for 2nd and 3rd   files follow
Name of data file in RES2DINV format	
c:\data\file2.DAT	
.....	
.....	

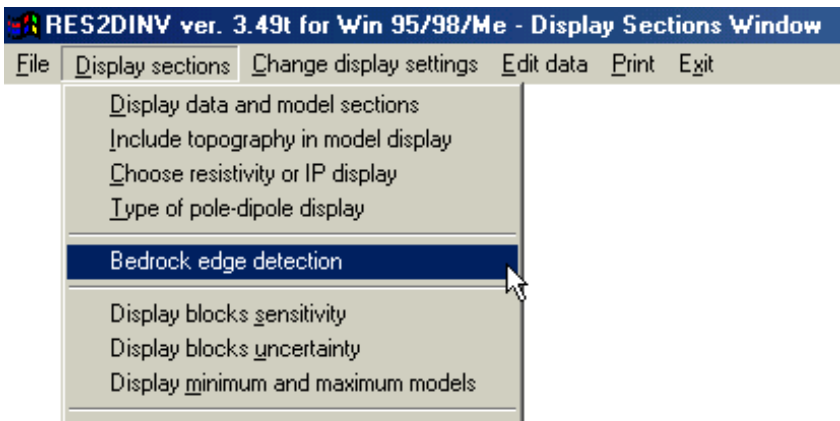
Name of Output file in RES2DINV format	Header
c:\data\file_123.DAT	Name of file to store combined data
End of file	

In some resistivity meter multi-electrode systems, each new record starts with a zero location for the first data electrodes. In order to combine different data files, the  $x$ -locations of the data points in some of the files will have to be shifted so that all of them have a common origin. In the above script file format, this is done by entering the coordinate of the first electrode for the survey line. In most cases, the direction of the lines are the same, for example the  $x$ -locations increase from the left to the right. However, an option is provided where the survey lines were measured in different directions.

### Appendix Q : Bedrock edge detection

In this option, the program attempts to pick the bedrock interface from the model section and saves the  $x$  and  $y$  coordinates in an ASCII file. This method is most successful where the bedrock has a sharp interface with the overlying soil. One typical situation is shown in Figure 32. This survey was conducted to map the a diorite bedrock with an intention of extending an existing quarry (Turnbull 1986). The overburden has resistivities of less than 100 ohm.m while the diorite has a resistivity of up to several hundred ohm.m.

The bedrock edge detection function is available within the 'Display' window, as shown below.



On clicking this menu option, the model section will first be drawn, and then the following dialog box is shown. On clicking the 'Edge detection' dialog is shown.

There are 3 main parameters that the user need to select. The first is to set upper and lower limits for the location of the boundary. By default, the program will set them from 0 m. (on the ground surface) until the maximum depth extent of the inversion model. In most cases, the upper limit is commonly changed, particularly where there are large resistivity anomalies near the surface (for example boulders). In this particular example, the minimum depth is set at 15 m. for the bedrock interface.

The second important parameter is a minimum value for the bedrock. In this example, a value of 150 ohm.m was chosen that probably corresponds to partially weathered diorite. The third parameter is the maximum change in the bedrock depth between adjacent electrodes. This is to prevent spikes in the bedrock profile.

In most cases, the default values for the other parameters should work well. By default, it is assumed that the bedrock has a higher resistivity than the overburden. However, a provision is made for cases where the bedrock or a subsurface layer of interest has a lower resistivity.

**Edge detection**
✕

**The depth range of your model is 84.872**

**Please enter the upper and lower limit of the depth where the bedrock is likely to be found.**

Upper limit :-  Lower limit :-

**Please enter the bedrock resistivity value.**

**Do you want to use the maximum gradient as the marker for the edge of the bedrock?**

No                       Yes

**Please select the type of change of the resistivity across the bedrock boundary.**

Increases       Decreases       Either

**Do you want to use the first or last boundary that the program finds?**

Last                       First

**Please enter the maximum change in bedrock depth between adjacent electrodes.**

For most situations, the robust model inversion option should be used (Appendix K). This normally produces a sharper bedrock boundary in the inversion model. Also, a model where cells have widths of half the actual unit electrode spacing (Appendix O) is recommended. For example the Stud Farm survey was conducted with a unit electrode spacing of 25 m., but inversion model below uses smaller cell widths.



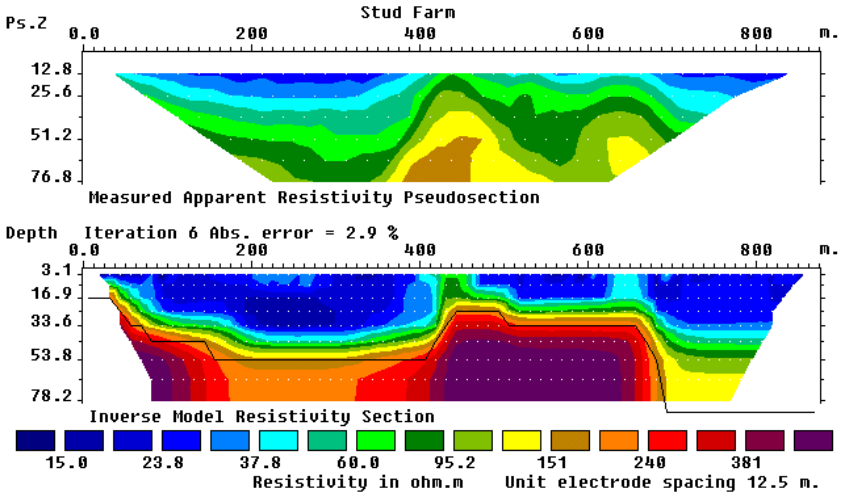


Figure 32. Apparent resistivity pseudosection from the Stud Farm survey together with the inversion model. The interpreted bedrock profile is also shown. Note that the bedrock on the right end of the line is below the maximum depth of investigation of the survey line.

### Appendix R : Time-lapse resistivity inversion

In studying the changes of the subsurface resistivity with time, two-dimensional resistivity imaging surveys are often repeated over the same line at different times. Such studies include the flow of water through the vadose zone, changes in the water table due to water extraction (Barker and Moore 1998), flow of chemical pollutants and leakage from dams.

