E M 2 D
Documentation

Zonge Data Processing

Two-dimensional AMT Modeling

Version 4.00

Scott MacInnes
Mykle Raymond
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E M 2 D

Table of Contents

Table of Contents (continued)

Introduction

EM2D is a finite element program which computes apparent resistivity and impedance phase responses of two-dimensional models illuminated by a plane-wave source field. Models may include both subsurface structure and surface topography on cross sections up to one hundred dipole lengths long and twenty five dipole lengths deep. Model sections may have one to nine distinct geologic units, with each unit assigned a resistivity and an optional Cole-Cole IP dispersion.

Modeling results may be calculated for TM mode, TE mode or both source polarizations. Calculated model-response data are stored in a tabular ASCII file format, which facilitates plotting by generic contouring programs.

EM2D is particularly convenient for models which include topography. EM2D can read topographic profile information from a tabular file format and automatically adjusts its finite element mesh to follow the profile. Topographic-correction factors can be calculated using models with a uniform subsurface resistivity or topography and geology can be modeled together to capture the interaction between terrain and structure.
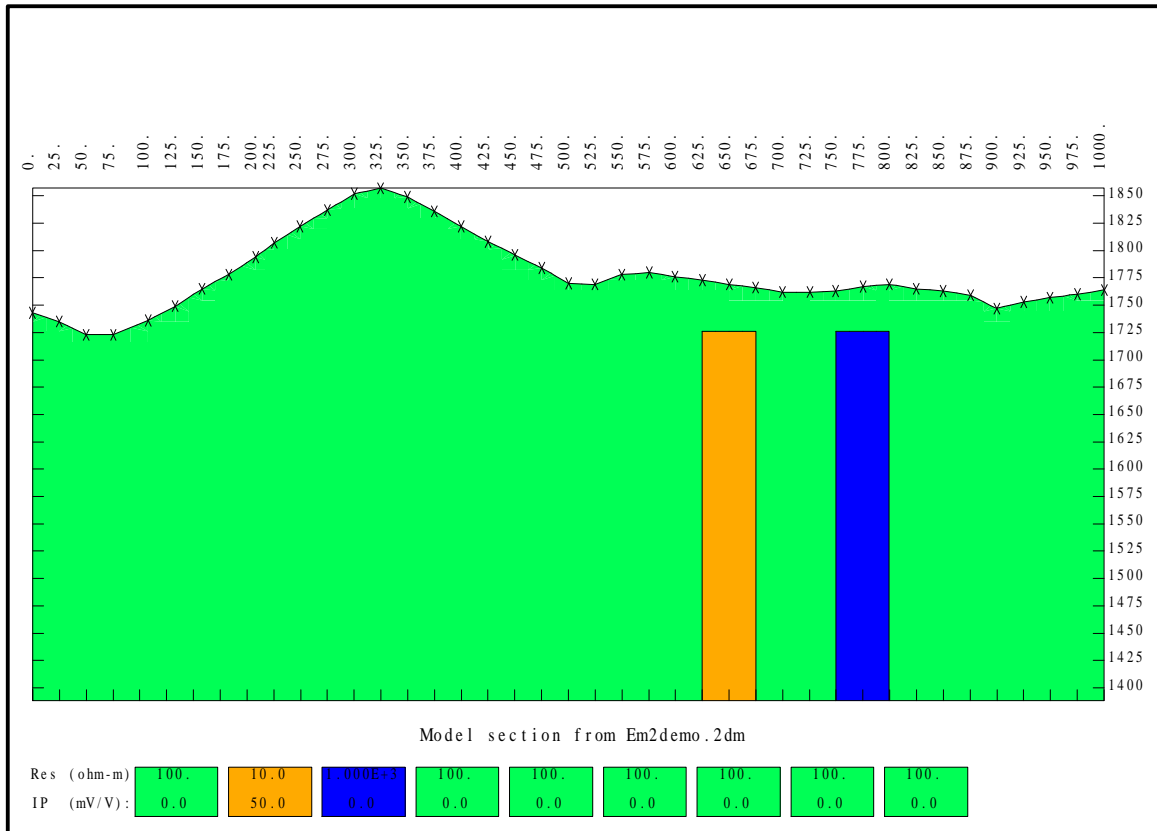
Figure 1: Cross-section of two-dimensional geologic model with topography. Up to nine geologic units may be used in the model, with each unit assigned resistivity and optional Cole-Cole IP properties. Fill colors reflect resistivity, blue represents resistive material and red or magenta indicates a conductive unit. Model sections can be one hundred dipole lengths long and twentyfive dipole lengths deep. Model responses are calculated as MT/AMT apparent resistivity and impedance phase for TM mode and/or TE mode plane-wave sources.

Installation

Hardware Configuration

EM2D runs on PC's using a MS Windows operating system configured with High Color (16 bit) graphics.

Installation Procedure

Each distribution copy of EM2D 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 MS-Windows. 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 EM2D 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 EM2D 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 EM2D 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 EM2D from, usually floppy drive A: or B:, and the target hard drive letter and path in which EM2D should be installed. It is usually easiest to put EM2D 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 #EM2D.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, EM2D may be run from the command line, from the start menu or from a Windows desktop shortcut.

After installation, the EM2D subdirectory should have the following files:

EM2D program files:
    EM2D.EXE   - model creation and editing program.
    REM2D.EXE   - model-response calculation program.
    EM2DREG.EXE - registration program.
    GRAPHICW.CHR- graphics font file.

Sample data files:
    EM2DEMO.MDE - data processing annotation and control file.
    EM2DEMO.STN - station location and topography file.
    EM2DEMO.2DM - model-parameter file.
    EM2DEMO.MTD - calculated data in tabular-format file.
    EM2DEMO.DAT - calculated EM field values in tabular-format file.
    EM2DEMO.Z2D - calculated data in ZPLOT-format 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. REM2D 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 EM2D 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 EM2D'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 EM2D. 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.

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 PCs running Windows NT or 2000, 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
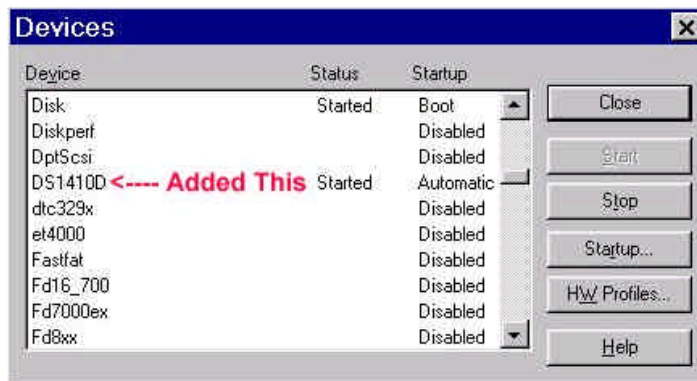
Test the software registration by executing STEMREG from the EM2D hard-disk directory. You should see text like:

<div align="center">

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

</div>

A software registration check is done every time REM2D is initiated. REM2D calls EM2DREG 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 Configuration

Your computer must by set to the High Color (16 bit) graphics mode to correctly EM2D model sections. The file GRAPHICW.CHR should be somewhere on the MS-DOS path, usually in the same directory in which EM2D was installed.

For hardcopy of model sections, EM2D offers several options. Model sections may be printed via the Windows print manager or saved in a file for later use. Color-filled model sections may be saved in Windows metafiles (*.WMF), in Computer Graphics Metafiles (*.CGM) or Postscript (*.PS).

Many graphics programs (such as Surfer, Photoshop, Corel Draw or Paint Shop Pro) and text editors (such as MS-Word) will import WMF format files. Graphics programs can be used for interactive editing of the model section to make it more suitable for report figures.

CGM format files may also be imported into many graphics programs and provide a way to display model sections on computers not using a Windows operating system.

Postscript files may be dumped directly to some printers or rasterized for other printers using utilities such as Ghostscript.

