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Inversion of plane-wave electromagnetic data for layered earth models
using a graphical user interface (Version 1.0)

by

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SYSTEM REQUIREMENTS

Hardware Needed

The minimum hardware is: a 386 (DX or SX) IBM compatible PC with at least 2 Mb RAM (i.e., 1 Mb conventional and 1 Mb extended or XMS memory), a 387 math coprocessor, an EGA or VGA video adapter and monitor, a hard disk with more than 1 Mb free space, and a 1.2 Mb floppy disk drive. The current version of this program requires 586,268 bytes of free XMS memory.

Software Needed

MS-DOS 3.0 or higher, and RSoft (TM) Inc. RPlot Scientific Graphics (Version 2.00). [See Appendix 2 for an order form for the RPlot package, currently available at $149 plus $5 shipping.]

INTRODUCTION

Overview

This report is provided as a reference guide to define the basic graphical user interface (GUI) responses needed to perform forward or inverse modeling of plane-wave electromagnetic (EM) data using an IBM compatible personal computer (PC). The underlying model used is a one-dimensional (1-D) horizontal layered earth with parameters being the layer resistivities and thicknesses below the earth's surface. Details of the geophysical and mathematical modeling are given by many authors (e.g., see Ward and Hohmann, 1988, and Wait, 1962, for a theoretical treatment of the 1-D plane-wave problem), and therefore will not be repeated here. The program in this report is named INVPW (for INVersion of Plane-Wave data).

Scope of This Guide

Ideally, a program using a GUI should not require a detailed reference guide, provided the user is familiar with the subject matter of the application program. That is, a good GUI-type program should be sufficiently intuitive with program prompts and graphical displays so that the user has a visual reminder of the required response in order to properly solve the problem at hand. If the GUI is completely comprehensive, then a reference guide would be redundant. However, as will be evident in what follows, a lot of compromises to this ideal situation are sometimes necessary in practice, and thus a few basic "rules" need to be defined first.

This report has been developed to be about 90 percent reference material, with the first 10 percent devoted to getting started using a few basic definitions. Thus, for a user in

a hurry, it is only necessary to read the following material down to the section METHOD OF COMPUTATION. The rest of the report is mainly detailed material for reference purposes (e.g., HotKey options, post plotting options, and troubleshooting), and may not be needed initially for all experienced users.

Conventions Used in This Guide

The notation: <Key> (e.g., <Enter>, <y> or <n>) used in prompt messages means that a user should respond by pressing that key, without pressing any additional key; i.e., the <Key> is a "HotKey", and requires only a single key-stroke. Here, <y> or <n> is used to answer "yes" or "no" to various questions. Other HotKey's used are <Esc>, <Home>, <End>, <Up-Arrow>, <Down-Arrow>, and various function keys: <F1>, <F2>,..., etc. Note that <AnyKey> means that any key can be pressed, except a control key: <Ctrl>, <Alt>, or <Shift>.

Prompts for numerical values must *always* be followed by pressing the <Enter> or <Return> key, e.g., 100 <Enter>. Certain parameter changes require syntax of the form: r2=100 <Enter> to change the resistivity of layer 2, for example; a long version is also allowed as rho2=100 <Enter>, or rh2=100 <Enter> if you want to type more letters. Layer parameters are denoted as "rho" (resistivity in ohm-m) and "h" (thickness in m), and "nl" is the number of layers.

The interaction screen has four subdivisions (or windows--defined later) for text messages and user responses. Text windows are temporarily saved in memory and replaced by a full screen when curves are drawn graphically. After a graph is displayed, pressing <AnyKey> will restore the text windows as previously displayed. A limitation in the present version of this GUI program does not allow graphical and text windows to be placed simultaneously on the viewing screen. This is mainly due to the hardware and software presently employed. A HotKey is available to flip back-and-forth between text and graphic screens to partially overcome this limitation.

GETTING STARTED

Installing Software

The supplied diskette contains the executable program INVPW.EXE, less the required RPlot Scientific Graphics Package. The diskette also contains test data sets (see Appendix 1 for names of the distributed files). To read all files to a current subdirectory, simply insert the supplied diskette in drive a: and type:

copy a:*.*

Remove the diskette. To run program INVPW from any other directory, make sure the installed directory (and RPlot directory) is in the PATH statement in your AUTOEXEC.BAT file at boot time. (See your DOS manual for an explanation of the PATH statement.) If a new PATH is edited in the AUTOEXEC.BAT file, then reboot your system before running INVPW for the first time.

Quick Start

To run a test problem (supplied on the distributed disk) using the apparent resistivity data file APPRES.DAT (contains free-field data columns: frequency and apparent resistivity), type the command:

invpw

Read the Welcome Screen, and press <AnyKey> to continue. At this point, four windows are displayed with the titles:

1. Mode Selection (Top Left of Screen)
2. Parameters (Middle of Screen)
3. Messages (Bottom of Screen)
4. Layered Model (Top Right of Screen)

Look at the information in the Message window for what to do next.

A detailed tutorial on running any forward or inverse problem is given in the section STEPS TO RUN SOFTWARE; however, you could try various options on your own, by following the prompts in the Parameter window (but always looking at the Message window for reminders on active <Keys>, etc.). If you enter incorrect responses, an "{Error}: ..." message (in green) will appear in the Parameter window indicating what went wrong, and followed by a repeat prompt to continue. (Refer to the section TROUBLESHOOTING for additional information on specific error messages.)

Some words of caution: Don't try to type ahead (or too fast), and be sure to read each message completely--at least until you become familiar with all the prompt options.

Note that the Layered Model window will be updated when each model parameter is entered. To correct a value before <Enter> is pressed, use the <BackSpace> key. Also, all run information (forward and/or inverse modeling) will be saved in an output file for any option selected, and serves as a history file of all action taken; in one case, the output file also becomes an input file for subsequent processing. Similarly, various RPlot files are also saved in your subdirectory for possible post plotting (e.g., laser printing, importing to word processors, etc.; see the section POST PLOTTING OPTIONS for more details.)

