SCS2D

DOCUMENTATION

ZONGE Data Processing

Two-Dimensional, Smooth-Model CSAMT Inversion

version 3.00

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Introduction

Smooth-model inversion is a robust method for converting far-field CSAMT or natural-source AMT data to resistivity model cross-sections. SCS2D inverts observed apparent resistivity and impedance phase data from a line of soundings to determine resistivities in a model cross-section. Either TM-mode data, TE-mode or both may be inverted. To start the inversion, the model cross-section is usually given a background resistivity generated from a moving average of apparent resistivity data or a 1d smooth-model inversion section. Specific geologic structure may be added to the background model if there is drill-log or geologic-mapping information available. During the inversion, model-section-pixel resistivities are adjusted iteratively until calculated apparent resistivity and impedance phases are as close as possible to observed data, consistent with model constraints. Model constraints include background-model constraints, which restrict the difference between the inversion model and a background model section, which represents known geology, and smoothness constraints, which limit resistivity variation from pixel to pixel.

To calculate apparent resistivity and impedance phase for a given model section, SCS2D uses a two-dimensional, finite-element algorithm to calculate far-field CSAMT or natural-source MT data. To model areas with rough terrain, the finite-element mesh is draped over an along-line topographic profile. Either TM or TE-mode data can be calculated for scalar, vector or tensor survey configurations for frequencies ranging from less than 0.01 Hz to 10 kHz.

Inverting apparent resistivity and impedance phase to smoothly varying model sections is an effective way to display the information inherent in CSAMT and AMT measurements. As smooth-model inversion does not require any preliminary information about geologic structure, observed data are automatically transformed to a resistivity model cross-section providing an image of the subsurface. Model sections generated with smoothness constraints are complementary to more specialized inversions incorporating specific geologic models.
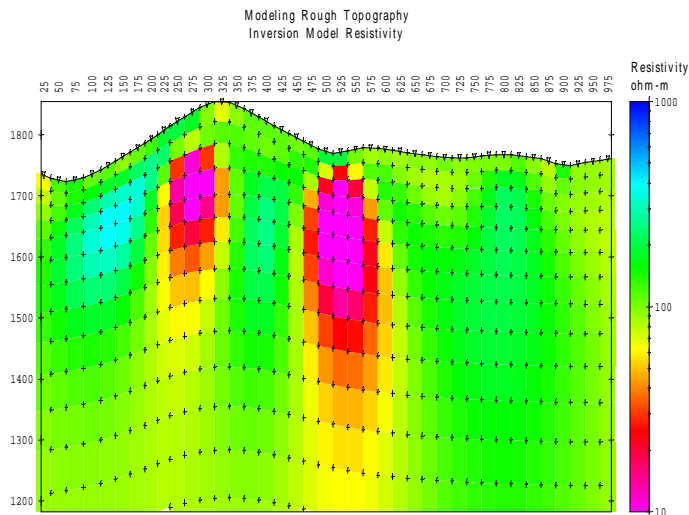
SCS2D uses data grouped by line, one line per data file. Observed data are TM and/or TE-mode apparent resistivity and impedance phase measured over a broad band of frequencies. SCS2D model sections are always perpendicular to strike, but may be oriented at an oblique angle relative to field grid coordinate axes. Station locations are specified with grid east, grid north and elevation coordinates. Distances are specified in m, km, ft or kft and azimuths are given in degrees clockwise from grid north. SCS2D v2.10 is restricted to modeling far-field data, but future versions will include near-field, controlled-source calculations for grounded electric bipole and horizontal loop transmitter antennas.

Installation

Minimum Hardware Configuration

SCS2D runs on PCs using MS Windows with graphics set to high color (16-bit) mode.

Installation Procedure

Each distribution copy of SCS2D programs may be installed on more than one computer, but it comes with either a key-disk software registration system compatible with Windows 95/98 or a parallel port hardware-lock or "dongle" compatible with Windows 95/98/ME/NT/2000. Backup copies of installed files may be made freely, but they will function only with valid software registration.

Key-disk software registration can be moved from the distribution disk to a hard-drive for extensive use on one computer. Key-disk registration may later be moved back to the distribution disk for installation on another computer. Once SCS2D and hardware lock software is installed, dongles may be moved from one computer to another, but should only be removed or added with computer and printer power off.

Installing program and sample data files

A SETUP program is provided to install SCS2D programs to your hard drive. SETUP copies files to your hard drive and unzips them, but does not make any changes to operating system files.

To install SCS2D program files from a 3.5"disk, place the distribution disk in a floppy disk drive and log-on to that drive. Then type "SETUP" and press Enter. You will see a screen title showing the program's name and version number. Below the title block a set of highlighted fields specify the source drive you are installing SCS2D from, usually floppy drive A: or B:, and the target hard drive letter and path in which SCS2D should be installed. It is usually easiest to put SCS2D programs in a directory which is already on your computer's MS-DOS path. You can move from field to field in the SETUP program's screen by pressing the Tab key to move forward and Shift+Tab to move backward. To cycle through disk drive letters, press the space bar or left and right arrow keys. Select drive letters and edit the target path to suit your computer's configuration. When you press F10, SETUP will verify your edited changes and will extract files from #SCS2D.EXE to your target directory.

If you are installing programs from a CD, SETUP allows you to move groups of program files from the distribution CD to a target hard-drive directory. As with floppy-disk installation, it is usually easiest to put modeling programs from a CD into a single directory on your computer's MS-DOS path (such as c:\datpro). Using a single directory reduces the length of the MS-DOS path string.

SETUP does not alter any of your computer's system configuration files. After installation, SCS2D may be run from the command line, from the start menu or from a Windows desktop shortcut.

After installation, the target subdirectory should have the following files:

SCS2D program files:
    SCS2D.EXE   - model building, editing and review
    RSCS1D.EXE   - natural or controlled-source 1d smooth-model inversion
    RSCS2D.EXE   - natural or far-field 2d smooth-model inversion
    SCS2DREG.EXE - registration program.

Sample data files:
    SCSDEMO.MDE   - Zonge data processing control and plot annotation
    SCSDEMO.STN   - station grid coordinates in a tabular format
    SCSDEMO.AVG   - averaged field data and estimated error in a tabular format
    SCSDEMO.ZCR   - averaged field data in Zonge ZPLOT plotting format
    SCSDEMO.MTM - SCS2D inversion control and model section file
    SCSDEMO.MTD   - SCS2D observed and calculated data file

Note that sample data files must be read/writeable. Test data files distributed from a CD-ROM may need their attributes modified from read only to read and write.

Moving key-disk software registration to your hard drive.

Key-disk software registration may be left on the distribution disk. RSCS1D and RSCS2D will then run only when the distribution disk is present in your floppy-disk drive. For more convenience, you can move key-disk registration to your hard-drive. When this is done, the 3.5" key-disk will not be required to operate the program.   However, if the hard disk is transferred to another person, reformatted or corrupted, that copy of the protection is lost.   One spare copy of the software registration is included on each distribution disk.

IF your software was provided for demonstration purposes, then software registration may NOT be moved to a hard disk. Typically, the registration is set to expire 30 days after you first use the program. Registration may be reset by purchasing SCS2D and obtaining a reset code by fax or email.

The utility EVMOVE.COM is provided on the distribution key disk.   Assuming that the 3.5" distribution disk is in drive A: and that your hard drive is labeled C:, type

"EVMOVE A: C:" to move a copy of software registration from drive A: to drive C:
"EVMOVE C: A:" to recall a copy of software registration from drive C: to drive A:

Installing a hardware lock

A parallel-port hardware lock or dongle is required for computers running Windows NT. Using SCS2D's hardware-lock registration system requires additional configuration steps. If your program comes with a parallel-port hardware lock, install it by turning off power to your computer and printer. Unplug the parallel-port printer cable from the back of your computer and plug the hardware lock into your computer's 25-pin parallel port. Then plug the parallel printer cable into the hardware lock, piggyback fashion.

You do not have to have a printer physically installed for the hardware lock to function. If you do have a printer connected, it must be turned on and on-line when you run SCS2D. If you have more than one parallel port, it makes no difference which one you use.

Note that you must ensure the end of the hardware lock labeled "Computer" is connected to your computer's parallel port. It is possible to plug the hardware lock in backwards, which may damage the hardware lock, the parallel port or both.

SETUP32

This file needs to be executed once to install a driver that allows the hardware-lock software to access the parallel port. The driver file is DS1410D.SYS, which is put into your computer's driver directory. After rebooting, you will see this driver listed in the 'Devices'. (START / Settings / Control Panel / Devices). This driver is automatically started when your computer boots up.

Execute the program SETUP32, then reboot your PC. After re-booting a PC running Windows NT or 2000, the list of 'Devices' should include a new driver, DS1410D
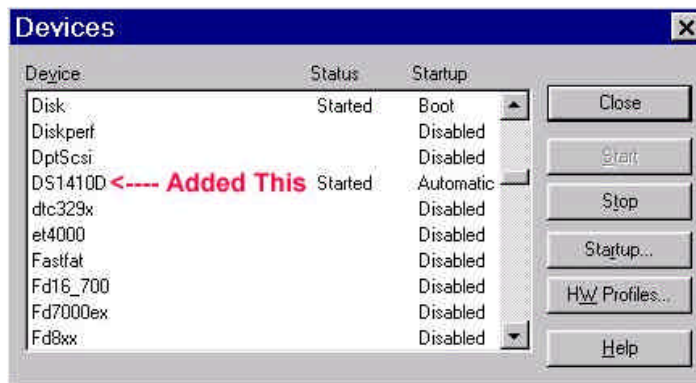
Test the software registration by executing SCS2DREG from the scs2d hard-disk directory. You should see text like:

```
Registered to: Alaska Earth Sciences Serial # 1099
          Copyright 1999 Zonge Engineering
                 All Rights Reserved.
```

A software registration check is done every time RSCS1D or RSCS2D are initiated. Both programs call SCS2DREG to check for valid software registration. Key-disk systems make a software check, while hardware-lock systems look for an appropriate hardware key or "dongle" in the parallel port.

Graphics

SCS2D builds new models and allows quick review and editing of inversion-model sections. It provides options for model-section plotting with adjustable color ranges and allows zooming in on model details. SCS2D can save model-section plots in windows metafiles, computer-graphics metafiles, postscript or Zonge ZPLOT files for later pasting into report documents. Your windows graphics display should be set to 16-bt "high color" or "true color" for SCS2D use.

For more finished model-section plots, program MODSECT and its associated files may be used to plot model sections. MODSECT shows model section plots on screen and can export plots to windows metafiles, write script, control and data files for Oasis Montage, or write script and data files for Surfer v6.0 or v7.0. MODSECT documentation details its hardcopy plot options.

Program Use

Overview

SCS2D is a set of programs for inverting far-field CSAMT or AMT data into a smoothly varying model section. Models are created and edited using SCS2D, while RSCS1D and RSCS2D do the numeric-intensive work of inversion. RSCS1D inverts natural- or controlled-source data to a smooth-model section using a 1d model under each sounding point. RSCS2D inverts natural- or far-field controlled-source data using a 2d forward model. Information is exchanged between SCS2D, RSCS1D and RSCS2D via ASCII text files with file names passed as command-line parameters. SCS2D data and model files may be altered directly with a text editor, but editing is usually easier with the interactive functions build into SCS2D. All files generated for a particular data set are given the same file-name stem, with file-name extensions used to flag file type. Survey configuration, inversion control and model section information is placed in files with the extension *.MTM. Observed and calculated data are saved in files with the extension *.MTD.

SCS2D's **New** model option reads observed field data from Zonge-format *.AVG, *.Z or *.MTD files. *.AVG are preferable to *.Z files because they include measurement-error estimates. If you are starting with field data saved in a format that is not recognized by SCS2D, *.MTD files are the easiest to create with a spreadsheet. Survey configuration and annotation information such as line number, station spacing, and transmitter bipole location, length and orientation, is read from optional Zonge-format *.MDE files. SCS2D also looks for an optional *.STN file to collect topographic profile information. If a *.STN file is present, SCS2D adjusts the model section to follow the file's topographic profile. If an appropriate *.STN file is not available, SCS2D sets elevations to zero along the top of a flat model section. Observed apparent resistivity values are averaged to generate default starting and background models with a uniform resistivity. After building a new model section, SCS2D writes *.MTM and *.MTD files for input to the core inversion program, RSCS2D.EXE.

Two-dimensional, smooth-model inversions are calculated by RSCS2D, the core inversion program. RSCS2D reads *.MTM and *.MTD files, modifies the inversion-model section to improve the fit between observed and calculated data, and then updates both *.MTM and *.MTD files when it is finished. RSCS2D also writes inversion iteration information to a *.LOG file and any error messages to the screen and to an *.ERR file. To invert one line, RSCS2D may be called directly from SCS2D by choosing the **Invert** menu option. Alternatively, a group of lines may be inverted sequentially by first creating SCS2D files for each line and then driving RSCS2D with a batch file containing the commands "start /w rscs2d line1", "start /w rscs2d line2", etc. for each line. After the batch file is finished, *.LOG files may be reviewed to see how the inversions went.

After inversion, model sections may be immediately reviewed with SCS2D. It includes options for zooming in on details, changing color-fill limits and editing model properties. At any point, the current model section may be printed via the windows print-manager or saved in windows metafile (*.WMF) computer-graphics metafile (*.CGM), postscript (*.PS), Zonge ZPLOT (*.ZMD) files for later pasting into report text or other graphics.

More finished model-section plots are possible by using MODSECT to export windows metafiles, drive MS-DOS-version GeoSoft plotting programs or write Surfer v6 script and data files.

All SCS2D programs can be run from the Windows Start|Run menu, from desktop short cuts, from the command line or from batch files. To allow batch file operation, RSCS1D and RSCS2D look for an input file name on the command line. If the command line is empty, they show an "Open File" dialog bock listing all SCS2D model files in the current working directory.

Typical SCS2D Data Processing Sequence

Program names are **CAPITALIZED.** Files are boxed.