EM2D modeling results in *.Z2D files can be contoured with the Zonge Engineering program ZPLOT. ZPLOT produces HPGL files with black and white contoured and posted pseudosection plots. Plotting EM2D *.Z2D files produces pseudosection plots of apparent resistivity and impedance phase. EM2D results are also stored in tabular *.MTD files, which are suitable use with Zonge's 2D inversion program SCS2D, spreadsheets or general-purpose contouring programs like Golden Software's Surfer.

Recall Procedure

To recall EM2D back to the distribution disk, place the distribution disk in a floppy-disk drive and log on to that drive, then type "RECALL" and press enter. RECALL displays a screen with fields for the drive and directory where EM2D is installed and for the letter of the floppy drive holding the distribution disk. Edit the source drive and path to match your computer's configuration and then press F10 to start the RECALL procedure. RECALL erases EM2D.EXE, REM2D.EXE, EM2DREG.EXE and EM2DEMO.* from the "recall from" directory. It leaves behind GRAPHICW.CHR, a graphics font file which may be used by other programs.

Program Use

EM2D is used for creating, reviewing and editing model files. Tools for performing editing and review tasks may be selected from menus displayed along the top of the screen. Once a model is ready, selecting Run from the main menu calls the auxiliary program, REM2D to calculate apparent resistivity and impedance phase. Running EM2D from the start menu or typing EM2D from the command line in an MS-DOS box brings up EM2D's initial menu, which allows you to choose between **New**, **Open** and **Exit**. Choosing **New** creates a new model, choosing **Open** opens an existing model file, while selecting **Exit** exits EM2D.

EM2D - model-file creation

Choosing **New** from the initial menu opens a dialog screen with fields specifying the new model's characteristics, while **Open** will allow selection from existing EM2D *.2DM files and will then send EM2D directly to the graphical model-editing display described after this section.

EM2D **New**, model file name and descriptive text:
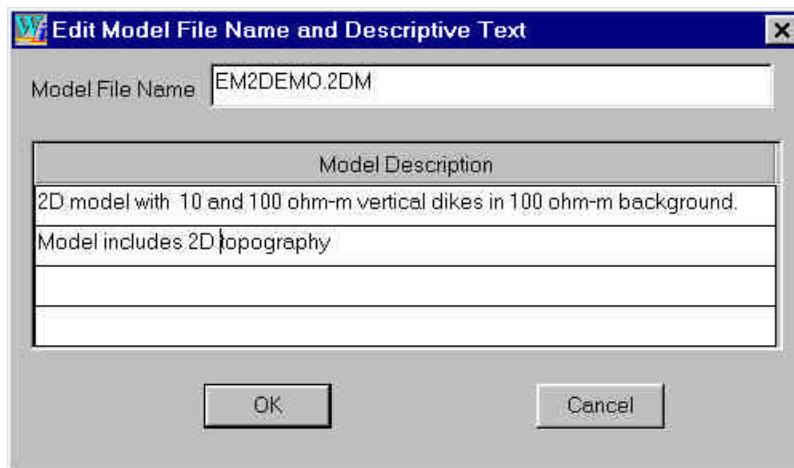
"EM2D" is the default name given to a completely new model, and should be changed to something specific to each project. To recreate EM2DEMO sample files from scratch, edit the model-parameter file name to EM2DEMO.2DM. Up to four lines of text may be used to describe the model.

Dialog screen entries may be changed by typing over default values. Fields can be edited in any sequence by moving from one field to the next using the mouse or with the tab and shift+tab keys. When the OK button is selected with a mouse click EM2D continues on to the next dialog screen.

EM2D **New**, set finite-element mesh parameters:

The "set finite-element mesh parameters" dialog screen sets the boundaries and size of EM2D's finite-element mesh. In this screen, I have edited the station interval and dipole length from 50 to 25. I have also specified a model section width of 1000 m by setting the first station to 0 and the last station to 1000. I changed model depth extent from 1000 to 400 m.

"Dipole Lengths" are specified in units of m, km, ft or kft. The length units selected to specify dipole lengths must be the same as units used for *.STN file grid east, north and elevation coordinates.

"Station Numbers per Dipole" controls the scaling of station numbers relative to dipole lengths. Station numbers should be proportional to distance along line. When reading topographic profiles, EM2D uses coordinates from *.STN files to associate station numbers with distance along line, accommodating any survey irregularities. If a *.STN file is not specified, the ratio between "Dipole Length" and "Stations per Dipole" is used to scale station numbers to distance along line.

"First Station" and "Last Station" locate the left and right edges of the model section. Their maximum separation is limited by Station Numbers per Dipole and an upper bound of 200 columns of finite elements across the model section.

Model element shapes near the surface are set as a height/width ratio. Element height/width may vary between 0.5 and 2.0, but 1.0 is near optimal. The model's depth extent can also be varied, but it should be enough for total topographic relief plus five+ dipole lengths. If EM2D can not build a model with sufficient depth extent using 50 equal-height rows of elements, it geometrically increases row height with depth, and reports the amount of row-to-row increase as a "Row Thickness Multiplier".

"Mesh cells per dipole" controls finite-element cell sizes and can be 2, 3 or 4. Using fewer finite-element cells per dipole reduces file size and computational effort, while increasing "mesh cells per dipole" allows more model-section detail. In most cases, the default setting of two finite elements per dipole length is satisfactory.

When calculating model responses, REM2D attempts to keep finite elements less than 0.2 skin depths in height or width by subdividing EM2D's original finite-element mesh even further, up to the point where REM2D runs out of array space. REM2D generates a warning message if it is not able to subdivide its internal computational mesh sufficiently at high frequencies, but it continues to calculate model responses. If computational accuracy is important and your model section includes low-resistivity units near the surface, try to keep your model section as small as is practical, so that a more finely subdivided computational mesh is possible before REM2D's array space is exhausted.

EM2D updates related entries whenever the cursor moves between dialog fields. With each new entry the finite-element mesh size is updated and displayed.

EM2D allows the option of reading topographic data from a tabular *.STN file. *.STN files have columns of station number, grid east, grid north and elevation (see file format descriptions in appendix A). For example, you can read topographic information from file EM2DEMO.STN by selecting the "Get Topography" button and choosing "EM2DEMO.STN" from the list of available *.STN files. EM2D prompts you for a *.STN file name and reads the file when you select the "OK" button. If you select "Cancel" it does not attempt to read a *.STN file.

Once EM2D's mesh parameters are set, it shows a dialog screen titled "Edit Resistivity/IP Properties":
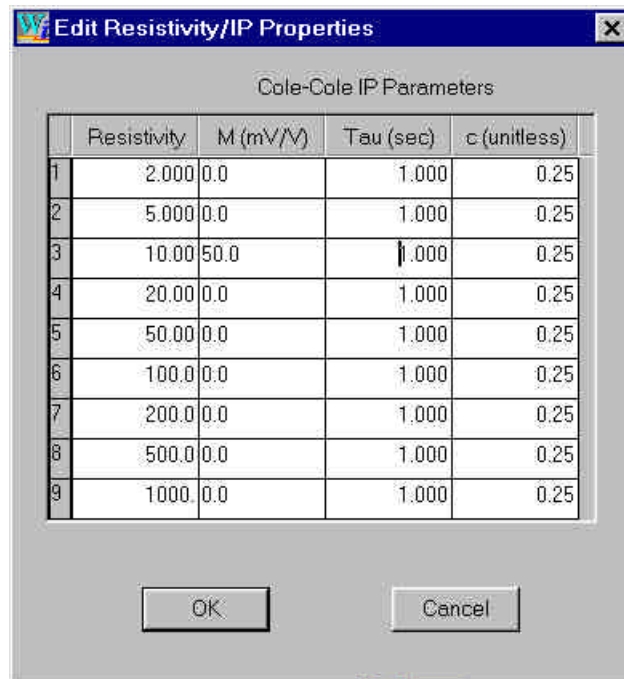
EM2D models use complex resistivities with a single optional Cole-Cole dispersion:

$$\hat{\mathbf{r}} = \mathbf{r} \cdot \left(1 - \frac{m}{1000} \cdot \left(1 - \frac{1}{1 + \left(i \cdot \mathbf{v} \cdot \mathbf{t} \right)^c} \right) \right)$$

Model resistivities are given default values ranging from 2 to 1000 ohm-m in logarithmic steps. Cole-Cole IP chargeabilities are initialized to 0 mV/V. The model mesh is initialized to an uniform resistivity of 100 ohm-m using resistivity/IP unit number 6.