The rest of this guide is for detailed reference purposes; however, a user unfamiliar with forward or inverse EM modeling methods may want to continue reading.

METHOD OF COMPUTATION

The main idea of using a GUI-type program is to graphically display prompts, user responses, and multiple curves drawn of all computed EM response functions. An attempt has been made in program INVPW to minimize the amount of interactive typing required by assuming as much information about the problem as possible that can be inferred from any observed data read; e.g., number of observations, frequency range, plotting scales, etc.

Forward Mode

The EM solution for an incident plane-wave on the earth's surface over a 1-D horizontally layered model is well-known. A good summary can be found in Ward and Hohmann (1988; p.183-198) or Wait (1962; p. 8-17). Since these books are readily available, I will omit listing all the plane-wave equations here. It should be noted, however, that I have used the quasi-static approximation (i.e., neglecting displacement currents) and a normally incident angle (0 degrees from normal) in computing the forward EM plane-wave field responses for this program.

The basic formulation for the surface impedance $Z(\omega)$ at angular frequency $\omega > 0$ is a recurrence relation in terms of the layered earth parameters, ρ_i and h_i, $i = 1,...,nl$, where for layer i, ρ_i is the resistivity (in ohm-m), h_i is the thickness (in m), and nl is the number of horizontal isotropic layers. (Allowable range is $1 \leq nl \leq 10$ in INVPW.)

In selecting the Forward Mode, one can either generate families of apparent resistivity and/or phase curves, by varying any model parameter(s) at each interaction, or superimpose a set of curves over a given observed data set. At any time in the forward modeling, one can choose to Flip Modes (see below) to Inverse Mode via the < Home > key, provided an observed data set was first loaded as an option.

Inverse Mode

The method used to invert plane-wave observed data for 1-D layered earth models follows an algorithm by Anderson (1982), which describes an adaptive nonlinear least-squares method for constrained minimization problems. The original algorithm for unconstrained solutions was originally published by Dennis et al. (1979; 1981), and was used by Anderson (1982) to perform general constrained nonlinear regression. The latter approach is used in a somewhat modified form for program INVPW.

The forward calculation used in the inverse solution is the same as that described above. Note that repeated forward solutions are needed for estimating partial derivatives required in the Inverse Mode, however, the user may ignore the details here. More information on the adaptive least-squares algorithm can be found in Anderson (1982) and Dennis et al. (1979; 1981).

In an attempt to relieve the user of complicated options in performing an inverse solution for a given observed data set, I have devised a set of default control parameters to handle many typical situations. Thus the program automatically obtains as much information about the given observed data and parameters as possible, such as data ranges and parameter bounds, and proceeds with an inversion attempt with minimal user input. For difficult cases, some control parameters may be overridden as described in the section OPTIONAL DEFAULT SET FILE.

The Inverse Mode requires a list-directed (free-field) observed data file containing columns of paired or triplet data (e.g., frequency, apparent resistivity, and/or phase of surface impedance). The data file must be stored in the current directory before running INVPW. An example of an observed data file is given in a later section. Requirements of the observed data file are listed in section I below.

During the interaction of fitting a layered earth model to observed data, parameters can be entered (or changed) at various stages after attempting a least-squares solution. Options are provided to hold a parameter(s) fixed (or unfixed) at certain points. Trying to find a good starting model might be facilitated graphically by first going into Forward Mode, and then use the flip to Inverse Mode option; in some cases, one could flip back to Forward Mode if unsuccessful with finding a good starting inverse model.

STEPS TO RUN SOFTWARE

In general, the following steps (I-V) may be used to run program INVPW for any given forward and/or inverse problem. Step I is required only as a preprocessing step to prepare data for options requiring an observed data input file. The other steps noted are dependent on the option(s) selected at run time.

In all steps, the user is prompted for an output file name, where a summary of all activity (forward and/or inverse) is listed; the output file has more information about the modeling (especially in Inverse Mode) that was done, and is an ASCII formatted file for possible printing later.

I.   Free-field Observed Data Files

Program INVPW uses only an ASCII free-field observed data file format. The data

file must have a separate record corresponding to each unique frequency. The only format restriction is that each data record cannot have any missing values (depending on the data file type, defined below), and that the first or frequency column is in ascending order (and greater than 0). Each data element must be separated by a "space" or "," in each record; values with a decimal point are not necessarily required. It is also helpful if all data files are named with the .DAT suffix (so that one of the HotKey's will function properly--see HotKey Options below). Units are: frequency (Hz), apparent resistivity (ohm-m), and phase (deg.).

There are three possible observed data file types (2 or 3 columns) with separate records for each frequency as described above:

(1)   Frequency and Apparent Resistivity (<r> type). A third column, if present, will be ignored. The apparent resistivity column must have all values > 0. A data file of this type is APPRES.DAT on the supplied diskette.

(2)   Frequency and Phase of Surface Impedance (<p> type). A third column, if present, will be ignored. The phase column must have all values between -90 and 90. A data file of this type is PHASE.DAT on the supplied diskette.

(3)   Frequency, Apparent Resistivity, and Phase (<b> type). The third column (Phase) is always required here. The apparent resistivity column must have all values > 0 and the phase column must have all values between -90 and 90. An example data file of this type is BOTH.DAT on the supplied diskette.

In file types (1) and (2), the maximum number of records (n) must be such that $n \leq 500$. However, for joint inversion in file type (3), $n \leq 250$ is required. These are arbitrary limits but are considered more than adequate for most plane-wave forward or inverse modeling.

II.   Observed Data Plot Only

This Mode selection (from the main menu) requires an observed data file. (The data is always listed in the output file when this option is used.) It is helpful if all data files have the .DAT suffix so that the <F10> key can be used to invoke the command DIR *.DAT in the Parameter window. When this option is chosen, the program returns to the main menu after viewing the plot(s). To continue, another Mode must be selected.

III.   Forward Mode

There are two possible options in Forward Mode:

(1)   Forward: Curves Only

This option does not require an observed data file. The main use of this option is to run program INVPW to produce a family of forward curves without displaying discrete observed data. Since no observed data are used, the user is prompted to give a minimum x-axis frequency (x1), maximum frequency (xm), and number of frequency points per decade (nx). In this case, selecting the <Home> key to flip to Inverse Mode is disallowed.