*.AVG, *.Z or *.MTD (observed field data)
*.MDE (optional survey configuration and line annotation)
*.STN (optional station grid coordinates and elevations)

↓

SCS2D ← Gather observed data and build a new model section.

↓

*.MTM (survey configuration, inversion control
        and model section)
*.MTD (observed and calculated data)

← **SCS2D** ← Edit model.

↓

RSCS2D ← Invert model and update SCS2D files.

↓

*.MTM (updated model section)
*.MTD (updated with calculated data)
*.LOG (inversion iteration log)
*.ERR (any error messages)

Prepare color-shaded resistivity-model-section plots.

| **SCS2D** | **MODSECT + MS-DOS GeoSoft** | **MODSECT** |

*??.WMF (windows metafile)
*??.CGM (computer graphics metafile)
*??.PS   (post script)
*??.GRD (Surfer grid)

?? = RI = inversion resistivity
RB = background resistivity
RW = background resistivity weight
RS = normalized resistivity sensitivity

R*.PLT
R*.ATT
R*.GRD
R*.ZON

R*.BAS (resistivity plot script)
R*.LVL (log(resistivity) contour levels)
R*.BLN (model section blanking)
R*S.DAT (observed and calculated data)
R*S.TXT (axes annotation)

↓

GS Scripter + SURFER v6

↓

R*.SRF (resistivity plot)
R*S.DAT (data for posted values)
R*S.TXT (axis annotation)

Inversion Criteria

RSCS1D and RSCS2D attempt to simultaneously minimize the difference between observed and calculated data, the difference between background and inversion models, and inversion-model roughness. It uses a root-mean-square (RMS) error criteria to measure data misfit, distance from an a priori background model and model roughness:

$$\varepsilon_{total} = \sqrt{\frac{\varepsilon_{data}^2 + smth^2 \cdot \varepsilon_{model}^2}{nobs + nx \cdot nz}}$$

$$\varepsilon_{data}^2 = \sum_{i=1}^{nobs} \left(\frac{d_{obs_i} - d_{mod_i}}{d_{err_i}} \right)^2$$

$$\varepsilon_{model}^2 = dpW0^2 \cdot \sum_{i=1}^{nz}\sum_{j=1}^{nx} \left(p_{i,j}^k \cdot dpW_{i,j} \right)^2 + dxW0^2 \cdot \sum_{i=1}^{nz}\sum_{j=1}^{nx-1} \left(\left(p_{i,j+1}^k - p_{i,j}^k \right) \cdot dxW_{i,j} \right)^2 + dzW0^2 \cdot \sum_{i=1}^{nz-1}\sum_{j=1}^{nx} \left(\left(p_{+1,i}^k - p_{i-1,j}^k \right) \cdot dzW_{i,j} \right)^2$$

where

nobs = number of observed data values.

d_{obs_i} = observed log(apparent resistivity) and impedance phase.

d_{mod_i} = calculated log(apparent resistivity) and impedance phase.

d_{err_i} = observed data error, $d_{err_i} \geq$ ErrFloor.

ErrFloor = observed data error floor in log(resistivity) or mrads.

nz = number of node rows in inversion model mesh.

nx = number of node columns in inversion model mesh.

$p_{i,j}^k$ = inversion model parameter at iteration k, log(resistivity) - background value.

$p_{err_{i,j}}$ = inversion model error, log(resistivity) or phase mrads.

$smth = ResSmth \cdot nobs/(nx \cdot nz)$ during resistivity inversion.

dpW0 = relative weight given to starting model, ResdpW.

dxW0 = relative weight given to horizontal smoothness constraint, ResdxW.

dzW0 = relative weight given to vertical smoothness constraint, ResdzW.

$dxW_{i,j}$ = array of horizontal smoothness weights from *.IPM file.

$dzW_{i,j}$ = array of vertical smoothness weights from *.IPM file.

RSCS1D and RSCS2D report an average RMS data residual (sqrt(ε_{data}/nobs)), average RMS model constraint residual (sqrt(ε_{model}/(nx*nz))), RMS minimization criteria (ε_{total}) and largest model parameter change after each inversion iteration. Model updates are not accepted if they increase ε_{total}. If an inversion step fails to improve ε_{total}, both programs use a line-search to find a more cautious step length that will lower the inversion resdidual. Inversion is halted if the maximum step size is too small, if improvement to ε_{total} drops below a cutoff threshold, or if the maximum number of iterations is reached.

Tradeoff between Fitting Data and Model Constraints

Silver Bell CSAMT Line 28

<= ResSmth = 100

<= ResSmth = 31.6

<= ResSmth = 0.1

10

3

1

RMS Observed-Calculated Data

RMS Model Roughness
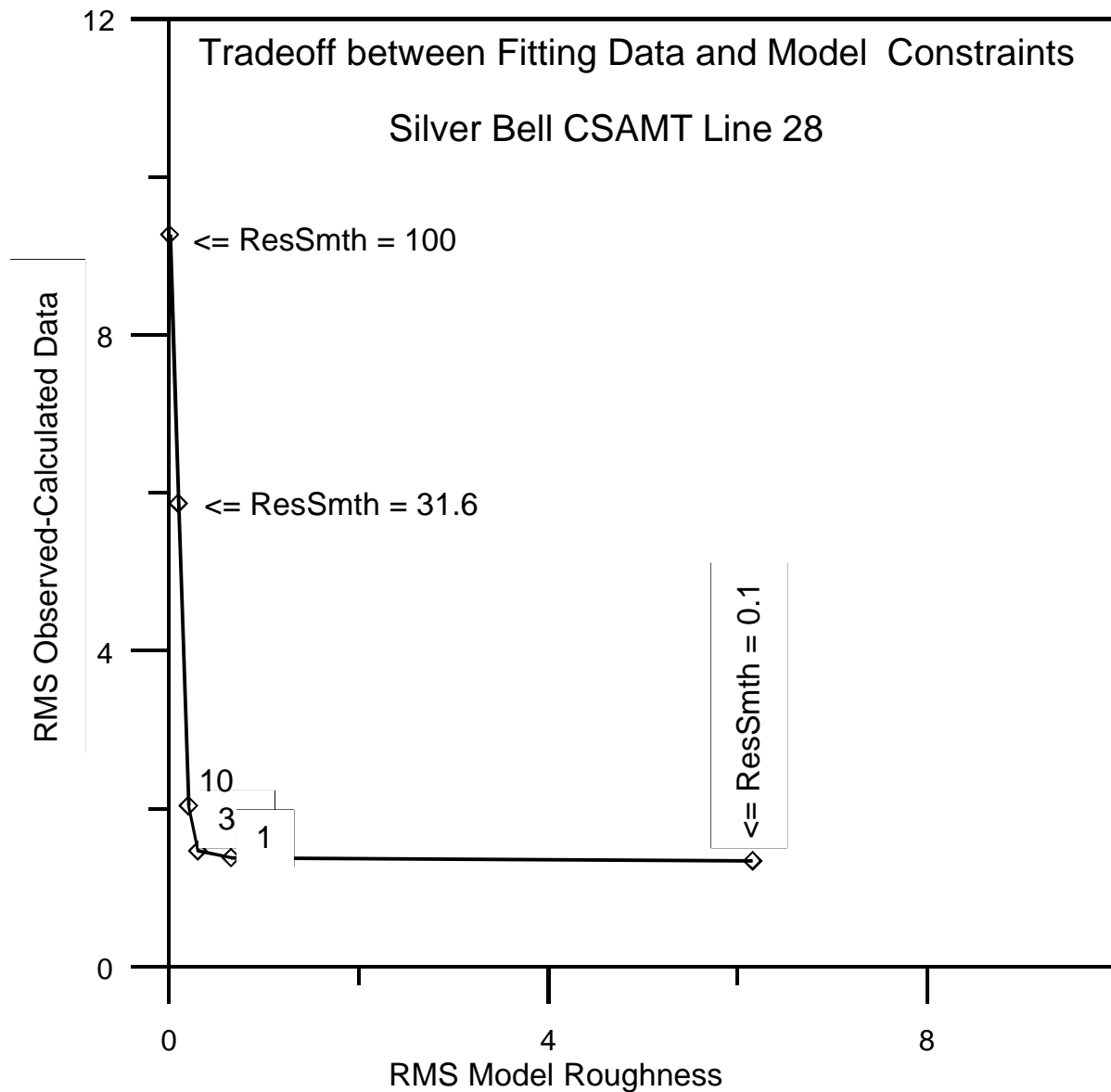
Inverting a data set with different values of ResSmth shows the tradeoff between fitting observed data and honoring model constraints. Plotting root-mean-square (RMS) observed - calculated data residuals versus RMS model roughness shows how a ResSmth=100 returns a poorly fitting, but very smooth model with a large observed - calculated data residual and a small model-constraint residual. Conversely, using ResSmth = 0.1 gives a good fit to observed data, but the inverted model section is rough. Using ResSmth = 3 is nearly optimal for this example, returning both a good fit to observed data and a smooth model. While inverting data, RSCS1D and RSCS2D display a similar plot on the lower-left corner of the screen to show how well the inversion is progressing.

Outline of SCS2D's Menu Structure

File
    New   = build new model section and save model in .MTM and .MTD files
    Open   = open existing model for review or editing
    Save   = save current model in .MTM and .MTD files
    Save As   = modify file name and then save current model
    Exit Menu = return to main menu
Review Data = shows log-log plots of observed and calculated data
Edit Model
    Re-Initialize Model = resets background and inversion model to uniform resistivity value
                 and background-model-constraint weights to default values.
    Edit Model Title = modify title and descriptive text
    Edit Model Section = draw geology on model sections
        Inversion model resistivity
        Background model resistivity
        Background resistivity weight
    Edit Inversion Controls = modify model-constraint weights, data-error floor and stopping criteria
    Edit Gradient Constraints = modify smoothness constraints between model pixels
    Auto-Sharpen Constraints = filter gradient constraints to "focus" inversion image
    Exit Menu = return to main menu
View
    Zoom
        Zoom In   = magnify view by a factor of two
        Zoom Back   = reduce view by a factor of two
        Zoom Rectangle = select viewed area by setting rectangle corners with mouse
        Zoom All   = view entire model section
        Pan   = move view's center point
    Adjust Colors = set color-fill minimum, maximum and contour increment
    Select View Parameter = select model parameter for cross-section plot
        Inversion model resistivity
        Background model resistivity
        Background resistivity weight
        Inversion resistivity sensitivity
    Show/Hide Gradient Constraints = toggle gradient constraint display on or off
    Exit Menu   = return to main menu
Plot File = make hardcopy plot or plot file
    To Printer = plot current model section on printer via Windows Print Manager
    *.WMF   = windows metafile, may be pasted into other plots or documents
    *.CGM   = computer graphics metafile, may be pasted into other plots or documents
    *.PS   = color postscript file
    *.ZMD   = Zonge-format *.Z file for ZPLOT plotting program
    Exit Menu = return to main menu
**1D CS/NS Inversion**   = calls RSCS1D to invert current model
2D NS Inversion   = calls RSCS2D to invert current model
**Exit**   = exit SCS2D

Menu Options

New Model Option

To build a new model using the sample SCS2D field-data file SCS2DEM.AVG, run SCS2D from a working directory holding SCS2D.AVG and select the **New** option from the initial menu or from **File** on the main menu. SCS2D will first display a file selection dialog. SCS2D allows input from Zonge-AMT-format *.AVG, *.Z or *.MTD files. Least favored are *.Z files, as they do not include estimated measurement error. AMT-format *.AVG files are more suitable, as they include measurement error estimates based on repeat readings of each measurement. SCS2D can read also data from *.MTD files, which are easy to create with a spreadsheet if you are starting with data tabulated in a format that SCS2D does not already recognize. In the absence of measurement error information, set observed apparent resistivity and impedance phase error values to constant values, such as 5 percent for apparent resistivity and 50 mrad for impedance phase. Formats for all three SCS2D input file types are described in an appendix to this document. When starting a new-model build, SCS2D will display all data files in the current directory that have an appropriate file-name extension for observed-data input.
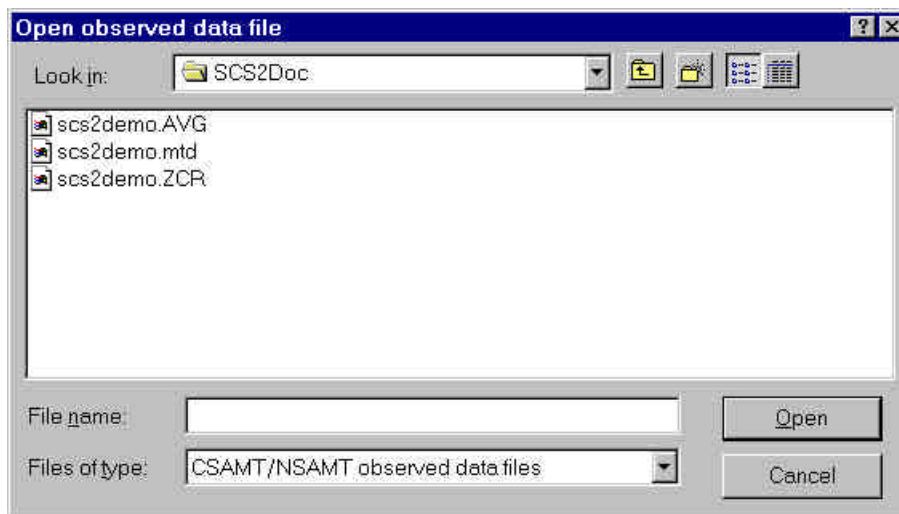
To follow this example using sample files distributed with SCS2D, select the field-data file SCS2DEMO.AVG by moving the mouse cursor over the SCS2DEMO.AVG name and clicking the left mouse button. Then mouse click on the **Open** button to open the data file and continue. SCS2D first looks for an optional *.MDE file to get survey annotation and configuration information, then it opens the field-data file. When reading *.AVG files which include a column of static-corrected apparent resistivities, SCS2D asks you to choose static-corrected or uncorrected data. Is generally appropriate to use uncorrected data in SCS2D, since it does a good job of modeling static offsets by introducing small near-surface features and some static offsets are caused by topography, which SCS2D models directly.