Our example EM2DEMO model uses three distinct geologic units. Background areas are filled with resistivity/IP unit 6 (100 ohm-m and 0 mV/V). A conductive, chargeable vertical dike is drawn with resistivity/IP unit 3 (10 ohm-m and an IP Cole-Cole dispersion with m = 10 mV/V, tau = 1 sec and c=0.25). While resistivity/IP 9 is used to draw a vertical dike with a resistivity of 1000 ohm-m and no IP properties.

When you are finished editing resistivity/IP properties select the "OK" button to continue on to the next dialog screen.

EM2D follows its resistivity/IP dialog screen with a dialog showing source parameters.
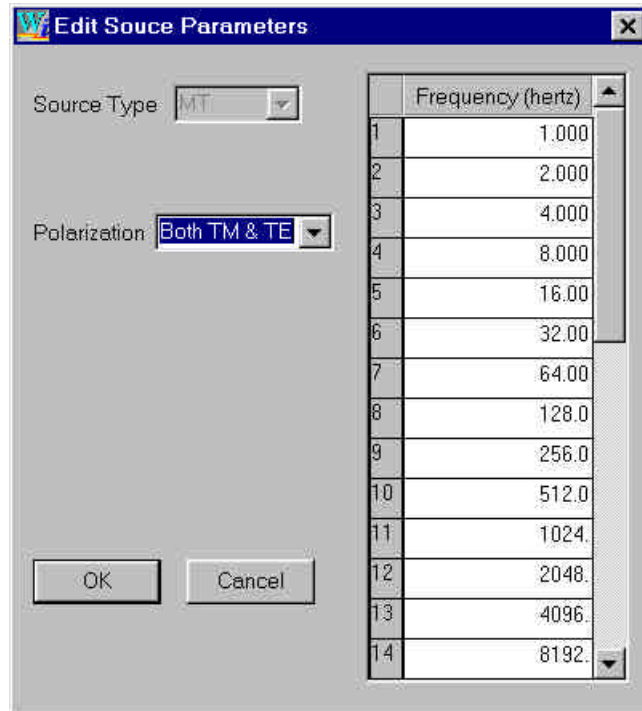
EM2D is currently restricted to plane-wave sources, with the addition of controlled source options planned as a future update, so "Source Type" is restricted to "MT". "Source Polarization" can be cycled through "Both TM & TE", "TM only" (E perpendicular to strike) or "TE only" (E parallel to strike). Up to 32 source frequencies may be specified and can range between 10^{-9} and 10^9 hertz. Fourteen default frequencies are set to range from 1 to 8192 hertz in binary steps.

After specification of default values for a new model or after the name of an existing model is entered, EM2D draws a cross section of the current model. Each resistivity/IP unit is given a distinct color. Resistivity/IP units are also indicated by integer codes. 0 indicates air, while 1 through 9 can be assigned arbitrary resistivities and IP values. Interfaces between units are outlined by solid lines. When the section is plotted at a sufficiently detailed scale, dotted lines indicate the size and location of finite-element cells. Receiver locations are marked by small crosses.
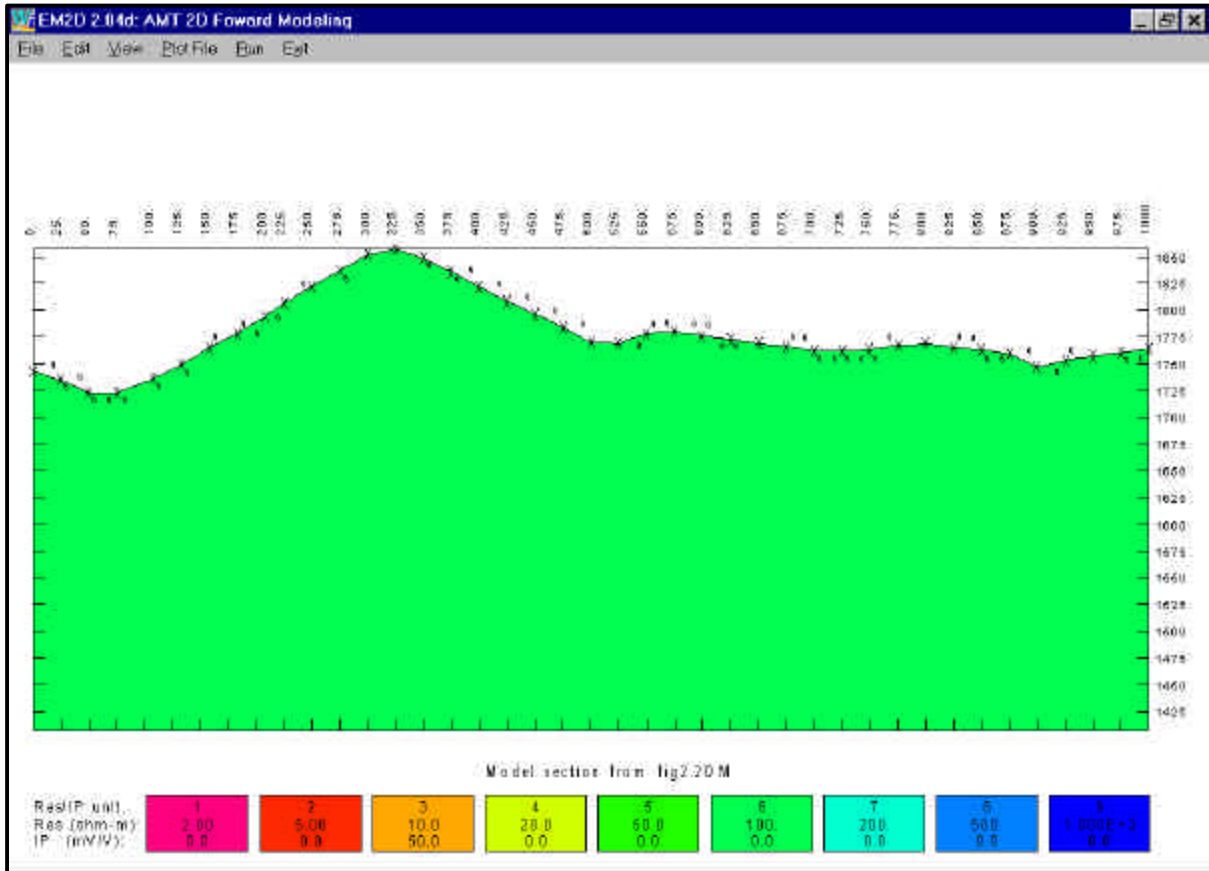
Figure 2: Initial model section with topography read from EM2DEMO.STN. Resistivity/IP unit 6 is used to initialize the model section to uniform resistivity and IP properties. EM2D's **Edit** menu may be used to draw geologic structure in the model section, change model resistivity/IP properties or to modify source parameters.
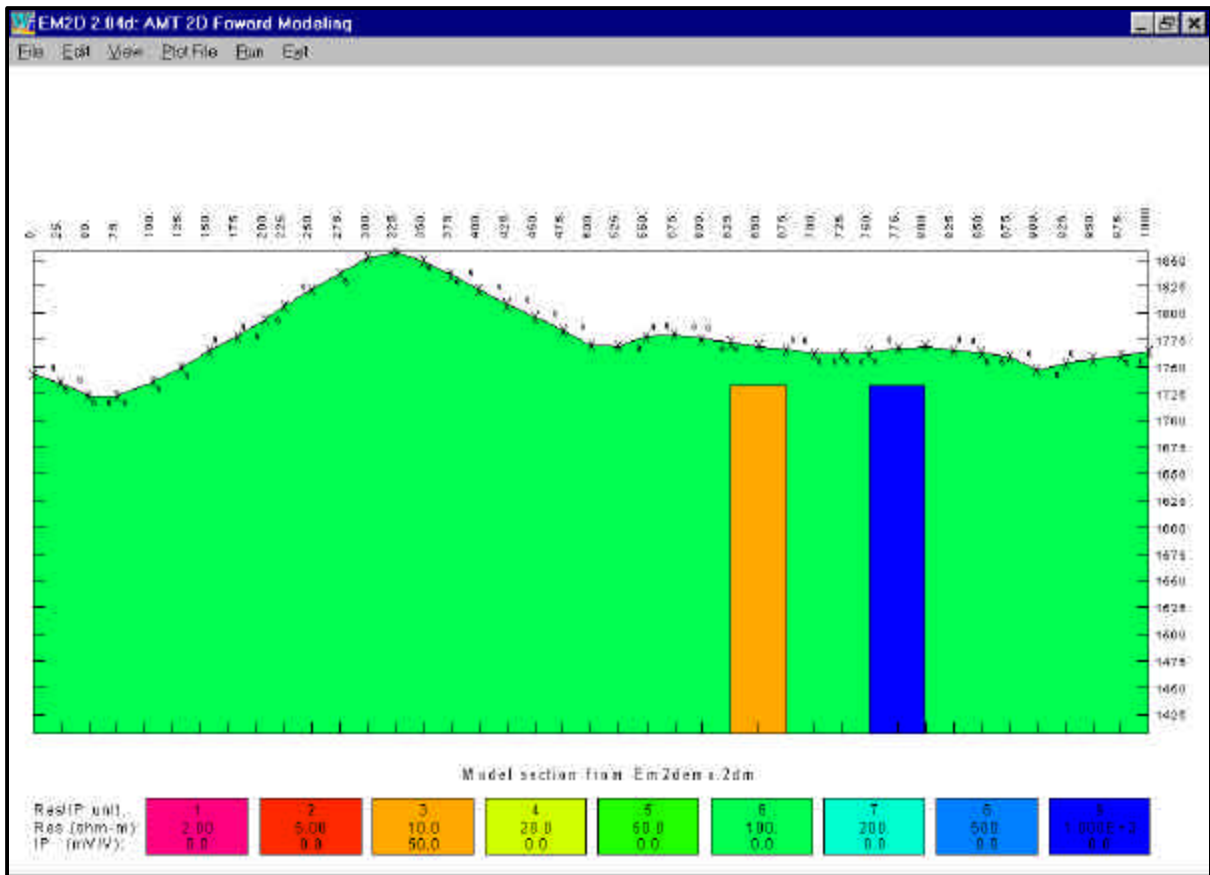
Figure 3: Cross section of model with two vertical dikes under rough topography. This model is stored in EM2DEMO.2DM and EM2DEMO.MTD. EM2D options are displayed in a horizontal menu across the top of the screen. You can select a menu item by clicking on it with the mouse or by simultaneously pressing the Alt key and the key matching a selection's underlined letter.