(2)   Forward: Curves & Obs.Data

This option requires an observed data file. This option can be useful to try various approximate starting models superimposed over the observed data prior to attempting the Inverse Mode. After a few parameter changes (including varying nl), one could then try the Flip Mode <Home> key to use the last model as a starting guess for inverse modeling. Note that you can always flip back to Forward Mode from Inverse Mode as well.

IV.   Inverse Mode

There are two possible options in Inverse Mode:

(1)   Inverse: Initialize & Start

This option requires an observed data file. This is the primary starting point with an observed data set and an initial attempt of inverse modeling. The observed data can be viewed (and reviewed) prior to entering a starting model guess. (Since it helps to see the curves while estimating layered parameters, a HotKey <F1> is available at various points to refresh the screen between text and graphical screens.)

As mentioned in the METHOD OF COMPUTATION section, many control parameters for typical problems are set to reasonable default values (e.g., NITER=25 sets the maximum number of nonlinear least-squares iterations allowed to converge). Also the data set itself is used to determine the number of observations (n) by counting records until end-of-file, etc. Each data set is scanned for possible data errors before allowing the run to continue; however, not all errors can be easily detected, and this is one of the reasons why a prior data plot is useful.

After the data file is accepted by INVPW, a starting model is required. It is suggested that the fewest number of layers as necessary should be used to try to graphically find a "best-fit". Subsequent modeling can be used to insert (or delete) additional layers as deemed necessary. When the program begins computing an inverse solution, the message

... INVPW is running ... Please wait ...

means a pause in response time should be expected. Observe that the least-squares solution will appear updated in the Layered Model window. Parameters can be held fixed (or unfixed) at certain times as noted in the Message window; this may be necessary if too many layers are attempted that are not detectable with the given observed data.

At this point, either an acceptable least-squares solution has been obtained (at least graphically as a good fit), or other starting models may be indicated. In the latter case, one could Flip Modes to the forward case in an attempt to find forward curves better suited as a new starting model; then, you could Flip Modes back again to the Inverse Mode with a better starting guess.

(2)   Inverse: Modify & Restart

This option requires a previous output file (which is always generated), and in turn lists the observed data file that was used. At the prompt to enter the "Restart file name", you must supply the exact file name, which must exist in the current directory. (If a suffix of .OUT was used, then the <F9> key can be used to give a directory listing of *.OUT files in the Parameter window.)

If the Restart file exists, program INVPW asks if you want to view the last plot, and then asks for a RUN number of the curve (or inverse solution) to modify and restart. This RUN number must correspond to an inverse run (not a forward run); if the inverse RUN number is valid, the last solution layered parameters will be updated in the Layered Model window.

At this point, any model parameter (or nl) must be changed as defined in the Message window to continue, and then proceed as in step IV(1) with additional inverse runs.

V.   HotKey Options

As already noted, many HotKey's are used during forward or inverse modeling to perform some immediate action. All active HotKey's will be summarized in the bottom Message window at various stages during the interaction. Most of the user responses to enter information in the Parameter window should be obvious, after reading the Message window definitions. However, for completeness, the following table lists all HotKey's possible:

HotKey	Meaning or Action Taken
<AnyKey>	Continue by pressing any non-control key.
<Enter>	Continue by pressing only the "Enter" key.
<UpArrow>	Scroll Mode window upward to highlight option.
<DownArrow>	Scroll Mode window downward to highlight option.
<Esc>	Cancel operation (returns for new Mode).
<End>	End program INVPW (returns to DOS).
<Home>	Flip Mode (to opposite type).
<y>	Answer "yes" (do not press <Enter> after <y>).
<n>	Answer "no" (do not press <Enter> after <n>).
<r>	Select apparent resistivity curve type.
<p>	Select phase curve type.
<b>	Select both apparent resistivity & phase types.
<F1>	Replot (replace text screen with graphic screen).
<F2>	Delete curve(s).
<F3>	Undelete curve(s).
<F4>	Fix/Unfix a parameter.
<F5>	More changes to make.
<F9>	List file names via DOS command: DIR *.OUT
<F10>	List file names via DOS command: DIR *.DAT

Plot and Replot Options

Function keys <F1>, <F2>, and <F3> provide ways to modify the graphic screen at certain times during the interaction. For example, when many curves are displayed for a large number of RUNs, one can use <F2> to ask for a range of RUNs to be temporarily removed from plotting; however, any curve or individual set of curves can also be undeleted using <F3> to restore deleted curves again. Note that no additional computations are done via <F2> or <F3> in this manner, but only a control plot file (suffix .PCS, .PC1, or .PC2) is modified in this case. All curves can always be restored after exiting INVPW (see POST PLOTTING OPTIONS section below).

Flip Modes

Perhaps the most useful HotKey option is the ability to Flip Modes between forward or inverse interactions. This option is active immediately after a forward or inverse curve has been displayed. At this point, if the <Home> key is pressed, you are asked if you want to flip to the opposite mode. If the answer is <n> (in case you made a mistake), then control returns back to the present mode. However, if the answer is <y>, then the Mode window will reflect the flipped mode with an "*" character in front of the new mode. One can then proceed with the new mode as if originally selected. Using the Flip Mode option interactively can be a very useful way to investigate hard to fit data sets.