For time-lapse experiments, the changes in the subsurface resistivity are estimated by using changes in the apparent resistivity measurements. Thus accurate results can only be obtained if the apparent resistivity values themselves are sufficiently accurate. It is best to avoid using the dipole-dipole and pole-dipole arrays in such experiments if larger spacings are used due to the relatively low signal to noise ratios. It might be safer to use the Wenner array or preferably the Wenner-Schlumberger array. Otherwise, strange results might be obtained.

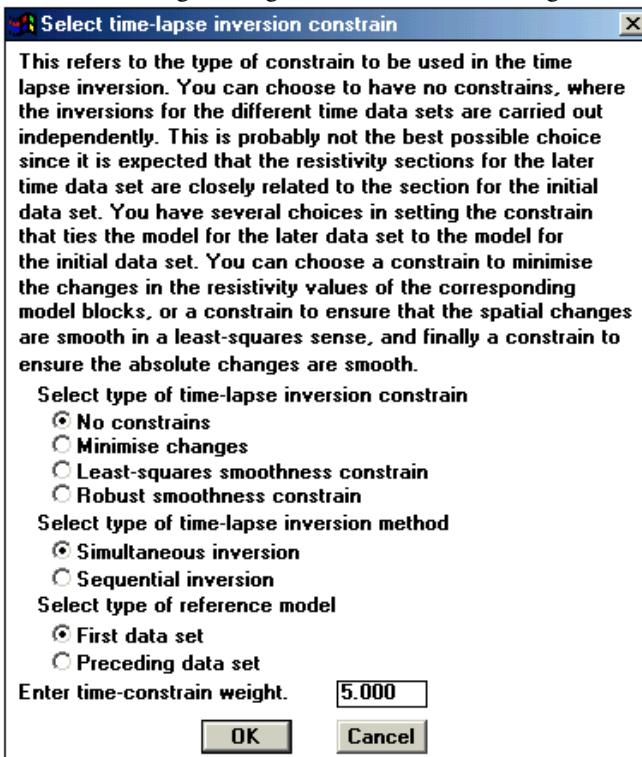
The file TIMELAPS.DAT is an example data file with 3 sets of apparent resistivity data. The upper part of the file together with comments about the data format is as follows.

<i>TIMELAPS.DAT file</i>	<i>Comments</i>
Example time-lapse data	Title
1.00	Unit electrode spacing
7	Array type, Wenner-Schlumberger in this   example
350	Number of datum points
1	Mid-point of x-location of array is given
0	No I.P. data
Time sequence data	Header to indicate time-lapse data
Number of time sections	Header
3	Number of time series
Time unit	Header
Hours	Unit used in time measurement
Second time section interval	Header
1.0	Time difference for second time data set
Second time section interval	Header
2.0	Time difference for third time data set
1.50 1.00 1.0 11.868 11.868 11.868	The format for each datum point is as follows :
2.50 1.00 1.0 11.867 11.867 11.867	x-location, "a" electrode spacing, "n" factor,
3.50 1.00 1.0 11.863 11.863 11.863	apparent resistivity for first data set, apparent
4.50 1.00 1.0 11.859 11.860 11.860	resistivity for second data set,
5.50 1.00 1.0 11.855 11.856 11.856	apparent resistivity for third data set.
6.50 1.00 1.0 11.851 11.851 11.851	

The data format is largely similar to the normal data set with only one set of readings. For a time-lapse data file, the main difference is the extra section just

before the data block with the apparent resistivity values. Here the header "Time sequence data" is used to indicate the presence of the extra data sets corresponding to the later time measurements. The following part of this extra section contains information on the number of time series measurements (3 in this example). The maximum number of time series data sets allowed is 12 if the computer has at least 256 MB RAM, and 6 if the memory available is less. For each data point, the format for the initial part is identical to that used for the normal data sets. The only addition is that after the apparent resistivity value for the first data set, the corresponding apparent resistivity values for the later time data sets are given.

This program allows the use of joint inversion techniques using different types of cross model constrains. When you select the "Select time-lapse inversion method" under the "Change settings" menu, the follow dialog box is shown.



In the first set of options in the dialog box, several possible constrains which guides the inversion process for multi-time data sets provided. Frequently, the data from time-lapse surveys conducted at different times are inverted independently. This method corresponds to the "No constrains" option in the above dialog box. The changes in the subsurface resistivity values are then

determined by comparing the model resistivity values obtained from the inversions of an initial data set and the later time data sets. In many cases, such an approach has given satisfactory results. However, in theory since the inversion of each data set is carried out independently, there is no guarantee that the differences in the resistivity values are only due to actual changes in the subsurface resistivity with time.

In this program, a joint inversion technique that uses the model from the initial data set to constrain the inversion of the later time data sets is used to minimise possible distortions (Loke 1999). The initial data set inversion model is used as a reference model in the inversion of the later time-lapse data sets. In the "Minimise changes" option, a simple damped least-squares constrain to minimise the differences in the model resistivity values between the initial model and the time-lapse model is used. The "Least-squares smoothness constrain" option uses a least-squares smoothness constrain to ensure that the differences in the model resistivity values vary in a smooth manner. Finally, in the "Robust smoothness constrain" option, a robust (Claerbout and Muir 1973) smoothness constrain which minimises the absolute changes in the model resistivity values is used.

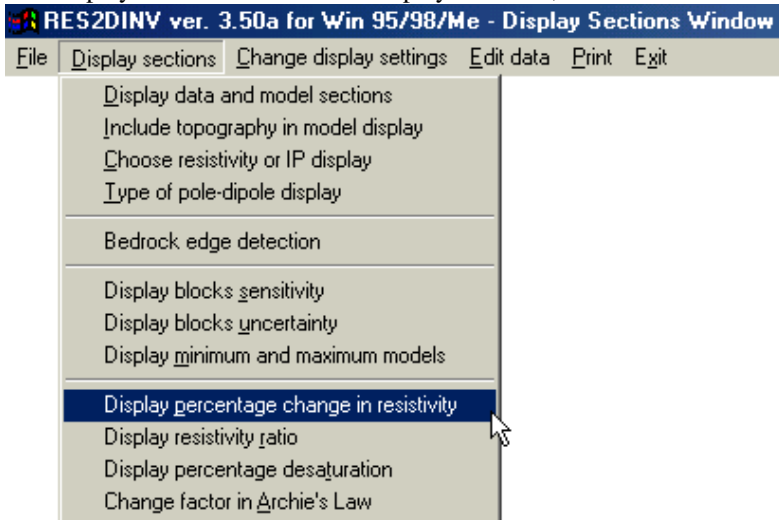
In the second set of options, the user can choose to carry out the inversion of all the time data sets simultaneously or sequentially. In the simultaneous inversion option, the inversion of the first or reference data set is followed by the inversion of the later time data sets in each iteration. Note that even if the "No constrains" options is chosen earlier, the model obtained at the final iteration for the first data set is still used as the starting model for the later time data sets.