File menu option

Clicking on **File** with the mouse or pressing **Alt+F** chooses the **File** option and brings up a second list of options, **New**, **Open**, **Save As**, **Save** and **Exit Menu**.

Choosing **New** allows you to create a new model by going through the sequence of steps described in the previous section.

Open scans the current directory for files with the extension ".2DM" and shows a list of EM2D model files from which you can make a choice.

<u>F</u>ile menu option (continued)

Save saves the current model to a file.

Save <u>A</u>s allows you to change the name of a model file before you save it.

E<u>x</u>it Menu returns to the main menu without taking any action.

<u>E</u>dit menu option

Choosing **Edit** brings up a submenu which offers **Draw Geology**, **Edit <u>R</u>es/IP**, **Edit <u>S</u>ource**, **Model Description**, **<u>V</u>iew** and **E<u>x</u>it Menu**.

<u>D</u>raw Geology submenu option

Geologic bodies are added to the model cross section by selecting <u>D</u>raw Geology. When <u>D</u>raw Geology is selected, a dialog box showing a choice of resistivity/IP units appears on the upper left corner of the screen. Choose a resistivity/IP unit and then click on the OK button. EM2D then shows an arrow mouse cursor and promps you to "Draw a closed polygon around area to be updated, marking each corner with a mouse click". EM2D leaves a small square on the first corner so that you can close the polygon on its starting point. Closing the polygonal outline on the first corner finishes the Draw Geology procedure and the model section is redrawn. Pressing ESC at any time aborts the <u>D</u>raw Geology procedure.

Edit <u>R</u>es/IP submenu option
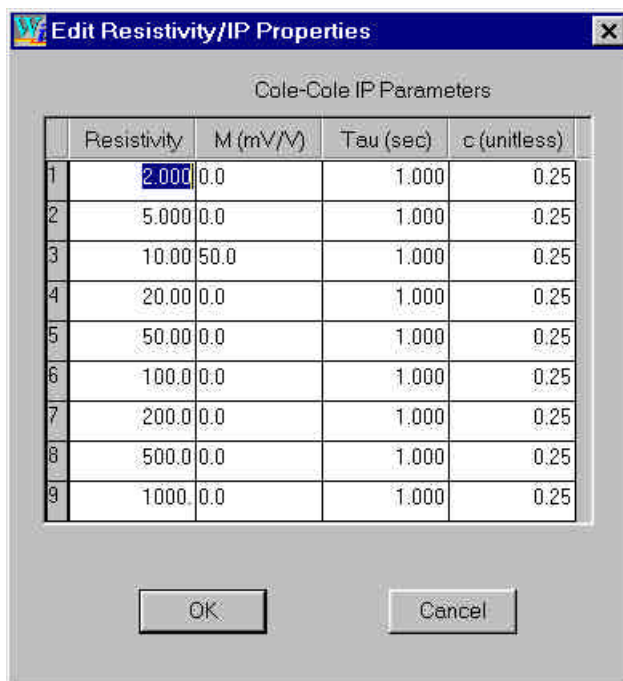
Changing entries in the resistivity and IP fields updates the physical properties associated with each resistivity/IP unit. Resistivities are given in ohm-meters (10^{-4} to $9.9*10^{4}$). IP properties are specified

as a Cole-Cole dispersion with m in mV/V (0 to 3000), tau in seconds (10^{-9} to 10^9) and c (0 to 1).

$$\hat{\mathbf{r}} = \mathbf{r} \cdot \left(1 - \frac{m}{1000} \cdot \left(1 - \frac{1}{1 + \left(i \cdot \mathbf{v} \cdot \mathbf{t} \right)^c} \right) \right)$$

Edit <u>S</u>ource submenu option
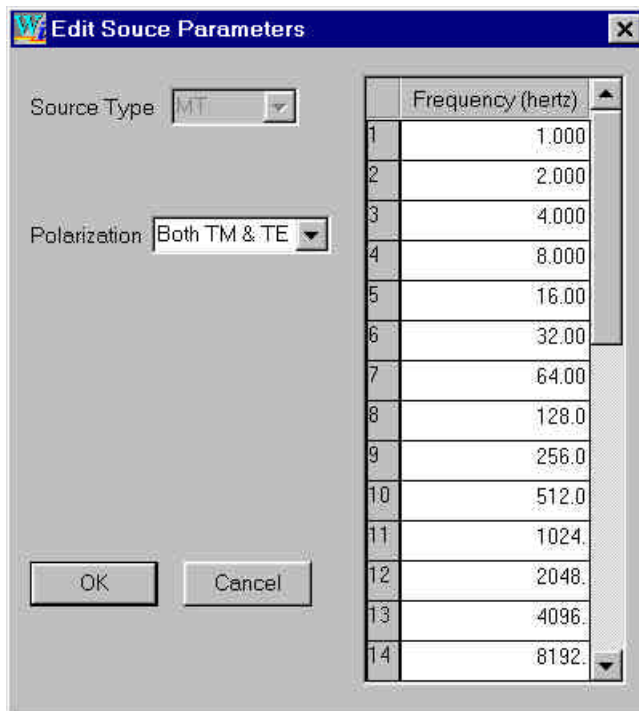
EM2D is currently restricted to plane-wave sources, with the addition of controlled source options planned for the future, so "Source Type" is restricted to "MT". Source "Polarization" can be cycled through "Both TM & TE", "TM only" (E perpendicular to strike) or "TE only" (E parallel to strike). Up to 32 source frequencies may be specified and can range from 10^{-9} to 10^9 hertz.