OPTIONAL DEFAULT SET FILE

If a file named INVPW.SET exists in the working subdirectory where INVPW is run, then certain control parameters can be set (i.e., overridden) from the default values used for typical cases. Refer to Anderson (1982) for a complete description of several inversion parameters used below. The control parameters and corresponding default values are summarized in the following table:

Parameter	Default	Action of SET File Control Parameter
iprt	-1	iprt=-1 gives a listing of all data points; iprt<-1 suppresses all calculated data points; iprt>0 gives detailed Inverse Mode lines and iprt=0 gives shorter lines. (All listings are given in the output file.)
nspline	0	nspline=0 means no spline interpolation is used to plot all computed curves; nspline>0 splines all computed curve plots. (nspline=2 or 3 is usually adequate.)
niter	25	maximum number of iterations allowed in Inverse Mode if no convergence obtained. (If this limit is reached, then no error statistics are given in the output file since a covariance matrix was not computed.)
iwt	2	iwt=2 will perform statistical weighting when in Inverse Mode so that all observations are weighted uniformly (this is highly recommended). One can use iwt=0 to treat all data without weights in the least-squares inversion. Do not use iwt=1.
sp	3	sp≥3 selects an upper/lower bound option in the adaptive nonlinear algorithm defined by Anderson (1982; table 1); sp=3 is the constrained regression option. sp<3 is not recommended for program INVPW. Also sp=3 is usually better than sp=4 here.

Parameter	Default	Action of SET File Control Parameter
rfactor	100	rfactor > 1 is used to automatically determine upper and lower bounds about each rho(i) when sp ≥ 3 in Inverse Mode as: bl(i) ≤ rho(i) ≤ bh(i), where bl(i)=pow10(rho(i)/rfactor)/10, bh(i)=pow10(rho(i)*rfactor), and pow10 is the nearest power-of-10.
hfactor	10	hfactor > 1 is used to automatically determine upper and lower bounds about each h(i) when sp ≥ 3 in Inverse Mode as: bl(i) ≤ h(i) ≤ bh(i), where bl(i)=pow10(h(i)/hfactor)/10, bh(i)=pow10(h(i)*hfactor), and pow10 is the nearest power-of-10.

The format of file INVPW.SET is in NAMELIST format (see any Fortran manual); e.g.,

$set iprt= -1,nspline= 2$

Note that parameter iprt=-2 can be used to reduce the length of the output files by suppressing the calculated data matrix lines. The other control parameters generally are adequate for "typical" observed data sets. However, changes might be required in some cases.

If file INVPW.SET does not exist in the working directory, then the above default control parameters will always be assumed.

EXAMPLE INPUT AND OUTPUT RESULTS

An example problem using the observed data file APPRES.DAT on the supplied diskette is listed in this section. To save space, only the given input file and output file listing is shown as run first in Forward Mode (RUN 1 and 2), followed by a flip to Inverse Mode (RUN 3).

Additionally, the INVPW.SET file contained the override parameters:

$set iprt= -2,nspline= 2$

Only the final graphic screen plot showing the observed data and all three RUNs is reproduced below; also various text screens during the interaction will not be given here. (The interested user may try to duplicate these results directly on his/her PC if desired.)

<u>Input File Example</u> -- Obs.Data File = APPRES.DAT (<r> type); from step I(1) above, columns 1 and 2 in this file are defined respectively as frequency and apparent resistivity:

```
1.00000      2.47650
1.58489      3.01728
2.51189      3.79039
3.98107      4.90962
6.30957      6.54917
10.0000      8.97700
15.8489     12.6065
25.1189     18.0764
39.8107     26.3717
63.0957     39.0007
100.000     58.2313
158.489     87.3183
251.189    130.394
398.107    190.905
630.957    266.107
1000.00    337.244
1584.89    371.812
2511.89    358.733
3981.07    326.557
6309.58    305.199
```

Output File Listing

The output file (generated for all Modes) contains a summary of all activity performed by the user during the entire interaction. The Forward Mode output is very simple, and mainly lists a few derived and input parameters (and possibly computed curve values if default parameter iprt=-1 is not changed--see above .SET file options). The Inverse Mode output is very similar to the format defined by Anderson (1982); the user is referred to the latter reference for all output parameter definitions used by the adaptive nonlinear least-squares algorithm (Dennis et al., 1979; 1981).

The output file listing for the above example (file name = TESTR.OUT) follows:

```
Program INVPW  --  Forward: Curves & Obs.Data  --  DATE:  08/06/92

Obs.Data File: appres.dat

Curve type: <r> = Apparent Resistivity in (ohm-m)

<Obs.Data>:    RUN =  0    FILE(s) = testr.*
    --------------------------------------------
     i    Freq          Appres

     1  0.1000000E+01  0.2476500E+01
     2  0.1584890E+01  0.3017280E+01
     3  0.2511890E+01  0.3790390E+01
     4  0.3981070E+01  0.4909620E+01
     5  0.6309570E+01  0.6549170E+01
     6  0.1000000E+02  0.8977000E+01
     7  0.1584890E+02  0.1260650E+02
     8  0.2511890E+02  0.1807640E+02
     9  0.3981070E+02  0.2637170E+02
```

```
10   0.6309570E+02   0.3900070E+02
11   0.1000000E+03   0.5823130E+02
12   0.1584890E+03   0.8731830E+02
13   0.2511890E+03   0.1303940E+03
14   0.3981070E+03   0.1909050E+03
15   0.6309570E+03   0.2661070E+03
16   0.1000000E+04   0.3372440E+03
17   0.1584890E+04   0.3718120E+03
18   0.2511890E+04   0.3587330E+03
19   0.3981070E+04   0.3265570E+03
20   0.6309580E+04   0.3051990E+03
```

```
<forward>:     RUN =  1     FILE(s) = testr.*
------------------------------------------------
nl=   2  xl=    1.000000      nx=    5 xm=   6309.580

rho()=
     0.4000000E+03   0.4000000E+01
h()=
     0.2000000E+03


RUN=  1  CPU=     0.000 (s) =   0.000 (m)

<forward>:     RUN =  2     FILE(s) = testr.*
------------------------------------------------
nl=   2  xl=    1.000000      nx=    5 xm=   6309.580

rho()=
     0.2000000E+03   0.5000000E+00
h()=
     0.2000000E+03


RUN=  2  CPU=     0.000 (s) =   0.000 (m)

Program INVPW  --  Inverse: Initialize & Start  --  DATE:  08/06/92

<inverse>:     RUN =  3     FILE(s) = testr.*
------------------------------------------------


n=         20     k=         3     ip=         0     m=          1
iwt=        2     ider=      1     iprt=      -2     niter=     25
sp=         3

parameter lower bounds: bl=

 0.10000000E+00   0.10000000E-02   0.10000000E+02

initial parameters: b=

 0.20000000E+03   0.50000000E+00   0.20000000E+03

parameter higher bounds: bh=

 0.10000000E+06   0.10000000E+03   0.10000000E+05
** itr_pw (ider=0) or nl2sno (ider=1) called **

       i       initial x(i)       d(i)

       1       0.447251E-01       0.131E+04
       2       0.706992E-01       0.443E+02
       3       0.138350E+00       0.448E+03
```

```
    it     nf       f          df        cosmax       var

     0      1   0.145E+03                0.819E+00
     2      3   0.122E+00   0.358E+01   0.111E+00   0.164E+02
     4      5   0.120E+00   0.284E-05   0.294E-02   0.159E-03
     5      6   0.120E+00  -0.151E-05   0.294E-02   0.779E-04
```