In the sequential inversion option, the full inversion of the first data set is first carried out for about 5 iterations (or the selected number of iterations). The model for the first data set for the final iteration is then used as the reference model for the inversion of the later time data sets. The inversion of the later time data sets starts only after the completion of the inversion of the first data set. This sequential inversion is useful when the model section has very large resistivity contrasts.

By default, the model obtained for the first data set is used as the reference model for all the later time data sets, i.e. the same reference model is used for all the other data sets. In case where there is a large change in the resistivity of the models from the first to the last data set, an option is provided where the model for the preceding data set is used as the reference model. In this case, the model for the first data set is used as the reference model for the second data set, while the model for the second data set is used as the reference model for the third data set, and similarly for the other data sets.

The last option, the time-constrain weight, gives the relative importance given to keeping the later time models as similar as possible to the reference model. If a large weight is used, for example 10.0, the models for the later time data sets will be kept very similar to the reference model. This effectively minimises changes across the time models and reduces the possibility of noise in the data sets causing spurious changes between the models. However, this is at the expense of increasing the data misfit, i.e. the RMS difference between the calculated and measured data. By default, a value of 3.0 is used for the time-constrain weight. A value of 1.0 gives equal importance to minimising the time changes in the model and minimising the RMS data error.

After carrying out the inversion of the time-lapse data set, please switch to the "Display" window to read in the results in the inversion file. Several options are provided to display the results from the time-lapse models. The options designed specifically for time-lapse inversion models are given near the bottom of the "Display sections" list in the "Display" window, as shown below.



The "Display percentage change in resistivity" option will display the change in the model resistivity obtained from the inversion of a later time data set compared with the reference model from the inversion of the first data set. The "Display resistivity ratio" option will display the ratio of resistivities of the later time model compared with the reference model.

After displaying the sections with the percentage change in the model resistivity values, you can change the time-lapse data set selected by using the 'Home' and 'End' keys. By default the results for the last time-lapse data set will

be shown. You can show the results of an earlier data set by pressing the 'Home' key.

Just below the menu options to display the time-sections, there is a " Change factor in Archie's Law" sub-option. Archie's Law which gives the relationship between the resistivity of a porous rock and the fluid saturation factor is applicable for certain types of rocks and sediments, particularly those that have a low clay content. In the case, the electrical conduction is assumed to be through the fluids filling the pores of the rock. Archie's Law is given by

$$\rho = a\rho_w\phi^{-m}$$

where  $\rho$  is the rock resistivity,  $\rho_w$  is fluid resistivity,  $\phi$  is the fraction of the rock filled with the fluid, while  $a$  and  $m$  are two empirical parameters (Keller and Frischknecht 1966). For most rocks,  $a$  is about 1 while  $m$  is about 2. Under certain special conditions, the above equation can be used to determine the change in the fluid saturation or fluid resistivity with time.

If initially the subsurface material is saturated with water, and the change in the resistivity is caused by withdrawal of water (i.e. a reduction in the fraction per unit volume of the rock which is filled with water), the desaturation factor (Keller and Frischknecht 1966) can be calculated from the change in the subsurface resistivity. To calculate the desaturation factor, the value of the  $m$  parameter in Archie's Law is needed. By default it is set to 2.0 but this value can be changed by the user.

On the other extreme, consider a case where the fluid saturation factor does not change but the resistivity of the fluid changes (for example in tracer experiments with a conductive salt below the water table). The ratio of the resistivity of the fluid at the later time to the initial resistivity can be calculated directly from the model resistivities.

It must be emphasised that the above two situations are ideal cases. The results are only valid if Archie's Law holds for the subsurface medium. In many cases, the relationship between the medium resistivity and water content is much more complicated (Olivar et al. 1990).

As an example of a field experiment of time-lapse measurements, Figures 33 and 34 shows the results from the tests on the flow of water through the unsaturated zone conducted in Birmingham (Barker and Moore, 1998). Forty thousand litres of water was poured on the ground surface near the 24 metres mark along the survey line (Figure 33) over a period of 10 hours. The initial data set collected before the water irrigation began together with the corresponding inversion model is shown in Figures 33a and 33b. The

subsurface consists of sand and gravel is highly inhomogeneous. As a comparison, Figure 33c shows the inversion model for the data collected after the irrigation of the ground surface was completed. The distribution of the water is not very clear from a direct comparison of the inversion models alone.

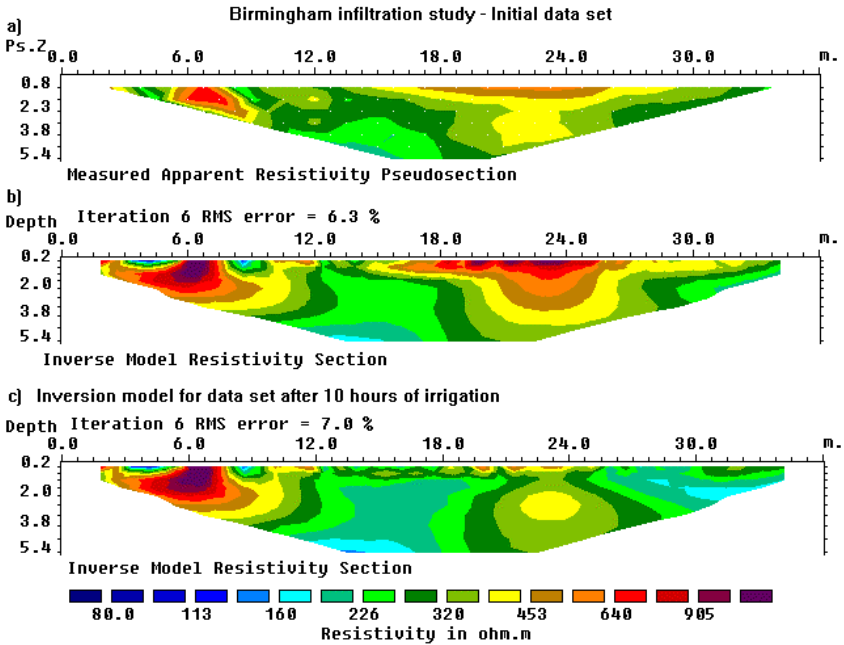


Figure 33. (a) The apparent resistivity and (b) inversion model sections from the survey conducted at the beginning of the Birmingham infiltration study. This shows the results from the initial data set which forms the base model in the joint inversion with the later time data sets. As a comparison, the model obtained from the inversion of the data set collected after 10 hours of irrigation is shown in (c).