Model Description submenu option
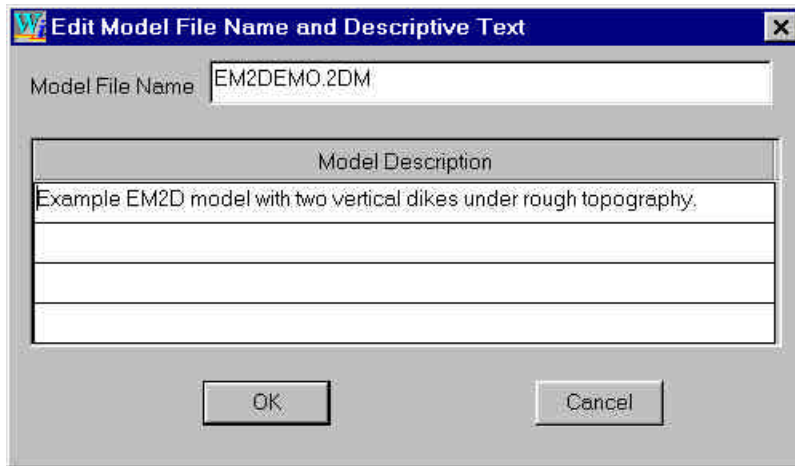
The model file name may be changed in the "Model Description" dialog box or in the "File" menu "Save As" option. Up to four lines of descriptive text may be entered and are saved in *.2DM files.

Exit Menu returns to the main menu.

View menu option

"View" may be selected from either the Edit menu or from the Main menu. Selecting "View" brings up options for changing the current plot window. Menu choices by clicking a choice with the mouse or by simultaneously pressing Alt plus the menu choice's underlined letter.

Select "Zoom In" to look at the model section in more detail.

"Zoom Back" gives a less detailed view.

For "Zoom Rectangle" you specify two corners on a box around the next plot window.

"Zoom All" recovers a view of the entire model section.

"Pan" allows you to move the plot window laterally without changing the plot's scale.

"Exit Menu" returns you to the previous menu.

Plot File menu option

Model-section plots can be saved to a file using the "Plot File" menu option. Selecting "Plot File" brings up a sub-menu with choices for "To Printer", "WMF", "CGM", "PS" or "Exit Menu".

"To Printer" uses the Window Print manager to plot the model section on whatever printer you have connected to your PC. On black and white printers, color fills are rendered as shades of gray.

"WMF", or Windows Metafile, is a graphics file format specifically for Windows programs. WMF files retain color-fill information and can be imported into nearly all Windows graphics programs (Corel Draw, Adobe Photoshop, Paint Shop Pro, Surfer) or editors (i.e. MS Word).

"CGM", or Computer Graphics Metafile, is a second graphics file format. CGM files retain color-fill information and can be imported into some graphics programs (i.e. Paint Shop Pro) or editors (i.e. MS Word). CGM files will be helpful for moving model section plots to computers not using a Windows operating system.

"PS", or PostScript, is a common graphics format which retains color-fill information and which can be dumped directly to Postscript printers or rasterized by utilities such as Ghostscript.

Exit Menu returns to the main menu without taking any action.

<u>R</u>un option

Selecting "Run" from the main menu calls REM2D.EXE to calculate apparent resistivity and impedance phase values for the current model. REM2D returns control to EM2D after it is finished. Model section and survey configuration information is stored in files with the extension ".2DM" . Station locations and calculated data are stored in files with the extension ".MTD". REM2D reads *.2DM and *.MTD files, calculated apparent resistivity and impedance phase, then puts the result back into *.MTD files.

REM2D may also be run directly from the command line in a MS-DOS box. To evaluate the example model EM2DEMO, type "REM2D EM2DEMO". Program REM2D will read the files EM2DEMO.2DM and EM2DEMO.MTD, calculate apparent resistivity and impedance phase responses for model EM2DEMO, and write calculated values in an updated EM2DEMO.MTD and a new EM2DEMO.Z2D. REM2D also saves screen output, including any warning or error messages, in EM2DEMO.LOG.

EM2DEMO.LOG holds a summary record of the model, listing descriptive text, source polarization and model resistivity and phase. An alphanumeric plot of the model cross section verifies correct mesh input. The cross section is oriented with elevations increasing to the left and station numbers increasing upward. Station number locations for each node column are listed left of the cross section.

For better numerical accuracy, REM2D adds wide margins to the sides and bottom of the finite-element mesh, moving mesh boundaries well away from the plotted edges of model sections. REM2D also tries to keep finite-element cell dimensions below 0.2 skin depths by subdividing the mesh. It stops its automated subdividing procedure with a warning when it runs out of array space, but continues to calculate model responses.

Modeling results are written into an updated copy of *.MTD and into a *.Z format file with the extension *.Z2D. The Zonge pseudosection contouring program ZPLOT can be used to create black and white plots of modeling results. For the example files, typing "ZPLOT EM2DEMO.Z2D" produces four HPGL plot files, EM2DEMO.X01 to EM2DEMO.X04. *.X01 holds a calculated TM-mode apparent resistivity pseudosection plot, *.X02 holds a calculated TM-mode impedance phase, *.X03 holds TE-mode apparent resistivity and *.X04 holds a TE-mode impedance phase pseudosection plot.

Partial listing of EM2DEMO.LOG

```
REM2D 4.00a: Two-dimensional AMT forward modeling.
Windows version implemented 15/April/01
Zonge Engineering and Research

Reading values from file em2demo.2DM
 Reading mesh parameters from em2demo.2DM
  Data for  81 by 37 mesh segment read from em2demo.2DM

 Reading data from em2demo.MTD
  41 station locations input from em2demo.MTD

 Model parameter summary:
 Sample EM2DEMO.* model

MT source with both polarizations.

 Mesh                 Cole-Cole IP Parameters
 Index  Resistivity   Chargeability   Time Constant   Exponent
  1        2.000           0.0            1.000          0.25
  2        5.000           0.0            1.000          0.25
  3        10.00          50.0            1.000          0.25
  .    .    .    .    .    .    .    .    .    .    .    .    .
  .    .    .    .    .    .    .    .    .    .    .    .    .
  .    .    .    .    .    .    .    .    .    .    .    .    .
   Station    Resistivity/IP indices for  81 by 51 node mesh:
    1000.0 <- station number at rightmost node.
     987.5 000000000011111111111111111111111111111111111111111
     975.0 000000000011111111111111111111111111111111111111111
       .    .    .    .    .    .    .    .    .    .    .    .    .
       .    .    .    .    .    .    .    .    .    .    .    .    .
        0.0 000000000000/1111111111111111111111111111111111111

 Left Edge Layers             Right Edge Layers
 Resistivity  Elevation (m)   Resistivity  Elevation (m)
   100.0         1745.          100.0         1764.

 Calculating fields for frequency       1.0
 Solving for E-parallel fields.
 Setting up finite-element mesh.
 Build matrix system for 125 by  83 mesh.
 Solve finite-element matrix system.
    .    .    .    .    .    .    .    .    .    .    .
    .    .    .    .    .    .    .    .    .    .    .
 Solving for E-perpendicular fields.
    .    .    .    .    .    .    .    .    .    .    .
    .    .    .    .    .    .    .    .    .    .    .
 Writing results into EM2DEMO.MTD
  574 data points written to EM2DEMO.MTD

 Writing results into EM2DEMO.Z2D
 2296 data points written to EM2DEMO.Z2D

 Elapsed CPU time is  5.94 minutes.
```