***** variability convergence *****

```
function      0.120279E+00   variability   0.778684E-04
func. evals        6          grad. evals        5
grad. norm    0.335317E+00   cosmax        0.294478E-02
```

```
     i       final x(i)         d(i)           g(i)

     1      0.545526E-01     0.160E+04      0.290E+00
     2      0.103435E+00     0.585E+02      0.837E-01
     3      0.154888E+00     0.603E+03      0.146E+00
```

covariance = scale * (j**t * j)**-1

```
row  1     0.5592E-08
row  2     0.1748E-07   0.5760E-05
row  3    -0.7752E-09  -0.2827E-06   0.5277E-07
```

** rmserr= 0.20759859E+01 ave|%res.err|= 0.103126E+01

```
covariance matrix
 1  0.5592E-08
 2  0.1748E-07   0.5760E-05
 3 -0.7752E-09  -0.2827E-06   0.5277E-07
```

```
correlation matrix
 1  0.1000E+01
 2  0.9742E-01   0.1000E+01
 3 -0.4512E-01  -0.5128E+00   0.1000E+01
```

```
  **parm_sol.    std_error    rel_error    % error **

 1  0.2974E+03   0.7478E-04   0.1371E-02   0.1371E+00
 2  0.1067E+01   0.2400E-02   0.2320E-01   0.2320E+01
 3  0.2478E+03   0.2297E-03   0.1483E-02   0.1483E+00
```

```
=================================================================
INVERSE SOLUTION SUMMARY:      RUN =  3      FILE(s) = testr.*

nl     rho          (% error)          h            (% error)      depth (sum h)

 1   0.2974028E+03 (0.137E+00)     0.2477531E+03 (0.148E+00)     0.2477531E+03
 2   0.1067052E+01 (0.232E+01)
=================================================================
RUN=  3  CPU=     0.330 (s) =    0.005 (m)
```

END of RUN(s). Date & Times:

 08/06/92

```
   Start = 12:38:33.02
    Stop = 12:40:05.79
```

```
Elapsed =     1.546 (m)
CPU Sum =     0.005 (m) -- for all RUNs
```

Discussion of Results

Referring to the above output file listing, several comments concerning the interaction run that I made follows:

1.   The main menu Mode "Forward: Curves & Obs.Data" was selected.
2.   The observed data file name used was APPRES.DAT, and the type curve was "<r> = Apparent Resistivity in (ohm-m)".
3.   The observed data was listed with 20 observations.
4.   The number of layers (nl) was 2, and the resistivity (r[ho]) and thickness (h) values chosen for RUN 1 were:

nl	rho	h
1	400	200
2	4	

5.   A second forward curve (RUN 2) was run with modified parameters:

| nl	rho	h	
1	200	200	(I used r1=200 <Enter> here)
2	.5		(I used r2=.5 <Enter> here)

6.   After step 5 finished, the <Home> key was pressed to Flip Modes from forward to inverse. Here I answered <y> to continue, and also answered <y> to use the last model (RUN 2) as a starting model for the inversion (RUN 3). (Note that I could have modified any parameter before starting RUN 3, but the RUN 2 curve looked somewhat close to the observed data plot.) I then pressed <Enter> to begin the inversion for RUN 3.

7.   The inverse solution for RUN 3 was displayed in the Layered Model window as:

nl	rho	h	
1	297.4028	247.7531	
2	1.067052		1.0 % misfit

Note that 7-figures are printed (to handle most ranges), but not all decimal places are significant here. The output file gives the parameter %-errors, but are linear statistics for a nonlinear least-squares solution (provided convergence was obtained). When $nl \geq 6$, the Layered Model window is compressed into 6-columns, and only 2-figures are printed under multiple rho and h columns. Again, one should see the output file for complete results about any solution. The %-misfit above is rounded to 1-decimal place, and is the same as the ave| %res.err| value (E-format) in the output file. (Refer to Anderson, 1982 for all notations and definitions given in the output file listing above.)