After reading observed data from the input data file, SCS2D shows a dialog box for verification of the survey configuration.
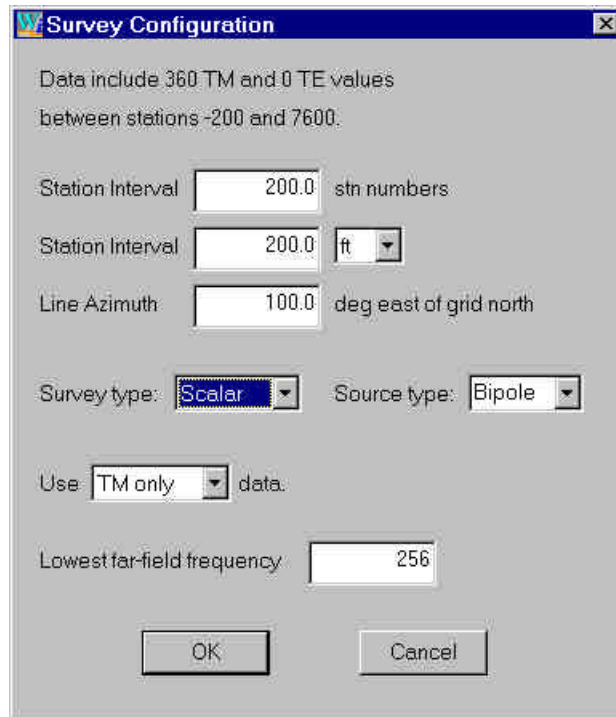
SCS2DEMO.AVG holds TM-mode scalar CSAMT data collected with 200 foot dipoles. Station numbers are distance along line in feet, so both the station interval and the station-interval length are 200. A station interval of 100 and a station-interval length of 100 feet could be used for more detailed modeling. These controlled source data were collected using a grounded bipole source placed 16000 feet north of line 28. The lowest far-field frequency in SCS2DEMO.AVG is 256 hertz.

Including transmitter specifications in *.MDE files is a good way to archive important survey-configuration information. SCS2D reads information about the transmitter type, size, location and orientation from SCS2DEMO.MDE and shows it in a dialog box for verification.
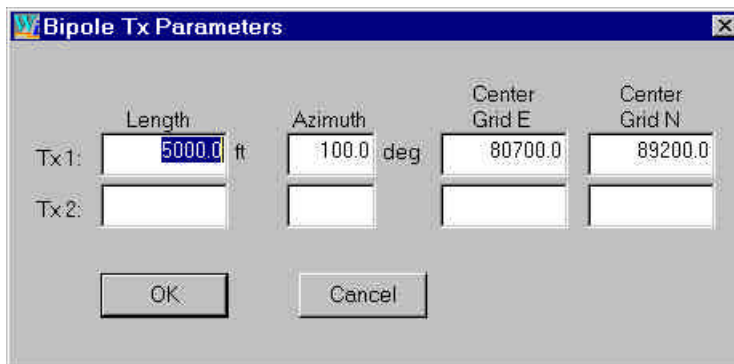
For tensor surveys, configuration information for two transmitters may be stored sequentially in *.MDE files.
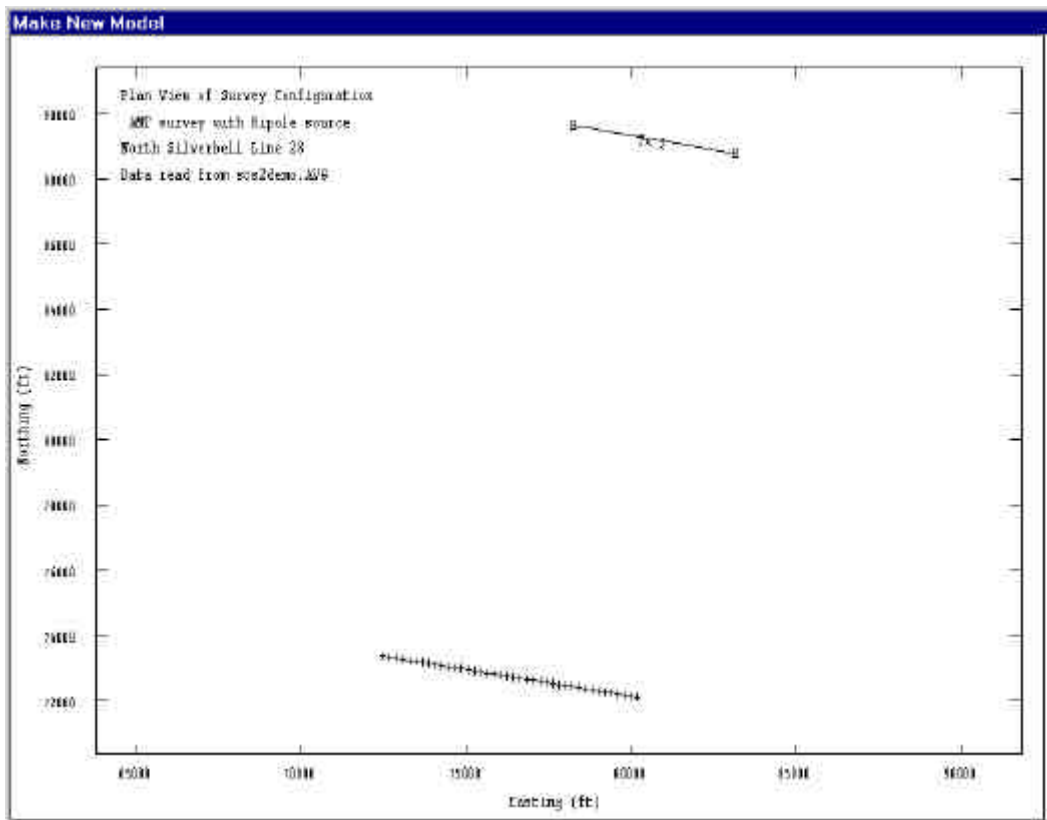
SCS2D reads station locations from an optional *.STN file and then shows a plan-map view of the survey line and transmitter to verify that there are no major errors in either transmitter or survey-line coordinates. If no appropriate *.STN files is present, you can click on the cancel button in the "open *.stn file" dialog box to skip *.STN file input and SCS2D will assign default station coordinates. However, *.STN files are required if you want to include topography in the model section and are recommended if you have data for a controlled-source survey or have a grid of multiple lines for which you may later want to plot modeling results as plan-map depth slices. Topographic modeling is improved by extending *.STN file data for two station intervals off both ends of the line.

Build New Inversion Model

Model Description

North Silverbell Line 28

for Zonge Engineering

Data from scs2demo.AVG

Model extends from stn `-700.00` to `8100.0` 44 dipole lengths.

Model Section Thickness:

Top row's thickness `150.0` ft

Row-to-Row Thickness Multiplier `1.10`

Number of rows `12`

Total thickness `3207.6` ft

Edit individual row thicknesses

Initialize background model resistivity with `2d moving average of data`

Save in `scs2demo` *.MTM and *.MTD files.

OK   Cancel

By default, the model section runs from two station intervals before the first electrode position on the line to two stations beyond the last, with a maximum model-section length of 200 station intervals. Station intervals are usually set equal to the TM-mode, electric-field dipole length, but may be halved to create models with more detail or doubled to create large-scale models. Soundings do not have to be located on integer multiples of the station interval, as SCS2D can interpolate between finite-element nodes to calculate data collected at irregularly spaced locations.

SCS2D uses an estimate of the maximum far-field, depth-of-investigation to set the default model-section depth extent. The height of the top row of model pixels can be varied from 0.25 to many times the station-interval length, but the height/width ratio of near-surface model pixels should be kept near one. The height of each subsequent row is increased by a row-to-row-height multiplier. Using rows with geometrically increasing heights improves SCS2D modeling results. The number of model-pixel rows or the row-to-row-height multiplier may be modified to change the model's depth extent. Total thickness is updated every time you click the mouse cursor in a new field. Model-pixel-row heights may be individually customized by selecting the **Edit individual row thickness** button. Up to twenty pixel rows may be used in SCS2D model sections. Using model sections with extra depth extent usually produces better inversion results than models with too little depth extent. Model sections can always be trimmed back after inversion to get final plots with more limited depth extent. In this example I have increased the number of model pixel rows from five to eight, for a total model depth extent of 1715 feet.

There are three options for setting background-model resistivity. A **2d moving-average of data** is good for natural source data. Data are mapped to the model section using station location and Bostick depths. A second option is a **moving average of 1d model**, which runs RSCS1D to get a 1d smooth-model section and then applies a 2d moving-average filter to get smooth background resistivities. Averaging 1d smooth-model sections is often useful with controlled-source data because it can estimate of deep basement resistivity from low-frequency, near-field data, data which is not otherwise used during RSCS2D's far-field-only inversion. A third alternative is to use a **uniform resistivity**, which is initialized to a geometric average of far-field observed apparent resistivities weighted by 1/frequency^2. The best background values for RSCS2D are average deep basement resistivities.
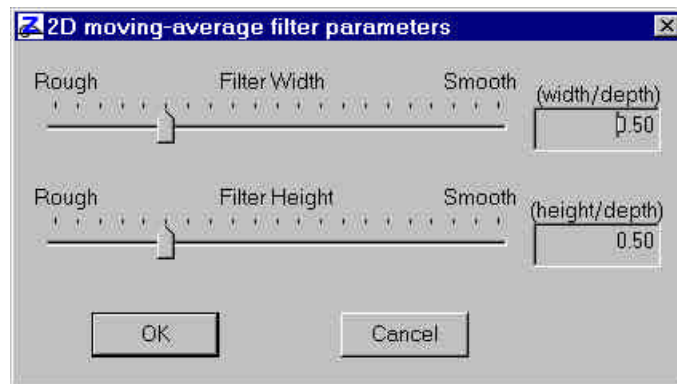
2d moving averages use a low-pass filter which increases in size with increasing model-section-pixel depth. Filter width and height are proportional to model-section pixel depth and the two constants of proportionality may be varied. Widening the filter increases its smoothing effect.

To include drill hole or geologic model information in the inversion, the **Edit** | **Edit Model Section** | **Background Model Resistivity** menu option may be used to add specific geologic structure to the background model section after the new model build is complete.

Selecting the **OK** button on the "build new inversion model" dialog box leads to a dialog box showing inversion-control parameters.
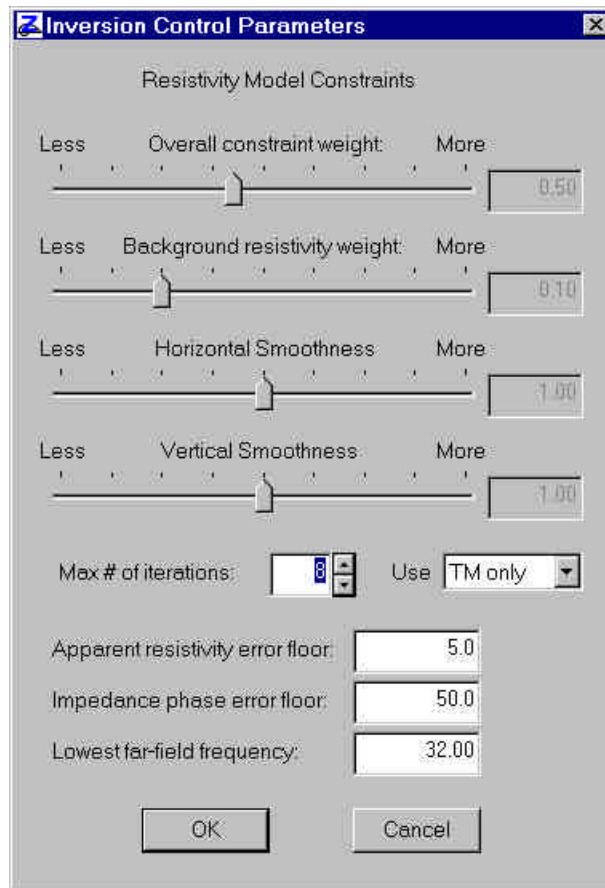
Model constraint weights may be adjusted by moving track-bar pointers with the mouse. To adjust a constraint weight, put the mouse cursor on a pointer, hold down the left mouse button and move the mouse. Reducing a model constraint weight makes the constraint less important relative to matching observed data. If horizontal resistivity smoothness is set to "more", the inverted resistivity model will be very smooth from side-to-side, looking like a layered model. Increasing vertical smoothness weighting favors dike-like model features.

Most of the improvement during inversion happens in the first two to four iterations. Reducing the maximum number of iterations from eight to four will speed up preliminary inversions. SCS2D allows you to invert with "TM only", "TE only" or "TM & TE" mode data. If you select "TE only" for a data set which includes only TM data, RSCS2D will show an error message complaining that there is no valid data and will abort the inversion.

Apparent resistivity and impedance error floor values set minimum observed data error and affect the balance between fitting observed data and honoring model constraints. Measurement repeatability often generates an overly optimistic error estimate for inversion, because it does not take into account modeling error generated by using a simple two-dimensional section to represent a complex three-dimensional world.

The lowest-far-field frequency is used to set the boundary between high-frequency, far-field data which can be modeled by a plane-wave source and low-frequency, transition-zone and near-field data, which must be modeled using the full three-dimensional electromagnetic source fields. Although RSCS2D v2.10 only models far-field data, it saves data of all frequencies in its *.MTD files, so that the lowest-far-field frequency may be reset with **Edit Model | Edit Inversion Controls** after looking at log-log plots of observed data in **Review Data**. If the transition-zone frequency varies along line, the far-field floor may be set to the lowest far-field frequency for the line, and then individual data points with transition-zone behavior at higher frequencies may be skipped in **Review**

Data to get the equivalent of a variable far-field floor. RSCS1D ignores the far-field floor and uses data of all frequencies, but it does honor skip flags.

Default SCS2D values work well most of the time, but some data-set inversions may be improved by a different trade-off between fitting field data and maintaining a smooth model section. Experimenting with different model constraint weights and observed-data error floors may improve your inversion results.