Figure 4: TM-mode (E perpendicular to strike) apparent resistivity and impedance phase pseudosections plotted using program ZPLOT and input files EM2DEMO.MDE plus EM2DEMO.Z2M. The pseudosections were generated by typing "ZPLOT EM2DEMO.Z2D". TM source polarization data are strongly affected by topography, with apparent resistivity lows centered over topographic highs. MT-mode data resolve lateral resistivity contrast well. Note the strong response over the resistive dike centered under station 775.
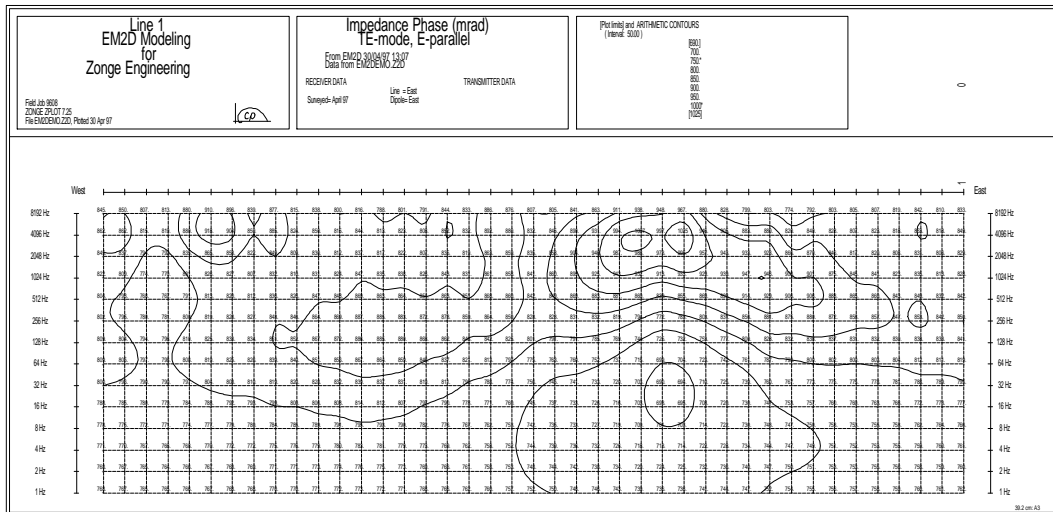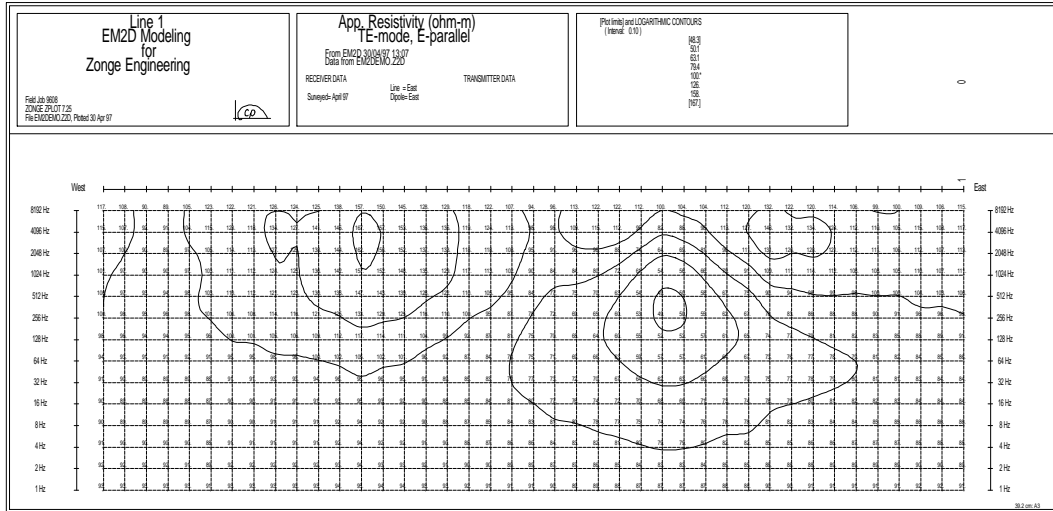
Figure 5: TE-mode (E parallel to strike) apparent resistivity and impedance phase pseudosections plotted with ZPLOT.EXE reading EM2DEMO.MDE and EM2DEMO.Z2M. TE-mode polarization data are not strongly affected by topography, having weak apparent resistivity highs over topographic highs. TE-mode data are good for mapping conductive units, notice the strong response over the conductive dike centered under station 650.

References

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Rijo, L., 1977, Modeling of electric and electromagnetic data: unpublished PhD dissertation, Dept. of Geology and Geophysics, University of Utah.

Rodi, W.L., 1976, A technique for improving the accuracy of finite element solutions for magnetotelluric data, Geophys. J. R. astr. Soc., v44, p483-506.

Wannamaker, P.E., Stodt, J.A., and Rijo, L., 1987, PW2D, Finite element program for solution of magnetotelluric responses of two-dimensional earth resistivity structure, Univ. of Utah Research Inst, Earth Science Lab Report, ESL-158.

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Appendix A: File Format Documentation

*.MDE File (Zonge data-processing-control file)

*.MDE files hold annotation and Zonge data-processing-control information. A *.MDE-file consists of one or mode 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 is followed by an equal sign "=", then the mode's value. Spaces may be included between elements of the mode line. Spaces in values defined as text are included as part of the text string. Only one mode per line is recognized.

EM2D ignores lines preceeded by a "!" , so mode records may be skipped or temporarily disabled by putting a "!" in the first column before the "$" character.

*.MDE-file listing:
```
  $   CLIENT=Zonge Engineering
  $ PROJECT=EM2D Modeling
  $ JOBNUMB=9500
  $ JOBDATE=April 96
  $ JOBLINE=EM2DEMO
  $ BRGLINE=East
  $ BRGBACK=West
  $    STNLO=  -800.0
  $    STNHI=   800.0
  $ LBLDELT=   100.0
  $ STNDELT=   100.0
  $ ASPACE= 100m
  $   UNITS=  m
  $ auto=yes
  $ zplot:sizex=1.5
  $ zplot:sizey=0.75
```

*.MDE-file variables:
 CLIENT   - Name of company running survey.
 PROJECT - Project name.
 JOBNUMB - Job number.
 JOBDATE - Date when survey was conducted.
 JOBLINE   - Line number.
 BRGLINE   - Forward line bearing (in direction of increasing station numbers).
 BRGBACK - Line back bearing (in direction of decreasing station numbers).
 STNLO   - Low unscaled station number.
 STNHI   - High unscaled station number.
 STNDELT - Unscaled station-number increment.   Default: STNDELT=1.0
 LBLFRST   - First scaled station number corresponding to unscaled station= STNLO.
                  Default: LBLFRST=STNLO
 LBLDELT   - Scaled station-number increment along axis.   Default: LBLDELT=STNDELT
 ASPACE   - Dipole length (length units).
 UNITS   - Length units (m, km, ft, kft).
 AUTO   - yes = batch file processing mode.
 ZPLOT: SIZEX - horizontal plot scale (LBLDELT/cm).
 ZPLOT: SIZEY - vertical plot scale (data points/cm).

---

*.STN File (station location coordinates)

*.STN files hold information about station locations in a simple tabular format. A *.STN file should have at least two records, corresponding to the first and last stations. Additional records may be necessary to trace out topographic changes or the surface trace of curved lines. Modeling programs assume that station numbers represent distance along line. Location coordinates for stations which are not explicitly listed in the *.STN file are calculate by linear interpolation between station numbers. Comment lines preceded by a "!", "\". "/" or """ in column 1 may be inserted anywhere in the file.