8. The final graphical display showing the observed data, RUN 1 and 2 forward curves, and RUN 3 inverse solution (calculated curve) is reproduced below (imported RPlot file via WordPerfect):
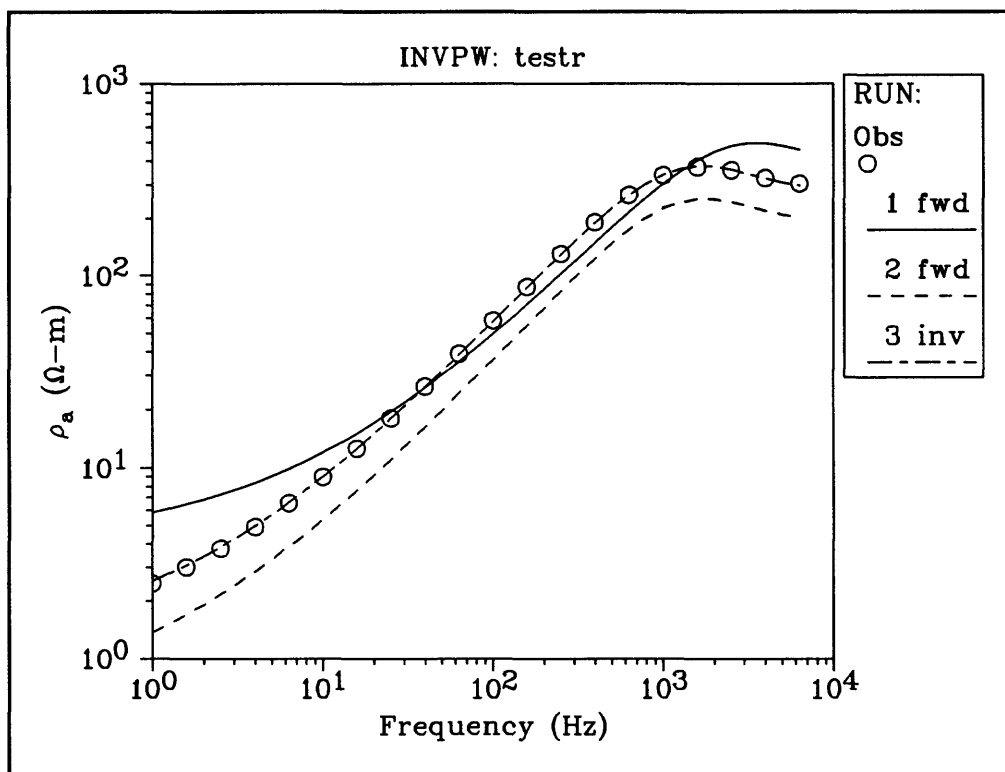
The upper-right legend in the graph denotes the RUN numbers with a following notation "fwd" (forward) and "inv" (inverse) Modes. The first notation is "Obs" (observed), and refers to the plotted observed points denoted by "O". Each RUN number curve has a different line-type immediately below the RUN number in the legend, and is displayed in color on a VGA monitor. The color and line-type scheme for the first 3 RUNs are:

RUN	Color	Line-Type
1	Yellow	Solid
2	Light Green	Uniform Dash
3	Light Red	Variable Dash
...		

If more than about 9 RUNs are used, the bottom of the legend may be clipped, unless <F2> is used to temporarily delete selected curves.

9.   More details on the inverse solution for RUN 3 are given in the output file TESTR.OUT (the name I used) under the heading: "INVERSE SOLUTION SUMMARY". (See above output file listing).

In the summary, the linear parameter resolution (or % errors) are noted in parentheses following the nonlinear parameter solution, but expressed in Fortran exponential format (instead of the g-format used in the Layered Model window). By looking at the plot and the resolution statistics, the fit appears good, but perhaps adding another layer (nl=3) would give even a better result.

In fact, the data in file APPRES.DAT was previously generated by using the "Forward: Curves Only" Mode with the known model parameters:

nl	rho	h	(exact known model)
1	300	200	
2	100	50	
3	1		

I leave it as an exercise for the user (if desired) to see if the above known model can be approximated better using a 3-layer parameter estimate in the Inverse Mode. I would suggest using the main menu Mode "Inverse: Modify & Restart" using output file TESTR.OUT as a Restart file, and select the inverse solution for RUN 3 to modify; then insert a new layer (e.g., after layer 1) with some reasonable guesses for the new second layer parameters. At the Change Parameter prompt, begin by typing: nl=3 < Enter >. (Note that INVPW will automatically reorder the previous values in the Layered Model window, so that reentering existing values are not necessary; also a new layer can be inserted immediately after the surface by using an index of 0; layers can be inserted/deleted interactively by using a different nl than last used, and responding to the prompts for new values.)

Other Observed Data Files

The distributed diskette also contains the following observed data files (all based on the computed known model in comment 9 above):

PHASE.DAT   (the corresponding phase to file APPRES.DAT)
BOTH.DAT   (both APPRES.DAT and PHASE.DAT in one file)

Using phase data alone, it is more difficult to obtain a unique solution compared with using apparent resistivity alone. It is usually best to use "both" apparent resistivity and phase data via joint inversion (this is the < b > option for three-column data files defined previously). Again, it may be instructive to try your hand at using either the PHASE.DAT or BOTH.DAT data sets to see if the known model can be recovered.

Conclusions About Inversion

I would like to point out that "real" field data measured over a limited frequency range that contains instrumental noise would always make finding proper (or acceptable) least-squares solutions much more difficult than in the above example. In many cases, it may be necessary to hold some parameters fixed that cannot be sufficiently resolved due to insufficient data (or when trying too many layers).

Perhaps the usefulness of this program to view graphically the observed data along with a search for a probable 1-D layered model may be its greatest advantage. Certainly the ability to flip between forward and inverse modes at any time should make the search easier.

POST PLOTTING OPTIONS

RPlot System (CopyRight by RSoft, Inc.)

Various post plotting capabilities are easily provided using the RPlot Graphical Package. After a final curve plot is obtained from INVPW on-line, it is possible to modify some of the generated plot files for subsequent hard copy output to laser printers, changing fonts, importing to word processors (as done in the above section), etc. The RPlot package is very versatile, and has many special options for controlling a printer, plot resolution, paper orientation, etc.

It is beyond the scope of this report to indicate all possible RPlot usage as a "stand-alone" plot package. Note, however, that INVPW produces as a by-product several RPlot-type files in the current directory; specifically, the file name prefix (denoted [prefix] below) is taken the same as in the output file name. The RPlot-type files would be:

[prefix].PCS (if <r> or <p> type curves)
[prefix].000 (a list-directed copy of the obs.data file)
[prefix].001 (possible splined curve for RUN 1)
[prefix].002 (possible splined curve for RUN 2)

... etc ...

[prefix].PC1 and [prefix].PC2 (if <b> type curves)
[prefix].100 and [prefix].200 (copy of obs.data <r> and <p>)
[prefix].101 and [prefix].201 (possible splined curves for RUN 1)
[prefix].102 and [prefix].202 (possible splined curves for RUN 2)

... etc ...

The above RPlot files with a suffix .PCS (or .PC1 and .PC2) are automatically generated by program INVPW to contain standard fonts and other RPlot control plot options. It is very easy to change these files to produce other RPlot effects after running INVPW. For example, to just view the very last graphic screen after exiting INVPW, simply type:

plot @[prefix].PCS (or .PC1; or .PC2)

where [prefix] is the output file prefix name (without the [ ]'s).