Select the **OK** button once you are happy with values in the "Inversion Control Parameters" dialog box and want to continue or select the **Cancel** button to abort the new-model build. Selecting **OK** brings up a "Save As" file-name dialog box to give you a chance to change SCS2D file names.
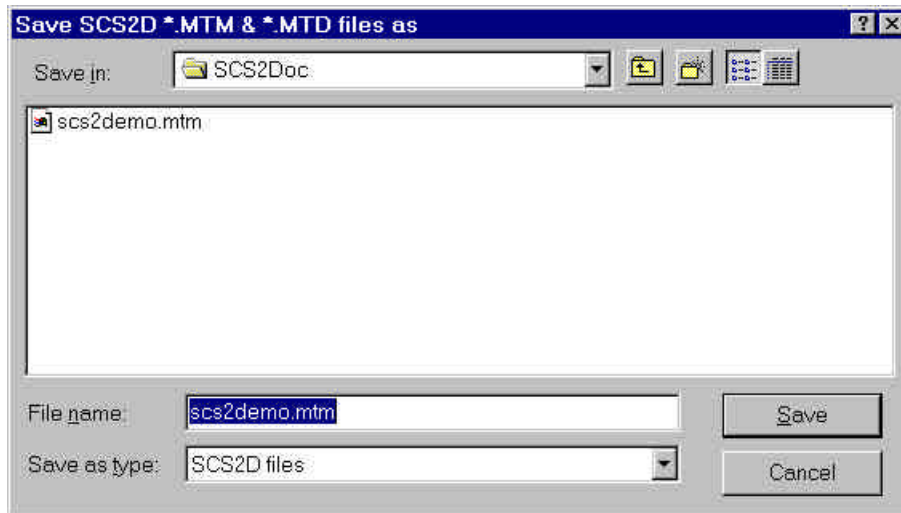
Go right to the **Save** button if you are happy with the default file name or you may enter a different name in the "file name" field and then click on **Save**. If you are about to overwrite existing files, SCS2D give you a warning and a chance to go back and change file names, otherwise SCS2D writes a *.MTM + *.MTD file set, returns to the main menu and plots the new model section

North Silverbell Line 28
Inversion Model Resistivity
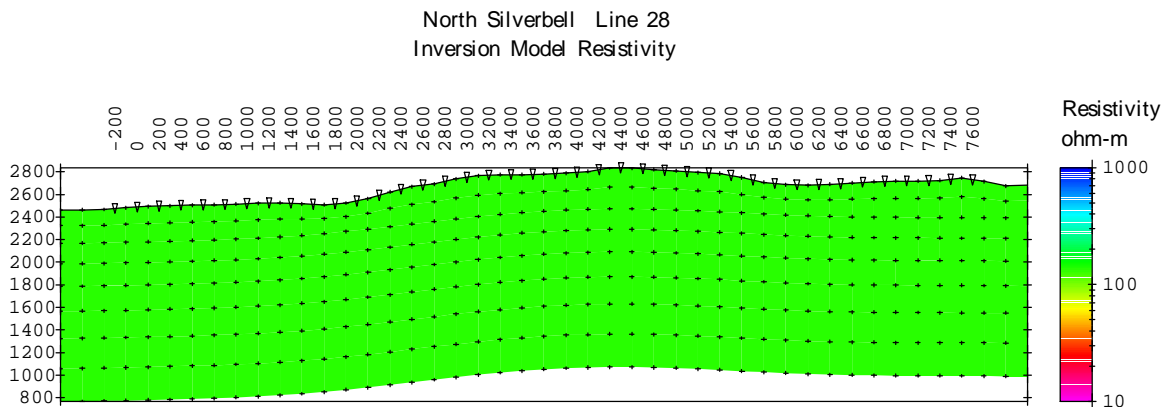
New model section built using data from SCS2DEMO.AVG, SCS2DEMO.MDE and SCS2DEMO.STN with the lowest far-field frequency set to 256 hertz, eight rows of model pixels and a uniform background resistivity.

Review Data Menu Option

It is often helpful to look at log-log plots of observed data after building a new model. Selecting **Review Data** from the main menu generates log10(apparent resistivity) versus log10(frequency) plots of individual sounding curves.
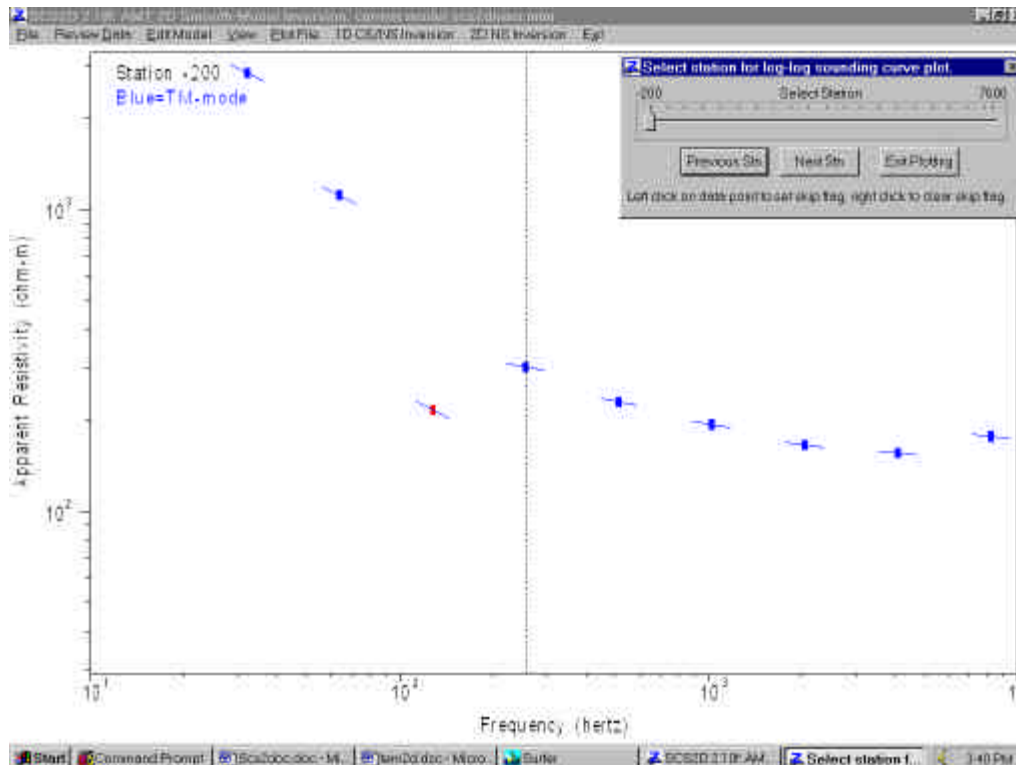
Observed apparent resistivity values are indicated by posted squares with TM-mode data in blue and TE-mode data in green. Skipped data values are indicated with a red square. Apparent resistivity and impedance phase pairs may be skipped by left clicking on a data point. Skip flags may be cleared with a right click. Apparent resistivity error is indicated by short vertical lines, which may not be visible if estimated measurement error is small. Sloping lines indicate slope derived from impedance phase. After an inversion is run, calculated apparent resistivities are shown by a solid curve.

A vertical dashed line marks the lowest far-field frequency, which may be reset using menu choice **Edit Model | Edit Inversion Controls**. The lowest far-field frequency is set to 256 hertz in this example.

You can move from station to station by clicking **Previous Stn** or **Next Stn** buttons in the "select station" dialog box or by moving the dialog's track-bar cursor with the mouse (put the mouse pointer on the track-bar cursor and hold the left mouse key down). Clicking on **Exit Plotting** or pressing the ESC key returns you to the main menu.

1D CS/NS Inversion Menu Option

An existing model may be inverted using all unskipped data by selecting the **1D CS/NS Inversion** menu option from SCS2D's main menu, or by running RSCS1D.EXE from a MS-DOS command line, from a short cut or from a batch file. RSCS1D sequentially inverts data for each station using models with many horizontal layers to approximate smooth resistivity variation with depth. Although

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its geologic modeling is more restricted than RSCS2D, RSCS1D does calculate 3d fields around controlled-source transmitters, so it is useful for getting estimates of deep basement resistivity from low-frequency, controlled-source data.

2D NS Inversion Menu Option

An existing model may be inverted using far-field data by selecting the **2D NS Inversion** menu option from SCS2D's main menu, by running RSCS2D.EXE from a MS-DOS command line, from a short cut or from a batch file. After creating a new model section from SCS2DEMO.AVG, select **2D NS Inversion** from the main menu to start RSCS2D. RSCS2D inverts the starting model in SCS2DEMO.MTM so as to fit the observed data in SCS2DEMO.MTD, subject to model constraints. RSCS2D shows the current model section as it is updated with each inversion iteration.
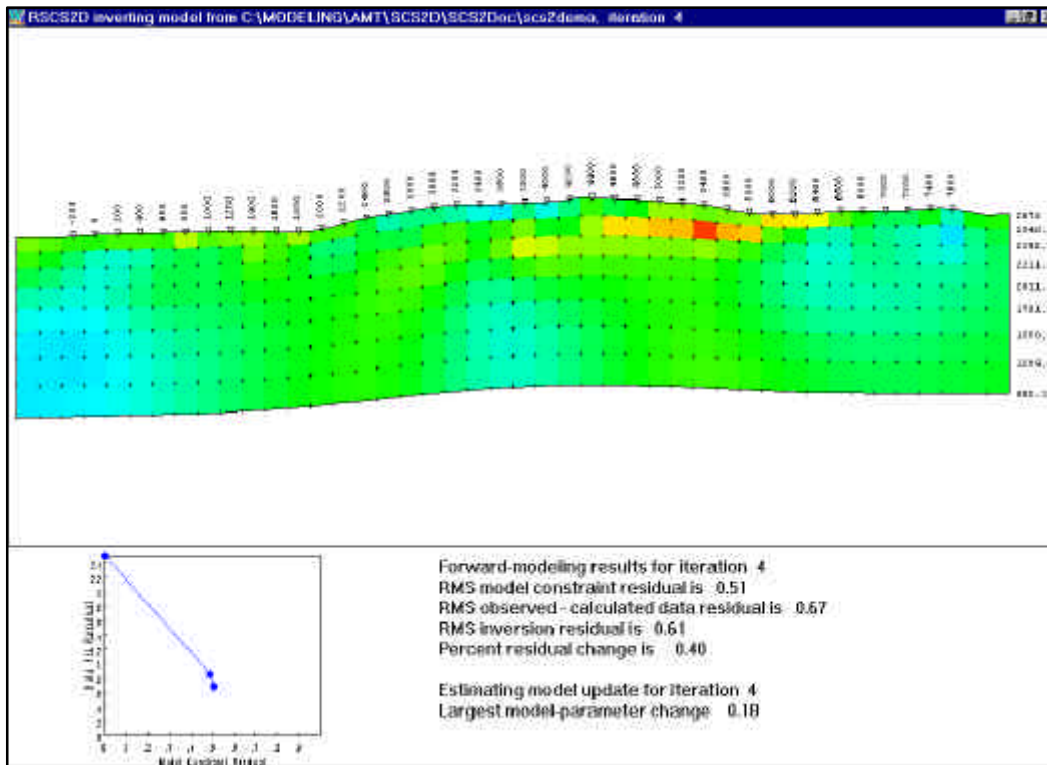
RSCS2D plots the inversion model section across the top two-thirds of its window. Scrolling text describing the inversion's progress is shown on the lower right quarter of the window and a plot of model-constraint residuals versus observed-calculated data residuals is displayed on the lower left. RSCS2D usually makes rapid progress during the first few inversion iterations and then tapers off to small incremental improvements.

Plotting data-fit residuals versus model-constraint residuals emphasizes the trade-off between fitting observed data versus maintaining a smoothly varying model. A new model is very smooth, but its calculated data do not match observed field data very well. That puts a trade-off plot point high on the vertical axis, indicating a very small model-constraint residual and a large data-fit residual. As the inversion progresses, RSCS2D improves the fit to observed data at the expense of larger model-constraint residuals and plot points move down and to the left.

The trade off between fitting data and maintaining a smooth model can be varied by adjusting model-constraint weighting parameters with S2CSD's **Edit Model** | **Edit Inversion Controls** menu option. If you are inclined to experiment, you can try inversions with a range of model-constraint

weights. Lowering model-constraint weighting improves the fit to observed data, up to a point.
Using very low model-constraint weights will not produce a perfect fit to observed data, but it will
generate a rough model, so the final trade-off plot point will be near the horizontal axis and off to the
right. Final results from repeated inversion runs with model constraint weights varying from large to
small should trace out a hyperbola-like curve with asymptotic arms near the positive x and y axis.
Optimal model-constraint weights give a final plot point as close as possible to the trade-off-plot
origin.

Work from smooth towards rough models when running repeating inversions with the same data set.
RSCS2D does a better job at adding structure to a smooth model than it does at smoothing a rough
model section.   Adding the parameter Res0=100 to the *.MTM namelist block resets the starting
model to 100 ohm-m. You can also include inversion control parameters when you run RS2DIPW
from the command line or from a batch file.   Typing "RSCS2D scs2demo –res0=250" on the
command line will restart RSCS2D with the SCS2DEMO.MTM inversion model set to 250 ohm-m.

When an inversion is running, you can minimize RSCS2D to a text label on the Windows task bar by
clicking on the small box with a minus sign at the upper right corner of RSCS2D's window. Clicking
on the small x on the upper-right corner of RSCS2D's window aborts the inversion run. RSCS2D
does not update *.MTM or *.MTD files until after it has successfully finished an inversion, so stopping
part way through an inversion will leave your SCS2D files unmodified.