The water distribution is more easily determined from a plot of the percentage change in the subsurface resistivity in the inversion models for the data sets taken at different times (Figure 34) when compared with the initial data set model. The data set collected at 5 hours after the pumping began shows a reduction in the resistivity (of up to over 50 percent) near the ground surface in the vicinity of the 24 metres mark. The near-surface low resistivity zone reaches its maximum extent and maximum amplitude after about 10 hours when the pumping was stopped (Figure 34b). Twelve hours after the pumping was stopped, the low resistivity plume has spread downwards and slightly outwards due to infiltration of the water through the unsaturated zone. There is a

decrease in the maximum percentage reduction in the resistivity values near the surface due to migration of the water from the near surface zone. This effect of the spreading of the plume becomes increasingly more pronounced after 24 hours, 36 hours and 52 hours (Figures 34d, 34d, 34f) due to further migration of the water. Note that the bottom boundary of the zone with approximately 20 percent reduction in the resistivity values tends to flatten out at a depth of about 3 metres (Figure 28e) where the plume from the surface meets the water table.

**Missing data** :- If a measurement was missing from a time series, enter 0.0 as the value of the apparent resistivity for that particular time series. The program will assume that a zero value is an indication of a missing data point.



## Birmingham infiltration study

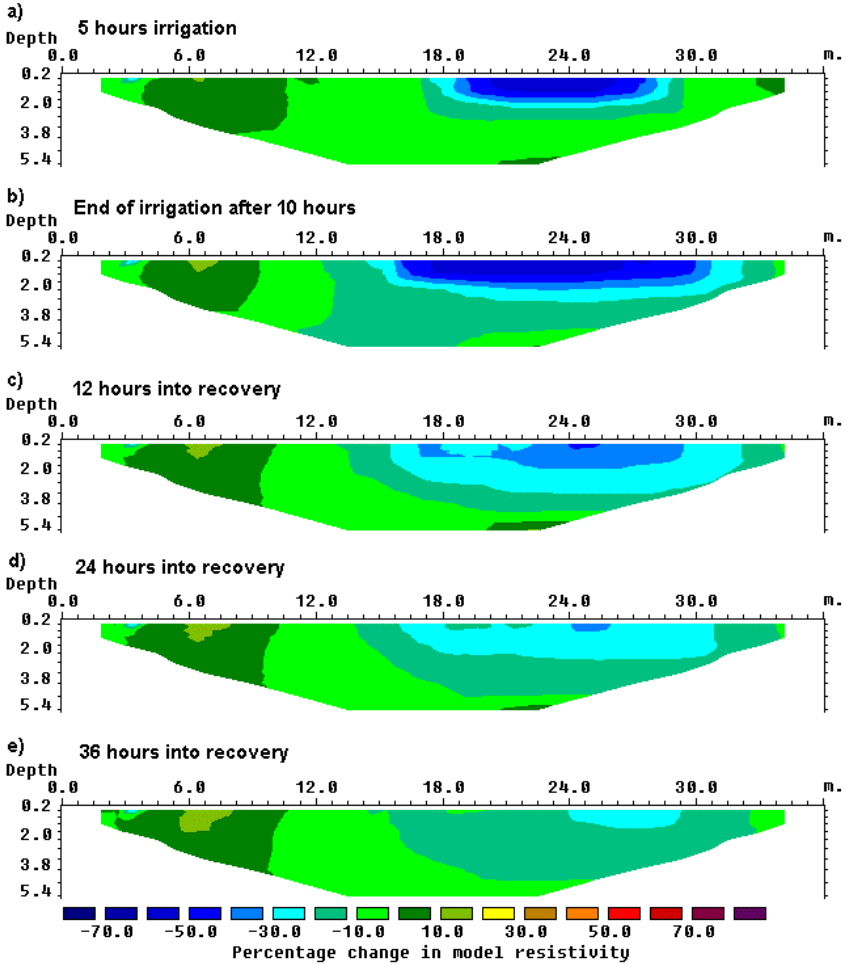


Figure 34. Sections showing the change in the subsurface resistivity values with time obtained from the inversion of the data sets collected during the infiltration and recovery phases of the study.

### Appendix S : Incorporating data noise estimates

Some types of resistivity surveying instruments record an estimate of the random noise for each measurement. This is usually made by repeating the same measurement several times. The data error estimate is then calculated from the standard deviation in the readings. This actually gives a measure of the repeatability in the readings, i.e. the random noise. Note that this data error estimate does not include sources of systematic errors such as coupling between the cables.

To include the data error estimate in a data file, the error values are entered after the apparent resistivity value. The file MODEL35\_N.DAT is an example of a data file from a surface survey with the error values. Part of the file is shown below with an explanation of the changes needed.

<u>MODEL35_N.DAT</u>	<u>Comments</u>
Block Model	Title
1.00	Unit electrode spacing
7	Wenner-Schlumberger array
230	Number of data points
1	Type of x-location (center)
0	No IP
Error estimate for data present	Header to indicate error values
	present
Type of error estimate (0=same unit as data)	Header for type of error
0	0 to indicate it is same unit as data
	value
1.500 1.000 1.000 10.0145 0.1434	x-loc., 'a' value, 'n' value, apparent
2.500 1.000 1.000 9.9706 0.1882	resistivity, data point error value
3.500 1.000 1.000 10.3357 0.1761	

Note there are two new additions in the data format. Firstly, just before the section of the file with the measured apparent resistivity data points, there are 3 extra lines. The first line 'Error estimate for data present' is a header to indicate that the data file contains the data error estimates. The second new line is a header to explain the use of the next line. The third line contains a flag to indicate to the program the units used in the error estimate. At present, use a value of '0' to indicate that the error value has the same units as the data value. For example, if the measurements are given as ohm.m, then the error values must also be in ohm.m. The measurements in most instruments are given as resistance values (i.e. ohm), or voltage plus current values which can be converted to resistance values. To calculate the apparent resistivity value, the resistance value is multiplied by a geometric factor. The error value recorded by the instrument is probably in the form of a resistance (ohm) value. Thus the error estimate recorded by the instrument must also be multiplied by the same

geometric factor before it is entered into the DAT file format used by this program.