Refer to the RPlot User's Manual on how to modify any .PCS file for special effects. One easy exclude/include modification to a .PCS file is to insert/delete a "!" character at the beginning of a line (i.e., anything after an ! is treated as a comment). For example, this is how curves are deleted (or undeleted) while running INVPW. Thus, all curves that were deleted while running INVPW can easily be replotted after exit by removing the ! on all RUN lines (near the end of the file). Note that for the above example plot in this report, the .PCS file was modified to remove the bottom line text message of the plot by inserting the "!" character in the line

!/tb'Press <AnyKey> to Continue'

One very useful RPlot post plotting option is the ability to import a final graphic file from INVPW directly into most current word-processing files for IBM compatible PCs. RPlot can generate an HPGL, CGM, or EPS formatted file for this purpose. For example, the .PCS comment line !/pf can be changed to /pf and the above plot command re-executed to produce an HPGL file with the suffix .PLT; this file can then be imported directly into WordPerfect, or other word processors. (Again, refer to the RPlot User's Manual for more information.)

TROUBLESHOOTING

A multitude of built-in error messages are provided by program INVPW. Most user entry errors are detected immediately after the associated prompt in the Parameter window; the syntax of the error message is:

{Error}: ... message here ...

The error message is displayed in "green" in the Parameter window, and is followed (usually) by another prompt to reenter with a correct value (or HotKey). In some cases, it may be necessary to cancel the Mode using the <Esc> key, or to try another option defined in the Message window. Sometimes, pressing <Enter> a second time may be necessary to make active a previous set of option keys (use this approach only to get out of a jam!). Also, <Ctrl-C> can be used to abort the DOS run at certain times.

Some Specific Error Messages and Possible Solutions

{Error}: BAD Syntax, ...TRY Again...

>   This is a catch-all when invalid numbers or names are entered. Do not enter non-numeric characters when entering numbers, although + or . characters are allowed in entered numbers.

>   When making parameter changes, the correct syntax must be:

>   <name>[layer] = <value> <Enter>

>   where [layer] is required (without the [ ]'s) only for a layer parameter name; e.g., r2=100<Enter> -or- rho2=100<Enter> -and- nl=3<Enter>   (Note: the "=" character must always be used here.)

>   When [un]fixing a layer parameter, the correct syntax must be:

>   [-] <name> <layer> <Enter>

>   where [-] is optionally used to unfix a layer parameter name; e.g., r2<Enter> will FIX r2, and -r2<Enter> will UNFIX r2. (Note: the "=" character cannot be used here.)

{Error}: Invalid KEY, ...TRY Again...

>   Only keys listed in the Message window can be pressed. Generally, this error is when <y>, <n>, <r>, <p>, or <b> was required. The only way out, in this case, is to enter one of these keys (without a following <Enter> key!).

{Error}: file name has 0 chars.
{Error}: file name missing a "."
{Error}: file name missing prefix.
{Error}: file name missing prefix.>9 chrs.
{Error}: file name suffix cannot begin with ".pc"

>   This group of messages all pertain to entering an invalid file name. The rule under MS-DOS is that a file name prefix must have 8 or fewer characters before the "." separator (always required in program INVPW), followed by 3 or fewer characters for the file name suffix; e.g., 12345678.123 is a valid file name (but usually a letter is used to start the file name prefix).

In program INVPW, file names without the "." separator are not allowed, since the program uses the [prefix.] to create all the RPlot associated files. It is suggested that all observed data files have a .DAT suffix (so that the <F10> HotKey is functional), and output files have a suffix different than .DAT (e.g, .OUT or .LIS).

The last file name error above (".PC" suffix) is to avoid any conflicts with RPlot .PCS (or .PC1 and .PC2) plot files. Simply choose another file name with a different suffix to continue.

{Error}: No changes were made for this RUN (?)...TRY Again, or Quit

This error occurs when continuing (i.e., pressing <Enter> without making any parameter changes) from the previous RUN. Sometimes this is really not an error, but an oversight by the user; other times this can occur when flipping Modes. In the latter case, simply change any parameter before ending the changes with a null <Enter>.

{Error}: Cannot open Restart file
{Error}: BAD Restart file; no Obs.Data File line (?)
{Error}: BAD Restart file; no Obs.Data File name (?)
{Error}: BAD Restart file: Curve type wrong!

A previous "output" file must be used as a Restart "input" file. If a suffix of .OUT was used, then the <F9> key can be pressed to display all *.OUT file names in the current directory. Note that this Mode (Inverse: Modify & Restart) can only be restarted from an existing output file that contained at least one Inverse Mode run. This also implies that all associated RPlot files must exist in the current directory in order to replot the previous results prior to restarting.

{Error}: Cannot open Obs.Data file!
{Error}: BAD Syntax in Obs.Data file!!
{Error}: Improper numeric fields in Obs.Data file
{Error}: nobs>500 in Obs.Data file
{Error}: App.Res. <=0 in Obs.Data file
{Error}: Phase <-90 or >90 in Obs.Data file
{Error}: Freq. <=0.0 or not ascending in Obs.Data file

These errors all pertain to an invalid (or unknown) observed data file. It may also be due to entering the wrong curve type (<r>, <p>, or <b>) corresponding to the selected data file. See the section STEPS TO RUN SOFTWARE (Free-field Observed Data Files) for the proper file syntax to use.

Other Undocumented Problems

If other undocumented errors occur using INVPW with seemingly proper observed data files, then I would appreciate receiving feedback information from users. Even though several tests were made during a beta-testing stage, errors of omission (or other unknown errors) may still exist in the present version.

Future Plans

Version 1.0 of INVPW should be called about 1.5 due to the changes already made while developing this program. I intend to look for economical ways to display text and graphic screens simultaneously (possibly using MS-Windows and another Fortran compiler); if and when this is happens, perhaps an improved Version 2.0 (or 3.0) will become available in the future. Meanwhile, the present version will hopefully serve as a good starting point for fast plane-wave inversion using a 386 (or 486) 32-bit PC.