Column 1: station numbers. Station numbers can be in any unit, but they should be proportional to distance along line. *.STN file station numbers should correspond to the shifted and scaled numbering system defined by *.MDE file keywords STNLO, STNDELT, LBLFRST and LBLDELT.

Column 2: x coordinate = grid east in LengthUnits (m,km,ft,kft).

Column 3: y coordinate = grid north in LengthUnits (m,km,ft,kft).

Column 4: z coordinate = elevation in LengthUnits (m,km,ft,kft).

*.STN-file listing:

```
"Stn"   "GridE" "GridN" "Elev"
! Sample station file for EM2D.
0       378144   3009969     1743
25      378157   3009990     1735
50      378169   3010012     1723
75      378182   3010034     1723
100     378198   3010062     1736
125     378211   3010084     1749
.       .        .           .
.       .        .           .
.       .        .           .
875     378582   3010727     1759
900     378594   3010748     1747
925     378607   3010770     1753
950     378619   3010791     1757
975     378632   3010813     1760
1000    378644   3010835     1764
```

*.2DM File (model-parameter file)

```
&EM2D
 Header(1)='From EM2D v4.00a  25/04/97',
 Header(2)='EM2D example model including topography and vertical dikes.',
 LengthUnits='m',
 SourceType='MT',SourceMode='both',
 Freq( 1)= 1.000E+0
 Freq( 2)= 2.000E+0
 Freq( 3)= 4.000E+0
 Freq( 4)= 8.000E+0
 Freq( 5)= 1.600E+1
 Freq( 6)= 3.200E+1
 Freq( 7)= 6.400E+1
 Freq( 8)= 1.280E+2
 Freq( 9)= 2.560E+2
 Freq(10)= 5.120E+2
 Freq(11)= 1.024E+3
 Freq(12)= 2.048E+3
 Freq(13)= 4.096E+3
 Freq(14)= 8.192E+3 /
&MESH2D
 DipoleLength=25.,StnPerDipole=25.,StnBeg=0.,StnEnd=1000.,
 RES(1)=100.0,CC_M(1)=0.0,CC_T(1)=1.000,CC_C(1)=0.25,
 RES(2)=10.00,CC_M(2)=50.0,CC_T(2)=1.000,CC_C(2)=0.25,
 RES(3)=1000.,CC_M(3)=0.0,CC_T(3)=1.000,CC_C(3)=0.25,
 RES(4)=100.0,CC_M(4)=0.0,CC_T(4)=1.000,CC_C(4)=0.25,
 RES(5)=100.0,CC_M(5)=0.0,CC_T(5)=1.000,CC_C(5)=0.25,
 RES(6)=100.0,CC_M(6)=0.0,CC_T(6)=1.000,CC_C(6)=0.25,
 RES(7)=100.0,CC_M(7)=0.0,CC_T(7)=1.000,CC_C(7)=0.25,
 RES(8)=100.0,CC_M(8)=0.0,CC_T(8)=1.000,CC_C(8)=0.25,
 RES(9)=100.0,CC_M(9)=0.0,CC_T(9)=1.000,CC_C(9)=0.25,
 NXNODE= 81,NZNODE=51 /
  0.,  378144.,  3009969.,
1857.0,1847.6,1838.3,1828.9,1819.5,1810.1,1800.8,1791.4,1782.0,1772.6,
1763.3,1753.9,1743.0,1735.1,1725.8,1716.4,1707.0,1697.6,1688.3,1678.9,
1669.5,1660.1,1650.8,1641.4,1632.0,1622.6,1613.3,1603.9,1594.5,1585.1,
1575.8,1566.4,1557.0,1547.6,1538.3,1528.9,1519.5,1510.1,1500.8,1491.4,
1482.0,1472.6,1463.3,1453.9,1444.5,1435.1,1425.8,1416.4,1407.0,1397.6,
1388.3,
'000000000000001111111111111111111111111111111111'
'000000000000001111111111111111111111111111111111'
'000000000000001111111111111111111111111111111111'
'000000000000001111111111111111111111111111111111'
 12.5,  378150.5,  3009979.5,
1857.0,1847.6,1838.3,1828.9,1819.5,1810.1,1800.8,1791.4,1782.0,1772.6,
1763.3,1753.9,1744.5,1739.0,1725.8,1716.4,1707.0,1697.6,1688.3,1678.9,
1669.5,1660.1,1650.8,1641.4,1632.0,1622.6,1613.3,1603.9,1594.5,1585.1,
1575.8,1566.4,1557.0,1547.6,1538.3,1528.9,1519.5,1510.1,1500.8,1491.4,
1482.0,1472.6,1463.3,1453.9,1444.5,1435.1,1425.8,1416.4,1407.0,1397.6,
1388.3,
'000000000000001111111111111111111111111111111111'
 .  .  .  .  .  .  .  .  .  .  .  .
 .  .  .  .  .  .  .  .  .  .  .  .
 .  .  .  .  .  .  .  .  .  .  .  .
```

Two Fortran namelist blocks occupy the first section of *.2DM files. EM2D namelist parameters specifying AMT survey parameters can be given in any order between the character strings "&EM2D" marking the beginning of the "EM2D" namelist block and its closing symbol, "/". Finite-element mesh parameters are placed in a second namelist block, "MESH2D", begun with "$MESH2D" and closed with "/".

EM2D Namelist parameters:
```
Header         - free-format describing model.
LengthUnits    - distance units (m, km, ft, or kft).
SourceType     - EM source type (MT).
SourceMode     - EM source polarization (TM, TE, or both).
Frequency(*)   - source frequencies (hertz).
```

MESH2D Namelist parameters:
```
DipoleLength  - dipole length (LengthUnits).
StnPerDipole  - dipole length (station number units).
StnBeg        - first station to include in model.
StnEnd        - last station to include in model.
Res(*)        - model resistivities (ohm-m) (10⁻⁴ < res <10⁴).
CC_M(*)       - Cole-Cole chargeability (mV/V) (0 < m < 3000).
CC_T(*)       - Cole-Cole time constant (sec) (10⁻⁹ < tau < 10⁹).
CC_C(*)       - Cole-Cole exponent (unitless) (0 < c < 1).
NXNODE        - number of node columns in finite-element mesh.
NZNODE        - number of node rows in finite-element mesh.
```

The `Res(*)` line reads: model resistivities (ohm-m) (10^{-4} < res < 10^4). The `CC_T(*)` line reads: Cole-Cole time constant (sec) (10^{-9} < tau < 10^9).

The second section of *.2DM files contains two types of records in an alternating sequence. Records specifying coordinates for a vertical column of mesh nodes sandwich record blocks defining mesh-cell properties.

Vertical columns of mesh nodes are first located horizontally by three values: station number, grid east, and grid north. Station numbers are proportional to distance along line, although station-location variation due to surveying error or slope correction can be accommodated. Grid east and grid north values should be accurate and are given in the same LengthUnits used to specify elevation and DipoleLength. The three horizontal-location values are followed by NZNODE elevation values, one elevation value for every node in the vertical column. EM2D's finite element mesh allows vertical displacement of mesh nodes, primarily to allow more accurate modeling of topography. All 3+NZNODE node-location values are read free-format, so spacing and line breaks are not important. Values must be in order and separated by spaces or commas.

Numbers specifying node locations sandwich record blocks specifying cell properties. A group of four lines, each line NZNODE-1 characters long, defines the physical properties of a column of elements. The first line indicates the properties of triangular subcell 1, the second line triangular subcell 2, etc (see figure 5).

The last record in a *.2DM files should be a list of node locations along the edge of the finite-element mesh. There should be a total of NXNODE node-location record blocks and NXNODE-1 cell-property blocks. A mesh can be subdivided by increasing the value of NXNODE and inserting additional node-location and cell-property record blocks in the middle of a *.2DM file.