While running, RSCS2D creates a *.LOG file with text recording how the inversion proceeded. If any
error conditions come up during an inversion, RSCS2D will also create a *.ERR file to hold error
messages. When run from the **2D NS Inversion** menu option, RSCS2D returns control to SCS2D
after it is finished. SCS2D then displays the inverted model section. Inversion resistivity is shown by
default.
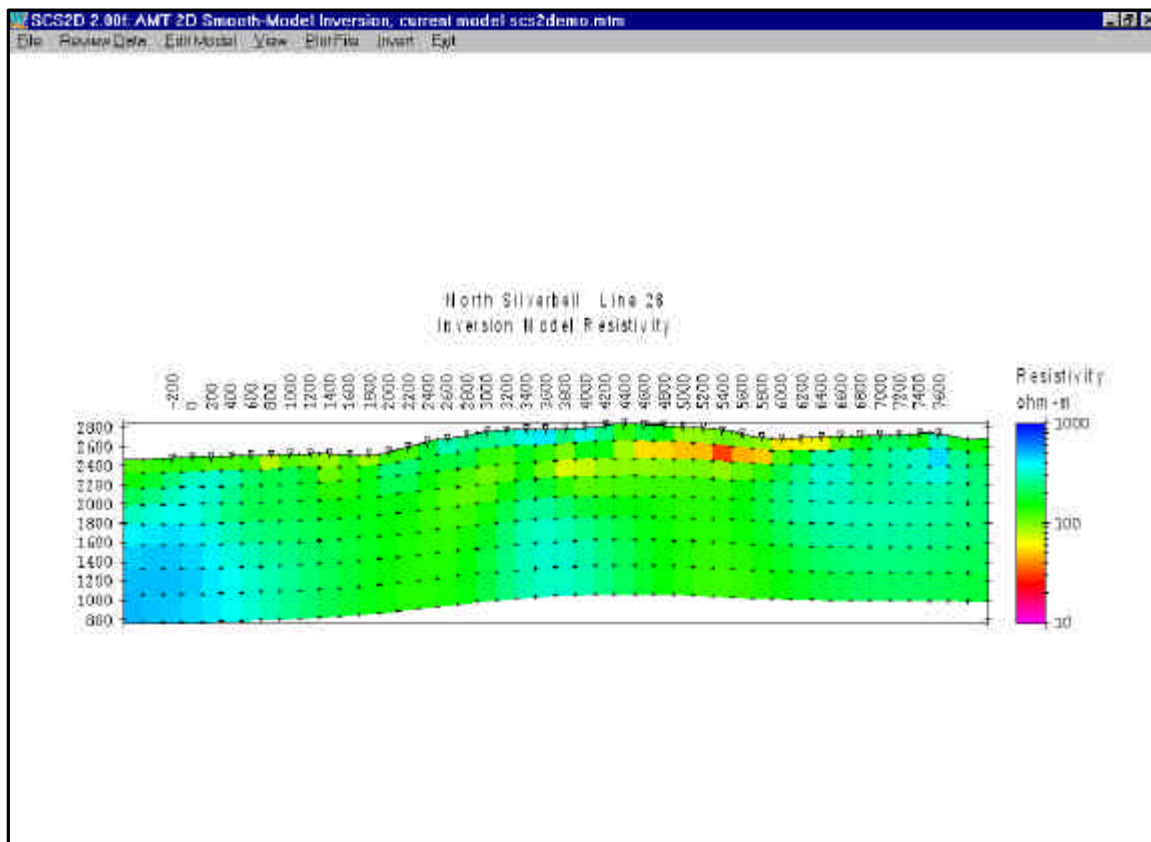
Another interesting model property is model sensitivity. Selecting **View** | **Select View Parameter** | **Inversion Resistivity Sensitivity** brings up a plot of normalized sensitivity.
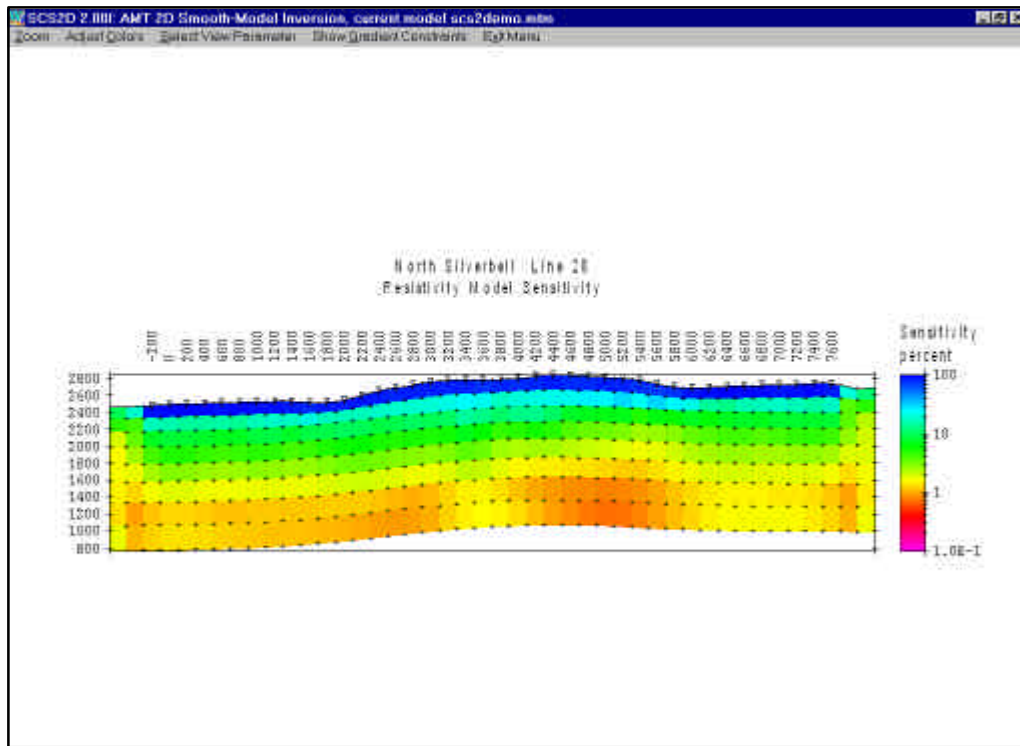
Model parameter sensitivities are saved as percentage values. Areas with 100 percent values are fully resolved by observed data. As data resolution of model-section features drops off, so does percent sensitivity. One to two percent sensitivity roughly contours the maximum depth of investigation. Model structure below the one percent sensitivity contour is primarily controlled by model constraints, not field data. Broad conductive areas reduce the maximum depth of investigation, while high resistivity features increase the depth of investigation relative to a uniform half space.

Model-section details may be examined by looking at part of the section with **View** | **Zoom** | **Zoom In** or **Zoom Rectangle**. You can move around in a magnified view of the model section with the **Zoom** | **Pan** menu option. To get back to a plot of the entire section, select **Zoom Back** or **Zoom All**.

Color-fill limits may be adjusted with the **View** | **Adjust Colors** menu option.
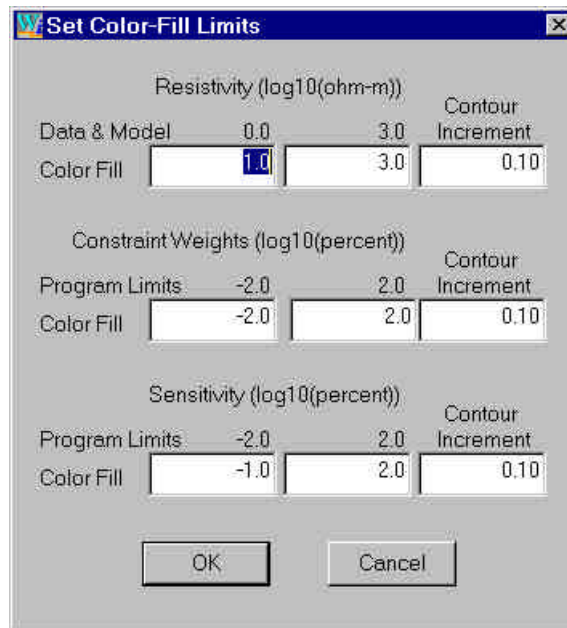
SCS2D's set color-fill limits dialog box includes fields for editing resistivity color-fill limits in units of log10(ohm-m). Constraint weight and model sensitivity color limits are also in log10 units. SCS2D saves color-fill limits in *.MTM files, so that they don't have to be reset when you reopen an existing model file set.

Editing gradient constraints

After running a preliminary inversion it is sometimes helpful to cut smoothness constraints in areas with steep model-section gradients indicating high-contrast contacts. A common case is inversion of data collected in areas with conductive overburden. A preliminary inversion will give a good indication of overburden thickness, but the interaction between smoothness constraints and the high contrast between overburden and basement can obscure deeper features. Cutting smoothness constraints along the bottom of the overburden layer and then re-running the inversion often improves resolution of basement features.

Basic steps can be illustrated with SCS2DEMO.MTM after a first inversion run. Open the SCS2DEMO file set by running SCS2D, selecting **Open** from the initial menu and then selecting S2CSDEMO.MTM from the open-file dialog box list. SCS2D will then show the SCS2DEMO inversion resistivity model section and main-menu options. Select **Edit Model** | **Edit Gradient Constraints** and a "Select new gradient constraint value" dialog box will appear in the upper left corner of your monitor screen. To cut gradient constraints move the track-bar cursor left to the "Low = Cut" setting by dragging it with your mouse (put the mouse pointer on the track-bar cursor and hold the left mouse key down). Then click on the **OK** button. SCS2D will now show the model section with an overlay of color-coded lines between model pixels. The lines represent gradient-constraint weights. Cool colors indicate low weight, green is neutral and warm colors indicate high gradient-constraint weights. You can draw in the new gradient constraint value along boundaries between pixels by moving the mouse cursor to model pixel corners and clicking the left mouse button at every point you wish to place a line-segment endpoint. When you have finished drawing a polygonal line tracing out your gradient-constraint change, click the right mouse button. SCS2D will update the model section with new line colors indicating current gradient-constraint weights.
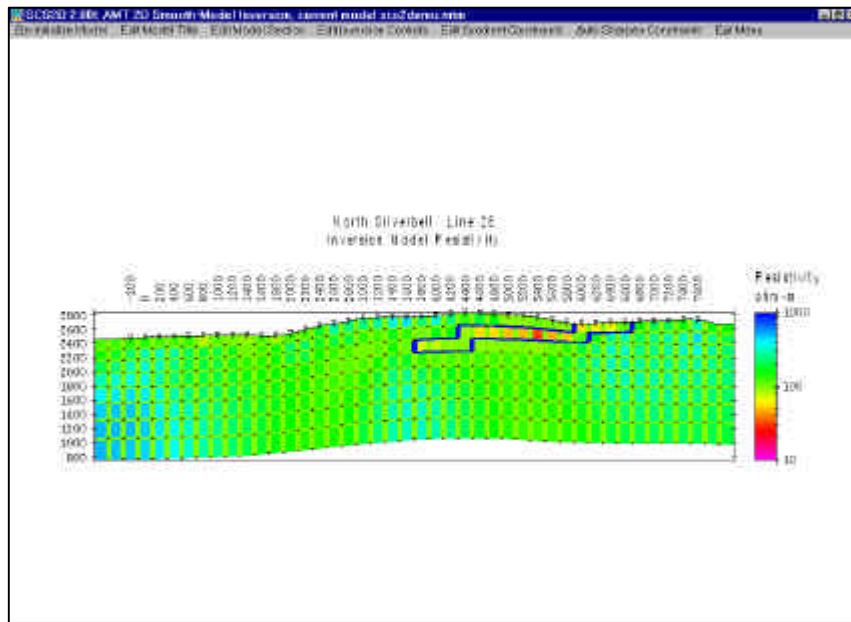
Blue lines between model pixels show where I have sheared gradient constraints along the edge of a low resistivity feature in SCS2DEMO.MTM. I used **View** | **Zoom** | **Zoom Rectangle** to get a magnified plot of the most interesting area. Then I used **Edit Model** | **Edit Gradient Constraints** to turn on the gradient constraint display and cut gradient constraints around the edge of the low resistivity.   After editing gradient constraints, I used **View** | **Zoom** | **Zoom All** to view the entire model section. **View** | **Hide Gradient Constraints** will turn off the gradient constraint display if you want to get back to a normal view of the model section. Next is re-running the inversion with the **Invert** menu choice to update inversion-model resistivity.
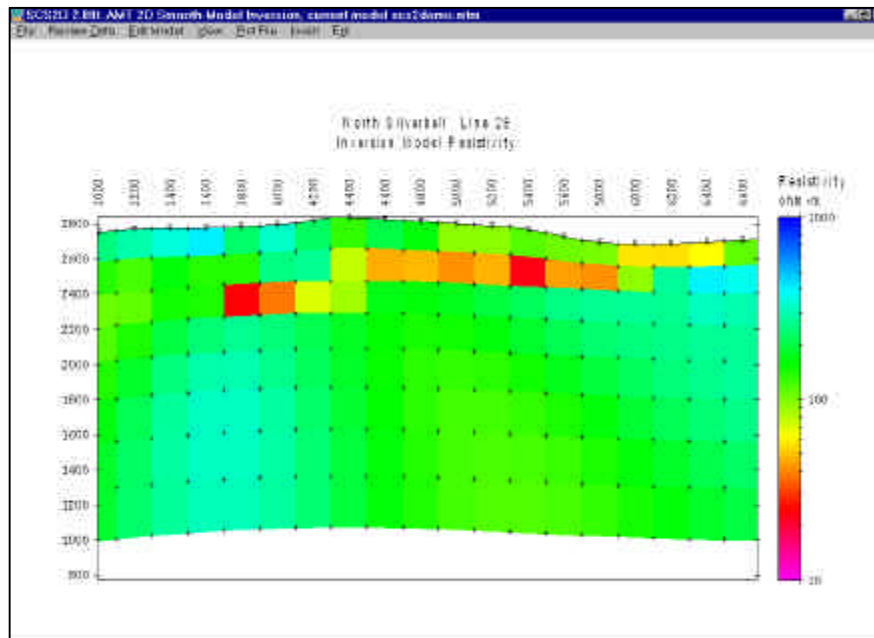
Re-running the inversion with gradient constraints cut around the low resistivity area, lets RSCS2D introduce a sharp offset between low resistivity and surrounding higher resistivity host material. Here, I have used **View | Zoom Rectangle** to select a detailed view of the model section.