ACKNOWLEDGMENTS

I would like to thank Dave Fitterman, Brian Rodriguez, Bob Horton, Adel Zohdy, Dal Stanley, and Doug Klein, (all from USGS) for their review comments and/or running an earlier version of this program during the beta-testing and development stages. Many of their suggestions for improvement to the present version were adopted where feasible.

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APPENDIX 1. -- Source and Executable Codes (less RPlot Software)

The source code for program INVPW (less the RPlot Software, available via Appendix 2) was written in extended Fortran-77 language. The Fortran compiler, window library, and protected mode 386 operating system used to generated INVPW.EXE was:

Lahey F77L-EM/32 (Version 5.00)
Lahey SpinDrift Windows Library (Version 2.01)
Lahey/Phar Lap 386|DOS-Extender (Version 4.1L)

The Lahey Fortran system allows calling an MS-DOS command internally and returning like a normal subprogram call. In this way, I was able to interface the RPlot Software (commercially available from RSoft, Inc.) without needing additional plotting graphics in the source file INVPW.PC. It should be noted that the RPlot software (written mostly in C) is not a subroutine package, but rather, a separate "stand-alone" plot system that utilizes a full-screen in graphics mode. Also note that Lahey's Windows Library does not support a mouse, so only the < ArrowKey > 's can be used to select menu objects in text windows.

If desired, this program can be executed using MS-Windows (3.0 or higher) in enhanced mode via the DOS compatibility box or by double-clicking the DOS icon; however, the RPlot graphics cannot be entirely rescaled using the present version of RPlot, and will be clipped if resizing the DOS window.

Note that the distributed protected mode executable program (INVPW.EXE) has been bound with the Phar Lap 386|DOS-Extender and is royalty-free to end users. The only additional software that is required to execute INVPW.EXE is the RPlot Graphics Package available from RSoft, Inc. (see Appendix 2 for an ordering form).

Method of Ordering

The source and executable code for program INVPW (less RPlot Software) can be ordered by the open-file report number(s) indicated on the title page. Copies of this report and diskette (described below) can be obtained for a nominal cost (current cost unknown) by contacting:

U.S. Geological Survey Phone: (303) 236-7476
Open-File Services Section FAX: (303) 236-1972
Mail Stop 902
Box 25425, Federal Center
Denver, CO 80225

Floppy Diskette Files

The following files are supplied on a 1.2 Mb (high-density) diskette for this report:

READ.ME --   List of files on this diskette, and any last minute notes.
INVPW.PC --   Complete PC Fortran-77 source file (less RPlot Software).
INVPW.EXE -- Linked and bound protected mode executable program.
                   (Requires the RPlot system from Appendix 2 at run-time).

INVPW.WP -- WordPerfect 5.1 file used to produce this report.
                   (This file can be used to generate additional copies, etc.)

APPRES.DAT -- Apparent resistivity Obs.Data file ($<r>$ type).
PHASE.DAT -- Phase of Surf. Imp. Obs.Data file ($<p>$ type).
BOTH.DAT --   Both App.Res. & Phase Obs.Data file ($<b>$ type).

TESTR.OUT -- Output file from the example problem in this report.
TESTR.PCS -- RPlot control file from the example problem.
TESTR.000 -- RPlot Obs.Data file from the example problem.
TESTR.001 -- RPlot RUN = 1 file from the example problem.
TESTR.002 -- RPlot RUN = 2 file from the example problem.
TESTR.003 -- RPlot RUN = 3 file from the example problem.

WELCOME.PCS -- Welcome screen for INVPW (an RPlot .PCS file).

APPENDIX 2. -- RPlot Software Order Form

Program INVPW cannot function without having the RPlot Graphics Library and executables on the hard disk stored in a suitable subdirectory and in the DOS PATH. The RPlot Graphics (Version 2.00) is available from RSoft, Inc. using the attached RSoft order form. (Permission was granted by RSoft, Inc. to include a current copy of their order form in this report.)

RSoft, Inc., RPlot Graphics Order Form (Version 2.00) starts on the next page:

SYSTEM REQUIREMENTS:

RPlot will run on an IBM PC, XT, AT, PS/2 or compatible computer with 256K free RAM, a CGA, EGA, VGA or Hercules video adapter, and MS-DOS version 3.0 or higher. The software supports Epson compatible dot matrix printers, HP LaserJet/DeskJet and compatible printers, as well as PostScript printers. Note that an ASCII text editor must be used in conjunction with this program (e.g. the line editor EDLIN which is supplied with DOS, or preferably any screen-oriented text editor). Use of a math coprocessor is recommended.

GUARANTEE AND SUPPORT:

RPlot is guaranteed for 30 days and is 100% refundable. RSoft provides technical support free of charge to any registered user. Users who discover a software error in a particular situation will receive a free updated version as soon as it becomes available.

PRICING:

RPlot is available for only $149.00. For educational institutions, RPlot is discounted to $99.00. Call RSoft for other discounting and site licensing information.

ACKNOWLEDGMENTS:

All product names referred to above are trademarks or registered trademarks of their respective manufactures.

RPlot Order Form

	Ship To:	Bill To:
Name	_____	_____
Affiliation	_____	_____
Address	_____	_____
City,State,Zip	_____	_____
Phone	_____	_____

	Quantity	Price (see above)		Amount	Diskette Size:
Rplot	_____ x	_____	=	_____	☐ 5 ¼ "
Tax (NY residents add appropriate sales tax)				_____	☐ 3 ½ "
Shipping & Handling ($5.00 + $3.00 ea addnl;				_____	
add $2.00 extra for UPS 2nd-day service)					
			TOTAL	_____	

Payment Method:
   ☐ Check or Money Order (made payable to RSoft, Inc.)
   ☐ Purchase Order (recognized institutions only) PO # _____

Note to Purchaser:
   Name _____ How you heard of RPlot _____

Send Order To:
     RSoft™, Inc. ● 345 Riverside Drive ● Suite 2G ● New York, NY 10025
     Phone: (212) 666-0959 ● FAX: (212) 666-3962