The use of the flag for the unit used by the error value makes it possible for future versions of the program to allow the use of other units for the error value, for example the data in ohm.m while the error in ohm. Another possibility is the error given as a percentage value.

The least-squares equation in (2) is modified to the following equation

$$\left( \mathbf{J}^T \mathbf{W}_d^T \mathbf{W}_d \mathbf{J} + \mu \mathbf{F} \right) \mathbf{d} = \mathbf{J}^T \mathbf{W}_d^T \mathbf{W}_d \mathbf{g} - \mu \mathbf{F} \mathbf{q}_k$$

where  $\mathbf{W}_d$  is a diagonal weighting matrix that incorporates the effect of the data errors. Data points with a smaller error are given a greater weight in the inversion process.

In an ideal situation, the noise estimate should be measured (for example by reciprocal measurements). However, in most field surveys such noise estimates are not measured due to time constraints. In such a situation, the best option is probably to use the 'Robust data constraint' option (Appendix K) so that the effect of outliers in the data on the inversion model is minimized. With this option, a linear weight is given to the difference between the measured and calculated apparent resistivity values. This makes the inversion result less sensitive to outliers compared to the normal least-squares constraint where the square of the difference between the measured and calculated apparent resistivity values is used.

### Appendix T : Incorporating boundaries of known layers

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

The file CLIFLAYER4.DAT is an example data file where the boundary between a gravel and underlying clay layer is known from a seismic refraction survey (Scott *et al.* 2000). Part of the file is shown below with an explanation of the changes needed.

CLIFLAYER4.DAT			Comments
Clifton			Title
2			Unit electrode spacing
1			Wenner array
392			Number of data points
1			Type of x-location (center)
0			No IP
3	2	58.63305	x-loc., 'a' value, apparent resistivity
5	2	56.77204	Second data point
7	2	54.79331	Third data point
.			Other data points
.			
48	32	18.1012	
50	32	17.94035	Last data point
0			No topography
0			No fixed regions
0			No water layer
Sharp layers present			Header to indicate sharp boundaries present
Number of boundaries			Information header
2			Number of boundaries, two in this case
Boundary 1 parameters			Header for first boundary
Boundary type			Header for type of boundary
Layer			Layer type
Group weight			Header for weight, for future use
1.0			Enter 1.0 here, not used at present
Number of points on boundary			Header
16			16 points for this boundary
x and z coordinates of pts			Header
0.0 2.3			x-location and depth of first point
18.0 2.3			x-location and depth of second point
.			x-location and depth of other points
.			along the boundary
88.0 3.2			x-location and depth of second last point

92.0 3.2	x-location and depth of last point
Boundary 2 parameters	Header for second boundary
Boundary type	Header for type of boundary
Layer	Layer type
Group Weight	Header for weight, for future use
1.0	Enter 1.0 here, not used at present
Number of points on boundary	Header
3	3 points for this boundary
x and z coordinates of points	Header
0.0 6.7	x-location and depth of first point
45 6.7	x-location and depth of second point
92 6.7	x-location and depth of last point
0	end with a few zero's
0	
0	

In the above example, there are two boundaries. If there is more boundaries, the section with 'Boundary 3 parameters' until the x-location and depth of the last point along the second boundary is repeated. The file MODEL\_BOUNDARY\_GENERAL.DAT gives an example of a data file with the general array format with only one boundary.

Figure 35 shows the inversion of the CLIFLAYER4.DAT data set using different inversion options. The first model using the smooth inversion method shows a gradational transition between the sand and underlying lower resistivity clay layer (Figure 35b). The depth to the boundary is not well determined. The use of the blocky or robust inversion method (Loke et al. 2003) gives a much sharper boundary (Figure 35c). The addition of the boundary from the seismic refraction survey helps to further sharpen the boundary (Figure 35d).

The greatest limitation of this option at present is that the depths to the layers are fixed throughout the inversion. An option to allow the depths to be automatically changed will probably be added in a future update.

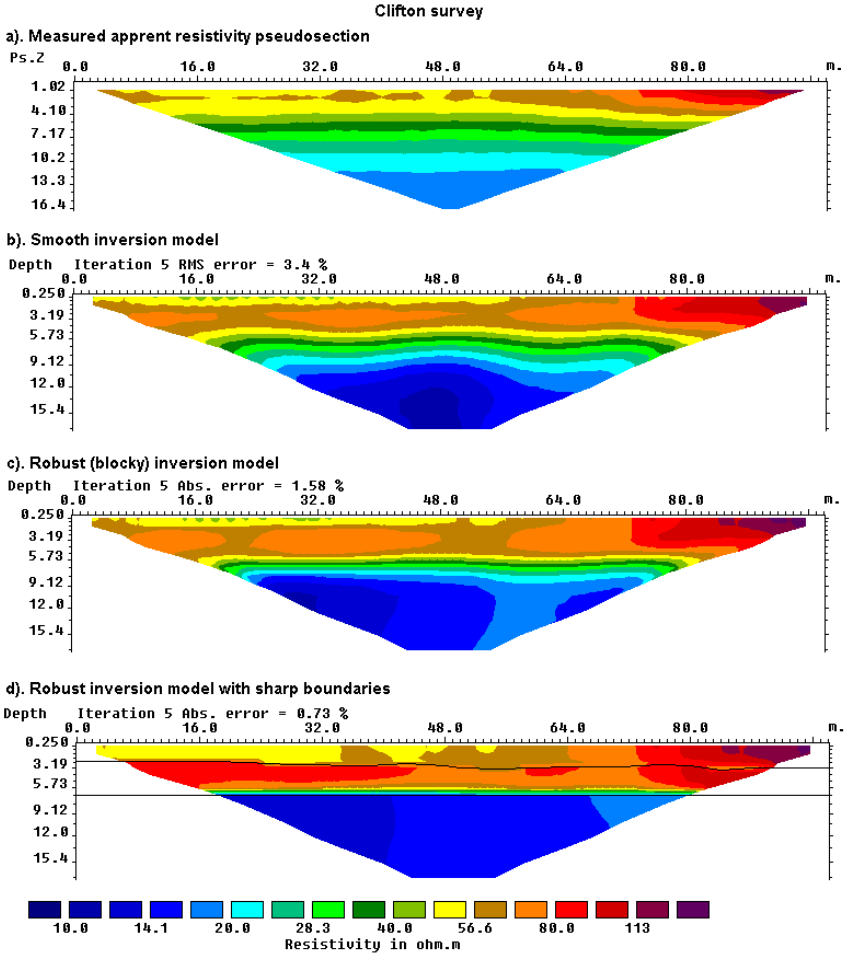


Figure 35. Models for the Clifton survey from the different inversion methods are shown together. Note the boundary between the high resistivity sand layer and the underlying low resistivity clay layer is much better resolved in the blocky and sharp boundary inversion methods.