Auto-Sharpen Constraints

The idea of weakening smoothness constraints in areas with steep gradients has been automated in the **Edit Model | Auto-Sharpen Constraint** function. After running a preliminary inversion, you can select **Edit Model | Auto-Sharpen Constraint** to make smoothness constraint weights proportional to inversion resistivity gradients. Smoothness constraints are lowered in areas with high resistivity gradients and are increased in areas with low resistivity gradients using the filter

$$\text{dxzW} = 10^{\left\{\left(-\frac{4}{p}\right)\text{atan}\left(\frac{|g|-\text{filter\_midpoint}}{\text{filter\_width}}\right)\right\}}$$

Where dxzW = dxW on vertical edges and dzW on horizontal edges, g = gradient = the difference between log(resistivity) along edges between model pixels, filter_midpoint defaults to the average gradient value and filter_width defaults to standard deviation of model-section gradients. When the gradient between adjacent model pixels is much less than filter_midpoint, dxzW approaches 10^2. Conversely, when the gradient between adjacent model pixels is much larger than filter_midpoint, dxzW approaches 10^{-2}. The result is to make flat areas flatter and steep areas steeper, increasing the contrast between model-section features. SCS2D shows a dialog box which allows you to change filter_midpoint and filter_width
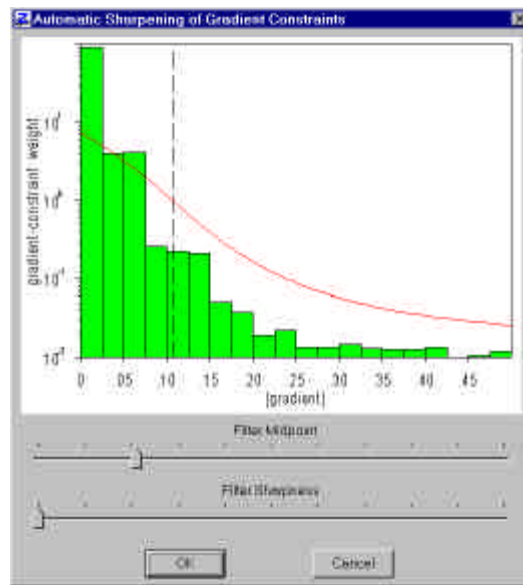
Green histogram bars indicate the number of pixel-to-pixel gradient values at each gradient level. A red line shows how the auto-sharpening filter maps gradient values to dxW and dzW smoothness-constraint weighting. Filter_midpoint, indicated by a vertical dashed line, defaults to the model section's average gradient magnitude value and filter_width, controlling filter sharpness, defaults to gradient standard deviation. Filter midpoint and width may be adjusted by dragging the trackbar pointers with the mouse cursor. Running a preliminary inversion with **2D NS Inversion**, then **Edit Model | Auto-Sharpen Constraints** and rerunning **2D NS Inversion** sharpens the contrast between model-section features.

North Silverbell   Line 28
Inversion Model Resistivity
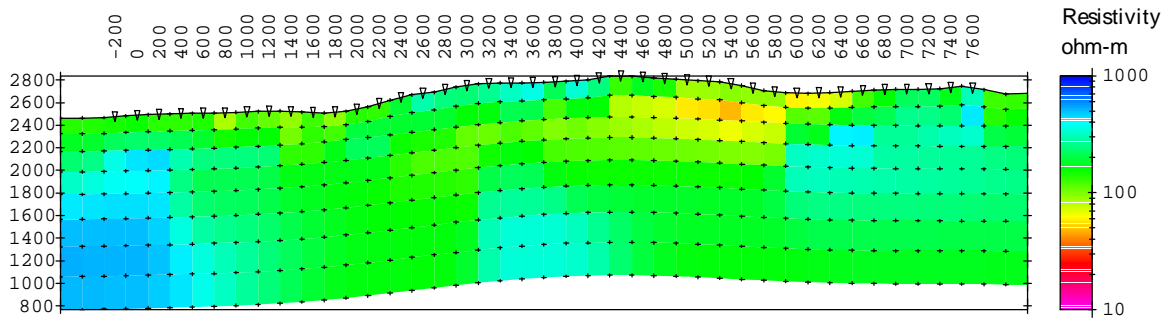
Inverting long lines

SCS2D can build lines up to 200 dipole lengths long and RSCS2D will invert them in one piece, although inversion of a long line will take some time. Using a PC with the maximum available amount of RAM will speed up inversion of large models.

RSCS2D command-line parameters

To facilitate sequential inversion of multiple lines from a batch file or repeated inversion of one line with varying constraint weights, RSCS2D takes model-file names and inversion-control parameters as command-line arguments. Inversion-control parameters set from the command line override values set in *.MTM files. As an example, a batch files with the following two lines:

```
start /w rscs2d Line1 –Res0=100
start /w rscs2d Line2 –Res0=100
```

will invert LINE1.MTM + LINE1.MTD and LINE2.MTM + LINE2.MTD with the resistivity starting model set to 100 ohm-m. Using the Windows command-line function "start /w" instructs Windows to wait until RSCS2D is done with Line1 before starting "rscs2d Line2". The command line argument -Res0=100 sets the inversion starting model to 100 ohm-m. Resetting the starting model to near background is a good idea when re-inverting models after editing model constraint weighting or background geology. Command line arguments for inversion-control parameters are preceded by a - character and the parameter name is separated from its value by a = character. Multiple command-line arguments must be separated by one or more spaces.

Command line arguments are also handy for running repeated inversion on one line with varying model-constraint weights. Using

```
start /w rscs2d scs2demo –ResSmth=4 –Res0=100
copy scs2demo.mtm scs2demo1.mtm
copy scs2demo.mtd scs2demo1.mtd
copy scs2demo.log scs2demo1.log

start /w rscs2d scs2demo –ResSmth=1 –Res0=100
copy scs2demo.mtm scs2demo2.mtm
copy scs2demo.mtd scs2demo2.mtd
copy scs2demo.log scs2demo2.log

start /w rscs2d scs2demo –ResSmth=0.25 –Res0=100
copy scs2demo.mtm scs2demo3.mtm
copy scs2demo.mtd scs2demo3.mtd
copy scs2demo.log scs2demo3.log
```

will generate three sets of inversion results with model-constraint weighting set to 4, 1 and 0.25 with the –ResSmth= command line argument. Using –Res0=100 each time resets the starting model to 100 ohm-m, making the inversion results more consistent.

Inversion control parameters which can be used as command line arguments:
Res0   - sets starting model resistivity to a constant value.
StnBeg   - first station to use in inversion = left edge of active model section.
StnEnd   - last station to use in inversion = right edge of active model section.
NResIter   - maximum number of iterations during resistivity inversion (0 to 32).
ResSmth   - tradeoff between resistivity data and constraints (0.01 to 100).
ResdpW   - relative weight of resistivity background model (0.01 to 100).
ResdxW   - relative weight of horizontal resistivity smoothness (0.01 to 100).
ResdzW   - relative weight of vertical resistivity smoothness (0.01 to 100).

Model-section plotting using MODSECT

Typing "MODSECT SCS2DEMO" brings up a more polished model-section plot. MODSECT can export model-section plots to windows metafiles for pasting into MS-Word documents, it drive MS-DOS version GeoSoft program to create GeoSoft-format plots, or it can write Surfer v6 script and data files for automated plot production with Surfer for Windows.

Note that since MODSECT prefixes "R" and "P" to file names to distinguish between resistivity and IP plots, the original file names should have seven or fewer characters. If the original file name stem has more than seven characters, the last character will be automatically dropped.
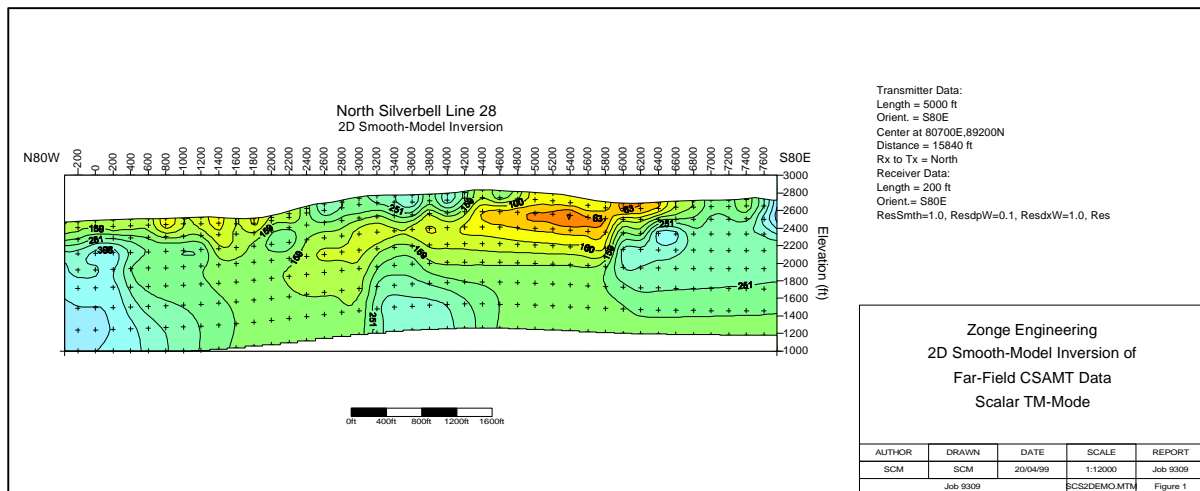
Resistivity inversion results from SCSDEMO plotted with MODSECT, GS Scripter and Surfer for Windows v6.0. The low-resistivity layer tracks a supergene enrichment zone.

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Appendix A: Data-File Format Documentation

*.MDE File Format (line annotation, survey configuration and data processing control)

*.MDE files hold plot annotation and Zonge data-processing-control information. A *.MDE-file consists of one or mode lines, each of which begins with a "$" in the first column, optionally followed by a program name and colon ":". The name of the mode keyword is followed by an equal sign "=", then a value to assign to that variable. Spaces may be included between elements of a mode line. Spaces in values defined as text will be included in the text string.

Partial listing of SCS2DEMO.MDE:

```
$ COMPANY=Zonge Engineering
$  CLIENT=Zonge Engineering
$ PROJECT=North Silverbell
$ JOBNUMB= 9309
$ JOBDATE=Nov 93
$ JOBLINE=28
$ BRGLINE=S80E
$ BRGBACK=N80W
$   UNITS=  FEET
$ STNLO  =   -2.0
$ STNDELT=    2.0
$ LBLFRST= -200.0
$ LBLDELT=  200.0
$  TXTYPE= Bipole
$   TXLEN= 5000
$   TXBRG= S80E
$   TXCX =80700
$   TXCY =89200
$   RXLEN=200
```

STNLO, LBLFRST, STNDELT and LBLDELT can be used to shift and scale station numbers from values used in *.AVG and *.Z files to some other station number system. STNLO and LBLFRST may be used to define a station-number shift. STNDELT and LBLDELT may be used to scale station number increments. Default values produce no station-number shifting or scaling.

STNLO   - first station number in *.RAW, *.AVG and *.Z file station number units.
LBLFRST   - first station number in scaled and shifted station number units.
STNDELT   - station number increment in *.RAW, *.AVG and *.Z file station # units.
LBLDELT   - station number increment in scaled and shifted station number units.

RXLEN and/or ASPACE are used to set default station increments in length units.
RXLEN = ASPACE - receiver dipole length (length units).

The following mode keywords are used by SCS2D for default positioning and orientation of controlled-source transmitter antennas. For tensor surveys, there should be two sets of transmitter-antenna modes.

LENUNITS - length units used for distances (m, km, ft or kft).
TXTYPE   - transmitter type (bipole,loop,natural).
TXLEN   - transmitter bipole length or loop length and width (length units).
TXBRG   - transmitter antenna bearing in N??E format.
TXCX   - transmitter antenna center grid E coordinate (length units).
TXCY   - transmitter antenna center grid N coordinate (length units).