Numbers specifying node locations sandwich record blocks specifying cell properties. A group of four lines, each line NZNODE-1 characters long, defines the physical properties of a column of elements. The first line indicates the properties of triangular subcell 1, the second triangular subcell 2, etc (see figure 5).

The last record in a *.2DM files should be a list of node locations along the edge of the finite-element mesh. There should be a total of NXNODE node-location record blocks and NXNODE-1 cell-property blocks.
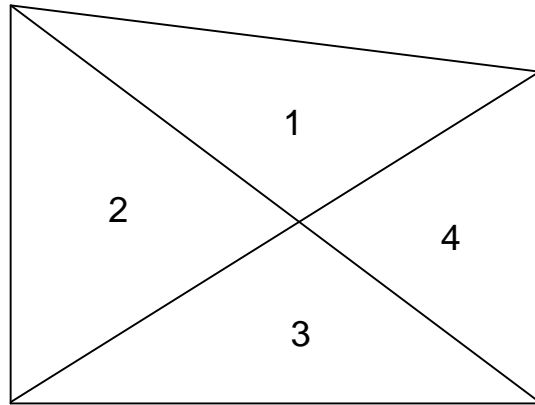
Figure 5: Groups of four triangular subcells, indexed 1 to 4, are combined into trapezoidal elements with vertical sides and possibly sloping top or bottom edges. Individual resistivity and IP properties may be specified for each triangular subcell.

*.MTD File (model-data file)

Receiver location, frequency, Cagnaird apparent resistivity and impedance phase values are stored in *.MTD files. The tabular format combines TM and TE mode data on one record. Values are separated by commas, with missing values shown by commas bracketing an blank space or no space. Comment lines beginning with a "!", "\", "/", or """ can be included anywhere in the file.

Partial *.IPD-file listing:

```
"Stn" "GridE" "GridN" "Elev" "Freq" "AR_TM" "AR_TM_err" "ZP_TM" "ZP_TM_err" "AR_TE"
"AR_TE_err" "ZP_TE" "ZP_TE_err"
"Data from EM2D v4.00a  Date:29/0/98  Time:17:00"
0,378144,3009969,1743,1.0000E+0,101.3,2.0,646.2,20.0,93.14,2.0,767.7,20.0,
0,378144,3009969,1743,2.0000E+0,92.60,2.0,679.9,20.0,91.94,2.0,768.2,20.0,
0,378144,3009969,1743,4.0000E+0,86.83,2.0,706.1,20.0,90.79,2.0,771.4,20.0,
0,378144,3009969,1743,8.0000E+0,83.06,2.0,725.2,20.0,89.95,2.0,777.9,20.0,
0,378144,3009969,1743,1.6000E+1,80.56,2.0,736.7,20.0,89.91,2.0,788.0,20.0,
0,378144,3009969,1743,3.2000E+1,78.54,2.0,740.1,20.0,91.18,2.0,799.9,20.0,
0,378144,3009969,1743,6.4000E+1,76.01,2.0,737.9,20.0,94.04,2.0,808.6,20.0,
0,378144,3009969,1743,1.2800E+2,72.83,2.0,739.0,20.0,97.57,2.0,808.5,20.0,
0,378144,3009969,1743,2.5600E+2,70.48,2.0,744.7,20.0,99.75,2.0,802.4,20.0,
0,378144,3009969,1743,5.1200E+2,68.58,2.0,746.5,20.0,100.1,2.0,804.1,20.0,
0,378144,3009969,1743,1.0240E+3,66.45,2.0,749.2,20.0,101.4,2.0,822.0,20.0,
0,378144,3009969,1743,2.0480E+3,65.24,2.0,756.2,20.0,106.6,2.0,845.1,20.0,
0,378144,3009969,1743,4.0960E+3,64.84,2.0,759.2,20.0,114.5,2.0,861.5,20.0,
0,378144,3009969,1743,8.1920E+3,68.98,2.0,795.7,20.0,116.5,2.0,844.5,20.0,
25,378157,3009990,1735,1.0000E+0,143.0,2.0,644.2,20.0,92.98,2.0,766.7,20.0,
25,378157,3009990,1735,2.0000E+0,130.5,2.0,677.6,20.0,91.71,2.0,766.9,20.0,
25,378157,3009990,1735,4.0000E+0,122.1,2.0,703.2,20.0,90.43,2.0,769.5,20.0,
 .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .
 .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .
 .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .   .
```
_____

Record 1 is a list of column headers indicating the data type in each column. Record 2 is a comment line showing the program name and version, along with the date and time when the file was updated. All remaining records in EM2DEMO.MTD specify individual dipole-dipole data points.

Column Number: Associated data type:
- 1: station number (proportional to distance along line).
- 2: station grid east (length units).
- 3: station grid north (length units).
- 4: station grid elevation (length units).
- 5: frequency (hertz).
- 6: TM-mode apparent resistivity (ohm-m).
- 7: TM-mode apparent resistivity error (percent) (for use by inversion programs).
- 8: TM-mode impedance phase (mrad).
- 9: TM-mode impedance phase error (mrad) (for use by inversion programs).
- 10: TE-mode apparent resistivity (ohm-m).
- 11: TE-mode apparent resistivity error (percent) (for use by inversion programs).
- 12: TE-mode impedance phase (mrad).
- 13: TE-mode impedance phase error (mrad) (for use by inversion programs).

*.Z2D File (Zonge plotting program ZPLOT *.Z file)

*.Z files hold data in an (x,y,z) format specialized for the Zonge plotting program ZPLOT.

_____

```
Partial *.Z2D-file listing: ! Modeling results from REM2D v3.10d
 1: $ ZPLOT: DATA= FLOG
 2: EM2D v2.02c Contour Plot Z-File
 3: Cl Cn Ce Ns Nd Yl  Plot file  1
 4:  1 10  0  3  0  1
 5: App. Resistivity (ohm-m)
 6: TM-mode, E-perpendicular
 7: From EM2D v2.02c 30/04/97 13:07
 8: Data from EM2DEMO.Z2D
 9:IIxxxxxxxxYYYYYYYYzzzzzzzzzzzz
 2     0.0    9.00    1.013E+2
 2     0.0   10.00    9.260E+1
 2     0.0   11.00    8.683E+1
 2     0.0   12.00    8.306E+1
 2     0.0   13.00    8.056E+1
:     :      :          :
        :     :        :         :
    99: 9999.00
```

_____

Description of values in sample *.Z2D file:

Line #   Explanation:

1: $ ZPLOT: DATA= FLOG Keyword specifying vertical plot axis data type

2: REM2D v4.00a   Program name and version that generated this file.

3: Cl   Label for contour type: 0 = linear
                        1 = logarithmic
                        2 = pseudo-log

   Pseudo-log contours: positive and negative values 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.
    The "interval" is an integer power of ten: 10Ce

  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 = linear frequency
                        2 = log frequency
                        3 = linear depth

_____

Description of values in sample *.Z2D file (continued):

4: 1   Value of Cl: logarithmic contours

   5   Value of Cn: 5 contours per "interval"

   0   Value of Ce: interval = 100 = 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: linear frequency axis

5-8: Data description for this plot file. Two to six lines are available for plot annotation. ZPLOT plots these lines as title-block text, skipping the first column in each line.

 9: Header line for the data that follows:

   II - Command flag:
      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 values are interpolated
          for the bottom of the plot to improve the gridding.
      5 = Use to set plot limits, do not contour or post.
          Used for depth plots to set zero depth. Used to
          provide a margin around the data, as for plan maps.

   xxxxxxxx - X-coordinate, usually station coordinate.

   YYYYYYYY - Y-coordinate, not used for Flag = 3

   zzzzzzzz - Value to be plotted at X-Y for Flags 1, 2, 4.

   AAA - For Flag 1 or 2, ZPLOT posts any characters in the AAA
         column instead of the value in the zzzzzzzz column.

         For 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.

99: 9999.0 - End-Of-Plot indicator.