## **Appendix U : Special topography information for mineral exploration surveys**

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

However for mineral exploration surveys (with bigger budgets) it is common to carry out a detailed topographical survey before the resistivity and IP survey, and the electrodes are placed such that the true horizontal distance (rather than the surface distance) between the electrodes is constant. In areas with steep topography, it is possible for the vertical distance between two adjacent electrodes to exceed the horizontal distance (but still less than the surface distance). For surveys where the true horizontal distance is used for the x-location of the electrodes, the general array data format must be used (see Appendix L). Furthermore, the indicator for the type of x-location in the data file must be set to 1 (see the MIXED.DAT example in page 91, and also the description for such a case in pages 93 and 94).

## Appendix V : Plotting methods for the gradient array.

There is currently no standard method to plot the apparent resistivity data from surveys with gradient array. There are probably two types of surveys with the gradient array. The first and traditional type survey use very few different C1-C2 positions (usually only one with C1 and C2 located at the two ends of the line), but many different P1-P2 positions. This was mainly used in mineral exploration surveys.

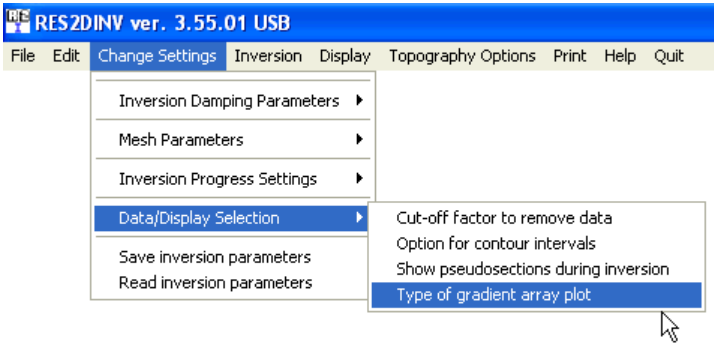
The second and modern type, mainly used with multi-channel multi-electrode resistivity meter systems, uses many different C1-C2 positions. To accommodate both possibilities, two types of data plotting options are available. As most surveys will likely to be carried out using the second type of survey with multiple C1-C2 positions, this is described in more detail. The papers by Dahlin and Zhou (2004, 2005) have some information about such surveys.

Firstly, a brief description of the data format for data from gradient array surveys. The general array data format (Appendix L) must be used with a sub-array number of 15. Below is the initial part of the example GRADIENT.DAT file with comments about the format.

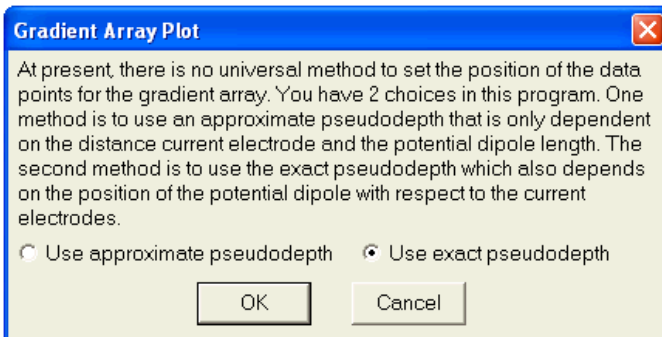
<i>GRADIENT.DAT file</i>	<i>Comments</i>
Gradient array	Title
1.0	Unit electrode spacing
11	Array type (11 for general array)
15	Sub-array type 15
Type of measurement (0=app. resistivity, 1=resistance)	Header
0	0 here to indicate apparent resistivity values
1792	Number of data points
1	Indicator for type of x-location
0	No IP values, 1 if I.P present
4 0.0,0.0 9.0,0.0 1.0,0.0 2.0,0.0 5.0588	The format for each data point is
4 1.0,0.0 10.0,0.0 2.0,0.0 3.0,0.0 5.0724	Number of electrodes used in
.	
.	
4 46.0,0.0 118.0,0.0 78.0,0.0 86.0,0.0 4.2571	Last two data
4 48.0,0.0 120.0,0.0 80.0,0.0 88.0,0.0 4.2258	points
0,0,0,0,0	End with a few zeros

To select the type of plotting method to use, before reading the data file, click 'Change Settings' and then 'Data/Display Selection', and then 'Type of gradient array plot' as shown in the following figure.





On selecting the ‘Type of gradient array’ sub-option, the following dialog box is shown.



The ‘Use exact pseudodepth’ choice is the default option. However, the program will automatically change to the approximate pseudodepth method if it finds the exact pseudodepth method is not suitable for the data file. This occurs for surveys with the traditional type of gradient arrays where only a few C1-C2 positions are used.

As an example, the plot of the GRADIENT.DAT file data set in the form of profiles is shown below.

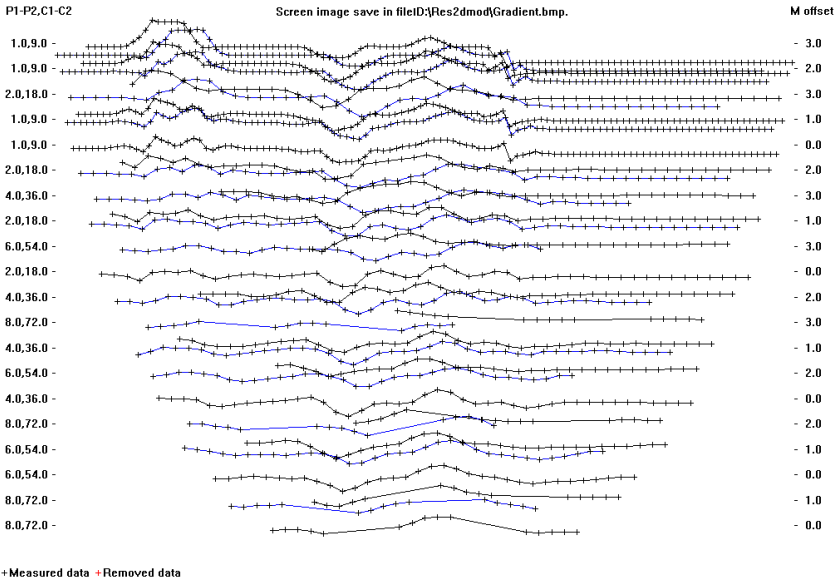


Figure 36. Plot of GRADIENT.DAT data in the form of profiles.