These modes are used to control plot annotation, scaling and color fill when making smooth-model-section plots with MODSECT. MODSECT documentation includes a description of each mode keyword.

```
$ MODSECT: PLOT = Surfer
$ MODSECT: LNUNITS = ft
$ MODSECT: LNTITLE1 = North Silverbell Line 28
$ MODSECT: LNTITLE2 = 2D Smooth-Model Inversion
$ MODSECT: BRGLEFT= N80W
$ MODSECT: BRGRIGHT= S80E
$ MODSECT: TBTITLE1 = Zonge Engineering
$ MODSECT: TBTITLE2 = 2D Smooth-Model Inversion of
$ MODSECT: TBTITLE3 = Far-Field CSAMT Data
$ MODSECT: TBTITLE4 = Scalar TM-Mode
$ MODSECT: TBTITLE5 = Scalar Far-field CSAMT Data
$ MODSECT: TBLABEL1 = AUTHOR
$ MODSECT: TBLABEL2 = DRAWN
$ MODSECT: TBLABEL3 = DATE
$ MODSECT: TBLABEL4 = SCALE
$ MODSECT: TBLABEL5 = REPORT
$ MODSECT: TBLABEL6 = REF:
$ MODSECT: TBTEXT1 = SCM
$ MODSECT: TBTEXT2 = Zonge
$ MODSECT: TBTEXT3 = 15/Oct/99
$ MODSECT: TBTEXT4 = 1:12000
$ MODSECT: TBTEXT5 = Job 9309
$ MODSECT: TBTEXT6 = Job 9309
$ MODSECT: TBTEXT7 = Figure 1
$ MODSECT: TBGLOSS01 = Transmitter Data:
$ MODSECT: TBGLOSS02 = Length = 5000 ft
$ MODSECT: TBGLOSS03 = Orient. = S80E
$ MODSECT: TBGLOSS04 = Center at 80700E,89200N
$ MODSECT: TBGLOSS05 = Distance = 15840 ft
$ MODSECT: TBGLOSS06 = Rx to Tx = North
$ MODSECT: TBGLOSS07 = Receiver Data:
$ MODSECT: TBGLOSS08 = Length = 200 ft
$ MODSECT: TBGLOSS09 = Orient.= S80E
$ MODSECT: TBGLOSS10 = ResSmth=1.0, ResdpW=0.1, ResdxW=1.0, Res
$ MODSECT: XSCALE =   1.2000E+4   Horizontal scale  (plot X-axis)
$ MODSECT: YSCALE =   1.2000E+4   Vertical scale    (plot Y-axis)
$ MODSECT: YSIZE  =       14.00   Min plot height including margins (cm)
$ MODSECT: StnLeft  =     -300.   First station on left edge of plot
$ MODSECT: StnRight =     7700.   Last station on right edge of plot
$ MODSECT: StnDec   =        0    # station-number decimals (0 to 3)
$ MODSECT: StnInc   =     200.00  Station interval (stn #)
$ MODSECT: ElvMin   =    1000.00  Minimum elevation (plot Y-axis)
$ MODSECT: ElvMax   =    3000.00  Maximum elevation (plot Y-axis)
$ MODSECT: ElvInc   =     200.00  Elevation tick interval
$ MODSECT: TOPO   = YES           Draw line along topographic surface?
$ MODSECT: CNTVAR = Resistivity   Contour variable (resistivity or IP)
$ MODSECT: CRMIN  =        1.50   Res contour color minimum (log10(ohm-m))
$ MODSECT: CRMAX  =        3.00   Res contour color maximum (log10(ohm-m))
$ MODSECT: CRINC  =        0.10   Res contour interval (log10(ohm-m))
$ MODSECT: CRDEC  =        0      # res-contour-label decimals (0 to 3)
$ MODSECT: RScutoff =      1.00   Resistivity-sensitivity cutoff (percent)
```

*.STN File Format (station location and elevation)

*.STN files hold information about station locations in a tabular format. A *.STN file should have at least two entries, corresponding to the first and last stations. Additional entries may be necessary to trace out topographic changes or curved lines. SCS2D assumes that station numbers represent distance along line and uses station numbers to interpolate between coordinate records, if necessary. If station numbers are scaled or shifted by entries in the *.MDE file, **.STN-file station numbers should be in the scaled and shifted units defined by *.MDE LBLFRST and LBLDELT**, not the unscaled and unshifted units defined by STNBEG, STNDELT.   Left-justified comment lines beginning with a "!", "\", "/" or a "" may be included in *.stn files for annotation.

Partial listing of SCS2DEMO.STN:

```
 "Stn"    "GridE"   "GridN"    "Elev"
 -800     71899     73439      2465
 -600     72096     73407      2465
 -400     72293     73375      2460
 -200     72490     73343      2475
    0     72687     73311      2490
  200     72885     73279      2495
  400     73082     73246      2505
  600     73280     73214      2505
  800     73477     73182      2510
 1000     73674     73149      2520
 1200     73872     73117      2525
 1400     74069     73085      2525
    .        .         .         .
    .        .         .         .
    .        .         .         .
 7200     79792     72147      2718
 7400     79990     72115      2730
 7600     80187     72083      2760
 7800     80384     72051      2670
 8000     80581     72019      2680
 8200     80778     71987      2682
```

Note that the topographic profile in SCS2DEMO.STN extends several station intervals beyond either end of the line. Including elevation information beyond the extent of geophysical data improves topographic modeling.

Some grid coordinate systems, such as UTM coordinates, can generate very large coordinate values. SCS2D stores station locations as floating-point numbers with about six significant figures. It may be necessary to subtract a constant from large coordinate values in order to allow accurate representation with six significant figures.

*.STN file column definitions:

Stn   - station numbers, proportional to distance along line.
GridE   - grid east (length units specified in *.MTM file).
GridN   - grid north (length units).
Elev   - elevation or RL (length units).

*.AVG File Format (GDP CSAMT or AMT data averaged by AMTAVG or NSAVG)

SCS2D reads *.AVG files produced by the Zonge data-processing program AMTAVG. *.AVG files contain data averaged over repeat GDP readings, with measurement error estimated from variation between repeats.

Partial listing of file SCS2DEMO.AVG:

```
\ AMTAVG 7.20: "L28.FLD", Dated 93-11-17, Processed 19 Nov 93
\$ ASPACE=  200.ft
\$ XMTR  =   1.
\ ASTATIC v2.01 added TMARES/SRES column on 05/24/96
\ 5-point TMA Filter at 4096 hertz
skp Station Freq Comp Amps    Emag    Ephz    Hmag    Hphz Resistivity  Phase %Emag sEphz %Hmag sHphz  %Rho  sPhz TMARES/SRES
 2  0.  8192 ExHy 7.   7.1637e+3 -2555.4 2.6594e+0 3089.1 1.7716e+2  638.6  0.4  4.4  0.1 10.1  0.9  7.2 1.6584E+2
 2  0.  4096 ExHy 11.  6.6556e+3 -1749.9 3.5677e+0 -2371.4 1.6993e+2  621.6  0.1  1.8  0.8  8.3  0.8  9.9 1.5907E+2
 2  0.  2048 ExHy 16.  6.8889e+3 -1180.6 4.9804e+0 -1780.0 1.8684e+2  599.4  0.3  2.5  0.2  3.1  0.3  3.3 1.7490E+2
 2  0.  1024 ExHy 20.  7.2575e+3 -795.0 6.9107e+0 -1365.8 2.1540e+2  570.8  0.2  2.0  0.2  2.4  0.7  6.0 2.0164E+2
 2  0.   512 ExHy 22.  7.6680e+3 -608.6 9.5484e+0 -1141.3 2.5192e+2  532.7  0.7  7.2  0.1  1.6  1.2  8.6 2.3582E+2
 2  0.   256 ExHy 22.  8.5168e+3 -450.5 1.3391e+1 -1021.6 3.1604e+2  571.1  0.2  1.5  0.4  4.9  0.6  6.4 2.9585E+2
 2  0.   128 ExHy 22.  8.5507e+3 -1113.6 2.2357e+1 -1091.8 2.2856e+2  -21.8  0.3  2.4  0.5  3.3  0.5  1.1 2.1396E+2
 2  0.    64 ExHy 22.  2.4669e+4 -950.4 4.0949e+1 -769.0 1.1341e+3 -181.4  0.1  1.1  0.4  3.9  0.8  1.5 1.0616E+3
 2  0.    32 ExHy 22.  3.6149e+4 -357.9 5.3420e+1 -291.1 2.8619e+3  -66.8  0.1  0.9  0.4  4.3  0.6  2.9 2.6790E+3
 2  2.  8192 ExHy 7.   6.4907e+3 -2597.9 2.6594e+0 3089.1 1.4544e+2  596.1  0.3  4.0  0.1 10.1  0.9  7.4 1.5724E+2
 2  2.  4096 ExHy 11.  6.1855e+3 -1740.7 3.5677e+0 -2371.4 1.4677e+2  630.8  0.0  0.9  0.8  8.3  0.6  8.4 1.5867E+2
 2  2.  2048 ExHy 16.  6.3995e+3 -1155.5 4.9804e+0 -1780.0 1.6124e+2  624.4  0.2  1.7  0.2  3.1  0.3  3.0 1.7432E+2
 2  2.  1024 ExHy 20.  6.6290e+3 -759.6 6.9107e+0 -1365.8 1.7971e+2  606.2  0.1  1.1  0.2  2.4  0.5  4.4 1.9428E+2
 2  2.   512 ExHy 22.  6.8992e+3 -571.8 9.5484e+0 -1141.3 2.0394e+2  569.5  0.4  4.8  0.1  1.6  0.7  5.1 2.2048E+2
 2  2.   256 ExHy 22.  7.4206e+3 -413.4 1.3391e+1 -1021.6 2.3992e+2  608.2  0.2  1.3  0.4  4.9  0.6  6.5 2.5938E+2
 2  2.   128 ExHy 22.  7.3464e+3 -1077.4 2.2357e+1 -1091.8 1.6871e+2   14.5  0.3  3.3  0.5  3.3  0.6  0.2 1.8239E+2
 2  2.    64 ExHy 22.  2.0806e+4 -925.6 4.0949e+1 -769.0 8.0672e+2 -156.6  0.1  1.1  0.4  3.9  0.8  1.5 8.7214E+2
 2  2.    32 ExHy 22.  3.0245e+4 -345.0 5.3420e+1 -291.1 2.0034e+3  -53.8  0.1  0.8  0.4  4.3  0.6  2.8 2.1659E+3
 2  4.  8192 ExHy 7.   6.5220e+3 -2632.8 2.6594e+0 3089.1 1.4684e+2  561.2  0.3  3.9  0.1 10.1  0.9  7.4 1.5280E+2
 2  4.  4096 ExHy 11.  6.2180e+3 -1734.0 3.5677e+0 -2371.4 1.4832e+2  637.4  0.0  0.6  0.8  8.3  0.6  7.9 1.5434E+2
 2  4.  2048 ExHy 16.  6.3449e+3 -1132.1 4.9804e+0 -1780.0 1.5850e+2  647.8  0.1  1.2  0.2  3.1  0.3  2.7 1.6493E+2
 2  4.  1024 ExHy 20.  6.4338e+3 -728.9 6.9107e+0 -1365.8 1.6928e+2  636.9  0.1  0.7  0.2  2.4  0.4  3.8 1.7615E+2
 2  4.   512 ExHy 22.  6.5959e+3 -543.1 9.5484e+0 -1141.3 1.8640e+2  598.2  0.3  3.8  0.1  1.6  0.5  3.7 1.9397E+2
 2  4.   256 ExHy 22.  6.9569e+3 -387.4 1.3391e+1 -1021.6 2.1087e+2  634.2  0.1  1.3  0.4  4.9  0.6  6.7 2.1943E+2
 2  4.   128 ExHy 22.  6.9105e+3 -1043.6 2.2357e+1 -1091.8 1.4929e+2   48.2  0.4  4.4  0.5  3.3  0.7  1.8 1.5535E+2
 2  4.    64 ExHy 22.  1.8971e+4 -894.2 4.0949e+1 -769.0 6.7075e+2 -125.2  0.1  1.1  0.4  3.9  0.8  1.5 6.9798E+2
```

Left-justified comment lines preceded by a "\", "/", "!" or """"may be placed anywhere within *.AVG files. Data-processing mode lines proceeded by a "$" in column 1 may also be present at any location and apply to subsequent data. A column-label line must precede the numerical data. Numerical values are free format with columns separated by spaces or commas. Missing values are flagged by a "*". Column order from file to file is not fixed and not all columns may be present in a particular file.

CSAMT *.AVG file column definitions:

Skp   - skip flag, 2 = good data, 1= bad data, 0 = very bad data.
Station   - receiver station number in unscaled and unshifted units.
Comp   - measured E and H field component pair (ExHy=TM-mode or EyHx=TE-mode).
Amps   - peak-to-peak square-wave current = pi/4*Fourier component current (amps).
Freq.   - measurement frequency (hertz).
Emag   - electric-field magnitude (uV/(km*amp)=nV/(m*amp)).
Ephz   - electric-field phase (mrad).
Hmag   - magnetic-field magnitude (pT/amp).
Hphz   - magnetic-field phase (mrad).
Resistivity - Cagniard resistivity (ohm-m) .
Phase   - impedance phase = phase(E/H) (mrad).
%Emag   - E-field magnitude error = 100*standard_deviation(Emag)/Emag (percent).
sEphz   - E-field phase error = 100*standard_deviation of Ephz (mrad).
sHphz   - H-field phase error = 100*standard_deviation of Hphz (mrad).
%Hmag   - H-field magnitude error = 100*standard_deviation(Hmag)/Hmag (percent).
%Rho   - apparent resistivity error = 100*standard_deviation(Rho)/Rho (percent).
sPhz   - impedance phase error = standard deviation (mrad).
TMARES/SRES - static-corrected apparent resistivity (ohm-m) (added by ASTATIC).

*.Z file – for CSAMT pseudosections plotting with ZPLOT:

*.Z files are used for storing plot file data in multiple blocks of (skp,x,y,z) data. Numerical values are stored in a fixed format, so column position is important. Numerical field widths are indicated by the "IxYz" record preceding numerical data. A "IxYz" text string flags the beginning of a block of numerical (skp,x,y,z) data and a 9999.0 value flags the end of the block. For SCS2D input, the *.Z file must have matching blocks of apparent resistivity and impedance phase data. Apparent resistivities may be uncorrected, static-corrected or filtered.