Note the data set each pseudodepth is split into two profiles which are drawn in different colours. This is because there are two possible configurations with the same pseudodepth.

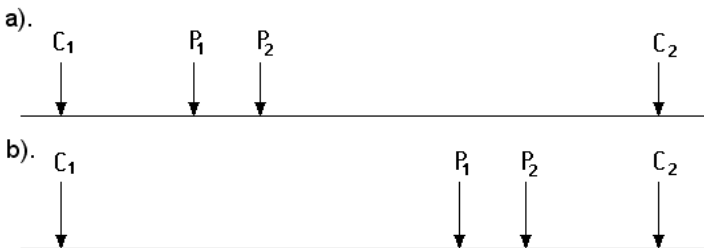


Figure 37. Two different configurations of the gradient array with the same pseudodepth but with the potential electrodes at different ends of the array. Gradient array configuration with (a) right parity and (b) left parity.

In the above example, the distance between the C1 and C2 electrodes are the same. The offset of the P1-P2 dipole from the C1 electrode in (a) is the same as the offset of the dipole from the C2 electrode in (b). However, the two configurations are sensitive to different parts of the subsurface (Dahlin and Zhou 2005). To provide a smooth plot for the profile, the data from the 'right' and 'left' configurations are plotted in different profiles.

The inversion model of the GRADIENT.DAT data set that also shows the plot of the data in apparent resistivity pseudosections is shown below.

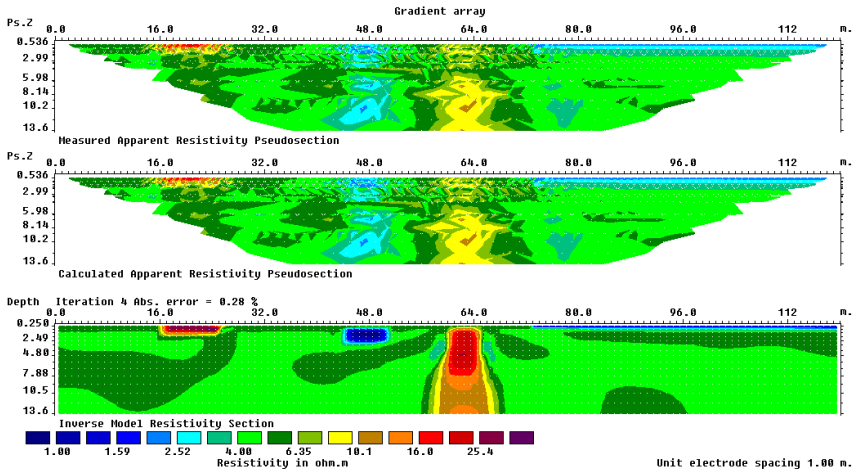


Figure 38. The inversion result of the GRADIENT.DAT data with the apparent resistivity and model sections.

### Special OhmMapper Note

Data collected by the OhmMapper system can be converted into the format used by the RES2DINV program using the 'DataMap for OhmMapper' program provided by Geometrics, Inc. This is a Windows 95/98/2000/NT based program. After starting the program, please click the EXPORT option to carry out the data conversion. For further details, please refer to the OhmMapper manual provided by Geometrics.

The figure below shows an example of a data set collected by the OhmMapper system together with the inversion model produced by the RES2DINV program. The survey was conducted over an area with weathered granite. The data set is given in the file OHMMAPPER.DAT. The measurements were made using the dipole-dipole array with a dipole length "a" spacing of 10 metres and with n values of 0.5 to 3.5 (Appendix A). The data set has 732 data points while the inversion model consist of 1240 cells. The inversion of this data set it took about 15 minutes on a 300 MHz Pentium II computer.

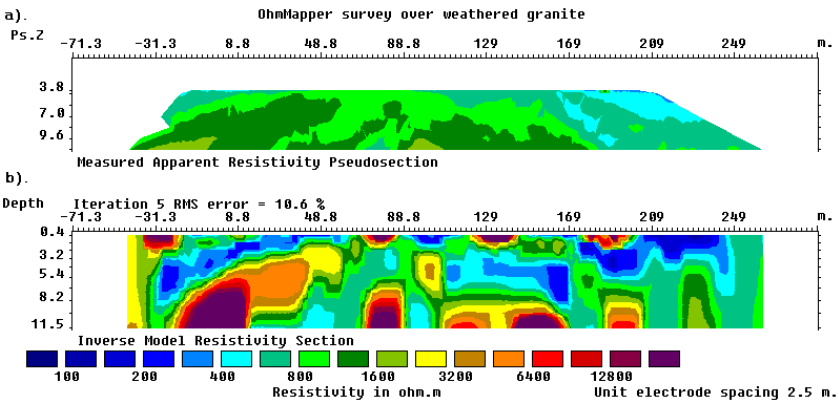


Figure 39 : (a) Apparent resistivity pseudosection measured with an OhmMapper mobile resistivity surveying system. (b) Model section obtained by RES2DINV program.

### **DISCLAIMER**

This software is provided "as is" without any express or implied warranties including its suitability for a particular purpose. Neither the author nor the subagent will assume responsibility for any damage or loss caused by the use of this program. In the event of program bugs, every effort will be made to correct the bugs and a replacement program will be provided for a nominal charge to cover postage and handling. Faulty dongles or program disks will be replaced free of charge within the first 6 months from the date of purchase to registered users. Registered users are entitled to free updates and support within the first year.

### **SUPPORT**

Please contact your distributor if you have any questions concerning this program. A frequent source of queries is when the results obtained are not what you expect, or the program refuses to accept your data file. In such a case, support will only be provided if a copy of the data file is sent together as an attachment with your email, preferably compressed into a ZIP file. The most common causes of problems are (a) the data in the DAT file is not given in the correct RES2DINV format (b) excessive noise in the data set (particularly for dipole-dipole surveys and/or IP data sets) (c) instrument malfunction or field survey errors. It is only possible to trace the source of the problem if a copy of the data file is provided.