Partial listing of SCS2DEMO.Z:

```
$ ZPLOT: DATA = FLOG
$ ASPACE = 200 ft
Contour Plot Z-File
 Cl Cn Ce Ns Nd Yl  Plot file  1
  1  5  0  3  1  1
 CSAMT SURVEY DATA
 STATIC-CORRECTED APP. RES.
 5-point TMA Filter at 4096 hertz
 ASTATIC v2.01a 05/24/96
IIxxxxxxxxYYYYYYYYzzzzzzzzzzzz
  2      -2.  14.000    2.832E+3
  2      -2.  15.000    1.113E+3
  2      -2.  16.000    2.168E+2
  2      -2.  17.000    2.999E+2
  2      -2.  18.000    2.307E+2
  2      -2.  19.000    1.941E+2
  2      -2.  20.000    1.666E+2
  2      -2.  21.000    1.567E+2
  2      -2.  22.000    1.772E+2
  2       0.  14.000    2.679E+3
  2       0.  15.000    1.062E+3
  .       .     .          .
  .       .     .          .
  .       .     .          .
  2      76.  20.000    2.448E+2
  2      76.  21.000    2.387E+2
  2      76.  22.000    2.530E+2
 9999.00
 Cl Cn Ce Ns Nd Yl  Plot file  2
  0 10  3  3  0  1
 CSAMT SURVEY DATA
 IMPEDANCE PHASE
 values in milliradians
IIxxxxxxxxYYYYYYYYzzzzzzzzzzzz
  2      -2.  14.000   -7.650E+1
  2      -2.  15.000   -1.974E+2
  2      -2.  16.000   -3.920E+1
  .       .     .          .
  .       .     .          .
  .       .     .          .
  2      76.  20.000    6.787E+2
  2      76.  21.000    6.589E+2
  2      76.  22.000    6.129E+2
 9999.00
```

Description of lines in sample *.Z file:

$ ZPLOT: DATA= FLOG - mode line, y-value data type (log(freq))
$ ASPACE = 200 ft - receiver dipole length
AMTAVG 7.20   - program name and version that generated this file.
Cl Cn Ce Ns Nd Yl   - labels for integer contour control flags.
        Cl - label for contour type: 0 = linear
                1 = logarithmic
                2 = pseudo-log: Pseudo-log contours = positive and negative values are contoured
                separately, using log10(abs(value)), plus a zero contour.
        Cn - label for number of contours per interval.
        Ce - label for exponent of the contour interval, interval=10^Ce.
        Ns - label for number of significant digits when posting values.
                Values: -1, 3, 4, 5. (-1 = free format for small values)
        Nd - label for the number of digits after the decimal.
        Yl - label for vertical axis: 0 = none
                1 = log frequency axis
                2 = linear frequency axis
                3 = linear depth
 1 5 0 3 1 1 - integer values for contour control flags.
        1 - value of Cl => logarithmic contours
        5 - value of Cn => 5 contours per "interval"
        0 - value of Ce => interval=10 <= > Ce=1
        3 - value of Ns => use 3 significant digits for contouring
        1 - value of Nd => plot 1 digit after the decimal
        1 - value of Yl => log frequency axis
 CSAMT SURVEY DATA   - Data description for this plot file. Two to six lines are available.
 CAGNIARD APP. RES.   Column one is not read by ZPLOT.
 values in ohm-m   ZPLOT plots these lines as title annotation.
 Data from ASTDEMO.AVG
IIxxxxxxxxYYYYYYYYzzzzzzzzzzzzz - Header line for the data that follows.
II - skip flag field:
        0 = Skip this line of data.
        1 = Omit for contouring, but post the bracketed value.
        2 = Use for contouring and post the value (most common).
        3 = Label a point or station by plotting a symbol under the X-axis at the X-coordinate.
        4 = Use for contouring, post the symbol and not the value. Used for depth plots where
             interpolated values are used at the bottom of the plot to improve gridding.
        5 = Use to set plot limits, do not contour or post. Used for depth plots to set zero depth.
            Also used to provide a margin around the data, as for plan maps.
xxxxxxxx - x value field, usually unscaled and unshifted station numbers.
YYYYYYYY - y value field, for CSAMT y=log2(freq)-9, not used when skip flag = 3
zzzzzzzzzzzzz - z value field, to be plotted at (x,y) when skip flag=1, 2, or 4.
AAA   - annotation field, when skip flag=1 or 2, ZPLOT posts any characters in the AAA column
            instead of plotting the z value. When skip flag=3, ZPLOT plots a symbol below the x-axis at
            the x-value according to an integer in column AAA. A zero or positive integer refers to
            symbols in TABLE 1 of the PLOT Manual. A negative integer refers to topographic symbols
            in the CTOPO Manual.
9999.0 - marks end of (stn,x,y,z) data block.

Appendix B: SCS2D-File Format Documentation

*.MTM File Format (survey configuration, inversion control and model section)

*.MTM files start with a fortran namelist block holding survey configuration and inversion-control parameters followed by a tabular numeric section describing the model cross-section. Left-justified comment lines starting with a "!", "/", "\" or "" may be placed anywhere before or after the namelist block, but not inside the namelist block.

Partial Listing of SCS2DEMO.MTM:

```
"Model updated by RSCS2D v2.10f  Date:19/04/99  Time:08:40"
&SCS2D
 Header(1)='North Silverbell  Line 28',
 Header(2)='for Zonge Engineering',
 Header(3)='Data from scs2demo.avg',
 StnBeg=-700.00,StnEnd=8100.00,StnPerDipole=200.00,
 DpLength=200.0,LengthUnits='ft',DpAzimuth=100.0,
 SurveyType='Scalar',TxType='Bipole',
 TxLength(1)=5000.,TxAzimuth(1)=100.0,
 TxGridE(1)=80700.0,TxGridN(1)=89200.0,
 NSweep=1,NResIter=16,ARerrFloor=5.0,ZPerrFloor=50.0,
 UseTM=T,UseTE=F,FarFieldFloor=256.0,
 ResSmth=1.000,ResdpW=0.100,ResdxW=1.000,ResdzW=1.000,
 CRMIN=1.00,CRMAX=3.00,CRINC=0.10,
 CWMIN=-2.00,CWMAX=2.00,CWINC=0.10,
 CSMIN=-1.00,CSMAX=2.00,CSINC=0.10,
 RMSdat=0.8018,RMSmod=0.7752,
/
"Stn","GridE","GridN","Elev","dpW","dxW","dzW","Res0","InvRes","ResSns"
-700.,71997.5,73423.,2465.,3.,1.,1.,184.6,111.7,10.98,
-700.,71997.5,73423.,2297.501,3.,1.,1.,184.6,153.1,4.26,
-700.,71997.5,73423.,2113.252,3.,1.,1.,184.6,226.1,1.81,
-700.,71997.5,73423.,1901.139,3.,1.,1.,184.6,308.3,1.77,
-700.,71997.5,73423.,1667.814,3.,1.,1.,184.6,371.4,2.76,
-700.,71997.5,73423.,1411.158,3.,1.,1.,184.6,371.4,2.76,
-500.,72194.5,73391.,2462.5,1.5,1.,1.,184.6,121.2,18.63,
-500.,72194.5,73391.,2297.515,1.5,1.,1.,184.6,184.7,5.25,
-500.,72194.5,73391.,2116.032,1.5,1.,1.,184.6,263.6,3.46,
-500.,72194.5,73391.,1903.919,1.5,1.,1.,184.6,336.9,2.23,
    .         .         .       .      .        .         .
    .         .         .       .      .        .         .
    .         .         .       .      .        .         .
7900.,80482.5,72035.,1894.154,3.,1.,1.,184.6,256.0,3.23,
7900.,80482.5,72035.,1637.498,3.,1.,1.,184.6,256.0,3.23,
8100.,80679.5,72003.,2681.,3.,1.,1.,184.6,175.6,13.61,
8100.,80679.5,72003.,2517.796,3.,1.,1.,184.6,231.8,5.23,
8100.,80679.5,72003.,2338.272,3.,1.,1.,184.6,262.7,2.29,
8100.,80679.5,72003.,2126.159,3.,1.,1.,184.6,264.3,2.15,
8100.,80679.5,72003.,1892.834,3.,1.,1.,184.6,256.0,3.23,
8100.,80679.5,72003.,1636.178,3.,1.,1.,184.6,256.0,3.23,
```

SCS2D *.MTM file fortran namelist block variables:

Header(1:4) - up to four lines of free-format text describing model.
StnBeg   - first station to include in inversion panel
StnEnd   - last station to include in inversion panel
StnperDipole- TM-mode dipole length in station numbers
DpLength   - TM-mode dipole length (LengthUnits)
DpAzimuth   - dipole azimuth (degrees east of grid north)
LengthUnits - character, distance units (m, km, ft or kft)
SurveyType - character, 'Scalar', 'Vector' or 'Tensor'
TxType   - character, 'Natural', 'Bipole' or 'Loop'
TxLength(1:2) - transmitter bipole length or loop width (LengthUnits)
TxAzimuth(1:2) - transmitter antenna azimuth (degrees east of grid north)
TxGridE(1:2)- Tx center grid east coordinates (LengthUnits)
TxGridN(1:2) - Tx center grid north coordinates (LengthUnits)
NSweep   - number of conjugate-gradient iterations (1 to 16)
NResIter   - number of inversion iterations (0 to 32)
ARerrFloor - minimum apparent resistivity error (percent)
ZPerrFloor - minimum impedance phase error (mrad)
UseTM   - logical, T = use TM-mode data in inversion (T or F)
UseTE   - logical, T = use TE-mode data in inversion (T or F)
FarFieldFloor - lowest far-field frequency (hertz)
ResSmth   - overall model constraint weighting (0.01 to 100)
ResdpW   - relative weight of background-model section (0.01 to 100)
ResdxW   - relative weight of horizontal smoothness constraints (0.01 to 100)
ResdzW   - relative weight of vertical smoothness constraints (0.01 to 100)
CRMIN - resistivity color-fill minimum (log10(ohm-m))
CRMAX   - resistivity color-fill maximum (log10(ohm-m))
CRINC   - resistivity contour increment (log10(ohm-m))
CWMIN   - constraint-weight color-fill minimum (unitless)
CWMAX   - constraint-weight color-fill maximum (unitless)
CWINC   - constraint-weight contour increment (unitless)
CSMIN   - normalized-sensitivity color-fill minimum (percent)
CSMAX   - normalized-sensitivity maximum (percent)
CSINC   - normalized-sensitivity contour increment (percent)
RMSdat   - root-mean-square(observed-calculated data)
RMSmod   - root-mean-square(model constraints)
 /   - marks end of namelist input block

SCS2D *.MTM column variables:

Column 1 - "Stn"   - station number at left edge of model pixel
Column 2 - "GridE" - station grid-east at left edge of model pixel (LengthUnits)
Column 3 - "GridN" - station grid-north at left edge of model pixel (LengthUnits)
Column 4 - "Elev"   - station elevation or RL at upper edge of pixel (+ upwards, LengthUnits)
Column 5 - "dpW"   - model pixel background-constraint weight
Column 6 - "dxW"   - pixel-to-pixel horizontal-gradient-constraint weight
Column 7 - "dzW"   - pixel-to-pixel vertical-gradient-constraint weight
Column 8 - "Res0"   - background-model pixel resistivity (ohm-m)
Column 9 - "InvRes" - inversion-model pixel resistivity (ohm-m)
Column 10 - "ResSns" - pixel sensitivity (percent)

*.MTD File Format
(observed and calculated apparent resistivity and impedance phase data)

*.MTD files start with a line of column labels followed by a tabular section holding observed and calculated data. Column numbers are separated by commas, with missing values shown by two commas in a row. Near-field data at frequencies below FarFieldFloor are included in *.MTD files, but SCS2D v2.10 does not calculate their model-response values. Left-justified comment lines starting with a "!", "/", "\" or "" may be placed anywhere in the file. Observed data are skipped by adding 5000 to the associated error value.

Partial Listing of SCS2DEMO.MTD:

(The line of column labels is wrapped onto two lines to fit on the page.)

```
"Stn","GridE","GridN","Elev","Freq","ARTMobs","ARTMerr","ZPTMobs","ZPTMerr","ARTEobs",
"ARTEerr","ZPTEobs","ZPTEerr","ARTMmod","ZPTMmod","ARTEmod","ZPTEmod"
"Modeling results updated by RSCS2D v2.00f  Date:19/04/99  Time:10:06"
"From S2D2D v2.00f  Date:19/04/99  Time:10:02:56"
-200.,72490.,73343.,2475.,32.00,2831.1,0.6,-76.5,3.0,,,,,,,,,
-200.,72490.,73343.,2475.,64.00,1112.5,0.8,-197.4,1.7,,,,,,,,,
-200.,72490.,73343.,2475.,128.0,216.76,0.5,-39.2,1.0,,,,,,,,,
-200.,72490.,73343.,2475.,256.0,299.77,1.0,556.2,6.4,,,,,300.00,602.0,,,
-200.,72490.,73343.,2475.,512.0,230.59,1.6,519.1,12.4,,,,,250.57,594.5,,,
-200.,72490.,73343.,2475.,1024.,194.0,1.0,568.3,6.0,,,,,208.71,605.0,,,
-200.,72490.,73343.,2475.,2048.,166.51,1.0,620.3,3.9,,,,,176.54,629.5,,,
-200.,72490.,73343.,2475.,4096.,156.64,1.0,676.2,9.9,,,,,154.88,660.9,,,
-200.,72490.,73343.,2475.,8192.,177.09,1.0,662.6,7.3,,,,,142.12,704.5,,,
 0.,72687.25,73311.,2487.5,32.00,2861.9,0.6,-66.8,2.9,,,,,,,,,
 0.,72687.25,73311.,2487.5,64.00,1134.1,0.8,-181.4,1.5,,,,,,,,,
 0.,72687.25,73311.,2487.5,128.0,228.56,0.5,-21.8,1.1,,,,,,,,,
 0.,72687.25,73311.,2487.5,256.0,316.04,1.0,571.1,6.4,,,,,327.17,602.3,,,
 0.,72687.25,73311.,2487.5,512.0,251.92,1.2,532.7,8.6,,,,,273.56,593.2,,,
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Column definitions:

Column 1 - "Stn"   - station number
Column 2 - "GridE"   - station grid east (LengthUnits)
Column 3 - "GridN"   - station grid north (LengthUnits)
Column 4 - "Elev"   - station elevation or RL (LengthUnits)
Column 5 - "Freq"   - frequency (hertz)
Column 6 - "ARTMobs"   - TM-mode observed apparent resistivity (ohm-m)
Column 7 - "ARTMerr"   - TM apparent resistivity error (percent)
Column 8 - "ZPTMobs"   - TM-mode observed impedance phase (mrad)
Column 9 - "ZPTMerr"   - TM impedance phase error (mrad)
Column 10 - "ARTEobs"   - TE-mode observed apparent resistivity (ohm-m)
Column 11 - "ARTEerr"   - TE apparent resistivity error (percent)
Column 12 - "ZPTEobs"   - TE-mode observed impedance phase (mrad)
Column 13 - "ZPTEerr"   - TE impedance phase error (mrad)
Column 14 - "ARTMmod"   - TM calculated apparent resistivity (ohm-m)
Column 15 - "ZPTMmod"   - TM calculated impedance phase (mrad)
Column 16 - "ARTEmod"   - TE calculated apparent resistivity (ohm-m)
Column 17   - "ZPTEmod"   - TE calculated impedance phase (mrad)

Observed data are skipped by adding 5000 to the associated error value, so any observed data with error greater than 5000 is not used by RSCS1D or RSCS2D.