Please note that support is only available for registered users of the full version of the program. It is not possible to provide technical support for users of the demo version of this software. For technical support, you can contact the software provider by email at the following addresses. Please attach a copy of your data file to your email.

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

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

- 1). Your dongle ID number. This ID number is displayed near the bottom of the initial information box when the RES2DINV program starts up if the dongle is attached to the computer.
- 2). The name of your company or institution.
- 3). Approximate date your company/institution purchased the software.

## What's New

Version 3.00 - Major upgrade to Windows 3.1 and 95. Maximum number of electrodes increased to 500. Multi-tasking support for Windows 95. Support for any Windows compatible graphics card and printer.

Version 3.01 - Improvements to finite-difference subroutine to calculate the Jacobian matrix which is now about twice as fast as the earlier versions.

Version 3.10 - Support for underwater surveys. Direct incorporation of topography into inversion model using a distorted finite-element grid.

Version 3.11 - The time taken by the finite-element subroutine to calculate the Jacobian matrix is reduced. An option to use a finer mesh for the finite-difference or finite-element forward modelling method is added.

Version 3.12 - Non-integer values for the “ $n$ ” factor for the dipole-dipole, pole-dipole and Wenner-Schlumberger arrays supported (please refer to Appendix A). The maximum limits for the number of data levels and model layers increased to 52 and 17 respectively.

Version 3.13 - The ratio of the largest electrode spacing to unit electrode spacing for the Wenner and pole-pole array was increased from 32 to 64. The maximum number of data levels is now 64. The maximum number of model layers was also increased to 18.

Version 3.20 - Support for IP data added.

Version 3.21 - The maximum number of electrodes was increased to 650. Improvements has been made to the disk-memory swapping subroutines so that for a given amount of RAM the number of datum points the program can handle is increased. For computer systems with more than one hard-disk drive, the program will automatically select the drive with the most free disk space to store the temporary disk swap files.

Version 3.22 - Slight improvements to the use of memory in the IP inversion section. The size of the IP data set that can be handled for a given amount of memory was increased. An option to optimise the damping factor automatically during the inversion process was added. Support for the “reverse” pole-dipole array added (see Appendix A). Support for a command line batch mode included (see Appendix I). An option to plot the model section in the form of rectangular blocks was also added.

Version 3.30 - Support for cross-borehole surveys added. An option to allow the number of model parameters to exceed the number of datum points was also added.

Version 3.31 - An option for a used defined model added. In this model, the user specifies the thickness of the first layer and the factor to increase the thickness for each subsequent deeper layer. The program will also automatically update the directory used for the input data files and the output inversion files listed in the RES2DINV.INI file.

Version 3.32 - An option to extend the subdivision of the subsurface into blocks to the edges of the survey line was added. Option to display the uncertainty in the model resistivity values was also added. Version 3.33 - An option to incorporate the effects of the remote electrodes used in surface resistivity surveys with the pole-pole and pole-dipole arrays was added.

Version 3.34 - A few bug fixes. The user can now scale the depths of the model layers so that the depth to the last layer can be much greater than the default limit allowed by the program. When the program saves the model values in the XYZ format, it will now also save the coordinates of the corners of the blocks in the model. An option to use a very fine mesh in the vertical direction for resistivity contrasts of greater than 250:1 was added, as well as an option for 6 nodes in the horizontal direction between adjacent electrodes.

Version 3.35 - The user can now set the maximum number of electrodes, from 150 to 1500, via the JACOBWIN.EXE program. Drawing of colour contour sections is now significantly faster on most computers.

Version 3.36 - A robust least-squares inversion option was added. For very noisy data with 'outliers', the resulting model will be less sensitive to such datum points when the robust data inversion method is selected. For areas where the subsurface geology has sharp interfaces, the robust model inversion method will give better results.

Version 3.40 - Support for non-conventional arrays for resistivity surveys.

Version 3.41 - Two new methods for topographic modelling using a damped distorted grid and the inverse Schwartz-Christoffel transformation added.

Version 3.42 - Support for remote electrodes for IP surveys.

Version 3.43 - Support for the Wenner Gamma array, and underwater surveys with non-conventional arrays. Maximum number of electrodes increased to 2000. The program has also been optimised for data sets where the unit

electrode spacing has been reduced by half of the actual value so as to get a model where the width of the blocks is half the usual size. This helps in cases where there are very large lateral resistivity variations near the surface.

Version 3.44 - Support for IP surveys with non-conventional arrays. This feature is useful in some cases where data from a series of overlapping collinear 1D sounding survey lines can be combined into a single 2-D data set to obtain a 2-D model.

Version 3.45 - Option to save results in SURFER format added. Also support for surveys with some electrodes underwater and some electrodes above the water surface level added.

Version 3.46 - Minor additions for data in general array format. Option to use a model with half the unit electrode spacing for data in general array format is added (see the file RATCMIX2.DAT for an example). It is now possible to carry out the inversion of data in the general array format with the demo version, but the results will only be displayed temporarily on the screen during the inversion. The damped distorted grid finite-element method is set as the default method for topographic modelling.

Version 3.47 – An option to carry out the inversion of IP data sequentially was added. Slight changes in the menu structure.

Version 3.48 – Support for up to 4 boreholes in cross-borehole option.

Version 3.49 – Incomplete Gauss-Newton inversion option added. Maximum number of electrodes increased to 4000, and maximum number of data points to 20000. Option to combine a number of 2-D data files in RES2DINV format into a single 3-D data file in RES3DINV format added.

Version 3.50 – Bedrock edge detection and time-lapse options added.

Version 3.51 – Option to include data noise estimates included.

Version 3.52 – Option for surveys with floating electrodes added. Support for topography in cross-borehole surveys included.

Version 3.53 – Sparse inversion option for very long survey lines (2000 to 16000 electrode positions) added. This method inverts the entire data set and model at a single time to produce a continuous and seamless model. New format for batch mode option script file which makes use of the files containing the inversion parameters produced by the RES2DINV program.



Version 3.54 – Option to include boundaries of layers from seismic or borehole surveys added.

Version 3.55 – Plot of profiles and pseudosections for the gradient array.